Optimum Water Pricing

and

Capacity Expansion

of

Water Supply Systems

By

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A Thesis Submitted for the Degree of
Doctor of Philosophy

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April 1995

Awarded 1995

To my parents Albert and Olwyn Connarty

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Abstract

The water resources capacity expansion problem has been examined. This included examining the sizing, sequencing and timing of future water resources projects as well as determining the optimum water price. A review of previous techniques used to solve the various capacity expansion problems is undertaken. A number of these techniques have been used to solve the various capacity expansion problems in this study. Three case studies encompassing the scope of the various capacity expansion problems have been used to compare the various methods adopted for this thesis.

The Canberra Water Supply System is utilised to examine the sequencing capacity expansion problem. The unit cost and equivalent cost methods are used for this study and a methodology is developed using these methods and various yield evaluation methods are used to estimate the yield of future projects. The equivalent cost method produced the best results in this case.

This method was then used to examine the optimum pricing and capacity expansion problem for the Canberra Water Supply System. In addition the effect of demand management on optimum price and capacity expansion was investigated.

The second case study examines the sizing and sequencing of projects for the South-East Queensland System. This also examines the possibility of increasing the size of projects once they are built as well as the case of not allowing a project to be upsized after its construction. The effect of pricing and demand management were also included within this case study. Four methods including the equivalent cost method, the unit cost method, a integer/linear programming model and a new method called genetic algorithms (GA) were used. The theory of GA is examined as there are inadequacies associated with the other techniques. In this case study, the GA produced the best sizing and sequencing of projects as well as the optimum water price.

The final case study sequences projects for the Perth Water Supply System, however in this case the operating cost of projects is included in the sequencing decision. The GA, equivalent cost and unit cost methods are utilised in this case study. The GA again produces the best results of all the methods used.

Although it was found that the GA method was superior to the other methods utilised, it was found the equivalent cost method was a very useful technique. It produced good solutions to difficult problems in only a handful of calculations. When simpler problems are examined (ie linear growth in demand and only capital cost considered), the equivalent cost method will produce the optimum sequence. In these cases, the equivalent cost method would be the better method as it takes less effort than the GA method to obtain an optimum sequence.

Statement of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to my thesis being made available for loan and photocopying if accepted for the award of the degree.

Signed **Date :**...7/4/95...

Acknowledgments

The author wishes to thank Associate Professor Graeme Dandy for his supervision of the work undertaken in this thesis. His guidance, comments and suggestions have helped enhance the work completed in this thesis. Without his invaluable help this research would have been considerably more difficult.

The author is also grateful for the support and friendship of his fellow postgraduate students. Special thanks must be given to Dr Carolyn Davies for her friendship and many valuable comments during this research and in the preparation of this thesis. Also, the author would like to thank, Laurie Murphy, Holger Maier and Philip Crawley for their comments and friendship over this time.

The help and guidance provided by the lectures and staff of the Departmental of Civil and Environmental Engineering at the University of Adelaide is very much appreciated by the author.

The author would like to acknowledge the support and friendship of his friends during the period of this research. In particular the author wishes to thank Rachel for her love and support.

Finally, the author wishes to thank his parents, Albert and Olwyn Connarty and family, Rhonda, Rosie and Luke, for their love and constant support over the duration of this research.

Chapter 1

Introduction

1.1 The Capacity Expansion Problem

It is the aim of a water supply authority to ensure that an adequate supply of water is always available to satisfy a community's demand for water. The problem facing a water authority is what to do when the projected demand for water is likely to exceed the available supply of water. The traditional solution to this problem is to increase the capacity of the water supply system. This can be achieved by developing a surface water resource, such as a dam or using a groundwater supply. An alternative solution to the problem is to reduce the demand for water. A reduction in demand can be achieved through a number of measures including the use of an efficient water pricing policy, restrictions policies and other voluntary measures. This will have the effect of delaying the need for the expansion of the water supply system and ensuring that an adequate supply of water exists at all times. Therefore, whether the capacity of the system is increased or the demand is reduced, the ultimate aim of the demand being less than the supply capacity will be achieved.

The water authority will try to achieve this objective at a minimum cost. Rather than make a decision every time the demand approaches the supply capacity, it is generally the case that the water authority will evaluate a sequence of future projects for a finite planning period. Traditionally, the water authority will try to obtain a sequence of projects for future expansion which minimises the present value of costs.

The water authority must also consider the price it charges for water. Setting the price for water has implications for revenue raising, however the price can also be used to reduce demand. Consequently, the setting of price will effect the timing and sequencing of future projects and therefore the present value of costs. In practice, the setting of the price for water is generally carried out independently of the sequencing of future projects and thus the best overall solution for the problem may not be obtained.

The actual capacity expansion problem can be defined in many ways. For the water resources case, the traditional definition is to sequence and time various future water resources alternatives. However, another problem is the size of development for each resource. For example, a dam can be any height (within a practical range) or a number of different pumping rates can be selected for groundwater schemes. The capacity expansion problem therefore includes the size, sequence and timing of future water resources projects. This problem can be examined so that the minimum present value of capital costs is obtained. Also, as different alternatives may have different annual operational and maintenance costs, the objective may also incorporate the present value of these costs. If the price of water is included in the problem, then the benefits associated with various price levels should be included in the analysis. Such benefits include the consumer surplus and revenue to the water authority.

1.2 The Objectives and Scope of this Thesis

The objectives of this study are :

1) To evaluate the performance of existing techniques in solving the pricing and capacity expansion problem;
2) To develop a methodology for the optimum water pricing and capacity expansion problem;
3) To investigate the importance of various parameters involved in the pricing and capacity expansion problem;
4) To develop a new technique to solve the pricing and capacity expansion problems examined; and
5) To indicate the parameters that should be considered when examining the water resources planning problem and the suitability of the various methods used to solve the pricing and capacity expansion problem.

The capacity expansion problems examined in this thesis are :

1) The sequencing and timing of water resources projects; and
2) The sizing, sequencing and timing of water resources projects

The inclusion of the operating cost of projects in the first of these problems is examined and the effect of price on these problem is also investigated. For each study, a sensitivity analysis on a number of parameters is undertaken. For the capacity expansion problems where minimisation of present value of capital cost is the objective, the effect of discount rate, demand growth rate and planning period are examined. When operating cost is included, the effect that this has on the sequence of projects is also investigated. For the second problem two situations regarding the sizing of projects were examined. These were that projects could and could not be increased in size, once they have been sequenced. For the case when projects could be increased in size, a sensitivity analysis on the cost which should apply in this case was performed. For the inclusion of price, the manner in which demand varies with price change is considered important. Thus, the sensitivity of the price elasticity of demand will be examined.

A review of previous techniques used to solve the various capacity expansion problems is undertaken. A number of these techniques have been adopted to solve the various capacity expansion problems in this study. Some obvious inadequacies of previous techniques are demonstrated and the need to develop a new method is evident. The theory of Genetic Algorithms (GA) is adopted for this purpose. This theory has not been previously applied to the water resources capacity expansion problem, although it has been used to solve other combinatorial problems. It is demonstrated that GAs can be adapted successfully to the capacity expansion and pricing problem. In addition, because GA theory uses pay-off information, it is considered that objectives, other than the economic objective could be incorporated within the GA technique. Such objectives may be social or environmental. Thus, the GA should have the ability to solve the water resources capacity expansion problem in a more complete and successful manner than existing techniques.

1.3 Outline of Thesis

The following description outlines the contents of each of the chapters within this thesis.

Chapter 2 discusses the previous literature related to the capacity expansion problem as well as the studies which cover the factors of pricing policy and demand functions. This includes the methods used and the problems they are applied to. The problems previously examined are not limited to the water resources field. The pricing studies generally examine the most effective pricing policy and the various benefits achieved with different policies. While the demand studies investigate the values for the price elasticity of demand for different case studies.

Chapter 3 outlines the basic methodology used in the thesis. This includes an outline of the present value technique and how pricing and demand management are included in the studies. The sequencing methods used in the thesis are defined and a number of yield evaluation methods are presented which will be applied to the Canberra case study in Chapter 4.

Chapter 4 uses some of the techniques presented in Chapter 3 to sequence projects for the Canberra Water Supply System. The sequencing and timing of projects in the Canberra System involves the evaluation of the yield of the existing system and that of future projects. The unit cost and equivalent cost sequencing methods are then used to sequence projects. The optimum price is also determined for this problem and the effects of different levels of demand management on optimum price, sequencing and timing are investigated.

Chapter 5 introduces the theory behind genetic algorithms (GA) and presents various adaptations to traditional GA theory to enable the capacity expansion problem to be modelled. These adaptations include changes in the coding of the GA, an examination of different crossover and mutation operators and the use of a new selection procedure. A brief summary of the previous problems examined by GAs and studies which examine the reason for the success of the traditional GA theory and variations to this theory, is presented.

Chapter 6 applies the GA theory developed in Chapter 5 along with previous methods presented in Chapter 3 to the sizing, sequencing and timing of projects for the South-East Queensland System. A brief analysis of the value of the GA parameters and GA model to be used is performed in this chapter. Apart from the sizing question being addressed, this study also examines the possibility of projects being increased in size once they have been built. A study is carried out on the effects of the values of discount rate, demand growth rate and cost of increasing the size of projects. The optimum price and effect of demand management is also investigated in this case study.

Chapter 7 uses GA theory to find the optimum sequence of projects when their operating cost is included in the analysis. The case study of the Perth Water Supply System is used in this chapter. The unit cost and equivalent cost methods presented in Chapter 3 are also applied in this case. In addition, an examination of whether it is beneficial to break up projects into smaller groups based on operating cost is performed.

Chapter 8 is a sensitivity analysis of the GA. This is performed to improve the GA models used in Chapters 6 and 7. This involves the examination of various GA models for three problems taken from the previous chapters. The effect of various values of probability of mutation and crossover are examined, as is the population size, the selection procedure and the coding structure in an attempt to find the best GA model.

Chapter 9 summarises the conclusions of the thesis. These incorporate the effect of the various parameters involved in the problems, the best sequencing methods for various problems and the best model parameters for the GA. A conclusion is also given on the appropriateness of the yield evaluation models used for the Canberra case study. Finally, possible future extensions to the work undertaken in this study are presented.

Chapter 2

Literature Review

2.1 Introduction

The following review examines the pricing and capacity expansion problem as investigated by previous researchers. This review has been divided into a number of sections in order to give a clear and easy-to-follow description of various aspects of the problem. The first sections include the studies which specifically examine the capacity expansion problem. The definition of capacity expansion as addressed here incorporates studies which examine the size of capacity expansions, the sequence of capacity expansion as well as the joint sizing and sequencing problem. In addition, the operation of the system will be examined separately in relation to the various definitions of capacity expansion. Of particular interest in these studies is the method used to solve the problem and the form of the objective function used.

Following this, the effect of price on demand will be investigated. Of particular interest in this section is the value of the price elasticity of demand. The price elasticity of demand is evaluated generally as part of studies which present demand models. The demand models are developed with econometric methods using time series and cross-sectional data. In addition, survey methods have been utilised as part of the evaluation of demand and price elasticity. Apart from price elasticity, estimates of income and climatic elasticities have also been determined in some studies. The most common climatic variables are rainfall, evapotranspiration, temperature and moisture deficit.

A brief review of the techniques utilised in demand management is then presented. This includes the effectiveness of various methods by themselves and in conjunction with each other in reducing demand. The primary demand management techniques are publicity and education campaigns, restriction policies, water efficient device retrofit and pricing structure. The reason for using demand management is that it can cause a delay in system augmentation which results in a lowering of costs.

The incorporation of price into the capacity expansion model is then examined. This combines the theories of both the capacity expansion problem and the pricing problem. In particular the usefulness and benefits associated with various pricing structures in providing more efficient capacity expansion policies is illustrated. The pricing policies examined include marginal and average cost pricing and these create different levels of benefits. In addition, the use of demand management techniques in conjunction with pricing and the capacity expansion decision is presented.

The review concludes by summarising the techniques used to solve the problems examined and highlighting the parameters of importance and where applicable, the expected range of values for these parameters.

2.2 Capacity Expansion

This section consists of a review of previous techniques used to provide a solution to the capacity expansion problem. The capacity expansion problem includes : (i) Determining the optimum time sequence of a set of projects with known supply capacities and costs, so as to meet projected demands over a planning period ; and (2) Determining the size and time sequence of projects with known cost versus supply capacity information, so as to meet projected demands over a planning period.

The methods used to solve the capacity expansion problem are optimisation, simulation and heuristics. The optimisation techniques used include dynamic, non-linear and linear programming. More information will be given on the techniques used in solving the problem as they are discussed in the following sections.

The primary objective of such problems is the minimisation of system cost. The cost can include capital cost, operating cost and flood damage cost among others. The only change to the objective occurs when benefits of capacity expansion are included in the analysis. For the water resources problem this may be due to the sale of water to consumers, consumer surplus, the value of crops produced using the supplied water or recreational benefits. For the capacity expansion problem discussed below, only Higle and Corrado (1992) use water benefits in their study and therefore have the objective of maximisation of net benefits. For the rest of the studies discussed, the objective will be the minimisation of costs.

2.2.1 Sizing the Capacity Expansions

A method used for capacity expansion is to find the optimum size of the expansion and using this size on a continuing basis. This is suitable for industries and facilities where fixed sized increments can be added easily. In water resources planning this may be the case for pipelines and water treatment plants but is rarely the case for reservoir expansion where the sizing of a particular reservoir is specific to the site of that reservoir. The sizing problem can be specified for linear or non-linear growth in demand (ie. usually exponential). The linear case is the easier of the two as once the optimum size is found, increments of this size will be built continually one after the other. However, for the non-linear demand case the optimum size changes as the demand changes.

The general theory behind sizing the capacity expansion is straightforward, particularly for linear demand growth. The theory for the linear case is presented by Manne (1961) and is illustrated in Figure 2.1.

In Figure 2.1 x is the expansion increment and D_0 and t_0 represent the initial demand and time where demand equals supply, respectively. Manne utilised a power cost function which exhibits economies of scale and used present value theory and discount rate in the study.

Manne showed that the higher the discount rate, the smaller the optimum expansion interval (x) for any given value for the economies of scale. Also, for increasing returns to scale, the optimum expansion interval increased for any given value of discount rate. It was also shown, that in general, for a particular cost function (C(x) given in Eq. 2.1 below), the optimum expansion interval could vary significantly but the value of the cost function would only change by a few percent.

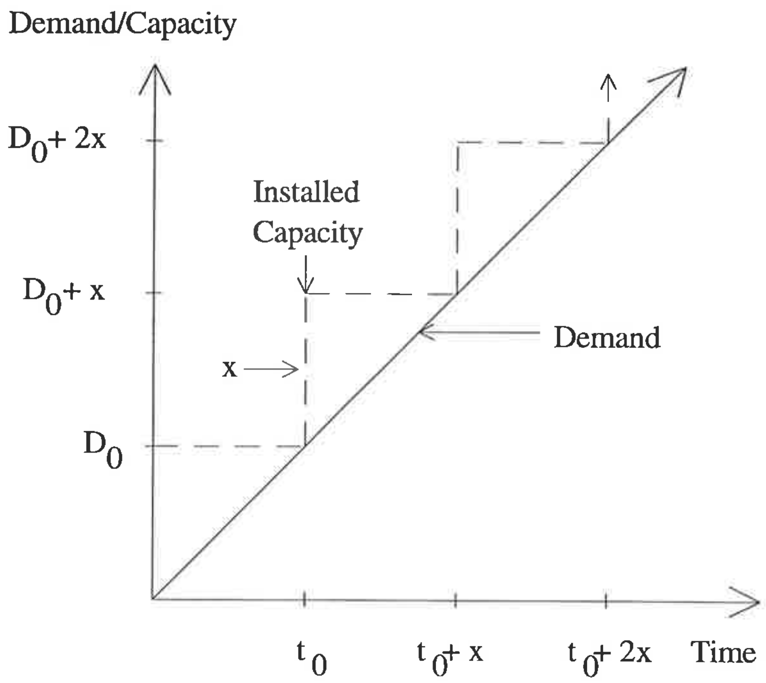

Figure 2.1 Growth of Demand and Capacity Over Time (Manne 1961)

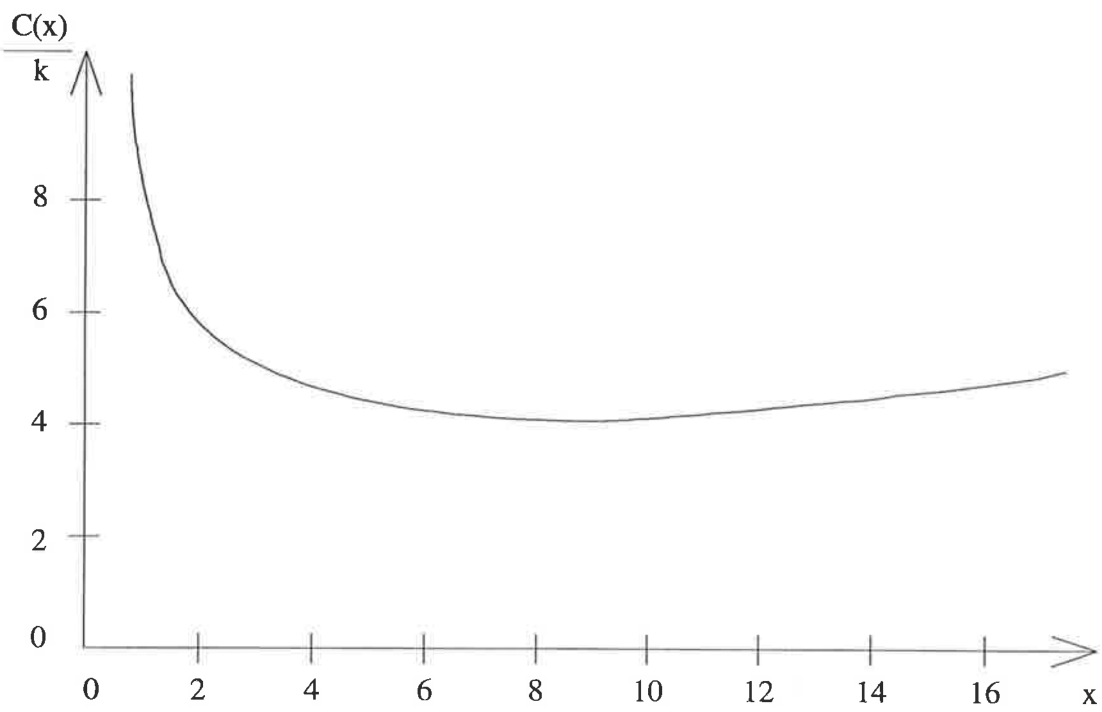

Figure 2.2 Cost vs Installation Size (Manne 1961)(r = 0.15, a = 0.50)

$$C(x) = kx^a + \exp^{-rx}C(x) \qquad (2.1)$$

where C(x) = the discounted future costs, r = discount rate, x = capacity increment size, a = economies of scale factor and k = a constant.

A typical relationship between cost and installation size is illustrated in Figure 2.2.

Manne (1961) showed that the optimal size of expansion, x, can be found by solving the following implicit equation:

$$a = \frac{rx}{\exp^{rx} - 1} \qquad (2.2)$$

Manne expanded on this theory by examining stochastic growth in demand, as well as the possibility of backlog in demand with an associated penalty cost. The theory of Manne (1961) can be applied to the water resources planning problem although backlogs and their associated cost may be difficult to define. Scarato (1969) has applied the theory to the water pipelines and water treatment plant capacity expansion problem. Scarato's (1969) findings were consistent with Manne's regarding economies of scale and discount rate and their subsequent effect on expansion intervals. In addition to this it was found that the optimum capacity expansion size occurred when trade-offs are made between economies of scale and efficient utilisation of capacity. Therefore the components (ie. pipelines and treatment plants) should have excess capacity when built to cater for demand over a specific period.

The conclusion on the efficient utilisation of capacity will be illustrated and used to explain particular pricing policies in studies involving price and capacity expansion (Dandy et al. 1984, 1985) which will be discussed in later sections of this review.

Another factor which may be examined as part of the capacity expansion problem is the inclusion of imports. The concept of imports is not generally applicable in the water resources planning, although backlogs in demand are a similar concept. However, imports can be used to satisfy demand for a short time in the case of extreme drought. The cost of importing water however is considerable, which is the reason why imports are not considered in the planning stage. Rather imports can be included when the problem of capacity expansion has numerous demand points for a product and a number of production centres. Such a problem was examined by Erlenkotter (1967) using the same concepts previously used by Manne (1961). With the inclusion of imports there is an associated penalty cost for transporting the product from a distant source. It may be noticed that this is similar to how Manne (1961) included backlogs of demand in his study. In fact Erlenkotter (1967) refers to the time that imports supply demand, as the backlog level. Erlenkotter found that as the penalty factor increased the optimum capacity increment and backlog increment increased, however, the difference between them decreased. In addition, the relationship between discount rate, and optimum cycle time as well as the economies of scale and optimum cycle time was illustrated for various fixed values of the penalty factor. The result of the study was the development of an expression for determining a lower bound for the optimum cycle expansion. This turns out to be the minimum admissible size to be competitive with the imported product.

The change in future demand from a linear to non-linear curve will cause a change in the sizing capacity expansion problem. This was examined by McDowell (1960) and Srinivasan (1967). For both studies the demand was assumed to be increasing exponentially with time. Therefore if the installation capacities (ie. the value of x in Figure 2.1) were to be the same for the entire planning period, the time which each one satisfies demand will decrease exponentially with time. The difference between the two studies is the cost function assumed. McDowell (1960) assumes the installation cost consists of a unit cost plus fixed cost whereas Srinivasan (1967) assumes that economies of scale exist and uses a power cost function similar to Equation 2.1. In addition, Srinivasan concentrates on the optimum cycle time rather than the optimum time capacity expansions last.

McDowell's results indicate that the optimum time that capacity expansions last decreases as the time period grows. On the other hand Srinivasan (1967) found for a cyclic optimum time period the capacity size increases exponentially. Both studies indicate that as the discount rate increased the optimum time an expansion lasts decreases.

In regard to changing the cost function it was that shown that as the economies of scale increased the optimum cycle time decreased (Srinivasan, 1967) and as the fixed component of installation cost (McDowell, 1960) increases the optimum time expansion increased.

As far as the economic planning period is concerned, McDowell (1960) found that as the discount rate and demand growth rate increase, so will the economic planning period.

If the demand growth rate was varied it was found that as the demand growth rate increased the economic planning size of facilities decreased. This is the same trend as for the discount rate but the demand growth rate has a more significant effect (McDowell, 1960). Srinivasan (1967) did not conclude or illustrate the effect of demand growth on optimum cycle time but rather determined that, if the growth rate approaches zero, the optimum cycle time for the exponential demand growth approaches the optimum time for the linear demand growth.

McDowell concluded his study by examining the same problem with linear growth. McDowell's results were similar to those of Manne (1961) and in fact produced a similar equation to Equation 2.2. The major differences related to the cost function used and the situations examined. It was concluded by McDowell that for more complex demand cases (ie. particularly exponential demand case), the lower the demand growth, the longer the optimal time and the higher the demand growth, the shorter the optimal time of expansion.

Apart from the above findings Srinivasan (1967) also produced two inequalities which identify upper and lower bounds for the optimum cycle time. These inequalities are dependent only on the economies of scale present, discount rate and the demand growth rate.

Another approach to the sizing of future reservoirs for the capacity expansion problem was provided by Higle and Corrado (1992). The approach adopted is different to the above methods as it considers the profit from water sales as well as the cost of the capacity expansion. The cost of capacity expansion in relation to actual capacity installed is not specified and demand functions are discussed rather than specifically included in the analysis. The result is a rule for optimal capacity expansion independent of future demand which is somewhat surprising. This rule states that if the income derived from an expansion was not at least equal to the uniform cost rate ($rC(x)$) then the expansion is not economically justifiable. Thus the rule means, if the profit raised from increasing the size of the possible facility is not greater than the cost of the increased size of facility then the greater size should not be built. Higle and Corrado (1992) suggest this rule be followed unless non economic reasons prevail to warrant the expansion. The study also briefly illustrates the use of imports to defer the capacity expansion decision. This concept was utilised previously by Erlenkotter (1967).

One concept which was encountered in the literature on capacity expansion was not only the expansion of capacity but also the contraction. Such a concept may not apply to water resources planning, but it could apply to the management of telephone systems and in the allocation of resources for the armed forces. Rocklin et al, (1984) investigated this concept using a dynamic programming model and assumed stochastic growth in demand rather than the deterministic demand examined in previous studies. The study also allows shortfalls to occur although like previous studies (Erlenkotter, 1967, Higgle and Corrado 1992, etc.) using a similar concept, a penalty cost is applied. The aim of the study was to find the optimal policy for capacity expansion/contraction which, includes the size of expansion/contraction, in order to minimise cost.

2.2.2 Sequencing Capacity Expansion

The optimum sequencing of capacity expansion will mainly encompass those situations where the size of different facilities are predetermined and sequenced, rather than the establishment of the optimum size and sequencing of facilities. Studies which evaluate the optimum size as well as sequence will be examined in the next section. The optimum sequencing problem can occur where capacity expansion is not a variable but rather the effective use of facilities is of importance. Problems where the effectiveness of a facility or variable is investigated are the job scheduling problem and the travelling salesman problem (TSP). Held and Karp (1962) investigated a sequencing procedure to solve these problems, as well as an assembly line balancing problem. Of interest is the use of binary state variables to schedule facilities for the job scheduling problem. Erlenkotter (1973a) adopts a similar methodology. The objective of the study was to minimise the cost for these problems using a dynamic programming procedure. The dynamic programming techniques produced for the various problems are successful for small examples but as the number of state variables increases, problems with complexity occur. In order to solve this, a technique called "successive approximation", which uses partitioning of ordered sets, was developed to obtain optimum schedules for large problems more efficiently.

The use of dynamic programming is predominant prior to 1980 for the sequencing of capacity expansion. Butcher et al (1969) develops a simple dynamic programming model after establishing that the ordering of projects using unit cost from lowest to highest value, was in fact an unsatisfactory method. The reason why this method does not work is that the discount rate and demand growth rate are not included in the process and these factors influence the optimum sequence. These factors are included in the model developed by Butcher et al. The dynamic programming model uses the quantity supplied as the decision variable and evaluates the cost of expansion of projects to satisfy the level of quantity supplied. This method examines all supply levels before exhaustion of the previous project.

Unlike Butcher et al. (1969), Morin and Esogbue (1971) recognised that due to discounting, projects are cheaper if they are expanded as late as possible without violating the water demand requirements. Therefore a project is only expanded when the previous project is exhausted. Thus all the supply levels between the exhausted capacity levels do not need to be included and a more efficient algorithm is produced. The methodology of Butcher et al, (1969) and Morin and Esogbue (1971) was shown by Erlenkotter (1973a) not to achieve the optimal sequence of projects. The reason stems from an assumption in the previous methods regarding the path to an optimal solution. An example is given which shows that the assumption is incorrect. Erlenkotter (1973a) then presents a dynamic programming model derived from previous models. The model utilises binary state variables to represent project expansion in a similar manner to the model of Held and Karp (1962) for job scheduling.

In deriving the sequencing model, Erlenkotter established two simple rules to simplify the sequencing problem. The first was called the " timing dominance property", where if two projects i and j have the following properties :

$$Z_i > Z_j \text{ and } C_i < C_j \tag{2.3}$$

where C_i and Z_i are the cost and yield of project i respectively, then project i will precede project j. A similar theorem was produced by Morin and Esogbue (1974) as a result of papers by Morin and Esogbue (1971) and Butcher et al. (1969) and states "..... for projects with either equal capacities or costs (or both) the project with the lowest ratio of cost to capacity will be sequenced first". As can be seen the only variation to (2.3) would be one of the inequality signs would be changed to an equality.

The second rule developed in Erlenkotter (1973a) was the establishment of an approximate solution approach. Erlenkotter developed the following formula for sequencing projects for a linear growth in demand:

$$\alpha_i(Z) = \frac{rC_i}{1 - \exp^{-\left(\frac{rZ_i}{\delta}\right)}} \tag{2.4}$$

where $\alpha_i(Z)$ is the equivalent cost per period for project i at capacity level Z, r is the discount rate, C_i is the cost of project i, Z_i is the yield of project i and δ is the demand growth rate (for the linear case). To convert the equation to the general (non-linear) case, replace:

$$\frac{Z_i}{\delta} \text{ by } \Delta_i(Z)$$

where $\Delta_i(Z)$ is the time interval until the next expansion is required following project i at capacity level Z.

The sequence is then found by arranging the projects in non-decreasing order of equivalent cost per period (α). In the case of linear demand, this simple procedure will provide the optimum sequence. This becomes particularly useful when you consider that, Butcher et al. (1969) established that the factors of discount rate and demand growth rate have a considerable effect on the sequencing of projects and therefore should be included in the sequencing decision. Thus, in general, the approximate method is expected to provide a better sequence of projects (ie. lower discounted cost) than the unit cost method. Finally, Erlenkotter stated that in general "... the approximate method could be potentially useful as a screening device for selecting a manageable set of projects for optimisation by dynamic programming".

Tsou et al. (1973) produced a search technique which is similar to that of Erlenkotter (1973a). It uses a variable termed the R-index. For all intents and purposes they are basically the same except the R-index utilises discrete timing intervals rather than continuous timing intervals for expansion. The R-index was defined by Tsou et al, (1973) as:

$$R_n(x) = \frac{C_n}{1-(1+r)^{t(x)-t(x+O_n)}} \tag{2.5}$$

where $R_n(x)$ = the R-index, C_n = the cost of project n, O_n = the output or yield of project i, $t(x)$ - $t(x + O_n)$ = the period for which project n will satisfy demand and r = the discount rate.

The optimum sequence is obtained in a similar manner as the equivalent cost method. Tsou et al. (1973) went a step further by developing a sensitivity analysis. Therefore if there was some doubt regarding the cost estimate used to evaluate the R-index, then the amount that the cost could vary before a change in sequence occurred could be determined. This sensitivity analysis can be used to select a more manageable set of projects on which more detailed cost analysis can be carried out.

Erlenkotter (1973b) examined the sequencing problem for interdependent hydro-electric projects. The previous methodology (Erlenkotter, 1973a) was altered to include interdependences between projects in technological and market areas. Interdependences are included by factoring up the generating capacity of the downstream plant when an upstream reservoir is added to the system. The method was compared to the unit cost method of sequencing. The example used examined interdependencies between projects assuming a non-decreasing demand projection. The dynamic programming method produced a sequence which reduced the discounted investment costs by 0.72 % compared to the sequence found by the unit cost method. This may appear to be small however for the example considered the absolute cost saving was $ 2.84 million which is quite substantial. This particular result substantiates the conclusions of Butcher et al. (1969) that the unit cost method does not give an optimum sequence of projects.

Morin (1973a, b) developed the imbedded state space dynamic programming algorithm which is similar to that developed by Morin and Esogbue (1971). However, unlike the previous algorithm which was shown by Erlenkotter (1973a) not to always find the optimum solution, the method presented here takes into consideration the special case which produced the non optimal results in the previous model. As part of the development of the new algorithm two situations were highlighted (Morin 1973a) where the algorithm used in Butcher et al (1969) will not produce an optimal solution. It was concluded that the error in the traditional approach is that it ignores the combinatorial nature of the problem. The imbedded state space dynamic programming algorithm exploits this combinatorial nature to find the optimum solution always. The method defines a series of state spaces which correspond to the number of projects sequenced. At each state space there will be a number of possible capacity levels which are simply the addition of the project capacities

The development of the algorithm in Morin (1973a) was for a one-dimensional sequencing or scheduling problem. The theory is extended in Morin (1973b) to incorporate the multi-dimensional problem. Thus not only is residential demand examined but irrigation, hydro-electric and recreational demands are also included. It is envisaged that such a model will enable real world problems to be modelled. The model was then applied to two situations and it was found that the optimum schedule and its discounted cost were sensitive to demand requirements. In addition, the discounted cost was found to be sensitive to the discount rate but the schedule was not.

Erlenkotter and Rodgers (1977) also utilise a dynamic programming approach for this problem. Their methodology assumes that projects are competitive but the timing decision of a project is independent of other projects. The model developed is an adapted and simplified version of models produced previously by the authors. The model presented incorporates a composite operating cost functions for projects. The composite operating cost functions is the shipment costs of a product to a demand area. The initial formulation was relaxed by removing some of the constraints in an effort to reduce computational effort while ensuring that the optimum sequence and timing decisions is still produced.

The problem which may be experienced with papers utilising dynamic programming is that when the problem becomes large they suffer dimensionality problems. One way to get around this is to devise a heuristic approach similar to Erlenkotter (1973a) and Tsou et al. (1973). In addition, an exclusion test similar to the time dominance theorem of Erlenkotter (1973a) or the theorem of Morin and Esogbue (1974), could be used to remove inferior projects from the set. Then the optimum sequence for the smaller project set could be found using dynamic programming. The alternative is to examine methods which are not as prone to dimensionality problems as dynamic programming.

A methodology using a Lagrangian relaxation and branch and bound technique was shown by Neebe and Rao (1983) not to experience the dimensionality problems of dynamic programming. The methodology utilises binary variables to define capacity expansion in a period. As part of the model a heuristic approach similar to Tsou and Mitten (1973) was developed to provide an upper bound for the procedure and to prune the branch and bound tree. The methodology was tested on various size problems and found to be successful in examining medium sized problems in a reasonable time. The theory is extended by the authors so that no expansion of a project occurs until the existing capacity is exhausted. The timing of projects is carried out over a continuous time horizon (Neebe and Rao, 1986). The methodology is changed to include integer capacity expansions and a demand function which passes through the system capacity points. Again the new technique is assessed by using a heuristic method (which was developed as a result of a private communication with Erlenkotter in 1985). The conclusions regarding size and solution time are the same as the earlier paper (Neebe and Rao, 1983). However, the developed heuristic produced good results, regardless the size of problem.

The use of binary variables is not restricted to any particular solution technique. Mdoda et al. (1988) also utilises binary variables (0 = not built, 1 = built) but adopts a mixed integer programming method as a solution technique. The capacity expansion decision in this case is whether to build a hydro-electric project or to import electricity from an exterior supplier. The study specifically examines the electricity demand in the Transkei, South Africa. The aim is to minimise capital and import cost, so that the electricity demands for the period 1991 to 2000 can be meet.

Another technique used is that of multicriteria linear programming. This is utilised by Urbaniak (1988) to determine the layout and sequence of a water supply and wastewater treatment system. The model presented includes water intakes, distribution network, recycling and discharging treatment plants. The model also considers water shortfall by including a penalty function (cost) for not supplying the required water or for violation of any of the constraints. The problem is solved with the aid of a parametric linear programming method. The method can be used to model varying criteria at the same time and can efficiently provide solutions to problems of realistic size.

2.2.3 Sizing and Sequencing of Capacity Expansion

The sizing and sequencing problem has been examined by separating the problem into the sizing of the projects and then the sequencing of the projects or by examining the combined problem. The sizing question can be examined by allowing continuous sizing to occur (Erlenkotter, 1976, Fong and Srinivasan 1981a, b and 1986) or by specifying a set of fixed sized increments (Dale, 1966, Erlenkotter, 1975b, Bean and Smith, 1985 and Nakashima et al., 1986). Fixed sized project sets may be used either to reduce the complexity of the problem or because there are only specified commercial sizes which can be used (ie. pipe diameters).

Nakashima et al. (1986) separate the problem into separate sizing and sequencing problems. They obtain the capacity and layout of water sources and transmission facilities. The capacity and layout of the facilities is determined by a multilevel solver. Here an initial solution to the layout problem is generated by the simplex method or the out-of-kilter algorithm (OKA developed by Fulkerson 1961) and the objective function is linearised and a series of linear problems are solved. The second level sizes the pipes and pumping facilities using linear programming. As part of this stage only a selected set of pipe diameters are tested. To find the optimum size a series of runs are performed using different sets of pipe diameters. Due to linearisation of the objective function an optimum solution to the level one problem cannot be guaranteed. In addition, the use of discrete pipe diameters may also result in non-optimal solutions. However, as previously mentioned such a step is justified, as in a real world problem the size of pipes are usually at discrete values. Another reason why such a method would produce non-optimal results, is the formulation and solving of the problem in two steps. The reason is that some of the possible combinations will be lost in the process and these lost alternatives may include the optimum (Erlenkotter, 1974).

The way to overcome this non-optimality problem is to consider the sizing and sequencing problem together. This can be achieved by using continuous sizing or discrete sizing of projects. In regard to the discrete sizing problem the process is to time the sizes of projects available throughout the planning period. The result is then a sequence or schedule of alternative sized facilities.

The simple theory is demonstrated by Dale (1966) who uses dynamic programming to schedule different sized facilities at a particular site. This study is particularly aimed at finding the expansion size of a hydro-electric project at one site and includes the benefits of excess supply and shortfalls in supply. The process used is similar to Butcher et al. (1969) but due to the particular problem being examined here, the problems of non-optimality (Erlenkotter, 1973a) experienced by the Butcher et al. (1969) method are not expected to occur.

The use of discrete sized projects at a site can be expanded to consider multiple sites (Erlenkotter, 1975b). If the reservoir problem is considered, the discrete sizes would vary between sites but for a product supply and production problem the sizes may be the same for all sites. The latter problem is examined by Erlenkotter (1975b). The basic approach used is an incomplete dynamic programming procedure involving an iterative technique. The process consists of the establishment of an initial expansion policy which is continually changed until no further improvement is found. In addition to this process, the study produces an approximate method similar to that of Erlenkotter (1973a) (ie. Eq. 2.4). The only change between the two methods is the addition of the transportation and operating cost to the capital cost of expansion (ie. added to rC_i in Eq 2.4) for this situation. Both methods were found to be superior to the SLOT heuristic (Manne ,1967) and dynamic programming by sub regions for two problems based on the nitrogenous fertiliser industry of India. The approximate method was found to be more efficient in time but its results were inferior than the incomplete dynamic programming procedure.

An iterative approach similar to Erlenkotter (1975b) is used in a series of studies by Fong and Srinivasan (1981a, b and 1986). The method varies in that a heuristic approach is used to solve the problem rather than dynamic programming and the sizing of a facility is continuous. The use of a heuristic approach results in a more flexible model than a dynamic programming model as there is no limit on the size of facility. The studies use a mixed integer programming formulation which includes multiple markets for the product, multiple producing regions and tries to satisfies demand in each market with capacity expansion and transportation from the producing regions at discrete times. The process works by obtaining an initial policy solution which the heuristic procedure adjusts by the swapping of capacity expansion between regions. The swapping of capacity continues until there is no further improvement in the solution and the minimum cost is found.

The variation between the studies relates to the cost function assumed and the level of complexity of the heuristic procedure. The initial study (Fong and Srinivasan, 1981b) assumes a cost function which exhibits economies of scale (ie. a power cost function) and the heuristic swaps capacity expansions between two regions. The follow up study (Fong and Srinivasan, 1981b) changes the cost function to include a fixed cost component as well as a linear component. As a result the heuristic is altered to reflect this change in cost function. In addition, a new initial solution method is introduced. The final paper (Fong and Srinivasan, 1986) allows the cost function to take any form and introduces imports as a means of satisfying demand. A new heuristic is developed called the simultaneous spatial-temporal move algorithm (SSTM) which allows a simultaneous move of capacity between regions and in time. The move in time is restricted however to reduce the time of computation but due to this restriction a small increase in the minimum system cost may occur.

The success of the studies and methodology produced was examined in each study. The initial heuristic (Fong and Srinivasan, 1981a) was found to outperform the simplex method in solving the formulation produced. This heuristic is compared in the latter studies to the improved heuristics. In addition, the latter studies (Fong and Srinivasan 1981b and 1986) utilise methods from the literature namely Hung-Rikker (1974) and approximate and incomplete dynamic programming (Erlenkotter, 1975b) and examples based on the nitrogenous fertiliser industry of India to test the heuristic developed. Both studies found the heuristics produced provided better solutions than the past methods utilised. In addition, the final study utilised an example with a concave cost function and found the SSTM algorithm produced better results than Jacobsen (1977) and Erlenkotter (1975b) methods. However, the SSTM algorithm was considerable slower than the Jacobsen (1977) method but marginally faster than the Erlenkotter (1975b) method. In regard to the heuristics, a comparison can not always be made between all of them, as all but the SSTM heuristic relate to specific cost functions. However, when a comparison is made between the various heuristics for specific cases, the SSTM heuristic produces the best solutions.

The methodology of allowing the size of capacity expansion to be a continuous variable was also adopted by Erlenkotter (1976). As is the case for other work by Erlenkotter, a dynamic programming procedure is utilised. The model included the possibilities of backlogs in demand (and associated penalty costs) and assumed linear demand and a fixed charge cost function for reservoir costing. It was shown by the study that a lengthy dynamic programming procedure is required to solve this problem. The reason is that the scale decision is dependent on future cost and therefore future scale and sequencing. Alternatively, a static procedure could be used (ie. the scale decision is evaluated separately from the sequencing decision) however, it is doubtful whether good project scales would be identified. The alternative could be to use a number of discrete levels of scale (Dale, 1966, Erlenkotter, 1975b, etc) but this would greatly increase the computational effort required to solve the sequencing problem.

The above studies have concentrated on the sizing and sequencing of projects for a specified time interval. Another way to examine the capacity expansion problem is to investigate the optimum planning period in which the first expansion is always optimal (Bean and Smith, 1985). Although this studies major concern is finding the optimum planning period and not the sequence or size of projects, it must consider these factors in its analysis. The study defines a planning period called the strong forecast horizon where the first expansion is always optimum. However, this period relies on knowing the forecast demand which the planner may not have or may only be approximate. Therefore an alternative planning period termed the ε-optimal forecast horizon is defined. This forecast horizon is independent of the demand function and is dependent on the cost of the project, required error in cost (ε) and the discount rate. It was found that using the theory developed in the study there was a considerable variation in forecast horizon and thus number of facilities employed, for only slight errors in cost.

2.2.4 Sizing, Sequencing and Operation of a Reservoir System

To obtain a solution to the sizing, sequencing and operation problem it is likely that rather than using one extensive model, a solution technique would involve multiple methods. A possible way to study the problem with a single model would be through undertaking a sensitivity analysis for the system in question. This may involve varying facility expansion size, stream hydrology and demand as well as other economic factors such as cost and discount rate. Such a technique is utilised by Manoel and Schonfeldt (1977). They developed a dynamic programming model with a stochastic loop for the problem of expanding the Adelaide Water Supply System. The stochastic loop is a process where by the catchment inflows, which have associated probabilities of occurring, are used in an iterative loop to provide the optimum operation policy and the corresponding present worth benefit. The present worth benefit is then used in the dynamic programming procedure to evaluate the best augmentation year. The Adelaide System reservoirs are aggregated in order to reduce the complexity of the problem. Although, this is not a direct way of establishing the size, sequence and operation of a system it may be a useful preliminary analysis technique (Manoel and Schonfeldt, 1977). However, the technique cannot guarantee an optimal solution as factors such as using fixed increments for augmentation, the use of aggregation and the use of a sensitivity analysis to obtain a solution will all contribute to the possibility that the solution is non-optimal.

One possible technique for solving the problem is by utilising a combination of methods. This may be achieved by solving the two separate problems of size and operation of a reservoir and the reservoir sequence and scheduling (Becker and Yeh 1974a, b, Braga et al., 1985). In this case the methods utilised are generally optimisation procedures such as dynamic programming or linear programming. Dual dynamic programming models were utilised by Becker and Yeh (1974a). The first model selects the size of a reservoir so that demands are met given a operating policy and reservoir configuration. The size is determined using fixed increments and the cost is assumed to be either a fixed charge cost function or a power cost function. The second model then selects the reservoir(s) to be expanded and their timing to achieve the least cost combination. The technique is applied to the Eel River System which consists of six reservoirs, five of which need to be sized and sequenced. It was found that different planning horizons resulted in different sequences. Becker and Yeh (1974b) exchange the dynamic programming model for sizing and operation of the system with a iterative linear programming model. With this change the decisions are now made at discrete 10 year intervals rather than on a continuous time scale (Becker and Yeh, 1974a). In addition, power generation is included in the model along with water supply. For the Eel River System the changes in the technique and water demand considerations produced a variation in the size and sequence of projects obtained. With the inclusion of power considerations and the use of linear programming, either different reservoirs were expanded or those which were the same were smaller.

A similar model to the dynamic programming model of Becker and Yeh (1974a) for scheduling and sequencing projects was used in conjunction with a simulation model and applied to the Sao Paulo Water Supply System, Brazil (Braga et al., 1985). The simulation model utilises historical streamflow data and rational operating rules to find the optimum operation and size of reservoirs and pumps. The problem involves multiple reservoirs and pump sites and allows multiple sizes of a facility per site. The results of the study indicate that the decision maker will have a further decision of whether to build the minimum cost reservoir size or to build the maximum size of a reservoir in order to increase the reliability of the system.

Alternatively, multiple models can be employed to solve the problem, where the first model sizes and schedules projects and subsequent model(s) determine the optimum operating policy (O'Laoghaire and Himmelblau, 1974, Chaturevedi and Srivastava, 1981 and Martin, 1987).

Such a process is utilised by O'Laoghaire and Himmelblau (1974) where a branch and bound technique (Little's branch and bound) solves the capital budgetary problem (ie. size and sequence) and the OKA obtains the optimum operating policy. The OKA is applied to a linear objective function and is used instead of traditional linear programming as it uses 1/15 to 1/20 of the running time. The OKA uses the primal and the dual of linear programming to produce a more efficient algorithm. These methods were used to overcome the problems with traditional optimisation techniques such as linear, non-linear and dynamic programming. Linear programming requires any non-linear functions in the model to be linearised resulting in approximations and is less efficient than the OKA, non-linear programming require projects to be independent which seldom occurs in a water resources problems and dynamic programming tends to have dimensionality problems for large systems. The study includes allowing three discrete reservoir sizes per site and a sensitivity analysis involving discount rate, demand growth rate, hydrology and cost. This sensitivity analysis showed no change in sequence for the majority of cases but for the case of both low demand and discount rate the sequence of projects varied. It was concluded that a sensitivity analysis can make planning of water systems more efficient and the technique developed was found to be efficient in obtaining an optimum solution.

The optimum operation of a system can also be obtained by using a simulation model. Chaturevedi and Srivastava (1981) use a simulation model for this purpose, in conjunction with a linear programming screening model. The screening model finds the optimum configuration, sizes and multipurpose releases which are then refined by the simulation model. The study includes the benefits and costs of reservoirs, hydroelectric and irrigation projects. The benefits and costs are non-linear functions which are piecewise linearised for solution using linear programming. Due to the nature of these functions, the process cannot guarantee an optimal solution. To achieve an optimum solution, a branch and bound or integer programming procedure would need to be considered rather than linear programming (Erlenkotter, 1974). Despite this, the study illustrated that the linear programming screening model produced realistic and improved designs over conventional methods.

Martin (1987) uses another approach to the same problem. Here a dynamic programming model and two generalised network programming models are used. The process developed is an iterative process between the models. Firstly, the sizing and scheduling of storages is found by dynamic programming (DPSIM-I) using average operating costs and secondly, a network model is used to estimate the true operating costs of the system defined in the first stage. This procedure continues until there is no change in system configuration. Two generalised network programming models are utilised. The first (AL-V) uses four 3 month periods in each year to calculate a more accurate operating cost. If no change in system configuration occurs with the new estimate of operating cost, a second network model is applied. The second network model (SIM-V) provides a more accurate estimate of operating cost as it uses a monthly time step. This cost is then utilised in DPSIM-I. When the system configuration remains the same, the process stops. This procedure is applied to the San Antonio-Guadalupe River System, Texas, for a 40 year planning period split into 10 year intervals. It should be noted that the only sizing decision which occurs is of pipe capacities and not reservoir capacities. The methodology was shown to be an improvement over other sequencing algorithms in analysing the impact of a critical drought period on scheduling policies (Martin, 1987).

The above methods size and sequence the projects and then determine an operating policy for the system. Alternatively, the operating policy is determined for various sizes of facility and then the sequence of various sized projects are determined (Bogle and O'Sullivan, 1979). In this case Bogle and O'Sullivan (1979) present a stochastic dynamic programming procedure to size and sequence the projects. Prior to this a operating transmission matrix and a cost matrix are determined for the different possible sizes of capacity expansion. These matrices are used in the dynamic programming routine so that when the size and sequence is obtained so is the respective operating policy. The result is the timing and sizing of plant facilities (ie. water treatment, pumping, etc.) for every year as well as the operating policy for the schedule produced. Discrete expansion levels were used and shortfall cost was included in the operating policy routine to ensure shortfalls are reduced in the operation of the system. It was found using an example that the time period plays a part in the timing of projects. In addition, the initial storage will not affect the long term project schedule but will contribute a large proportion of the overall cost and any benefits obtained in delaying expenditure (ie. projects) decrease as the discount rate is reduced.

A final procedure to examine the problem is one which uses multiple models which screen the solution set to reduce the problem to a workable size and then sizes, sequences and obtains the operating rules for the system (Jacoby and Loucks, 1972 and Major and Lenton, 1979). Jacoby and Loucks, 1972 utilise optimisation and simulation techniques to solve this problem. First, a static stochastic linear programming model screens all possible solutions, thus reducing the problem solution set. A static simulation model using 50 years of monthly synthetic streamflows and six periods per year then improves the operation of the system. The results are then entered into a dynamic screening model which schedules the new projects and obtains the operation of these and the existing projects in the system. The methodology includes the benefits and costs of recreation, flood control, hydroelectric power generation, water supply in order to obtain maximum system benefits. The study showed for the Delaware River System, the best existing plan gave only 73 % of the benefits found using this methodology. In the linear programming analysis several trail solutions were used to approximate non-linear functions. Separable programming would have been used except at the time of the study such algorithms were not available (Jacoby and Loucks, 1972). The use of trial solutions as well as the screening of projects before the final analysis will result in non-optimal results. However, it is noted by the authors that the aim of the method is not to produce an optimum solution but instead a superior management plan.

The use of a screening model was also utilised by Major and Lenton (1979). The screening model is a mixed-integer programming model which uses deterministic hydrology for three seasons per year. Binary variables (0,1) are included to indicate whether a facility is constructed. The output of the screening model is the best system configuration which maximises net national income. A simulation model then uses 50 years of synthetically generated four-monthly flows to check the reliability of the screening model result and adjusts the size of system components so that a specified reliability is obtained. Finally, the sequencing model sequences the sized projects from the simulation model for four consecutive ten year periods to obtain the maximisation of national income benefits. The methodology is applied to the Rio Colorado Basin which includes irrigation, hydro-electric and import/export requirements but does not examine the consumption of water by consumers. For this problem the screening model produces a number of solutions which vary in the level of irrigation or power requirements utilised. These are refined by the simulation model so that only three possible scenarios are examined in the sequencing model. The result of the study was a three phase development plan based on the output from the models and techniques utilised.

The problem with the above studies is that they all use multiple models to obtain a solution to the sizing, sequencing and operation problem. This can only guarantee a near optimal or good solution as not all possible combinations can be evaluated (Erlenkotter, 1975a). In particular, Erlenkotter (1975a) discussed this problem with reference to Becker and Yeh (1974a). In this case the solution would be non-optimal due to the calculation of size independently of sequence and the way in which interdependencies of projects have been included in the methodology. The first point relates to the problem of not considering all the possible combinations in the solution set and therefore the optimum may be missed. The second relates to the point that future scale decisions are dependent on previous scale decisions of the project and other projects in the system. That is, if a project is expanded at a later date on the same river it will affect the firm water output of an existing downstream reservoir. Erlenkotter (1975a) indicates that the definition of the variables in Becker and Yeh (1974a) will not convey such information. However, as reservoirs are complimentary their joint operation will either achieve a greater value or the same firm water level if operated separately (Becker and Yeh, 1975). A more rigorous analysis would be to extend the methodology of Erlenkotter (1973a) to include the scale decision (Erlenkotter, 1975a and Becker and Yeh, 1975), however such an extension would be limited to small problems due to computational problems. Thus, if a good solution is acceptable, then the method of Becker and Yeh (1974a) could be used, as this has the advantage of lower computational cost and effort (Erlenkotter, 1975a and Becker and Yeh, 1975).

A final approach to the problem is the use of a heuristic technique to determine the size, sequence and operation of a reservoir system. Sniedovich and Nielsen (1983) develop a procedure which uses a heuristic method to transform an optimum stochastic expansion solution to a deterministic policy. The reason for the splitting of the problem was due to the stochastic nature of streamflow records and the deterministic nature of the capacity expansion problem. This separation and transformation means an optimum solution cannot be guaranteed. Therefore, to evaluate the performance of the heuristic and to guarantee a good solution an upper bound is estimated by solving the stochastic case. The method works by determining the stochastic policy, from which two deterministic capacity expansion policies are obtained. These are used in an iterative process to provide a new solution. Once this solution is close to the upper bound the procedure stops. The result of the method is a policy giving the size of a facility at yearly intervals.

It was concluded that the heuristic method gave good results, which were quite close to the upper bound optimum solution (Sniedovich and Nielsen, 1983).

2.2.5 Sizing and Operation of a Reservoir System

The capacity expansion and operation of a system can include a variety of definitions. One is to find the sequence of projects and the operation of the system. Another, is to find the size of a reservoir and the operation of the reservoir in the system. This latter problem can also include the situation of finding the size of a reservoir without giving explicit consideration to the optimum operation of the reservoir. Although, the operation of the reservoir is required to obtain the best size for that reservoir.

The sequencing capacity expansion and operation of a system was examined by Razavian et al (1990). The method developed uses a simulation model to eliminate inferior alternatives from a project set and then uses an optimisation model to determine the best strategy from the remaining projects. The simulation model consists of a water routing procedure and an economic evaluation routine which evaluates the cost and benefits of the strategies after water allocation. The strategies are eliminated from further evaluation if the benefit cost ratio (B/C) is less than 1 and field delivery efficiency to irrigation sites is less than those strategies with B/C greater than 1 and when B/C ratio is low but greater than 1 and the delivery efficiency is not high enough to compensate for the low B/C ratio. The optimisation model is solved by linear programming and produces a tradeoff curve involving economic benefit and varying levels of environmental constraints. The method was used to examine the Platte River System. The economic benefits considered were irrigation, groundwater recharge, flood control and surface water recreation. As part of the study, regression analysis was used to develop a relationship between water loss, project cost and water inflow and an equation to evaluate surface water recreational benefits. The simulation model reduced the possible number of alternatives from 4000 to 1000. It was found that the economic benefits were fairly constant when environmental concerns were of low priority but as priority of environmental consideration approached the maximum level the economic benefits decreased considerably. A sensitivity analysis was performed for selected parameters but it was found for most environmental strategies the optimum development plans were not significantly effected.

The simulation model used above is primarily a screening model. This idea of screening projects from more extensive analysis has been used by Viessman et al. (1975). In this case the screening model utilises both simulation and optimisation techniques. In addition, the study concentrates on obtaining the size rather than the sequence of project as well as the operation of a system. The simulation model is used to produce constraints (ie. flood control) for the optimisation model. The technique utilises linear programming with any non-linear functions being linearised. The capacity of a reservoir consists of dead, active and flood capacity and is determined in conjunction with the operation of the reservoir. Included in the model are flood, recreation and wildlife benefits as well as operation, capital and flood damage costs. The technique was used to screen projects for the Elkhorn River Basin Nebraska.

A simulation model has also been used by Barry et al. (1977) for the sizing and operation problem . In this case the simulation model is a general model for the Upper Condamine River System. The simulation model evaluates possible future options of major dams, diversion channels and retention ponds. In addition, it determines the operation of these alternatives in conjunction with the region's aquifer. A digital modelling technique utilising simultaneous equations was developed to estimate water levels in the aquifer. The extremes of the water level that may be experienced in the aquifer were calculated and used in the simulation of the system.

The concept of linear programming to solve the size, layout and operation problem was used by Houck and Cohon (1978). Unlike Viessman et al. (1975), this study uses two linear programming routines to solve the non-linear problem.. The first linear programming model examines the design layout of the system while the second model deals with the operation of the system. The model is termed a sequential explicitly stochastic linear programming (SESLP) model as the output of one of the linear programs provides input for the other linear programming model. This exchange of output for input between the two models continues until the iteration process achieves the desired convergence. With the use of linear programming some constraints and the objective have to be linearised and discrete streamflows, storages and releases are adopted. Even with these adjustments for a two reservoir problem the methodology was found to be computationally burdensome. The methodology was altered to incorporate the SCORPIO (system coordinated performance-individual operation) method. This allows the individual operation of a reservoir to be examined while allowing the interaction of reservoirs to be explicitly considered. This reduced the problem size and it was concluded that without the SCORPIO method the SESLP model was impractical.

Houck then followed this study with subsequent work on linear decision rules (LDR) for the sizing and operation problem. However, Houck (1979) did not apply the theory of LDR but presented a chance constrained model with multiple linear decision rules for the application. The objective of the model is to minimise capacity with the restrictions placed on the minimum and maximum storage levels and the minimum permissible release. Theses restrictions are used to illustrate the formulation of constraints for the linear program. For each restriction it was found the conditional CDF could be piecewise linearised and solved with the simplex algorithm to find a global optimum. With the formulation of the linear programming constraints it was shown the linear program could be solved with the simplex algorithm to give a global optimum.

This theory was extended by Houck et al. (1980) to include economic efficiency benefits and hydro-electric energy generation as well as water supply reliability. The objective was allowed to remain the same or change to maximise net economic efficiency benefits which is a function of dam capacity and operating policy. Houck and Datta (1981) then compare the use of multiple LDR per season and a single LDR per season. The objective remained minimisation of reservoir capacity. In addition the number of intervals and seasons were also varied for the single and multiple LDR models. The multiple LDR model achieved superior results to the single LDR model and it was found that the more LDR per season the lower the capacities. In addition, the multiple LDR model performed closer to expected performance criteria when a simulation of the system was carried out (Houck and Datta, 1981). All the studies showed that LDR provide a fast and efficient method to obtain size and operation of reservoir systems. However, dimensionality problems are experienced when the size (ie. larger water supply systems) and complexity (ie. hydro-electric benefits included, more seasons, multiple LDR, etc.) of the problem increases (Houck and Datta, 1981 and Houck et al., 1980).

As illustrated earlier the use of screening models can be applied to the capacity expansion and operation problem (Viessman et al., 1975). This is done to reduce the complexity and dimensionality of the problem which may be solved by subsequent models. Similarly, various techniques can be used to identify a series of development plans rather than a specific plan to reduce the complexity of the problem. In addition, a set of solutions give an insight into the system being examined and allows the planner to use imagination and creativity to find the best solution (Chang et al., 1982). Chang et al. (1982) compares the performance of the hop-skip-jump, random generation and a branch and bound/screening techniques in providing a set of solutions within 10% of the optimum construction cost. The problem examined was the design layout of wastewater interceptors and treatment plant for specific wastewater sources. It was concluded that the branch and bound/screening model produced the best results in regard to cost and difference of the solution (Chang et al., 1982).

The remaining problem which can be defined as a capacity expansion and operation problem is that of obtaining reservoir size from operating rules and stream hydrology. One method used to solve this problem is that of linear programming. Two studies which primarily utilise linear programming are Nayak and Arora (1973) and Windsor and Chow (1972). However, one problem experienced with using linear programming for this problem is the linearisation of non-linear constraints and objectives. Nayak and Arora (1973) utilise separable programming while Windsor and Chow (1972) use mixed integer and separable programming to linearise non-linear functions. However, the use of separable programming can lead to non-optimal solutions due to the cost functions being non convex. To obtain a global optimum with separable programming the functions to be linearised must be convex. Otherwise only a local optimum can be guaranteed (Erlenkotter, 1974). Alternative methods for linearisation which could be used to produce an optimal solution are integer programming and branch and bound techniques. The latter of the two has shown encouraging results with this type of problem while integer programming will result in larger computational time requirements (Erlenkotter, 1974).

Of the two techniques Windsor and Chow (1972) present the more extensive model as they include the use of stochastic and historical streamflows, the sizing of reservoirs and inclusion of irrigation and hydro-electric power generation demands. In addition, the objective is the maximisation of system benefits which include such things as irrigation and hydro-electric benefits and costs, reservoir construction costs and recreational benefits. The method however, does not consider consumer water demands or the discounting of benefits and costs. Nayak and Arora (1973) on the other hand examines general water supply and includes flood damage, shortage, operation and maintenance costs and recreational benefits in its minimisation of the systems cost objective. One of their simplifications is that they assume there are only three to four possible sizes per reservoir site for the example considered. They found that the model developed exploited the economies of scale in the example used.

The linear programming technique has also been used by Lall and Miller (1988). In this case a penalty successive linear programming algorithm (developed by Zhang et al., 1985) has been used to maximise net revenue. The method also utilises simulation and a modified sequent peak algorithm to size reservoirs and hydro-electric sites. The complete model is considered a hybrid optimisation/simulation model and incorporates hydro-electric, recreational, irrigation, flood considerations as well as municipal and industrial demand requirements. The method was found to be efficient, however the desired reliabilities needed to be prespecified and simple operational rules adopted.

Linear programming was also incorporated in a intelligent decision support system (REZES) by Savic and Simonovic (1991). REZES incorporates ten mathematical models to solve the problems of reservoir design, real time operation and long term planning. The majority of the ten models utilise linear programming while the other models relying on dynamic programming or other derived algorithms. REZES, identifies the problem, formulates it with the most appropriate mathematical program, helps generate the input for the model and runs and evaluates the performance of the model. REZES obtains a specific solution and identifies the parameters used in the model that change the performance and results of the problem under examination. Of particular interest is the sizing and planning models utilised in REZES. The mathematical model for sizing reservoirs is an improved Rippl procedure (Rippl, 1883 and Simonovic, 1985) while two other mathematical procedures, to determine within-year yields and minimise total reservoir capacity, are based on models presented by Loucks et al. (1981).

The dynamic programming technique was also utilised by Trott and Yeh (1973). The study examines the Eel River System and uses a series of sub problems of low dimensionality to identify the optimum size of reservoirs. The method of solving by sub problems is due to the high dimensionality of the problem. This decomposition will not guarantee a global optimum and only a local optimum may be found. The series of smaller problems are solved by using an initial storage policy to maximise firm water from each reservoir and then using incremental dynamic programming to identify a new storage policy which increases the systems firm water. This process stops when there is a convergence on the firm water contract level. The aim is to maximise the net benefits of the system by finding the maximum firm water level and assuming a price for the firm water. As part of this study the effect of price on reservoir size is investigated. At the initial price no reservoir is sized, at the next price all but two reservoirs are sized to their maximum capacity. Further increases in price results in the reservoir's size increasing until they reach their capacity. At the second and third prices examined, the size of reservoirs for the system were similar to those determined by other studies (Becker and Yeh 1974a, b and Moore and Yeh, 1980). In addition, the examination of price enables the firm water contract level to be obtained for the Eel river system.

2.2.6 Operation of a Reservoir System

Operating rules for a reservoir system can be determined either by optimisation (ie. dynamic and linear programming) or simulation methods. The simulation models tend to be used for the testing of policies (Karamouz and Houck, 1982, Martin, 1983 and Louie et al., 1984) however, they can be used to develop operating policies (Barnes and Chung, 1986). The development of operating rules can also be directly achieved by the use of an optimisation technique. Stedinger et al. (1984) develop five stochastic dynamic programming models (SDP) to determine reservoir operation. The theory for determining operating rules is modified from previous theory to allow forecast flow to be used rather than previous period flows. It was found that losses were less using the forecast flow than previous period flow in the SDP, although the models can become computationally prohibitive with regard to cost as they are rerun every month. It was proposed that either method of determining the operating rules used in an SDP would produce better policies if better hydrological state variables are employed.

The dynamic programming technique can also be used in conjunction with other methods to create operating policies. Karamouz and Houck (1982) use regression analysis and a simulation model to refine and improve the annual and monthly operating rules developed by a dynamic programming model. The dynamic programming model determines the optimal operating rules for a reservoir. These rules are then used in a regression analysis to establish a general operating rule for the reservoir. The general rule is then tested using a simulation procedure to determine the losses in the system because of excess or deficient releases. The general rule developed by the regression analysis assumes a linear relationship between release and storage as well as release and inflow. A more complex relationship could have been used however the linear relationship has been found to be as good or better than the more complex rules (Bhaskar and Whitlach, 1980). In the case of the annual operating rules there was some improvement and for the monthly operating rules there was significant improvement over the rules developed by a previous method (Bhaskar and Whitlach, 1980).

The use of an optimisation model and a simulation model was also utilised by Louie et al. (1984). In this case the optimisation technique is parametric linear programming rather than dynamic programming. The objectives of the model are to ensure adequate water allocation and water quality and to reduce groundwater overdrafts. The methodology proceeds in a step fashion in which one objective at a time is optimised. The simulation model is used for the water quality objective and the influence coefficient method developed by Becker and Yeh (1972) is used to link the optimisation procedure and the simulation procedure. Once all objectives are optimised, a set of payoff tables between the objectives is determined. With these payoff tables, the original multiple objective problem can be converted to a constraint problem and solved using parametric linear programming. The result is a non-inferior solution sets which can be displayed as tradeoff curves between objectives. The best result depending on the priority of an objective can be found by inspection.

A similar technique to Louie et al. (1984) was described by Martin (1983). Here a method is developed which is analogous to a successive linear programming (SLP) technique and utilises two network programming models. This technique produces an operating policy for a multiple reservoir system with hydro-electric power generation as a consideration. The solution technique incorporates a three step procedure. Firstly, a solution is found for the least cost network flow problem by an iterative procedure. A Taylor's series approximation of the non-linear hydro-electric benefits is then performed to establish a benefit for each unit of water released from a particular storage level for each reservoir. This value is then placed into the network to determine the optimal storages and flows for the system to maximise the benefits of the system. This three step technique is incorporated into a water allocation model AL-V (Martin, 1981) and a multireservoir simulation and optimisation model SIM-V (Martin, 1982). The AL-V model solves the deterministic multiperiod operational problem and SIM-V analyses the system operation over a single period. The SIM-V analysis is iterative, as adjustments are made to monthly target storages and benefits and annual firm water requirements until the firm power generation is maximised. The monthly target storages and benefits for the optimal operating policy could also be determined through a detailed analysis of the AL-V model solutions. The technique produced a policy for the Arkansas-White-Red River System, which increased the firm power production of the system when compared to the value found by a previous study (Clauire-Pereira, 1978).

As can be seen in the above techniques, simulation is sometimes used to test an operating policy developed by other techniques. In addition, simulation can be used to develop operating policies. Barnes and Chung (1986) detail a simulation model utilised by the California Department of Water Resources (DWRSIM) to operate their system. The simulation model is adapted from the HEC-3 reservoir analysis model to incorporate specific detail about the California Water Supply. The simulation model uses either a adjusted historical streamflow data set or stochastically generated data to evaluate the yield and average annual delivery. Dynamic planning studies can be performed to evaluate future reservoirs performance but is not capable of sizing the new reservoirs. The study discuss the importance of including legal and institutional (as well as operational and physical) constraints on releases in an attempt to obtain realistic operation of the system. Chung et al. (1989) adapt this model to increase its efficiency and flexibility. The alteration to DWRSIM is the changing of the mass balance with the outer-of-kilter algorithm (OKA-Fulkerson, 1961) network flow model. The OKA produces a better balance among the system reservoir and allows the components comprised in the demand points and the storage level to be have different priorities enabling more efficient water balance and demand supply. The result of incorporating the OKA network flow model into DWRSIM was a reduced time for running the problem and a more flexible tool as only the input needs to be changed to alter the system rather than the model code.

As illustrated, the reservoir system operation problem has been solved with the use of both optimisation and simulation. The optimisation model can be used to define reservoir release rules, storage volume distribution functions and real time reservoir operation (Loucks, 1992). On the other hand simulation models are primarily use for evaluating operation policy but can be utilised with optimisation models to simulate real time operation (Loucks, 1992). An extension to the general simulation model is the theory of stochastic simulation models. This was illustrated by Loucks (1992) with the main benefits of such models being that they allow the calculation of the reliability of a particular variable, its resilience and vulnerability to different extents of failure. In addition, the probability distribution of an extent of failure for a variable may also be obtained. Loucks (1992) concludes the review by discussing the benefits and use of a decision support systems (ie. REZES-Savic and Simonovic, 1991) to link the optimisation or simulation models to user friendly input and output measures.

2.3 Pricing and Demand

The estimation of demand is an important factor in the evaluation of the capacity expansion problem. Subsequently, a variation in demand can affect the solution obtained for the capacity expansion problem (Butcher at el., 1969 and Morin, 1973). In addition, if demand model uncertainties are ignored in the analysis of a system then unreliable forecasts could be obtained leading to unreliable performance (Ng and Kuczera, 1991).

Factors which may cause demand to vary are price, household income, climatic conditions, household size and billing frequency to name just a few. Studies investigating these factors and development of demand models were reviewed by Boland et al. (1984) and Davies (1992).

2.3.1 Price Elasticity

Of particular interest for this study is the effect price has on demand. The main reason for this interest is that not only is price usually a major influence on demand but it can be altered by an authority to control demand. The manner in which demand changes with price variation, is defined by the price elasticity of demand. Boland et al. (1984) considered the annual long-run price elasticity for urban water demand to be between -0.20 to -0.40 regardless of the pricing structure (ie. either marginal or average pricing). This range is based on results of studies prior to 1984. In addition, changes in demand for a particular price change continue to vary over time. Therefore, the expected response will increase over time and the long-run price elasticity will be higher than the short-run price elasticity. The review of studies post-1984 (Davies, 1992) found that the majority of the price elasticities were in the range suggested by Boland et al. (1984). However, on occasions the value was found to be outside this range (Billings and Day, 1989, Billings, 1982, Al-Qunaibet and Johnston, 1985 and MWA, 1985).

The studies estimating price elasticity of demand for this study were found to be in the range of -0.053 to -1.57. This is somewhat a larger range than Boland et al. (1984) however, the -1.57 is the summer sprinkler demand in humid areas (Howe and Linaweaver) and the -0.053 is the residential demand only for one particular model in one study (Schneider and Whitlatch, 1991). Thus if the annual price elasticity is examined the majority of estimates would fall within the -0.20 to -0.40 range but there are those studies which estimate price elasticity to be more or less elastic. A range which would encompass all the price elasticity estimates would be -0.06 to -0.72. In addition, Dandy (1989) indicated a similar range for various urban systems in Australia of -0.1 to -0.75.

As mentioned there is a significant range of price elasticity of demand estimated in various studies. The range is brought about by the examination of different examples and the use of various models and data sets. In addition, some studies examine seasonal price elasticities, yearly price elasticity and examine inhouse and outhouse price elasticity of demand. Howe and Linaweaver (1967) examined inhouse and outhouse (sprinkler) demand and produced estimates of price elasticity for annual domestic demand (-0.23) as well as summer sprinkler demand and maximum day sprinkler demand for both humid (Eastern) and arid (Western) areas of the United States. Summer sprinkler demand was found to be elastic (-1.6) in humid areas and inelastic (-0.7) for dry areas. For maximum day sprinkler demand the dry regions had an inelastic demand, while the humid areas saw a response to price change, but not of the same magnitude as the average summer sprinkler demand.

The separation of inhouse and outhouse (sprinkler) demand was corrected by Howe (1982) as it was considered inappropriate to model demand in such a way. The study also included Nordin's (1976) bill difference variable in the demand model as well as the marginal pricing policy from the previous study. The result is that the estimates for price elasticity are lower than those obtained by Howe and Linaweaver (1967). It was found that overall inhouse elasticity was -0.06 and the summer season elasticity for the humid and arid areas were -0.860 and -0.519 respectively. This was thought to be a result of the inclusion of bill difference in the pricing policy.

For Washington D.C. in the United States (east or humid area) Carver and Boland (1980) found lower price elasticities for seasonal (summer) and non seasonal (winter) demand than Howe and Linaweaver (1967). The non-seasonal elasticity ranged from -0.02 to -0.70 using three models and the seasonal elasticity was found to be -0.11. The reasons for the discrepancy could be because of the data used (ie. includes commercial and industrial and not just household demand) or the price elasticity for water may have changed since the earlier study. In addition, the short-run elasticity was calculated and it is lower than the long-run elasticity (as expected).

A number of studies estimated price elasticity of demand for Tucson, Arizona (Young, 1973, Agthe and Billings, 1980, Billings, 1990 and Martin and Kulakowski, 1991). Young (1973) found two price elasticities due to a substantially increase in price in 1964. The price elasticity for the period 1946-1964 was -0.63 and after the price rose for a 7 year period the price elasticity was -0.41. Other factors which were thought to influence municipal water demand such as income, annual temperature variations and evaporation were found to have no influence at all. Agthe and Billings (1980) showed long-run price elasticity varied between -0.27 and -0.49, which includes the latter estimate of Young (1973). This study indicates a range of elasticities as it examined the effectiveness of five econometric models in modelling water demand. Of the five only the Kojck and the static model produced reasonable results. In addition for Tucson the short-run price elasticity was found to be lower than the long-run elasticity. However, unlike Young (1973), Agthe and Billings (1980) found income to have an effect on demand but the moisture deficit (including evapotranspiration) did not.

Billings (1990) produced slightly more elastic estimates of price elasticities than Agthe and Billings (1980) of -0.57 and -0.72 for Tucson. The two values come from linear and exponential demand models respectively. In addition, it was found that the short-run elasticity was lower than long-run elasticity for Tucson. This is considered to be the case in general (Boland et al., 1984). Martin and Kulakowski (1991) indicated that the price elasticity of demand for water in Tucson was between -0.26 and -0.70 based on previous studies. However, on a simple year to year analysis there appeared to be no set relationship between price and demand (ie. every year gave a different price elasticity). This conclusion is due to variables such as income and weather not being considered. The studies aim was to investigate whether price could be used as a conservation tool but it was found that a significant rise in price would be needed to reduce per capita demand due to low price elasticity. Billings and Day (1989) produced a price elasticity of -0.72 for the Southern Arizona area which includes Tucson.

A long-run price elasticity ranging between -0.14 and -0.44 was found for Denver metropolitan area (Jones and Morris, 1984). The estimate was found by using regression equations in linear, multiplicative and log form and performing ordinary least squares analysis. The data used was collected from a 1976 survey and water billing data for the same year and included instrumental price estimates, household income and size. In addition, the full rates structure and average price of water was utilised. Dandy (1987) also used survey data to estimate the long-run and short-run price elasticity of demand for Adelaide. The aim of the study is to predict annual seasonal water consumption using regression analysis of the pooled time series cross-sectional data. The long-run price elasticity was estimated to be between -0.35 and -0.47 and short-run (1 year) elasticity to be -0.10.

As part of a study of the use of price as a drought management tool for Honolulu, Moncur (1987) produced an estimate of long run elasticity of between -0.1 and -0.683. In addition, the study found short-run price elasticity to be more inelastic then long-run elasticity. Also, if price is used in conjunction with other demand management tools then the price elasticity effectively increases as there is a reduction in the price rise needed to reduce demand sufficiently. The use of price as a conservation tool was considered to be more effective during the summer period by Griffin and Chang (1990). The reason for this conclusion is that the summer price elasticity (-0.37 and -0.38) was found to be approximately twice the winter price elasticity (-0.16 and -0.19) and the summer demand is greater than the winter demand for water. The demand model produced was based on 30 communities in Texas and incorporated standard factors such as climate, income and average and marginal price. The study also includes sewer pricing in the demand model as it is directly related to the water consumption. It was concluded that any study not considering sewer rates in the prediction of water demand would be deficient as it would excludes an important explanatory variable.

Of all the studies examined only Berry and Bonem (1974) found price not to be significant in predicting municipal demand for a number of communities in New Mexico. The reasons for this were thought to be due to variation in the type of demand being considered in the studies. In this study the total yearly demand and the community demand, which included industrial, commercial and residential demand were investigated. However in the majority of other studies only residential, seasonal or daily demand is considered. In addition, for the study of Howe and Linaweaver (1967) it was considered that a better data set was utilised than was available for this study. Boland (1984) indicated that studies that report insignificant relationship between price and water use suffered from specific study effects. Such effects are improper specification of price or insufficient variance in price of the sample used in the study.

Berry and Bonem (1974) mentioned that the consideration of multiple demand such as industrial, residential and commercial demand led to price not being significant. However, Schneider and Whitlatch (1991) produced estimates of elasticity for the city of Columbus, Ohio, when considering demand for the residential, industrial, commercial as well as government and school user sectors. Regression equations were developed for all user sectors and a generalised least squares procedure produced estimates of the price elasticities as well as estimates of other elasticities. It was found that price was a significant factor in demand estimation for all but industrial demand. The best estimation of long-run price elasticity for residential demand was -0.202 although a number of models were tested and the range was between -0.053 to-0.685. For total metered demand the best estimate for long and short-run elasticity were -0.50 and-0.14 respectively. Thus, in Columbus the immediate change in demand due to a price change is approximately 28 % of the final response. In addition, due to a lag, a total response in total metered demand due to a change in a variable will take approximately 7 years. However, half that response will occur within the first 3 years.

All of the above studies utilise some econometric method to estimate demand and price elasticity. Thomas and Syme (1988) however examine the alternative procedure of contingent valuation approach "CV" for determining the price elasticity of demand for the Perth Water System. The approach is a dual survey method which evaluates consumer needs and attitudes. The price elasticity estimated by the CV technique was -0.22 compared to the range of -0.1 to -0.43 found when using time series analysis. The price elasticity was lower than expected however this is thought to be due to the private use of bores, high income groups, low water consumers and users who regard water as unimportant to their lifestyle. The CV technique was considered useful when insufficient time series data are available for econometric analysis to be carried out reliably. In addition, the CV technique highlighted the importance of complementary and substitute goods in controlling residential demand (ie. the study incorporated private bores as an alternative to water supply).

A number of studies have considered whether it is better to use average price or marginal price as the independent price variable in statistical studies of water demand. Only Jones and Morris (1984), Billings and Day (1989) and Griffin and Chang (1990) compare the effectiveness of using both price measures. Both Billings and Day (1989) and Griffin and Chang (1990) indicated that average price was better for predicting demand. However, Billings and Day (1989) found marginal price to be better in low income areas because consumers make a greater effort to understand ways of reducing their water bill as it takes up a higher percentage of their income. In addition, it was found that average price was better in high income or low price areas. On the other hand Jones and Morris (1984) found no real difference between using average price or the actual rating structure when predicting demand in the Denver metropolitan area. However, it was considered that using average price would produce an overestimation of the price and when information on actual price was used, consumption may increase as the actual price may be lower. In addition, there are limitations to the use of average price when there is a great difference between metered and unmetered use (Howe and Linaweaver, 1967; Jones and Morris, 1984). Billings (1990) discusses various reasons why using average price in demand modelling is superior to marginal price for Tucson, Arizona and in general. Billings (1990) consider there was little difference between the elasticities estimated by Agthe and Billings (1980) using marginal price and those obtained in this study using average price. In addition, using marginal price makes the demand model more complex and for no real increase in accuracy, so it is better to use the simpler average price. Also consumers seemed unaware of the pricing structure in use and therefore showed no response to marginal price signals.

Other studies investigating demand prediction have used marginal price by itself (Howe and Linaweaver, 1967, Carver and Boland, 1980, Moncur, 1987 and Schneider and Whitlatch, 1991) or with a lump sum charge (Agthe and Billings, 1980 and Howe, 1982).

2.3.2 Other Variables Affecting Water Demand

To model demand successfully variables other than price should be included in any model. However for this study the variable of importance, price, has been discussed. Other variables of some significance which have been considered in the past studies of demand modelling include income, property value and climatic conditions.

Increases in income are expected to cause increases in per capita demand. The income factor can be incorporated into the demand model either as income or property value as a surrogate (Davies, 1992). Estimates of income elasticity of demand range between 0.18 to 0.60 when using household incomes and 0.33 to 0.55 using property value (Davies 1992). In this study those models which utilise income produced the following income elasticity estimates. Berry and Bonem (1974) estimated a elasticity of 0.76 for municipal demand while Schneider and Whitlatch (1991) indicated a range between 0.144 to 0.458 for the same demand. In addition, Schneider and Whitlatch (1991) estimated for residential demand a range of 0.207 to 0.642 for income elasticity. This is a similar range to that indicated by Davies (1992). Billings (1990) produced values of income elasticity within the range suggested by Davies (1992). With two models, linear and exponential, the values estimated for total demand were 0.30 and 0.296 respectively. Griffin and Chang (1990) estimate elasticities for summer and winter of 0.30 and 0.48 respectively. Of those using property value Jones and Morris (1984) were included in the range indicated by Davies (1992) as was Howe and Linaweaver (1967) estimate of 0.47 for residential demand. Howe (1982) produced an estimate of income elasticity for winter demand of 0.22 which is considerably lower than that of Griffin and Chang (1990).

Only Agthe and Billings (1980) and Moncur (1987) produce estimates of income elasticity not within the range indicated by Davies (1992). Agthe and Billings (1980) estimate income elasticity to be between 1.33 to 7.83. They consider the high estimate to be due to water being a superior good in the desert climate of Tucson, Arizona. Moncur (1987) produced a lower range of 0.038 to 0.080 for Honolulu.

The only study examined which indicated that income does not affect demand significantly was that of Young (1973). Thus the estimates from the various studies would seem to indicate that the income elasticity is dependent of the demand specified, the income measure and the region being considered.

The climatic variable used in the various studies varies depending on the problem under investigation. Davies (1992) provides a summary table indicating elasticities for climatic variables for various studies. The most used climatic variables are temperature, evapotranspiration, rainfall and moisture deficit. Depending on the problem examined theses variables may or may not be important. For instance Young (1973) found rainfall to be important for Tucson, Arizona (desert climate) but evaporation and temperature were not. In addition, Berry and Bonem (1974) incorporated a moisture deficit variable in there model similar to Howe (1982) but found by regression analysis such a variable not to significantly effect demand. Whereas, Howe and Linaweaver (1967), Howe (1982), Carver and Boland (1980) and Agthe and Billings (1980) used moisture deficit and found it to have a significant effect on demand. The moisture deficit term is usually specified for summer months only as this time of the year is of critical importance for vegetation. The moisture deficit term is basically the evapotranspiration of the vegetation minus the rainfall in the study area.

Unlike Young (1973) in his study of Tucson Arizona, Billings and Day (1989) and Billings (1990) found temperature to have an effect on demand for Southern Arizona and Tucson respectively. In particular, Billings and Day (1989) found the extreme temperature (>58^{o} F) had a greater effect than average temperature. In addition, like Young (1973), rainfall was found to be significant for Southern Arizona (Billings and Day, 1989) as well as Tucson (Billings, 1990). However, Billings (1990) found only summer rainfall to be important for Tucson with winter rainfall having an insignificant effect on demand. Moncur (1987) and Schneider and Whitlatch (1991) also utilised and found rainfall to be a significant factor for their studies. However, Moncur (1987) used yearly rainfall whereas Schneider and Whitlatch (1991) used total summer rainfall. Griffin and Chang (1990) also used a variable based on rainfall however rather than using the amount of rainfall, the lack of rain was utilised. The climatic variable used is based on the number of days without significant rainfall multiplied by the average monthly temperature. This variable was found to affect demand for 30 communities in Texas.

2.3.3 Demand Management

The use of demand management is growing in popularity as a way of controlling demand and as an alternative to capacity expansion. A number of methods for demand management are reviewed by Davies (1992). The demand management measures previously utilised can be grouped into the following four categories; structural (ie. water saving devices), economic (ie. change in rates structure), operational (ie. restrictions) and sociopolitical (ie. publicity, education, legislation) (Flack and Greenberg 1987). The pricing or economic factor has been previously discussed in regard to how it affects demand. For the city of Melbourne, a change in the rate structure achieved a 2 % reduction in demand in addition to a 15 % reduction already achieved through other demand management measures (Duncan, 1991). The structure was changed from a water rate based solely on property value to a water charge based on property value plus a two part increasing block rate structure for water consumption. The structure was further changed to incorporate a price per use, in addition to the property value charge, for that water whose price was previously associated only with the property value. In addition, Moncur (1987), Billings and Day (1989), Daniell and Falkland (1989) and Martin and Kulakowski (1991) suggest price to be an effective demand management tool. However, for the Tucson Arizona case, it is consider that a substantial rise in price would be needed to reduce demand and a more effective technique would be one incorporating an education campaign coupled with water pricing reform (Martin and Kulakowski, 1991). The reason for this conclusion is the low price elasticity. Moncur (1987) also mentioned that price could be used on its own or with other demand management tools such as education and restriction policies. The benefit of this joint approach is that the price rise needed to reduce demand will be reduced due to the price elasticity being increased as a result of using another demand management technique.

Moncur (1987) and Martin and Kulakowski (1991) suggest the joint use of demand management techniques to increase the reduction in demand. Another technique is the use of television campaigns, publicity and education to make consumers more aware. Davies (1992) found that previous studies reported a reduction in water consumption of between 5 % (Maddaus et al., 1983) and 15 % (Duncan, 1991), when publicity and information programs were used. In addition, (Duncan, 1991) reported that reductions between 20 to 30 % of peak demands could be achieved by providing information on effective watering. Daniell and Falkland (1989) considered a television campaign as the most effective way of introducing restrictions to reduce the demand in the Canberra Water Supply System. However, Billings and Day (1989) considered publicity to have an insignificant influence on demand and if any effect is to occur it is only while publicity is maintained.

In regard to water efficient devices, studies reported that the savings ranged from 10 % to 32 % (Davies, 1992). Of these studies, Duncan (1991) suggested that the savings increased after the first year (ie. 17 % in the first year and 21 % in the second). Such water saving devices would include the retrofitting of household appliances such as toilet cisterns and shower roses. For the case of toilet cisterns, a 27 % saving in water can be achieved. When it is considered that 18 % of water use in the house is for toilet use then this accounts for a considerable saving. It is also thought that the toilet cistern may be further reduced to create further saving (Duncan, 1991). Compulsory fitting of water savings devices could be made mandatory by introducing legislation to this effect (Duncan, 1991).

The use of restrictions during drought periods was shown to reduce the yearly demand in Melbourne by 27 % during the 1982/83 drought (Duncan, 1991). Even two years after the drought the demand was still 15 % lower than pre-drought estimates. However, the continued reduction is contributed partly to a successful advertising campaign. Some studies indicate that restrictions were effective in reducing demand during drought periods (Davies, 1992). In particular, Bruvold (1979) reported a reduction in per capita use of between 20 and 50 % when using restrictions. However, on the other hand Davies (1992) reported on other studies which dispute the effectiveness of restrictions.

The use of multiple demand management tools has been reported by Duncan (1991). Although, the individual effects of the various technique on demand have been indicated, there is also an overall effect on demand. It was found that the overall total demand reduction based on estimates from pre-drought conditions was 16 % for Melbourne. The result of this is a reduced predicted demand growth of 2 % down from a pre drought estimate of 3 %. This reduction has lead to a delay of 6 to 16 years in future project augmentation depending on the future demand management levels for the Melbourne system. This delaying of projects corresponds to a reduction in present value of cost for new projects of between $32 and $75 million based on a 4 % discount rate. Thus, for the Melbourne water supply system, demand management and pricing have produced significant reduction in demand and therefore future augmentation costs.

In addition, the use of demand management techniques have been included by Rubinstein and Ortolano (1984) in a capacity expansion study. The demand management measures included were publicity/education campaign, a retrofit of households and three emergency demand management measures (ie. restrictions). The five demand management measures are all mutually exclusive. Further detail on the extent of this study will be covered in a later section. Also, Lane (1991) has incorporated demand management into the future demand forecast for a study of the future projects required for the South-East Queensland System. The demand management measures identified were the introduction of an effective metering and pricing structure, leakage detection and repair, restrictions on garden watering, community education and the use of water efficient appliances. The combined effect of the various demand management measures was to reduce demand by approximately 20 %.

2.4 Pricing Policy and Capacity Expansion

The inclusion of price into the capacity expansion problem requires the demand section of the problem to be investigated along with the capacity expansion section. The demand section basically examines how demand changes while the capacity expansion section is the sequencing of projects based on the evaluated demand. The demand section can be dealt with either simply or comprehensively. The difference is that the simple way assumes the demand changes with price change but the form of pricing policy is not examined, whereas a comprehensive technique involves the examination of pricing policy and how it alters the demand. With the more extensive examination of the demand side of the problem, two pricing policies are generally investigated. The two pricing policies investigated are marginal cost pricing and average cost pricing. In addition to this, the objective changes from the minimisation of cost to the maximisation of net benefits. Such benefits include revenue through sale of water, consumer surplus, operational and maintenance cost of the system as well as construction cost of new reservoirs.

A number of studies have investigated the merit of both marginal and average cost pricing in producing the maximum benefits of a water supply system (Riordan, 1971a, b, Gysi and Loucks, 1971, Dandy et al., 1984, 1985 and Swallow and Marin, 1988). The theory regarding the best pricing policy to obtain the best timing and sequencing of projects is defined by the following statement of Hirshleifer et al. (1960) which is reported in Riordan (1971a) :

> "In general, the best short-run solution is to have short-run marginal cost equal to price, and the best long-run solution (the optimum scale of plant) is achieved when long-run marginal cost and short-run marginal cost both equal price."

The model presented by Riordan (1971a, b) is an extension of a model by Hirshleifer et al. (1960). The model incorporates plant durability and makes it desirable to invest in fairly large discrete units of capacity. The inclusion of plant durability alters the definition of long-run marginal (LRMC) and long-run average (LRAC) costs for a water resource given by Hirshleifer et al. (1960). Previously, for the LRMC and LRAC to be unique and known, the fixed plant must be completely free to vary. However if the durability of such plant is considered, the LRMC and LRAC will not be unique, leading to a capacity expansion schedule which is reliant on the demand and growth characteristics of the community (Riordan, 1971a, b). The resulting model produces an optimum timing and sequencing schedule for capacity expansion using discrete dynamic programming. This is achieved by setting the price equal to the short-run marginal cost and then steadily raising it until the marginal benefits of capacity expansion exceed the marginal costs, at which time the capacity is expanded and the price drops to the short-run marginal cost of supply. The price steadily rises to ensure capacity is always greater than demand and therefore no shortfalls in demand are experienced.

This model is used to examine the effects of marginal cost pricing on the optimum expansion schedule of a water supply treatment facility (Riordan, 1971b). For this problem the peak daily demand is used which is assumed to be 1.6 times the annual average demand and the assumed price elasticity is -0.4. Both marginal cost pricing (MCP) and average cost pricing policy (ACP) are used so that a comparison can be made between policies. Although the comparison was difficult due to there being no unique ACP (and thus three were used), the study found that multistage MCP could result in an increase in benefits of 10-20% when compared with the ACP policies.

Gysi and Loucks (1971) extended Riordan's work by considering various pricing policies and including the expansion of the water sources as well as the water treatment plant. In regard to the reason for including expansion of water sources, it is considered by the authors that the majority of the cost is from the construction of water sources rather than water treatment facilities. In addition, the expansion of existing water supply is only allowed to be in identical fixed increments (ie. 10 million gallons per day). The different pricing policies considered were decreasing and increasing block rate (3 step structure), constant per unit, flat rate and summer differential rate. The demand model of Howe and Linaweaver (1967) was utilised with these pricing policies for a hypothetical case. This included various groups within the community with differing income levels and population growth rates. Utilising a forward moving dynamic programming technique and it was found that increasing block rate was superior to constant pricing and decreasing block rate. However, over a long period, low consumption per consumer and high marginal cost would occur. It was therefore concluded that a policy that uses both an increasing block rate structure and a summer differential rate would be the best policy as it rewards lower consumption, reduces rationing and increases net benefits.

Dandy et al. (1984) included administration constraints on price changes as an extension to the work of Hirshleifer et al. (1960) and Riordan (1971a, b). The administration constraints include such things as limiting the percentage change in price from one year to the next and ensuring cost recovery. This is done so that a more realistic pricing policy can be obtained. In addition, three pricing policies were used for a refined example presented in Riordan (1971b). The pricing polices used were unconstrained marginal cost pricing (MCP), average cost pricing (ACP) and constrained marginal cost pricing (CMCP).

The model was solved using a forward moving discrete dynamic programming algorithm. The model incorporates capacity expansion by considering fixed increments of additional capacity to be added to the existing capacity. The price is found by allowing fixed price increments to be added or subtracted from the previous price examined. The demand used to establish the capacity expansion schedule was maximum daily demand as used in Riordan (1971a, b). As was found in Riordan (1971b), MCP produced a larger net present value than ACP, however, the increase wasn't as significant as that found by Riordan (1971b). The inclusion of administration constraints (ie. CMCP policy) made a more realistic pricing policy, but lead to a decrease in net present value. This resulted in only a slight improvement over ACP. Another addition to previous models is the inclusion of a fixed costs term representing administration and billing costs to the net present value calculation.

This model is applied to a real world situation, of the Kitchener-Waterloo System in Ontario, Canada (Dandy et al., 1985). Unlike the previous study (Dandy et al., 1984) this study utilises a demand function which requires a defined price elasticity of demand. Thus, as a part of the study this varied to examine what changes if any it has on the capacity expansion decision. The initial value of price elasticity used was -0.3. In addition, the effect of varying growth rate in population, larger capacity increments and economies of scale were examined. As was previously found (Riordan, 1971b and Dandy et al., 1984) the optimum price approached the short-run marginal cost of supply and increased to delay new expansions. This effect is illustrated in Figure 2.3.

The study found the same conclusions apply as for Dandy et al. (1984) in regard to the various pricing policies. Thus it is considered constrained pricing policies are likely to be more beneficial than the average cost pricing. However, it is also considered by Dandy et al. (1985) that when the marginal cost falls below the average cost then consumption will increase, which conflicts with water conservation objectives. In addition, systems which experience economies of scale were found to produce greater benefits. Also it was shown that price elasticity effects the timing and benefits achieved with high price elasticities producing more benefits.

The above studies effectively evaluate and determine the best type of pricing policy. In particular, they advocate the use of marginal cost pricing policy rather than average or constant price policy. However, a marginal cost pricing policy can have its practical problems. These include not covering cost, political ramifications from altering price continually as illustrated in Figure 2.3 and assuming that markets equilibrate costlessly (Swallow and Marin, 1988). A solution to theses problems is to use a constant price which will guarantee a greater degree of cost recovery than when using a marginal cost pricing policy. Such a policy was developed by Swallow and Marin (1988). The optimum constant price is derived as a weighted average of the marginal cost of supply.

A simulation procedure applies the constant pricing policy to a hypothetical city (Dandy et al., 1984) and Riordan, 1971b). In addition, marginal cost pricing (Dandy et al., 1984 and Riordan 1971a, b) is used in a dynamic program to calculate the present value of the net willingness to pay for the capacity expansion of the system (capacity expansion in multiples of 0.625 million gallons per day). It was found that the constant pricing policy achieved 98.5% of the benefits obtained by marginal cost pricing policy. Also it was considered for this case that the effects of discount rate and demand growth rate were ambiguous.

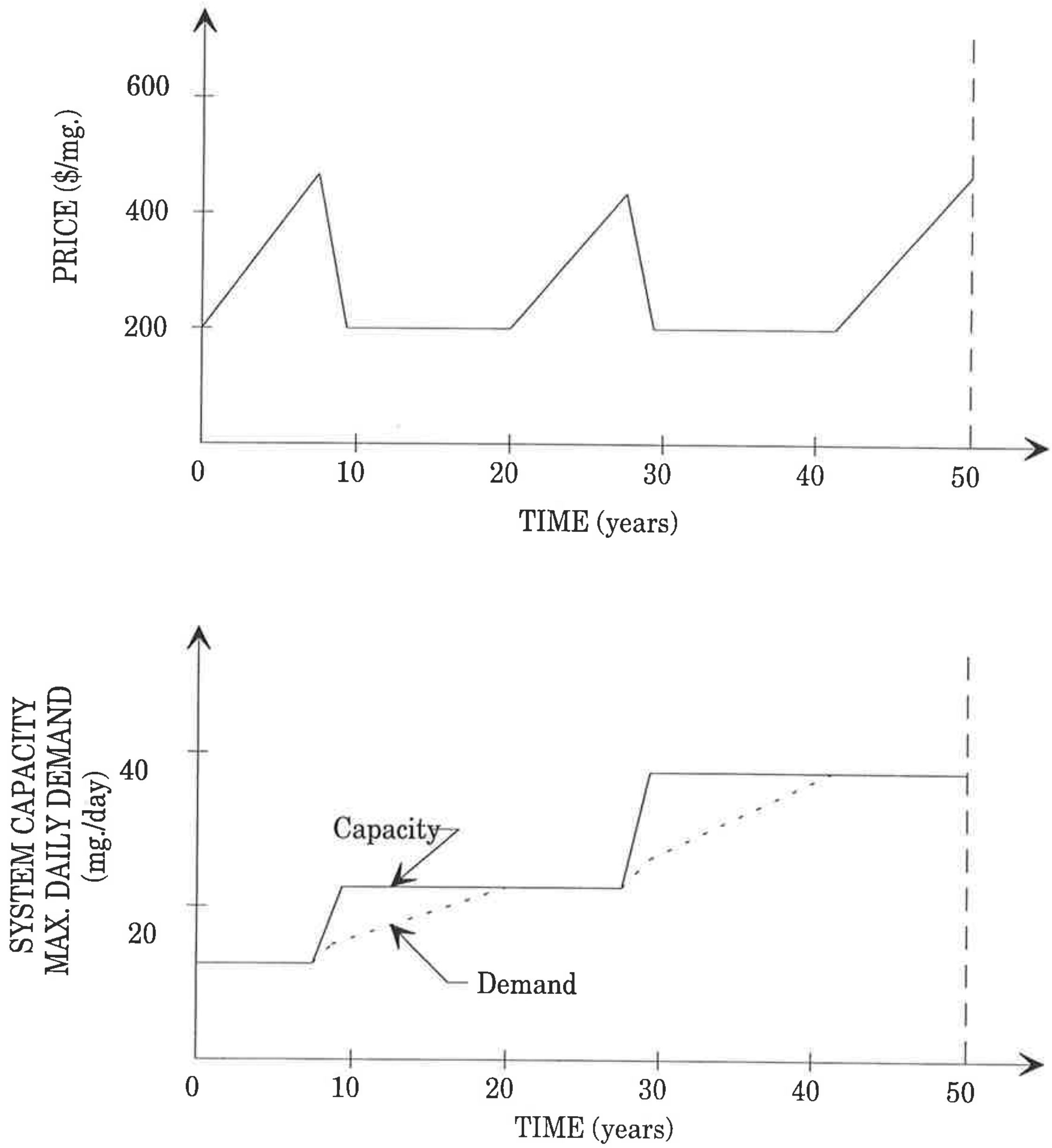

Figure 2.3 Price, Demand and Capacity Schedule for Marginal Cost Pricing (Dandy et al., 1984)

The above studies concentrate on providing a suitable pricing policy which increases the net benefits of capacity expansion to the system. An alternative method is to recognise that demand will change with price but not actually concentrating on the most effective pricing policy (Erlenkotter and Trippi, 1976, Kolo and Haimes, 1977 and Moore and Yeh, 1980). Erlenkotter and Trippi (1976) develop a model adapted from previous optimisation models for capacity expansion (Erlenkotter, 1970 and Erlenkotter and Rodgers, 1977) to establish the optimum timing and sequencing of project expansion while ensuring a pricing policy that maximises net profits over an infinite time period. An unusual aspect of this study is the determination of revenue without using price. The revenue term is given as a function of quantity supplied and demand growth and the optimum price is determined by dividing the optimum (maximum) revenue by the total quantity supplied to obtain that revenue. The authors considered the decisions of price, output and expansion investment are highly interdependent.

Kolo and Haimes (1977) expand on the problem by including resource allocation as well as fresh water, irrigation water, and power demands. To achieve this a hierarchal model is used. The lower level incorporates supply and demand models which are solved by various dynamic programming procedures, whereas the high level coordinates the outputs from the lower level supply and demand models. The higher level adjusts the price of water, which effects demand and supply inputs, until the overall optimum project sequence and operational policy is determined. At the higher level the objectives are decomposed and the Lagrangian of each sub objective is maximised.

The theory of including operation of a system in the pricing and capacity expansion problem was extended by Moore and Yeh (1980) to include the sizing of reservoirs in the capacity expansion problem. The model presented extends and modifies the model of Becker and Yeh (1974a) by incorporating a price sensitive demand curve that changes with time. The model allows only one reservoir to be developed at a time, only once over the planning period and a reservoirs capacity cannot decrease at any time. The model was developed for the Eel River System and a 50 year planning period with five year planning intervals was examined. In addition, the firm water level was only allowed to increase in discrete increments. In regard to the Eel River System, at high firm water levels the reservoir sizes determined were similar to those found in previous studies (Trott and Yeh, 1973 and Becker and Yeh, 1974a, b), although the timing was different. The study also adjust the price elasticity of demand using the values -0.7, -1.1 and -1.5. Although, from the previous discussion on price elasticity these values would appear high, the study found that there was no apparent effect on the planning decisions. However, the demand growth was found to effect the planning decisions. In addition, at high discount rates the optimum system capacity was affected but, not to the same extent as when demand growth was varied.

The incorporation of the price and capacity expansion problems has been examined by Billings (1990). However, this differs from the previous studies mentioned as it uses demand models to evaluate whether a particular project should be undertaken for Tucson, Arizona. The project is a one-off project so no sequencing is incorporated in the study. The evaluation of the project is based on the benefits obtained with or without the project from the extra supply available. The study concentrates on the development of linear and exponential demand models. The study uses a weighted average of the demand models with more emphasise placed on the exponential demand model. The reason for this is that the true demand response is expected to be somewhere between the two models and closer to that of the exponential demand model. The study found that with a low discount rate the project under examination is beneficial however, at a high discount rate the costs are greater than the benefits. If the high discount rate prevails then a charge for each new connection should be used to cover the cost. In addition, for a high value of the price elasticity of demand the benefits would be lower and the opposite is true for a reduced value of price elasticity. Finally, the study produced an internal rate of return of 4.86 % so any discount rate higher than this would result in the cost being greater than benefits and on an economic basis the project would not be worthwhile.

2.4.1 Pricing Policy and Reservoir Storage Estimation

As discussed previously, the price of water can effect the demand for water. Subsequently, this can lead to an effect on the supply and the storages within a reservoir. Riley and Scherer (1979) and Manning and Gallagher (1982) examine the effect that storage levels in a reservoir have on pricing policy.

Riley and Scherer (1979) determined that when inflow exceeds demand with no storage then price is set to cover operational costs and for demand greater than inflow, price increases to restrict demand to the level of inflow. Also, it is considered that the optimum price of water will never fall below the marginal treatment and operation costs. Thus a three step pricing policy which approximates the optimum pricing policy was presented. The approximation is necessary as there is difficulty in implementing the optimum policy in reality. The policy consists of a minimum price during winter months which is then increased to the marginal cost of storage capacity for summer when the reservoir is emptying. There is then another jump to reduce peak summer demand which corresponds to a price high enough to cover the marginal cost of purification capacity. Manning and Gallagher (1982) produced a similar conclusion in that when storage becomes exhausted price, should be set such that demand is the same as natural inflow. In addition to this, the price of water should increase at no less than the discount rate and price is set so that at the end of the interval in which it applies the storage contents are at a level to meet demand for the next interval.

In regard to optimal storage capacity it was considered that this occurs when the benefits of storage equal the cost of storage (Riley and Scherer, 1979 and Manning and Gallagher, 1982). Riley and Scherer (1979) added that to avoid shortages in this case, the price is set so that supply equals demand. The optimal storage capacity was also found to increase either when the price elasticity of demand or discount rate was small or the planning period was large (Manning and Gallagher, 1982).

2.4.2 Demand Management and Capacity Expansion

Another way to control demand other than using price is to use demand management techniques. Rubinstein and Ortolano (1984) incorporate demand management into a capacity expansion study. In this case the five demand management measures are considered as additional projects for sequencing. The various demand management plans are considered to be mutually exclusive. For example, a publicity and education campaign is included within restriction policies as well as being a demand management option separately. The objectives are examined are the minimisation of present value of costs (PVC) for project implementation and minimisation of costs in satisfying emergencies in supply. Rather than determining a specific solution a set of non-inferior solutions are found. This is achieved by assigning weights between objectives and varying these weights. Dynamic programming is used to solve the problem. The method was tested for an example with seven supply and five demand management alternatives for a ten year period. The study found that solutions which implement demand management measures earlier produce a lower PVC and higher expected costs of coping with emergencies than solutions which rely on supply alternatives.

The method of Rubinstein and Ortolano (1984) assigns a cost and an effectiveness in reducing demand for each demand management measure. Alternatively, Lane (1991) incorporates demand management into the problem by including it in the future demand forecasts. Both methods have their merits depending on the demand management technique used and if it is considered that there is a cost associated with that technique. If there is a significant cost associated with a demand management measure and it can be calculated then the method of Rubinstein and Ortolano (1984) would be advocated. However, if a cost cannot be determined or it is considered negligible the incorporation of demand management into demand forecasts would be suitable.

2.5 Augmentation Time of Capacity Expansion

The general condition for project augmentation for a water resource system is simply when demand equals supply. In some cases demand can exceed supply if importation of water is allowed. Another alteration to the general condition is by making the supply last longer by using some demand reduction methods. Both of these situations have been discussed in previous sections. The question which arises in these cases is when does augmentation of the system take place. Thus, the following section concentrates on the problem of augmentation of the existing system rather than which project to build next.

Kuczera and Ng (1994) is the only study which examines this problem. They utilise restrictions in supply to delay augmentation while maximising economic benefit. The economic benefits in this case consisted of the reduction in consumer surplus and revenue due to augmentation of the system in year t minus the present worth of augmentation.

The study was comprehensive in its consideration of demand as it examined domestic and industrial/commercial demand plus variability in demand due to socioeconomic and climatic factors. A network simulation model (WATHNET), a demand prediction model (WATDEM) and a economic evaluation model are used to evaluate the net economic benefits of augmentation.

The Newcastle headworks is used as a case study for the methodology. Two different restriction policies are examined for the Newcastle system and in each case 5000 replicates of inflows are used to simulate system performance for the period 1993 to 2010. As part of the study a price/demand relationship for Newcastle was determined. Included in this relationship is the subsistence level of domestic demand. The restriction policies split domestic demand into exhouse and inhouse demand with the severest restrictions being placed on exhouse demand.

The study found that there is not a major change in economic benefits for a wide range of augmentation times. So the decision maker can vary the augmentation time without significant loss in economic benefits. It was concluded by Kuczera and Ng (1994) that the economic loss methodology developed could provide a means to produce more efficient restriction policies for drought management, although the methodology depends on reliable price/demand information. In addition, the study showed the importance of optimising operating policy as well as the timing of augmentation.

This paper shows how pricing and restriction policies affect the capacity expansion decision and hence, why they should be included in the analysis.

Another factor which may need to be considered in the timing of system augmentation is the performance of the system. As mentioned previously, the basic theory of augmentation timing is when demand equals supply. Kuczera and Ng (1994) illustrated how this timing of the demand/supply condition may be altered by restriction policies. However, Sabet et al., (1991) illustrated how system performance criteria may be used for this purpose. The criteria used to evaluate system performance were frequency, intensity and duration of system failures which are considered to define the concepts of reliability, vulnerability and resiliency. Failures are defined as when the system cannot meet the demand for water.

The study examined the Sydney Water Supply System for a 40 year period. The timing of augmentation was investigated once the probability of restrictions approached a specified level. At this stage a augmentation would occur and the system performance would be continued to be monitored after augmentation. Two structural options (ie new reservoirs) and two non-structural options (ie. changes to operating policy) were considered as possible augmentations to the system.

Sabet et al., (1991) used a simulation model (HEADSYS) and synthetically generated streamflows for the system evaluation. It was found that the non-structural options maintained system performance standards for a portion of the planning period before augmentation using the structural options was required. Using only the structural options satisfied demand over the entire planning period to the desired performance criteria. This illustrates that non-structural effects on augmentation are likely to be short-term and structural options will be delayed rather than abandoned.

2.6 Overview

It is evident that various techniques have been used to solve the pricing and capacity expansion problems. These methods are generally optimisation techniques such as dynamic and linear programming, or heuristic methods. The problem experienced with optimisation techniques is that the when the problem becomes too large there are computation time and dimensionality problems. In situations where these problems exist, heuristic approaches can be successfully applied either as a solution technique or a screening procedure. Successful heuristics for the sequencing of projects have been developed by Erlenkotter (1973a) and Tsou et al. (1973) and for the size and sequencing problem by Fong and Srinivasan (1981a, b and 1986). Akileswaran et al. (1983) concluded that due to the complexity of the sequencing problem the heuristic decision rules developed by Erlenkotter (1973a) and Morin (1974, 1975) could be used to find the optimal sequence in linear time. This conclusion was made from the results of applying an evaluation method developed by Garey and Johnston (1979) called NP-completeness to the sequencing problem. Also, Akileswaran et al. (1983) stated that models purporting to solve the sequencing problem in its full generality will require exponential time at worst and thus for all but small problems the model will become impractical.

If this is the case for the sequencing problem then the introduction of sizing will only add further complexity. The solution to this problem has been to use a smaller problem set with continuous sizing or only allowing discrete sized increments to solve the sizing problem. Alternatively, heuristic approaches have been successfully applied to the problem with the heuristic model of Fong and Srinivasan (1981a, b and 1986) being a good example. This heuristic has been applied to the problem of transportation and production of goods to consumer areas rather than size and sequencing of water resources.

Of the methods encountered, the dynamic programming technique was the most prominent. An extensive review of dynamic programming techniques utilised in the field of water resource was produced by Yakowitz (1982). It was considered that of the dynamic programming (DP) techniques, differential DP was the better process for deterministic DP. Other DP techniques considered were discrete differential DP and state incremental DP. For the stochastic case discrete DP is extensively used. However, discrete DP suffers from the 'curse of dimensionality' and thus the problems examined for the stochastic case are generally smaller in size.

The introduction of system operation increases the complexity of the problem. The techniques utilised to solve this problem generally consist of a series of models. Again optimisation and heuristic techniques are used as well as simulation methods. The simulation methods are used to evaluate operating policies but are also used to determine the effectiveness of an operating policy. Yeh (1985) discovered in a review of methods used for reservoir operation and management that simulation was used to evaluate system performance and enhance the reliability of a system rather than optimise system operations. In addition, Yeh (1985) concluded that for reservoir operation the most popular methods were linear and dynamic programming. However, when using linear programming techniques problems with non-separable benefits and stochastic inflows are difficult to solve, while for dynamic programming the curse of dimensionality limits the number of reservoirs which can be included to around about four. Non-linear programming techniques have also been used but were used less frequently due to the complexity of the mathematics involved. Yeh (1985) also discusses real time operational techniques which are primarily concerned with optimal operation of a system for either short term (ie. hourly, weekly monthly) or long term objectives.

The significant factors for the capacity expansion problem were demand growth rate, discount rate and project cost. Neglecting of demand growth rate and discount rate in sequencing methods (ie. unit cost method) will lead to sub optimal results (Erlenkotter, 1973a and Butcher et al., 1969). In addition, demand is considered to play a more significant role than discount rate in the sequencing decision (Morin, 1973b). The most common demand functions used for the capacity expansion problem were reported by Luss (1982) to be:

(1) Linear growth : $D(t) = \mu + \delta t$

(2) Exponential growth : $D(t) = \mu \exp^{\delta t}$

(3) Saturation growth : $D(t) = \beta(1\text{-}\exp^{-\delta t})$

Of these the linear and exponential growth were the demand functions encountered in this review.

When examining the sizing problem the cost function plays an important role. The most prominent functions throughout the literature were reported by Luss (1982) to be

(1) Power cost function : $C(x) = Kx^a$

(2) Fixed charge cost function : $C(x) = c + bx$ or $C(x) = 0.0$, where $C(x)$ = the cost of a project with capacity x.

For the studies examined in this review when the power function is used and economies of scale are examined, the optimum size decision increased with increasing economies of scale. In addition, Dandy et al. (1985) found that systems which have increasing economies of scale (eg. a approaches 0.0), have greater benefits (eg. larger NPV).

In regard to pricing and its effect on demand, the studies examining this relationship are aiming to develop demand models using econometric techniques. From these demand models various elasticities are estimated, one of which is the price elasticity. Thomas and Syme (1988) vary from the econometric method by developing the contingent valuation approach (CV) to determine price elasticity. The estimates of price elasticity vary depending on the study examined, the data used and the other variables included in the model. The range of price elasticity for residential water demand is conservatively between -0.1 and -0.75 for various urban systems in Australia (Dandy, 1989). For the papers reviewed in this study the range was between -0.06 to -0.72. A more precise range was suggested by Boland et al. (1984) as -0.20 to -0.40. This range encompasses the majority of estimates produced.

Other factors considered to affect demand were income, climatic conditions and pricing policy. Income has a positive effect on demand and is considered to have a significant impact on demand. The income factor is incorporated into the demand model either as income or property value (Davies, 1992). When the total residential demand is examined using income the range of elasticity was 0.18 to 0.60 and using property value 0.33 to 0.55 (Davies 1992). Climatic variables also play a role in demand estimation although the importance of a particular climatic variable varies from study to study. The most common climatic variables used are rainfall, evapotranspiration, moisture deficit and temperature.

When using pricing policy in the capacity expansion problem, it is found that greater economic benefits are obtained when using marginal cost pricing rather than average cost pricing. However, there are administrative and political problems with marginal cost pricing as well as the assumption that the market adjust costlessly with price change which may not be correct. In addition, marginal cost pricing may not cover cost of system expansion. Dandy et al. (1984 and 1985) introduced administrative constraints to reduce the fluctuation of price. This resulted in a more realistic pricing policy but less benefits than marginal cost pricing without administrative constraints. Alternatively, Swallow and Marin (1988) produced a constant price policy based on the weighted averages of the marginal costs. This achieved 98.5 % of the benefits produced by using marginal cost pricing without the associated problems.

The effect of price on demand has been illustrated. Thus, pricing can be used as a demand management tool (Moncur, 1987, Duncan, 1991 and Davies, 1992). The effectiveness of the price as a demand management tool will be reliant on the price elasticity of demand. Alternatively, price can be used in conjunction with other demand management techniques to control demand. Such techniques are publicity and education campaigns, retrofitting of households with water efficient devices and restriction campaigns during drought periods. The effect of demand management techniques is to delay future augmentation of an existing system. For example, for the Melbourne Water Supply System, demand management resulted in future augmentation being delayed by between 6 to 16 years with a resultant saving of between \$32 and \$75 million in present value terms.

The final factor considered to be important for this problem is the selection of planning period. With different planning periods the size and sequencing decision will vary (Bogle and O'Sullivan, 1979 and Bean and Smith, 1985). In addition, it could be expected that the number of projects needed will vary with time period as will the benefits and costs.

Therefore, the factors to include in a capacity expansion model are discount rate, demand function, cost and yield of projects as well as the planning period. When price is included, the price elasticity should be included so the demand variation can be considered. The objective to use for the problem will vary from the minimisation of present value of costs for the capacity expansion problem to the maximisation of net benefits when price is included. If these factors are not involved in the capacity expansion model then sub optimal result may be produced.

Chapter 3

Methodology

3.1 Introduction

This chapter will outline the various methodologies used in this study. The theory of genetic algorithms which will be utilised for the South-East Queensland System and the Perth System case studies will be detailed in a later chapter.

The most commonly used economic evaluation method, examines an economic investment opportunity in terms of its net present value. This process has been used extensively in those studies detailed in the literature review in Chapter 2. The present value method is used as benefits and costs received in the future are considered to be less valuable than those received now. In addition, the further into the future benefits and costs are received the less value they have in present worth terms. Thus to compare investments it is necessary to evaluate all benefits and costs at a particular point in time. This point in time is usually chosen as the present time for simplicity. Thus the name present value. The amount that future benefits and costs are reduced depends on a rate which varies depending on the person making the investment decisions. This rate is called the discount rate and is usually equal to the opportunity cost of capital (Wilkes, 1983 and Dandy and Warner, 1989). The theory of present value and the determination of discount rate will be examined in this section.

A discussion on the pricing methodology utilised in this study will then follow. This will include the pricing policy adopted and the effect price changes have on demand (ie. price elasticity of demand). When pricing policy is included in the analysis benefits to the consumer and water authority need to be considered. These benefits are the revenue raised by the water authority and the consumer surplus. Although, the concept of the revenue is relatively straightforward, a detailed explanation will be presented for the consumer surplus benefit. The inclusion of these benefits will result in the objective becoming the maximisation of net present value of consumer benefits.

The various capacity expansion problems to be examined in this study are detailed in this chapter. These include the sequencing of future reservoir projects, the size and sequencing of future reservoir projects and the sequencing problem with the operating cost of the projects included in the evaluation. These cases will be discussed, particularly with reference to the various methods used to determine the optimum sequence of projects. There will be three methods presented here which include two heuristic methods and an optimisation method. The two heuristics are the unit cost method and the equivalent cost per period method developed by Erlenkotter (1973a). These methods will be used in all the capacity expansion problems to be examined. The changes required so that the methods can be used to examine the different problems will be illustrated. In addition, the two methods will be compared using a simple example. An integer/linear programming formulation will also be applied to the size and sequencing problem.

The final discussion will address the issue of yield evaluation techniques. These will be used for the Canberra case study where the yield of the existing system and future projects needs to be determined. Four methods will be utilised to estimate the existing system yield. These are two optimisation models, a network programming model and a simulation model. A full optimisation model will be utilised and detailed. In addition, an approximation to the optimisation model will be discussed. This model is the yield model (Loucks, 1976 and Loucks et al., 1981). It was designed to approximate the full optimisation model but take considerably less time to provide an estimation of yield. The accuracy of the yield model is tested in this study Both the optimisation model and yield model are formulated as linear programs. The network programming model is a commercially available package called WATHNET (Kuczera, 1990) and was developed to investigate a water supply systems performance rather than the yield of a system. Therefore for this study an iterative procedure is used to determine the yield of the Canberra system. The simulation model of the Canberra water supply system (Pink and Sooriyakumaran, 1988 and Pink, 1991) involves the actual operating rules of the existing Canberra water supply system and like WATHNET will not provide the yield of the system unless an iterative procedure is used.

3.2 Time Value of Money

It is generally accepted that the values of benefits and costs are greater in the present time than at some stage in the future (Wilkes, 1983, Bierman and Smidt, 1984, Dandy and Warner, 1989 and Price, 1993). Dandy and Warner (1989) suggest that human nature gives precedence to consumption of goods now rather than later and costs are delayed to the future if possible. There are a number of reasons why this occurs. Such reasons could be that the promise of money in the future is just a promise and there are many uncertainties in the future which may affect whether this payment occurs (Bierman and Smidt, 1984). In addition, in terms of investments, a dollar now is more important than one in the future due to the current investment possibilities (Bierman and Smidt, 1984). Although, these arguments relate to benefits, the same will apply to costs. A good analogy for the decrease in value of benefits and costs is the saying " a bird in the hand is worth two in the bush" (Bierman and Smidt, 1984 and Price, 1993).

The question is how to represent this qualitative reduction of benefits and costs in a quantitative manner. The answer is through discounting of the future benefits and costs. This is achieved by applying a present worth factor (Dandy and Warner, 1989) or discount factor (Price, 1993) which is represented by:

$$\frac{1}{(1+r)^n} \tag{3.1}$$

where r is called the discount rate and n is the number of years from the present time. The discount rate, r, is generally given as a percentage per annum (ie. 6%). Thus the present value of any future benefit or cost is calculated by the following formula:

$$P = \frac{F_n}{(1+r)^n} \tag{3.2}$$

where P is the present value and F_n is the future value of a benefit or cost in year n.

This discounting effect is then used in the net present value method to select projects. The net present value (NPV) of a project is simply the present value of benefits minus the present value of costs. The project with the highest NPV is the best option for selection.

When the benefits are not known or are considered the same for all projects it is simpler to calculate the present value of costs and the project with the lowest value is selected.

Other methods for selecting projects were examined by Bierman and Smidt (1984) and Dandy and Warner (1989). Bierman and Smidt (1984) examined the selection of projects via a payback method, return on investment, internal rate of return (IRR) and net present value. Of these, the NPV method was the only method to give a definite sequence for a four project example. The other methods gave sequences where two of the projects were equally likely to be the first project selected.

Dandy and Warner (1989) also found the NPV method was a superior method to the alternatives that were examined. These alternatives were payback period, equivalent annual worth (EAW), benefit/cost ratio (B/C) and internal rate of return. Although, it was found that NPV favours large projects when comparing mutually exclusive projects, this disadvantage was considered minor compared to its advantages over the other methods. The payback period fails to deal with the time value of money in a correct manner and is seldom used for this reason. The equivalent annual worth involves the calculation of NPV to achieve a value for each project and since it gives the same order of projects as NPV, the NPV method is favoured. The benefit/cost ratio has appeal with capital budgetary problems but there may be some ambiguity as to the definition of costs and benefits. For example, benefits are often savings in costs and costs may be reduction in benefits. The result is that different values of B/C occur which may change the order of projects. IRR has the benefit as it does not rely on a specific discount rate. However, to solve for the IRR a polynomial must be solved usually by trial and error and occasionally a number of possible values may be obtained for a particular project.

When using the NPV method, one consideration is the value that the discount rate should take. It is suggested that the discount rate should be equal to the opportunity cost of capital (Wilkes, 1983 and Dandy and Warner, 1989). The opportunity cost for the private sector varies in time and from company to company and is defined as the highest rate of return that can be obtained when extra capital is available. Thus, the discount rate is usually higher than the interest paid on borrowed capital (Dandy and Warner, 1989). For the public sector the discount rate is based on either the average yield of long term government bonds or the social opportunity cost or the social time preference rate. Although each method is justified the final decision on discount rate is usually political and the best method may be to carry out a sensitivity analysis using the discount rate (Dandy and Warner, 1989). The discount rate should be selected carefully as the value directly affects the selection of projects. Wilkes (1983) illustrated that a change in discount rate altered the sequence of projects when using the NPV criteria. In addition, an incorrect estimate of discount rate may result in the selection of a project which is not a viable option (NPV<0) when an appropriate discount rate is used.

Another factor (other than discount rate) which affects the value of future benefits and costs is the inflation rate. The inflation rate has the reverse effect on the benefits and costs of the discount rate, as it will tend to increase benefits and costs as time continues. There are two ways to incorporate inflation into the NPV criteria. The first is to work in actual dollars and use a nominal discount rate and the second is to use constant worth or real dollars and the real discount rate (Bierman and Smidt, 1984, Dandy and Warner, 1989 and Price, 1993). The nominal discount rate includes inflation while the real discount rate is the rate above inflation. For example, if the inflation rate is 10 %, the nominal discount rate may be 15 %, while the real discount rate is approximately 5 %. In addition, actual dollars increase with inflation while constant worth or real dollars stay the same over time. The first method is most commonly used for the private sector while the second method is used in public sector investments (Dandy and Warner, 1989). The second method has an advantage over the first method as it does not require detail on the forecast inflation rate, which will vary from year to year. This makes the incorporation of inflation difficult unless a constant rate is assumed.

The NPV is used in this study as it appears to be the best criteria to select projects. If the effect of discounting is considered then benefits and costs at different points in time cannot be directly compared or added and subtracted. Thus, those benefits and costs should be brought back to a reference point, namely the present or time zero, where the net present value of the benefits and costs can be found (Bierman and Smidt, 1984, Dandy and Warner, 1989 and Price, 1993). Therefore, the NPV method enables a comparison of benefits and costs of different projects at a particular point in time. In addition, when it is considered that all the studies reviewed previously have used discounting and the present value or net present value method then it would appear that the most appropriate selection method is NPV.

The evaluation of NPV will use constant worth or real dollars and the real discount rate. This is the primary method used for public sector investments (Dandy and Warner, 1989) and the water resource sequencing question is generally a public sector problem. In addition, a sensitivity analysis will be undertaken using various values of discount rate to examine the effect of discount rate on the capacity expansion decision.

3.3 Pricing Methodology

The pricing methodology used in this study follows the basic economic principles of supply and demand. This discussion relates primarily to the factors affecting the demand side of the problem, particularly price. The relationship between price and demand has been illustrated in the literature survey and will be further emphasised here. Of particular interest is the relationship between price and demand through the price elasticity of demand. In addition, the objective of maximisation of the net present value of benefits including pricing policies will be discussed. Finally, the possible effects of demand management measures on the demand and thus on the supply possibilities will be discussed.

There are numerous water rating structures which exist. Such rating structures include a fixed charge, uniform rate per unit, decreasing and increasing block rate, seasonal rate, excess usage charge and a mixed schedule (Dandy et al., 1983). The fixed charged rating structure applies a fixed charge per billing period. The uniform rate per unit sets the same price per unit of water for each consumer. Decreasing and increasing block structures are opposite forms of each other where the unit rates are lower for high consumption for the decreasing block system whereas the unit rates are lower for low consumption in an increasing block structure. The seasonal rate applies higher unit prices to summer usage. The excess usage charge is applied to usage in summer above an allowance level which is set at the consumers average winter consumption. The final rating structure, the mixed schedule, is a combination of the others structures mentioned.

Each of these methods of pricing have their advantage and disadvantages. For example, the fixed charge and decreasing block structures do not encourage conservation. However, a justification for using decreasing block structure is that fixed costs, such as interest payments and billing costs, should be recovered by charging higher prices for initial units of consumption. On the other hand, the increasing block structure penalises large consumers and encourage water consumption. The seasonal and excess use charges encourage reduction in peak consumption levels, particular in summer. This will help in alleviating difficulties with water supply components whose design capacities are based on peak daily or hourly demands (Dandy et al., 1983).

Of the various rating structure mentioned the mixed scheduling structure is the most commonly used. In fact, Lippiatt and Weber (1982) indicate that for a sample of 90 water utilities in the USA, approximately 98 % of these water utilities use a form of the mixed scheduling rating structure (Dandy et al., 1983). Such a method was also specified by Gallagher (1975) as being the most effective rating structure in terms of equity and cost recovery. Gallagher (1975) advocated a mixed structure using a fixed charge and a uniform rate per unit. In this case, the uniform rate per unit was set at the marginal cost of supply (or the marginal cost price) and the fixed charge was set so that cost recovery could be achieved. Marginal cost pricing involves the setting of the price at the short-run marginal cost of the system when the capacity exceeds supply. As the demand approaches the capacity of the system the price is increased to reduce demand. The price continues to increase until it is efficient to augment the existing capacity. At this time the price should return to the short-run marginal cost of supply. Figure 2.3 in Chapter 2 illustrates the theory of marginal cost pricing.

The marginal cost pricing policy was found to produce greater benefits than a constant or average cost pricing policies (Riordan 1971a, b, Gysi and Loucks, 1971, Dandy et al, 1984 and 1985 and Swallow and Marin, 1988). However, marginal cost pricing can be hard to apply in reality and there can be political ramifications from altering price continually. Also previous use of marginal cost pricing assumes that the market adjusts at no cost, however this is unlikely to be the case. In addition, when the marginal cost price is lower than the average price a water authority will not be able to cover costs. In this case a fixed charge would also be required to enable the costs of the system to be covered. Such a rating structure has been mentioned previously.

Rather than using the marginal cost price in the mixed rating structure it is also possible to use an average cost price. The average cost price is determined by dividing the total annual cost of supply by the total volume of water supplied. With the total system costs being considered in the determination of price there is no longer a need for a fixed charge in the rating structure as costs should be covered. Thus the rating structure will resemble the uniform rate per unit structure rather than the mixed rating structure. A problem with the average cost pricing policy is that it does not produce the same economic benefits as the other pricing structures. However, a benefit of average cost pricing is the fact it ensures cost recovery without the need for any additional charges. This is not the case with other pricing policies. In addition, the average cost pricing policy is easier to implement than a marginal cost pricing policy which will be constantly fluctuating over time. However, it is considered that the average cost price does not reflect the true cost of the water supply. For instance when the water supply system reaches its capacity the true cost of the water increases, however this is not demonstrated by the average cost pricing structure.

An alternative pricing policy is to use a constant cost price which is constant in time but if the constant cost price changes then the level of consumption will also change. A constant cost pricing policy will have the benefits of the average cost pricing policy of being politically acceptable and easy to implement while it is likely to achieve higher benefits than the average pricing policy. In addition, a constant cost pricing policy is more likely to cover costs better than a marginal cost pricing policy. However, the benefits of a constant cost price policy will be less than the marginal cost price policy although Swallow and Marin (1988) estimate for a particular case study that 98.5% of the benefits obtained by a marginal cost pricing policy can be obtained with a constant pricing policy, if the level of the constant price is optimised. Therefore, it was decided that a constant pricing policy would be used in this study. As all the cost will not be covered using a constant cost price, a fixed charge will also be required (ie. service charge or connection fee). Thus the rating structure to be used in this study will resemble a mixed rating structure advocated by Gallagher (1975). However, the main emphasise of this study will be on choosing the value of constant cost price rather than the value of the fixed charge. Neglecting the fixed charge in the evaluation is not expected to affect the analysis. The reason is that the price elasticity for water is low and the overall effect is expected to be only minimal (Swallow and Marin, 1988).

The traditional demand curve and relationship between price and demand is illustrated in Figure 3.1. This applies to a single household for a year and assumes all other factors are fixed, eg. income, price of other goods, etc.

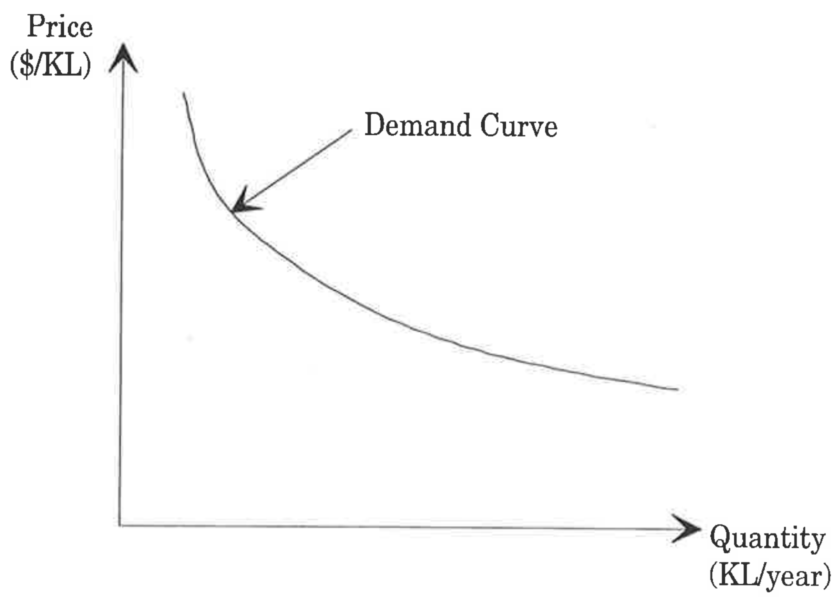

Figure 3.1 The Relationship between Price and Demand

The demand curve shown in Figure 3.1 assumes a constant price elasticity of demand. However, the demand curve will not always be represented in such a manner and it may in fact be linear or non-linear. In such cases the price elasticity of demand will vary along the curve. The particular case shown in Figure 3.1 can be represented by Equation 3.3.

$$Q_n(P_n) = Q_0\left(\frac{P_n}{P_0}\right)^{\beta} \tag{3.3}$$

where $Q_n(P_n)$ is the total demand in year n, for price P_n, Q_0 is the demand which corresponds to the price P_0, P_n is the price in year n and β is the price elasticity of demand for water. The value of Q_0 may change with time, which will shift the demand curve.

With the inclusion of price the objective of pricing and project sequencing will be the maximisation of the net present value of consumer benefits (NPV) because there are benefits to the consumer and water authority which are affected by the price of water. The minimisation of costs alone would lead to ever increasing price because as the price increases the demand decreases and so the present value of capital and operation and maintenance cost will also decrease. Therefore the benefits of price changes are included. The NPV can be defined by the following expression:

Net present value of consumer benefits (NPV) =
Consumer surplus + Producers revenue
- Operational costs - Capital costs

The definition of costs in the above expression are straight forward. The operational cost is simply the present value of annual operating costs given a operating cost per unit of water supplied and the amount of water supplied. The capital costs are the present value of capital costs resulting from the building of future projects. The producers revenue is simply the present value of revenue, with revenue being the price multiplied by the amount of water supplied. The consumer surplus however is a more complicated concept. The complication arises as the other terms in the NPV expression can be physically measured whereas the consumer surplus is an economic concept. The concept of consumer surplus is illustrated in Figure 3.2. It represents what the consumers would be willing to pay for water (ie. its value to them) less what they are actually required to pay.

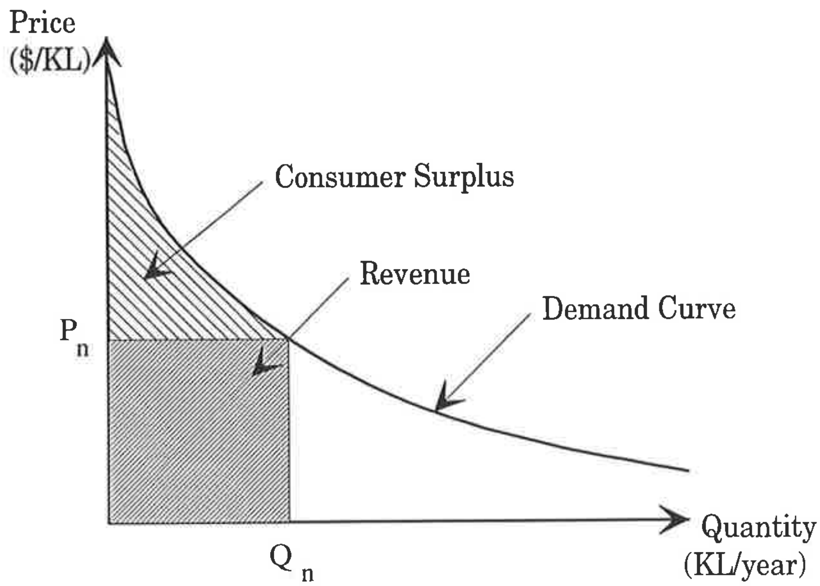

Figure 3.2 Consumer Surplus and Revenue when the Water Price is P_n ($/KL) and the Quantity is Q_n (KL/year)

From Figure 3.2 the consumer surplus is the area to the left of the demand curve above the price P_n. The expression for calculating consumer surplus assuming a constant price elasticity of demand is given by Equation 3.4.

$$\text{Consumer Surplus}_n = (1-\rho_n)\int_{P_n}^{P_n^u} Q_n(P)dP \qquad (3.4)$$

where P_n^u = the price in year n when demand is effectively zero and ρ_n is the system losses as a fraction of total volume supplied in year n. Substituting Equation 3.3 into Equation 3.4 results in Equation 3.5:

$$\text{Consumer Surplus}_n = (1-\rho_n)\int_{P_n}^{P_n^u} Q_0\left(\frac{P_n}{P_0}\right)^{\beta} dP$$
$$= \frac{(1-\rho_n)(Q_0)}{(1+\beta)}\left[\left(\frac{P_n^u}{P_0}\right)^{\beta} P_n^u - \left(\frac{P_n}{P_0}\right)^{\beta} P_n\right] \qquad (3.5)$$

The general expression for NPV using the definition of consumer surplus (Equation 3.5), is defined by Equation 3.6.

$$\text{NPV} = \sum_{n=1}^{N}\left((1-\rho_n)P_nQ_n + \frac{(1-\rho_n)(Q_0)}{(1+\beta)}\times\right.$$
$$\left.\left[\left(\frac{P_n^u}{P_0}\right)^{\beta} P_n^u - \left(\frac{P_n}{P_0}\right)^{\beta} P_n\right] - V_nQ_n\right)(1+r)^{-n} - \text{PVC} - \text{OPC} \qquad (3.6)$$

where Q_n is the supply from the system in each year n, V_n is the annual operation and maintenance cost ($/KL) and PVC is the present value of capital cost of future projects built during time period N. The term OPC is an additional cost for the annual operation and maintenance of new reservoirs. The annual value is a percentage of the initial capital cost of the new reservoir and is independent of the supply of the reservoir. The calculation of this value is as follows :

$$OPC = OC_i \left[\frac{1-(1+r)^{-(N-n_b)}}{r} \right] (1+r)^{-n_b} \tag{3.7}$$

where OC_i is the annual operating and maintenance cost of project i, in $ million, n_b is the year in which the new reservoir is built and N is the length of the time period.

The variation in the general expressions for consumer surplus and NPV will depend on the demand growth rate for a particular problem. In this study, the demand growth cases of exponential and linear demand growth are examined. The change in the consumer surplus and NPV, to incorporate the variation in demand growth, involves the replacement of the term Q_0 in Equations 3.3, 3.5 and 3.6, with the following expressions:

$$\text{Exponential demand growth :- } Q_0 = q_0[1+w]^n POP_0 \tag{3.8}$$

$$\text{Linear demand growth :- } Q_0 = q_0[1+wn]POP_0 \tag{3.9}$$

where q_0 is the initial demand per capita, w is the growth rate in the initial population per year and POP_0 is the initial population size.

The exponential demand growth case will apply for the Canberra case study in Chapter 4, while the linear demand growth case is assumed to apply for the South-East Queensland case study in Chapter 6. The composition and definition of the NPV for the Canberra case study and the South-East Queensland case study, are represented by Equations 3.6 and 3.7 with Q_0 being given by Equations 3.8 and 3.9 (respectively).

3.3.1 Demand Management

The concept of demand management has become popular in recent times. This is due to the fact that available water resources are becoming increasingly scarce and water authorities wish to encourage more efficient usage of water. The benefit of demand management techniques is that they act as an alternative to the augmentation of an existing supply. Thus demand management measures are a way to delay future cost to the water authority.

The demand management measures utilised can be grouped into the following four categories; structural (ie. water saving devices), economic (ie. change in rates structure), operational (ie. water restrictions) and sociopolitical (ie. publicity, education, legislation) (Flack and Greenberg, 1987). These methods may have two possible effects on the consumer's demand curve. Publicity campaigns, voluntary use of water saving appliances and voluntary restrictions would cause the demand curves for individual consumers to move down as shown in Figure 3.3 (Dandy and Connarty, 1994).

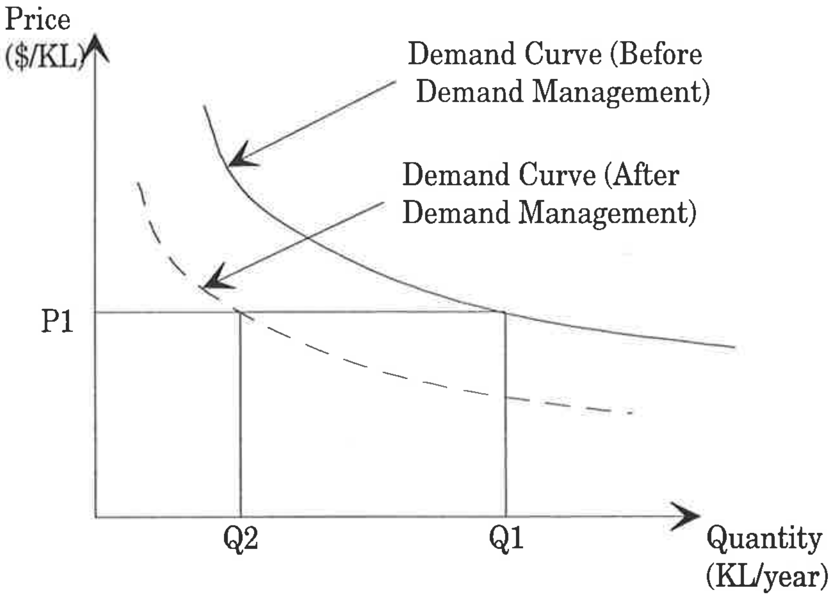

Figure 3.3 Effect of Voluntary Demand Management Measures

As shown this would cause the consumer to lower their consumption at any particular price P_1 ($/KL) from Q_1 (KL/year) to Q_2 (KL/year). There is a consequent loss of revenue to the water authority and loss of consumer surplus (although, presumably the consumers, having voluntarily reduced demand will feel some gain in utility by doing so).

Mandatory measures such as water restrictions or legislated use of water-efficient appliances will cause a restriction (or rationing) of demand as shown in Figure 3.4.

The effect on the consumer is to reduce their consumption from Q_1 (KL/year) to Q_3 (KL/year) with no significant change in the demand curve. Again there will be a loss in revenue and a loss in consumers surplus. The latter would appear to be smaller than for voluntary demand management measures.

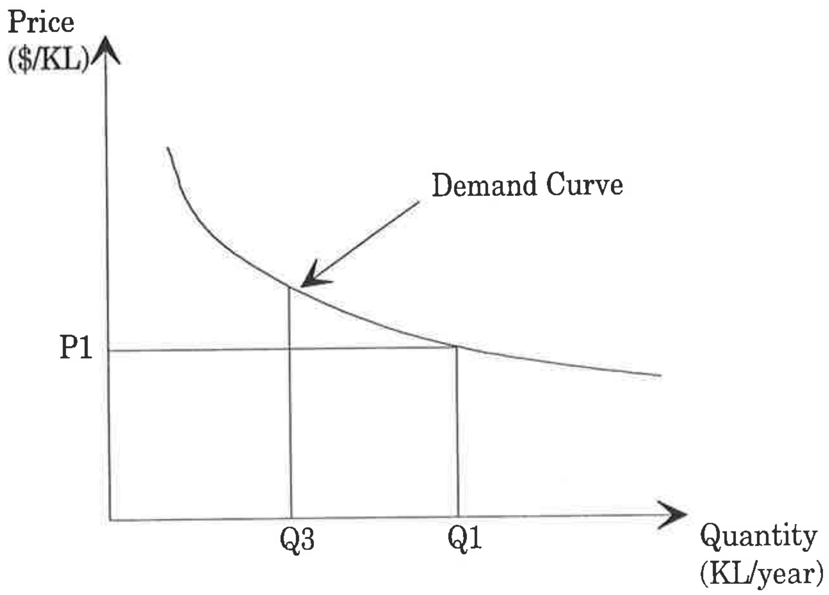

Figure 3.4 Effect of Mandatory Demand Management Measures

In previous studies, the demand management problem has been dealt with in two ways. Firstly, if the effectiveness and the cost of implementing demand management measures is known then various demand management techniques can be treated in a similar manner to possible new projects (Rubinstein and Ortolano, 1984). However, instead of increasing supply they will reduce demand. Alternatively, the effect of demand management techniques can be included in the future demand forecasts (Lane, 1991). This method is suitable if the cost of implementing a demand management technique is not known. In such a case the demand management techniques may be considered voluntary (eg. Figure 3.3). In this study as cost information is unknown for the various case studies in which demand management will be examined, it will be assumed that voluntary demand management occurs. As one of the case studies is on the South-East Queensland System examined by Lane (1991) then demand management will be considered in the future demand forecasts. In the other case study investigating demand management, the effect of demand management will be assumed to occur at the start of the time period. The levels of demand management which will be investigated are 10 and 20% reduction in per capita demand. It is assumed that a demand management measure will have an immediate effect rather than the expected lag due to implementation of the measure.

3.4 The Capacity Expansion of Future Water Resources

As discussed in the previous chapter the capacity expansion problem can encompass a variety of different issues depending on the definition used. It can involve the evaluation of the sizing of reservoirs or the sequencing of previously sized reservoirs. The size and sequence of reservoirs can also be determined. Alternatively, the objective may change which will result in a variation to the size or sequence of reservoirs.

In this study three different case studies will be utilised which examine three variations to the capacity expansion problem. The various case studies will examine the following problems :

1) The simple sequencing of reservoir projects,
2) The sizing and sequencing of reservoir projects; and
3) The sequencing of reservoir projects with the operation cost of the system incorporated in the evaluation.

The first two cases will examine optimum pricing policies in conjunction with capacity augmentation.

A brief description of each capacity expansion problem is given below.

3.4.1 Sequencing of Future Water Resources

The sequencing problem involves deciding on the order of implementation of a number of reservoir or groundwater projects given a specific size and yield for each reservoir. All reservoirs are assumed to be independent of each other so that the yield of any of the existing reservoirs will not change following the building of any particular reservoir. It is also assumed that only one reservoir can be built at any one time and no future extension of reservoirs is possible. The objective is the minimisation of the capital cost of the reservoirs. The inclusion of price simply changes the objective to the maximisation of system benefits and affects demand according to Equation 3.3

3.4.2 Sizing and Sequencing of Future Water Resources

The inclusion of size into the sequencing problem produces a more complex problem. For simplicity it is assumed that reservoirs have a number of discrete size levels at which they can be built. For the case study which examines this problem the number of sizes per project will be limited to three.

Traditionally, the sizing and sequencing problem would be solved by finding the preferred size of each project and then sequencing the projects. An addition to the methodology is the possibility of upsizing individual projects. Although this is not carried out in practice it does offer the potential for considerable economic savings. The normal practice is to size projects to their optimal size or the maximum size, the choice depending on the security required in a system. Although an optimal size may be obtained which is less than the maximum size, planners may consider it appropriate to build the maximum size to increase the security of the system.

It is rare to see projects upsized, and, if they are, it is usually the result of a new study rather than being part of the original plan. The main reason for not considering upsizing is that it is thought to be too expensive for the return in yield. The problem behind upsizing becoming too expensive is that there is a large initial set up cost. In addition, the yield produced may not be significant. Thus, if upsizing does occur it usually is to increase the security of the system. However, it is considered that the cost of upsizing is not as large as first thought and if upsizing was part of a planning strategy the set up cost may be lower. The main reason for examining the possibility of upsizing projects is that it is considered that significant savings in the present value of cost may be obtained by using the upsizing of projects. For example, if the augmentation cost of upsizing is similar to the incremental cost then a similar total cost will be spent whether augmentation of a reservoir takes place or not. However, due to discounting, when augmentation is allowed the cost will be discounted to a certain degree. The result is a lower present value of cost and a better sequence for the augmentation case.

Thus for the sizing and sequencing problem, two situations will be examined. They are the case where no upsizing can occur to future reservoirs and where upsizing is allowed to occur. The first to be described is the simple no upsizing case. This resembles the simple sequencing problem, however there are multiple decisions possible at each reservoir site. When a reservoir is built at a particular site, then no further development of that site can occur. In addition, reduction in the reservoir size is not allowed. This also applies for the upsizing case.

The upsizing case allows augmentation of reservoirs in the future. The problem associated with this case is deciding on the capital cost of upsizing. The upsizing cost is considered to be dependent on the incremental cost associated with the increase in size of a project. Rather than assuming a particular cost a number of different costs are examined. The various costs for upsizing examined were 100 %, 120 % and 150 % of the incremental cost. Although the upsizing cost is unlikely to be 100 % of the incremental cost this was examined to illustrate the possible changes in sequence, size and therefore cost which can be obtained when using upsizing. The most probable upsizing cost will lie in the range of 120 % to 150 % of the incremental cost. The yield of larger projects will also change with the building of a smaller project. The yield of a larger project will simply be the incremental yield of that project (ie. the difference in yield between the two sizes of project).

3.4.3 Operating Cost and the Sequencing of Future Water Resources Projects

In this case the operation of future projects and therefore their operating cost will be included in the sequencing of projects. The problem is primarily the same as the simple sequencing problem although the operating cost is included in the objective of minimisation of present value of costs. In addition, the operating cost is included based on a $ /GL supplied value. Thus, the way the various alternatives supply water will affect the present value of operating cost obtained. It is assumed for this study that once a project is built it will supply the future growth in demand. This is assumed for all projects built. However, more importantly, the full operating cost of an alternative (ie. $/year) will be assumed to apply from the time of augmentation to the end of the planning period, regardless of the amount of water supplied from that project.

3.5 Sequencing Methods for Capacity Expansion of Future Water Resources

The sequencing methods used consist of the optimisation technique of linear programming and the heuristic approaches of the unit cost method, the equivalent cost per period (Erlenkotter, 1973a) and a process called genetic algorithms (GA). The GA method will not be discussed in this section but will be detailed in Chapter 5. The various methods are applied to the sequencing problems mentioned above.

3.5.1 Unit Cost Sequencing

The unit cost method is used as a comparison for the other methods in the capacity expansion studies and to highlight the importance of demand growth and discount rate in the sequencing decision.

The unit cost method is simply the sequencing of projects based on their cost of providing a unit of yield per annum. The theory is that to provide the lowest PVC sequence, the user simply orders the possible projects from lowest unit cost to the highest unit cost. The unit cost (UC_i) of a project i, is calculated by dividing the capital cost (C_i) of the project by the yearly yield (Z_i) of the project. This is the method applied to independent projects and is illustrated by Equation 3.10 :

$$UC_i = C_i / Z_i \tag{3.10}$$

For the size and sequencing problem the unit cost of all projects are selected and the sizing which provides the lowest unit cost for a particular project is the size which is used. In the case of no upsizing the project sizes above or below the size of project chosen at a particular site are depleted from the future possible expansions. For the upsizing case all project sizes larger than that built have their cost recalculated depending on the upsizing cost increase being considered (ie. 100, 120 or 150 % of the increment cost). The unit cost is then recalculated for that particular project and the project is then ordered accordingly. This continues until all projects are built to their maximum size.

When including the operating cost into the unit cost sequencing method, Equation 3.10 changes to include operating cost. In addition, the discount rate is included in the new unit cost method. This method is utilised by the WAWA to help select their future water resource projects (Stokes and Stone, 1993). It is more complex than the traditional unit cost method given by Equation 3.10. The following equation defines the unit cost (UC_i) of project i as:

$$UC_i = \left(C_i + O_i / r\right) \times \left(r / Z_i\right) \tag{3.11}$$

where C_i is the initial capital cost of project i, O_i is the annual operational cost of project i, r is the discount rate and Z_i is the incremental yield of project i. The first part of the expression is the capital cost plus the approximate present value of operational cost (PVOC). The value O_i/r is only an approximation as the true present value of operating cost given a constant annual operating cost is shown in Equation 3.12.

$$PVOC = O_i \times \left[\frac{1-(1+r)^{-t}}{r}\right] \tag{3.12}$$

The value t is the time period the project is in operation and the system incurs the operating cost, O_i. Now if it is expected the project will last a considerable time (>100 years) then as t becomes increasingly large then the value of PVOC will get closer to the value O_i/r. Therefore the use of O_i/r is a good approximation of the PVOC. The assumption of a long time period is justified as even if the current project is replaced, the operational cost is likely to remain the same, if the replacement project is similar.

3.5.2 Equivalent Cost per Period Sequencing

The equivalent cost per period method (Erlenkotter, 1973a) has already been discussed in Chapter 2. This method sequences projects for an infinite time period over continuous time. It was primarily developed to consider only the capital cost of a project. The method itself is superior to the traditional unit cost method in sequencing projects so as to find the lowest present value of capital cost (PVCC). It is superior to the unit cost method as it considers not only the capital cost and yield of a project but also discount rate and demand growth rate. In fact Erlenkotter (1973a) has shown that this method will give an optimum solution for linear demand growth and an infinite time horizon. The method for obtaining the lowest PVC sequence is the same as the unit cost method. However, in this case the projects are ordered from the lowest to the highest value of the equivalent cost per period. The equivalent cost per period is defined by Equation 3.13.

$$\alpha_i(Z) = \frac{rC_i}{1 - \exp^{-\left(\frac{rZ_i}{\delta}\right)}} \qquad (3.13)$$

Here $\alpha_i(Z)$ is the equivalent cost per period for project i at capacity level Z, r is the discount rate, C_i is the cost of project i, Z_i is the yield of project i and δ is the demand growth rate (for the linear growth case). If the demand is non-linear, Equation 3.13 needs to be changed by replacing Z_i/δ by $\Delta_i(Z)$. The term $\Delta_i(Z)$ is defined as the time interval until the next expansion is required following project i at capacity level Z. This is can be represented by the following equation

$$\Delta_i(Z) = t(Z+Z_i) - t(Z) \qquad (3.14)$$

where t(Z) is the time at which the demand equals the capacity level Z.

When examining the size and sequencing problem, the equivalent cost per period will be calculated for all project sites and sizes. The process of size and sequencing the projects is the same as for the unit cost method except the equivalent cost per period is used.

The equivalent cost per period method is also used for the case when operating cost is included. In this case the present value of operating cost (O_i/r) is included in the numerator of Equation 3.13 to produce the following formula:

$$\alpha_i(Z) = \frac{r\left(C_i + O_i / r\right)}{1 - \exp^{-\left(\frac{rZ_i}{\delta}\right)}} \qquad (3.15)$$

The sequence is obtained by ordering the new equivalent cost per period from lowest to highest values. This equation is similar to that of Erlenkotter (1975) where transportation and operating cost are included in sequencing problem.

3.5.3 Comparison of Equivalent Cost and Unit Cost Sequencing methods

As has been mentioned previously, the unit cost sequencing method does not in general, produce a sequence which minimises the total discounted costs (Butcher et al., 1969 and Erlenkotter, 1973a). This can be demonstrated by a simple example.

Assume there is a water supply authority which needs to expand the current supply system to ensure demand is satisfied. The authority has four projects which it can proceed with, the details of which are given in Table 3.1.

Table 3.1 Project Costs and Yields

Project Number	Annual Yield (GL/year)	Capital Cost ($Million)	Cost/Yield ($/KL/year)
1	60	25	0.42
2	20	10	0.50
3	20	10	0.50
4	20	10	0.50

The discount rate (r) is assumed to be 6 percent and the demand is assumed to have linear growth with an annual growth rate (δ) is 5 GL/year. For these conditions, the planning period was set at 24 years but this will change when the demand growth rate is varied. When the demand growth rate doubles the planning period is shortened to 12 years and when it is halved it will be set at 48 years. These periods ensure that all projects are implemented, thus a true comparison can be made between the results of the equivalent cost method and the unit cost method of sequencing. The results of applying the initial data are given in Table 3.2.

Table 3.2 Sequencing of the Projects using the Unit Cost and the Equivalent Cost Method

Sequencing Option	Project Sequencing Order Run 1: δ=5 GL/year, r=6%				Present Value of Cost ($Million)
Unit Cost	1	2	3	4	37.024
Equivalent Cost (α)	2	3	4	1	36.619

This result shows that in this case, the unit cost method doesn't find an optimum solution and that the equivalent cost (α) method will produce a lower cost solution. The difference in present value is $0.405 million or 1.1%. The next stage is to vary the discount rate (r) and the demand growth rate (δ) from the initial conditions of Run 1 and examine the effects of the variation on the timing and sequencing decision. These results are given in Table 3.3.

It is evident from the results in Table 3.3 that the optimum sequencing of projects is dependent on both the discount rate and demand growth rate. This contradicts the results of Morin (1973) who indicated that the optimum sequence of projects is reliant on the demand growth rate but is not affected by the discount rate. The reason for the discrepancy, is that under certain conditions it is possible that the discount rate will not effect the optimum sequence of projects. For instance, in Table 3.3 the optimum sequence of projects obtained when using the 2.5 GL/year demand growth rate does not change with different discount rates. However, for the higher demand growth rates the optimum sequence of projects does change with a variation in discount rate. Thus it is possible that the observation of Morin (1973) is correct for a particular case, but as is seen here, it is not true in general. However the conclusion of Morin (1973) that both discount rate and the demand growth rate had an effect on the discounted cost was found to be true.

The true nature of the effects of demand growth rate and discount rate on the sequencing of projects in this particular case, can be obtained by examining the results further.

Table 3.3 Effects of Varying Discount Rate and Demand Growth Rate on the Timing and Sequencing Decision

Sequencing Option	Project Sequencing Order Run 2: δ=10 GL/year, r=6%				Present Value of Cost ($Million)
Unit Cost	1	2	3	4	43.908
Equivalent Cost (α)	1	2	3	4	43.908
Sequencing Option	Project Sequence Order Run 3: δ= 2.5 GL/year, r=6%				Present Value of Cost ($Million)
Unit Cost	1	2	3	4	29.992
Equivalent Cost (α)	2	3	4	1	26.385
Sequencing Option	Project Sequence Order Run 4: δ=5 GL/year, r=12%				Present Value of Cost ($Million)
Unit Cost	1	2	3	4	30.235
Equivalent Cost (α)	2	3	4	1	26.811
Sequencing Option	Project Sequence Order Run 5: δ=5 GL/year, r=3%				Present Value of Cost ($Million)
Unit Cost	1	2	3	4	43.782
Equivalent Cost (α)	1	2	3	4	43.782
Sequencing Option	Project Sequence Order Run 6: δ=10 GL/year, r=12%				Present Value of Cost ($Million)
Unit Cost	1	2	3	4	37.325
Equivalent Cost (α)	2	3	4	1	36.993
Sequencing Option	Project Sequence Order Run 7: δ=2.5 GL/year, r=3%				Present Value of Cost ($Million)
Unit Cost	1	2	3	4	36.868
Equivalent Cost (α)	2	3	4	1	36.424
Sequencing Option	Project Sequence Order Run 8: δ=2.5 GL/year, r=12%				Present Value of Cost ($Million)
Unit Cost	1	2	3	4	26.030
Equivalent Cost (α)	2	3	4	1	17.317
Sequencing Option	Project Sequence Order Run 9: δ=10.0 GL/year, r=3%				Present Value of Cost ($Million)
Unit Cost	1	2	3	4	48.710
Equivalent Cost (α)	1	2	3	4	48.710

It is evident that the method of using the equivalent cost per period produces lower or the same discounted costs to that of the unit cost method. When the discount rate and demand growth rate changes, the equivalent cost method has the ability to consider the changes and find a better sequence for the project set than may be achieved by the unit cost method. It appears from Runs 3,4 and 8, that when the discount rate is high or when the growth rate in demand is low or both (ie. Run 8), then the benefits of the equivalent cost method are greater. It is also evident that if the growth rate in demand is high or the discount rate is low or both, then the equivalent cost method produces the same sequence as the unit cost method and thus has the same discounted cost for this particular case.

Runs 6 and 7, are when both the discount rate and the demand growth rate are both either high or low. The benefit obtained by using the equivalent cost method is only marginal. These runs are cases which have the discount rate and the demand growth rate in the same proportion as Run 1. It appears that when the two factors are in the same ratio, the result is a similar discounted cost and the same sequence (in this particular example) for all cases.

The results from this simple example support the conclusion of Butcher et al., (1969) and Erlenkotter (1973a) that the unit cost method does not produce the lowest cost result. It is also evident that both the demand growth rate and the discount rate, affect the sequence and present value of cost. Thus, the discount rate and demand growth rate need to be considered in order to produce a low cost sequence of projects.

3.5.4 Integer/Linear Programming

The next method considered is the integer/linear programming method. The integer variables used are of the binary form. That is they may take either the value 1 or 0. The formulation of the model differs when considering the no upsizing and upsizing cases. For this reason an explanation of both will be given. The first formulation to be explained is the case of no upsizing allowed.

3.5.4.1 No Upsizing Allowed

In this formulation the decision variables are X_{ijk} , where $X_{ijk} = 1$ if project i of size j is implemented at the start of time period k ; and equals 0 otherwise. There are J possible sizes of each project. The objective of the model is to minimise the present value of costs which is determined by the following expression:

$$PVC = \sum_{k=1}^{T} \sum_{i=1}^{N} \sum_{j=1}^{J} \left(X_{ijk} \times C_{ij} \times (1+r)^{-k} \right) \tag{3.16}$$

where PVC is the present value of costs, C_{ij} is the cost of project i, size j, r is the discount rate, T is the number of time periods and N is the number of different project sites. The following constraints apply :

$$X_{ijk} = 0,1 \qquad \forall i, j, k \tag{3.17}$$

$$\sum_{j=1}^{J} \sum_{k=1}^{T} X_{ijk} \le 1 \qquad \forall i \tag{3.18}$$

The remaining constraint in the model ensures that the system yield equals or exceeds the demand for all time periods. This is specified by the following equation.

$$\sum_{m=1}^{k} \sum_{i=1}^{N} \sum_{j=1}^{J} \left(X_{ijm} \times Z_{ij} \right) + Y \ge D_k \qquad \forall k \tag{3.19}$$

where Z_{ij} is the yield of project i, size j, Y is the yield of the existing system at time zero, D_k is the demand at the end of time period k and m represents the number of time periods examined.

3.5.4.2 Upsizing Allowed

In this formulation there is one basic change to the theory which results in a significant change in the formulation from the previous case. The decision variable X_{ijk} is basically the same as for the no upsizing case, except it will equal 1 if project i is incremented from size j-1 to size j ; and equals 0 otherwise. The yield of project i, size j, (Z_{ij}), is now the incremental yield between project sizes j and j-1. In addition, a new binary decision variable Y_{ijk} is used to consider the upsizing of projects. When $Y_{ijk} = 1$, project i is upsized to a size j, at the start of time period k ; and equals 0 otherwise. With the inclusion of Y_{ijk}, Equation 3.16 changes to incorporate the change in upsizing cost. The objective of the model is again to minimise the present value of costs which is determined by the following expression:

$$PVC = \sum_{k=1}^{T} \sum_{i=1}^{N} \sum_{j=1}^{J} \left(\left[X_{ijk} + c1 \times Y_{ijk} \right] \times C_{ij} \times (1+r)^{-k} \right) \tag{3.20}$$

where PVC is the present value of costs, C_{ij} is the incremental cost of project i, size j, c1 is the increase in project cost due to upsizing, r is the discount rate, T is the number of time periods and N is the number of different project sites. If the upsizing cost is equal to 120 % of incremental cost then c1 will equal 0.2. The following constraints apply :

$$X_{ijk} = 0,1 \qquad \forall i, j, k \qquad (3.21)$$

$$\sum_{k=1}^{T} X_{ijk} \le 1 \qquad \forall i, j \qquad (3.22)$$

$$\left(\sum_{m=1}^{k} X_{ijm}\right) \ge \left(X_{ij'k}\right) \qquad \forall i, k, j < J \qquad (3.23)$$

where j' = j + 1. The value of Y_{ijk} is dependent on the value of X_{ijk} . Therefore, the following constraints are also used to ensure Y_{ijk} is assigned the correct value (A maximum value of J=3 is assumed) :

$$Y_{ijk} = 0,1 \qquad \forall i, j, k > 1 \qquad (3.24)$$

$$Y_{ijk} \ge X_{ijk} - X_{ij-1k} \qquad \forall i, j > 1, k \qquad (3.25)$$

$$Y_{ijk} \ge X_{ijk} - X_{i1k} \qquad \forall i, j = 3, k \qquad (3.26)$$

For Equation 3.24 when k=1, that is in the first period, there is no upsizing for if a project is built to size 2 or 3 then this is the initial size that the project is built to. Thus, no increase in upsizing cost needs to be considered and Y_{ijk} will equal 0. Equation 3.25 is to ensure that if any project is upsized after period one, the appropriate value of Y_{ijk} is assigned. For instance, if a project is built in period 1 and then upsized in period 2, the value of X_{ijk} is 1 for period 2, however, the value of X_{ij-1k} is 0, as the initial building of the project was not in period 2. Y_{ijk} has the value of 1 (ie. 1≥1-0) in period 2. Equation 3.26 is used to take account of the problem in Equation 3.25, when the first size is built in a previous period and then the next two sizes are built in the same period. If this occurs the result of Equation 3.25 will be Y_{ijk} equals 0 (ie. 0≥1-1) for site 3 (j=3), but it should be equal to 1 to account for the further increase in size and therefore cost. Equation 3.26 accounts for this by checking if the original building is in the same period when j=3. As it is not in this case, X_{i1k} will equal 0 so Y_{ijk} will be set to 1 (ie. 1≥1-0) in period 3. In addition, as Equation 3.25 is an inequality it will not be violated by this change in value of Y_{ijk} (ie. 1≥1-1). This last point is partly the reason an inequality is used in the model. The other reason is brought about by the other possible outcomes of Equations 3.25 and 3.26. Let us consider the outcome when the equation is changed so it is an equality (ie. both sides are equal). If a single addition is made to the initial size, but in a different period. This will mean that X_{ijk} will equal 1 for j equals 2 but 0 for j equals 3. Therefore if Y_{ijk} is calculated when j equals 2 the value obtained is 1 (ie. 1=1-

0). This is okay however, if Y_{ijk} is calculated when j equals 3 the value obtained is -1 (ie. -1=0-1). This will violate Equation 3.24 and no solution will be obtained. However, in this last case if an inequality is used and the value of Y_{ijk} must be either 0 or 1 the answer obtained will be 0 ($0 \geq 0-1$), which is correct.

The integer/linear programming formulations, were run using a linear programming optimisation package, LINGO (Schrage and Cunningham, 1991).

3.6 Yield Evaluation Techniques

The determination of system yield is an important consideration when planning extensions to a multiple reservoir system. The yield of a multiple reservoir system is defined as the quantity of water which can be supplied in each time step at a specified reliability (McMahon and Mein, 1978). Reliability is the probability of being in a non-failure state during any particular time period. Failure may relate to the imposition of restrictions of a specified magnitude or reaching the dead storage level in one or more reservoirs.

In this study, the safe historical yield will be used. This corresponds to the maximum yield which can be supplied with 100 % reliability for the total historical flow record. The yield of a multiple reservoir system depends on the following:

(a) the physical configuration of the system;
(b) the capacities of the reservoirs, pipelines and pumping stations;
(c) the statistical properties of the natural streamflows and evaporations; and
(d) reservoir operating rules.

Many techniques are available to estimate the yield of a single reservoir (McMahon and Mein, 1978). Most of these do not require the specification of operating rules, yet operating rules are an important consideration in the estimation of reservoir yields. This is especially true for multiple reservoir systems. The operating rules for an existing reservoir system may or may not be known explicitly. In the latter case, rules will need to be determined from the actions taken by the operators in specific situations and periods. Current operation may be based more on historical precedent and rules-of-thumb rather than aiming to satisfy an objective criterion. For a proposed new reservoir system (or expanded system) a set of reasonable operating rules need to be identified before it is possible to estimate the yield of the system.

The techniques available to estimate the yield of a multiple reservoir system include simulation, optimisation and combinations of optimisation and simulation. Simulation is undoubtedly the most commonly used technique with many authorities using custom built computer models of their system to assess its yield as well as to assist in operations and planning. A survey of major water authorities in Australia (McMahon and Gan, 1989) found that 88% of the authorities had used computer simulation to assess the yield of their headworks system. Daniell and Falkland (1989) discuss a simulation model to estimate the yield of the Canberra water supply system. This simulation model is further detailed by Pink and Sooriyakumaran (1988) and Pink (1991). Simulation was also used by Vogel and Hellstrom (1988) to investigate the variability in the safe yield for the eastern Massachusetts water supply system.

There are a number of generic simulation packages available (Wurbs, 1991 and Loucks, 1992). These include HEC-3 and HEC-5 (Feldman, 1986), MITSIM (Strzepek et al., 1989), RESQ (Ford, 1990) and IRAS (Loucks et al., 1993). These differ in terms of their capacities, interfaces, inputs and outputs.

Optimisation methods such as linear and dynamic programming can also be used to estimate system yield (Loucks et al., 1981). Optimisation methods have the advantage of not requiring operating rules to be defined but instead assume optimum operating decisions are made at every time step. In addition, most deterministic models assume perfect forecasts of future streamflows. For these reasons, yield estimates from many optimisation model represents an upper bound on what can be achieved in the actual operation of the system. However, optimisation methods can be used to give an approximation to the yield of an expanded system without having to consider detailed operating rules.

The use of optimisation models in determining the yield of a system can be limited. If the system being examined is large or requires a lengthy streamflow record to provide accurate yield estimates, the optimisation techniques may take considerable computation time to obtain a solution. Alternatively, an approximation to the optimisation method could be used. Such a method called the yield model was developed by Loucks (1976) and Loucks et al. (1981). The size of the problem is reduced by utilising over year reservoir storage for the annual yield and a within year storage to account for the seasonal fluctuations in yield. The yield model is formulated and solved using linear programming. A more detailed description of the yield model will follow this section.

The effectiveness of the yield model in reservoir design was examined by Stedinger et al. (1983). The yield model was compared with a linear programming (LP) model and chance constrained linear decision rule (LDR) models. All models were run for two cases. For the LP model, mean monthly and critical period flows were used. For the yield model ratios of expected inflows to a reservoir for mean and driest years were used and for the LDR model two LDR's were used. The yield model produced reasonable reservoir systems designs with release reliabilities near the targets, while the other models either produced inadequate or insufficient storage sizes, thus the efficiency and the reliability of the system varied depending on the model.

As mentioned, optimisation models do not require operating rules to determine yield estimates for a system. However, optimisation techniques can be used to define the operating rules of a system. Karamouz and Houck (1982) utilise optimisation in conjunction with regression analysis and simulation to obtain general, annual and monthly operating rules for a single reservoir. In addition, Martin (1983) used optimisation and simulation, within an iterative procedure to determine operating rules which maximise firm power benefits for a water system.

Another final class of models are the simulation models which use optimisation for determining operating decisions at each time step. The optimisation is usually carried out for each time step assuming only conditional expected inflows and demands, not the actual future values. Network linear programming is the commonly used optimisation procedure (Kuczera and Diment, 1988). Models of this type include SIMYLD-II (Texas Water Development Board, 1972), MODSIM (Labadie et al., 1984), WATHNET (Kuczera, 1990), DWRSIM (Chung et al., 1989) and the Acres model (Sigvaldason, 1976).

In using the above models either historical or synthetically generated streamflow data has to be chosen to estimate the yield of a system. The choice usually depends on the available length and reliability of the historical streamflow data. If a long and complete historical record is available then it is easier to use the historical record. If only a short record is available or the record is incomplete then synthetically generated data can be used. Vogel and Hellstrom (1988) compare the use of historical and synthetic generated data in determining the safe yield. They found that the use of synthetically generated data did not change the estimate of the medium safe yield from that found using historical data. A benefit associated with synthetically generated streamflow data is that a number of different drought sequences can be tested while still maintaining the particular system's characteristics. Although, considerably more effort is required to generate the data sets.

The majority of Australian water authorities use historical data to estimate yield while others utilise a series of different synthetic data generation techniques (McMahon and Gan, 1989). In the Canberra case study, historical streamflow data will be used because the historical record for the existing system is considered to be reliable and of adequate length (1912-1983). In addition, the same historical streamflow data was used by Pink and Sooriyakumaran (1988), Daniell and Falkland (1989) and Pink (1991) when evaluating the performance of the existing Canberra water supply system.

The value of safe yield may vary depending on the assumptions made with regard to streamflow length, reliability and operating rules. For instance, Vogel and Hellstrom (1988) considered the safe yield to depend on the planning period and long range reliability and that a single value of yield is unlikely and only an approximate value within an acceptable range for a specified reliability can be guaranteed. However, given the definition of safe yield above it is expected that a specific result will be obtained. Although, with different methods being utilised, it is likely different yield estimates will be obtained.

In this study the following techniques have been used to estimate the safe historical yield of a multiple reservoir system:

(1) an optimisation model that assumes perfect forecasts of future inflows;
(2) the yield model (Loucks et al., 1981);
(3) a generalised water supply simulation using network linear programming called WATHNET (Kuczera, 1990); and
(4) a simulation model of the actual system (ACTEW - Pink and Sooriyakumaran, 1988 and Pink, 1991).

The first three techniques use an optimisation procedure. Techniques (1) and (2) are both full optimisation techniques. They assume knowledge of the future inflows and can adjust operation and releases from reservoirs in previous periods, to provide the maximum possible yield of a system without shortfalls in supply occurring. Both methods operate the system optimally within and between periods rather than using operating rules. Essentially, the techniques assume optimum operation of the system in order to obtain the maximum yield. The difference between techniques (1) and (2) is that, technique (2) is an approximation of technique (1). The purpose of approximating the full optimisation model is to reduce the computation time required for the full optimisation. It will be mentioned later that because of the size of the optimisation model a reduced period is used to reduce computation time. This problem does not arise with the yield model and a much longer period can be investigated.

WATHNET uses a simulation process between time periods, however at every time period optimisation using network linear programming is performed. The optimisation is performed on a series of objectives built into the model. These are general objectives and are not specific to the system being examined. This technique differs from techniques (1) and (2) in that it does not anticipate future inflows and there is no optimisation of operations between time periods. To identify the safe yield of the system an iterative procedure needs to be undertaken by the user. The estimated yield of the system is input into the model and the model is run. If no shortfalls occur, the yield is incremented and retested, until a shortfall occurs. At this stage the increment is halved and the new estimated yield is tested. This continues until the maximum yield is obtained for no shortfalls in supply.

The fourth technique to be used, the ACTEW simulation model, is the only one which uses the specified operating rules of the system. The operating rules are based on the existing storage of the reservoir and the system and are independent on past and future inflow. There is no anticipation on future inflows and so there is no change in the current releases based on the possible future inflows. The model simply supplies the target yield for the particular period based on the operating rules of the system. This method will not obtain the maximum safe yield of the system directly, so the same iterative method as used with the WATHNET technique to obtain a maximum safe yield is also used for this technique.

A more detailed analysis of these techniques is provided below.

3.6.1 Method 1 : The Optimisation Model

The optimisation model is a linear programming model which uses perfect knowledge of future streamflows to maximise the total system yield.

The objective function is to maximise the total annual yield for all reservoirs, Y , ie. Max. Y.

The primary constraints in the model are based on water balance equations for all reservoirs. The basic form of these is given in Equation 3.27. For each reservoir, r and monthly period t this equation equates the final storage for the period, S^r_{t+1}, to the initial storage for the period, S^r_t, plus the natural inflow, Q^r_t, and the sum of releases from upstream reservoirs, U^r_t, less the excess release from this reservoir, R^r_t, the supply from the reservoir, Y^r_t, and the net evaporation loss, E^r_t, from the surface of the reservoir.

$$S^r_{t+1} = S^r_t + Q^r_t + U^r_t - R^r_t - Y^r_t - E^r_t \qquad \forall\, t, r \qquad (3.27)$$

The net evaporation loss for a period t depends on the depth of evaporation, the depth of precipitation and the surface area of the reservoir during this period. The surface area will be approximated by a linear function of the average storage volume for time period t (Figure 3.5) in which case the following equation can be written:

$$E^r_t = \left[\alpha^r + \Psi^r\left(\frac{S^r_t + S^r_{t+1}}{2}\right)\right]\left(e^r_t - p^r_t\right) \qquad \forall\, t, r \qquad (3.28)$$

where E^r_t = evaporation loss less precipitation for reservoir r in time period t; e^r_t = depth of evaporation in time period t, p^r_t = the depth of precipitation during the time period and α^r, Ψ^r = coefficients estimated from the surface area versus storage volume curve for reservoir r (Figure 3.5).

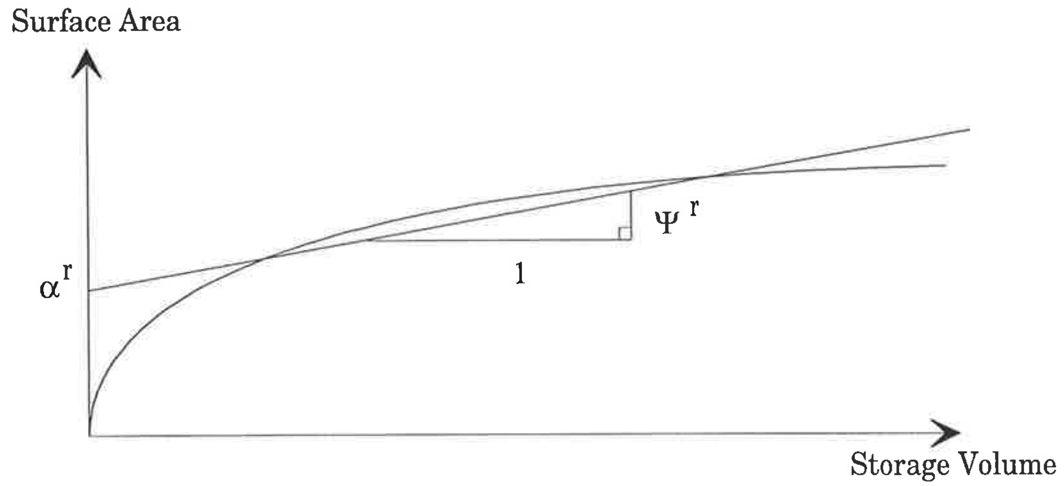

Figure 3.5 Surface Area versus Storage Volume

Thus substituting Equation 3.28 into Equation 3.27 gives the following:

$$S_{t+1}^{r}\left(1+\Psi^{r}\left(\frac{e_{t}^{r}-p_{t}^{r}}{2}\right)\right)$$
$$=S_{t}^{r}\left(1-\Psi^{r}\left(\frac{e_{t}^{r}-p_{t}^{r}}{2}\right)\right)+Q_{t}^{r}+U_{t}^{r}-Y_{t}^{r}-R_{t}^{r}-\alpha^{r}\left(e_{t}^{r}-p_{t}^{r}\right) \qquad \forall\ t, r \qquad (3.29)$$

Equation 3.29 defines the set of mass balance constraints. Other constraints include those for reservoir capacities, release requirements (riparian or minimum releases for streamflow), pipe capacities and water treatment plant capacities. The general form of these are given in the following equations.

Storage constraint -	$S_t^r \leq$ capacity for reservoir r	(3.30)
Release restriction -	$R_t^r \geq$ riparian release for reservoir r	(3.31)
	$R_t^r \leq$ pipe capacity for reservoir r	(3.32)
Supply restriction -	$Y_t^r \leq$ pipeline or water treatment plant capacity for reservoir r $\quad \forall\ t, r$	(3.33)

The unknowns in the above model are the volumes supplied from the reservoirs, Y_t^r, storage levels S_t^r and releases R_t^r and U_t^r. At this stage a clarification of equation (3.32) is required. It is usual to define the upper bound on releases as the spillway capacity. However, in the system which is modelled, releases other than that which contribute to the system yield, occur through a pipe or tunnel from the reservoir. Thus the upper limit on the release is the pipe capacity.

The sum of the supplies from each reservoir during month t must equal a specified fraction, f_t of the annual yield.

$$\text{ie. } \sum_{r} Y_t^r = f_t Y \qquad \forall\ t \qquad (3.34)$$

The time intervals chosen should be sufficiently small (eg. a month) so as to provide an accurate representation of system behaviour. However, the use of a monthly time step could result in the model becoming large and computationally intractable for a reasonable time horizon. Therefore only a limited length of the available record will be examined. This will include the critical period of the record so that the safe yield can be estimated.

3.6.2 Method 2 : The Yield Model

One limitation of the optimisation model is its size when long time periods are considered. In general, the longer the period addressed, the more representative the results are of the system operation. The use of a short time period to estimate yield, even if it includes the critical period of flows, may produce inaccurate results. Thus a method which can approximate the optimisation model but has the ability to use a long period of data without becoming computationally intractable may be used to estimate the yield. The method used in this study is called the yield model (Loucks et al., 1981) which is an approximation of the full optimisation model and is also based on linear programming. The yield model consists of a set of annual constraints similar to those in the optimisation model (with an annual instead of a monthly time step) and an additional set of within-year or monthly constraints based on a critical year. If there are minimum requirements for the volume to be supplied on a monthly basis, the addition of the within-year constraints is necessary. Otherwise, an analysis of a system based only on an annual time period will result in an optimistic estimation of the safe yield.

The number of constraints needed to model a particular system is substantially reduced for the yield model. For example, consider a water supply system with 5 reservoirs and 30 years of data. For the optimisation model with a monthly time step there would be 1800 water balance constraints (eg. Equation 3.29) to model the system accurately. With the yield model there would be 150 annual water balance constraints plus an additional 60 within-year constraints (ie. 12 constraints per reservoir).

As with the optimisation model the objective is to maximise the total system yield.

Equations 3.27, 3.31, 3.32 and 3.33 are used in the yield model with the exception that the time step is now annual rather than monthly. The remainder of the constraints in the yield model discussed, relate to the within-year or monthly period.

The general form of the water balance constraints for the within-year behaviour is given below (Loucks et al., 1981):

$$s^r_{m+1} = s^r_m + \beta^r_m \left(Y^r_c + \sum_m \varepsilon^r_m \right) - f_m Y^r_c - \varepsilon^r_m \quad \text{(if m=12, replace m+1 with 1)}$$

$$\forall \text{ m, r} \qquad (3.35)$$

where s^r_m, s^r_{m+1} = the within-year storage for reservoir r at the start of months m and m+1 (respectively); β^r_m = proportion of the total annual inflow for reservoir r which occurs during month m; Y^r_c = the annual volume supplied to demand sources from reservoir r during the critical year; ε^r_m = net evaporation loss for reservoir r in month m and f_m = fraction of the annual demand required in month m.

The within-year storage constraint is applied to the model to ensure that the monthly yield of a system can be supplied. An example of a situation where the monthly period is critical, may occur during summer months where inflows into reservoirs are low and the water demands are high. With the additional possibility of low storage levels, the situation may occur where the demand cannot be satisfied. The within-year constraint is designed to ensure that the monthly demand can always be satisfied for a specified reliability of the yield. An illustration of the problem of ignoring the within-year (monthly) constraint is shown in Figure 3.6.

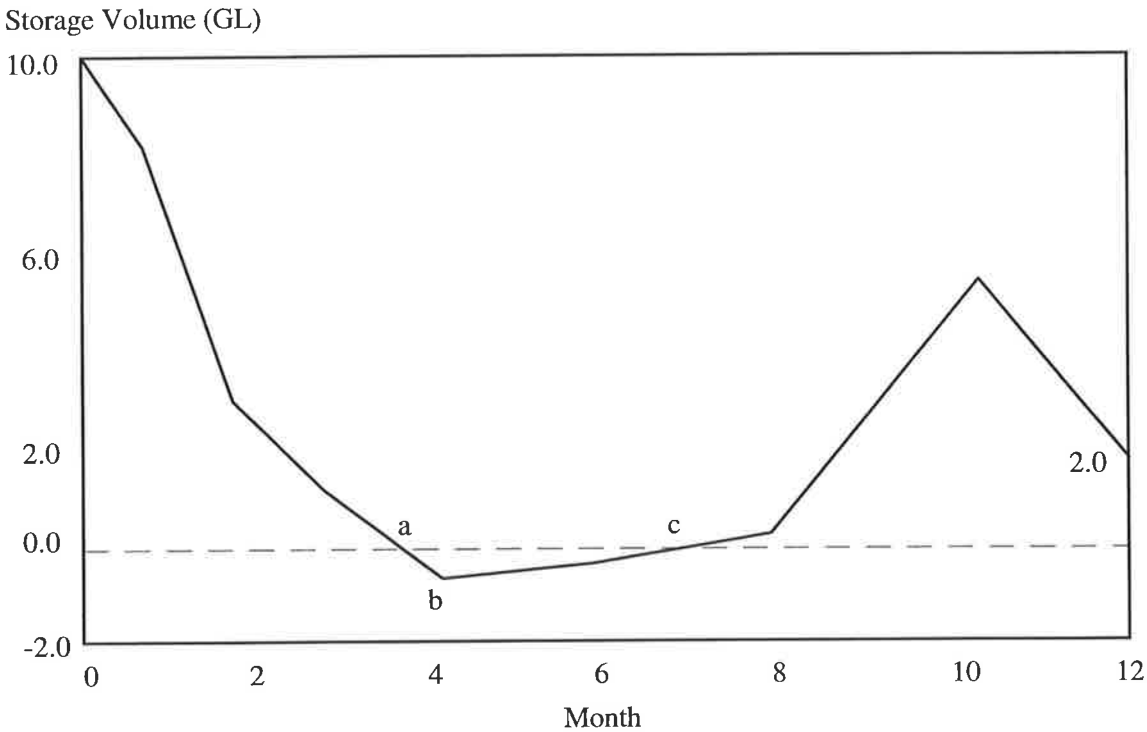

Figure 3.6 Storage Volume versus Time

Figure 3.6 shows the monthly fluctuations in storage volume of a reservoir during a dry year. The end of year storage values are 10 GL and 2 GL and therefore give the appearance that the system can satisfy the particular demand in question. However the area abc shows that the storage will fall below zero during the months 4 to 7. The safe yield of the system is defined as the annual demand which can be met without the reservoir becoming empty. In this case, the safe yield needs to be reduced because of the within-year constraints.

The β^r_m terms, in Equation 3.35, are usually selected to correspond to the driest year or the critical year of the record. The form of the evaporation expressions which incorporate both the annual and the within-year period are given below.

$$E^r_t = \alpha^r\left(e^r_t - p^r_t\right) + \left[S^r_t + \sum_m \left(\frac{s^r_m + s^r_{m+1}}{2}\right)\gamma^r_{mt}\right]\Psi^r\left(e^r_t - p^r_t\right) \quad \forall\ t, r \qquad (3.36)$$

where e^r_t, p^r_t = the depth of evaporation and precipitation at reservoir r during year t and γ^r_{mt} = fraction of net evaporation loss at reservoir r which occurs in month m of year t.

The expression for the within-year net evaporation volume loss in month m is:

$$\varepsilon^r_m = \gamma^r_{mt}\alpha^r\left(e^r_t - p^r_t\right) + \left(S^r_t + \frac{s^r_m + s^r_{m+1}}{2}\right)\gamma^r_{mt}\Psi^r\left(e^r_t - p^r_t\right) \quad \forall\ m, r \qquad (3.37)$$

where in Equation (3.37) the terms with the subscript t refer to the critical year. Therefore, S^r_t will equal the storage volume at the start of the critical year and e^r_t and p^r_t will be the depth of evaporation and precipitation in the critical year.

The final constraints in the yield model are a modification of the storage constraint (eg. Equation 3.30 in the optimisation model) to incorporate the within-year storage requirements. These changes are given in Equations 3.38 and 3.39.

$$s^r_m + K^r_y \le K^r_{ap} \quad \forall\ m, r \qquad (3.38)$$

and

$$S^r_t \le K^r_y \quad \forall\ t, r \qquad (3.39)$$

where K^r_y = the over year storage capacity of reservoir r and K^r_{ap} = the total storage capacity of reservoir r (ie. over-year plus within-year).

3.6.3 Method 3 : Network Linear Programming Model - WATHNET

WATHNET is a network linear programming package capable of simulating the operations of a water supply network (Kuczera, 1990). The package can use historical or stochastically generated streamflow and demand data. WATHNET is capable of running three different models :-

(1) Model S, a single-season simulation which uses streamflow and demand data for the current season to specify the flows within the network during that season, given some basic operational conditions. The model uses network linear programming to determine transfers between storages rather than using predefined rules (eg. operating curves for reservoirs).
(2) Model O, an optimisation model which examines all the seasons in the simulation rather than just the current season. The model has perfect knowledge about future inflows and this enables droughts to be anticipated and catered for by enabling storages to be as full as possible just prior to the drought. Thus the possibilities of demand shortfalls are reduced in frequency and magnitude.
(3) Model F, an optimisation model that finds the size of a new or current reservoir to ensure that there are no demand shortfalls in the system. This model is very similar to the previous optimisation model (Model O) and ensures that the smallest reservoir capacity is found to avoid shortfalls.

The model used in the case study is the single season operation model S. This model was chosen because it will produce results closest to those which may be expected in reality ie. the models O and F assume perfect foresight and the results obtained will be difficult, if not impossible to achieve under real operating conditions.

The model operates the system based on a hierarchy of five objectives which are ordered as follows:

(1) Satisfy demand at all demand zones;
(2) Satisfy all instream flow requirements;
(3) Ensure that reservoirs are at their end-of-season target volumes;
(4) Minimise delivery costs ; and
(5) Avoid unnecessary spills in the system.

All models ensure that continuity is obeyed throughout the system and that maximum capacity constraints are satisfied. A description of the processes involved in the WATHNET model can be found in Appendix A.

3.6.4 Method 4 : ACTEW Simulation Model

As a further basis for comparison for the three optimisation methods, a simulation model was used to determine the yield of the current system when explicit operating rules are considered. A simulation model developed for the Canberra Water Supply System (Pink and Sooriyakumaran, 1988 and Pink, 1991) was used for this purpose. This will be referred to as the ACTEW simulation model. As this model allows shortfalls in supply to occur, an iterative approach (discussed previously) was adopted to estimate the safe yield of the system. The operating rules for the Canberra System define magnitudes of flow in supply mains and from reservoirs based on the storage level of the particular reservoir as well as the total storage of all the reservoirs. The basic operation of the actual system will be discussed after the system is defined. The equations used in the model are similar to that outlined in the optimisation model.

The simulation model is written in FORTRAN code and is run with monthly time steps for the period 1912 to 1983.

3.7. Conclusions

The various methodologies and capacity expansion problems have been discussed and illustrated. The theory of present value and discounting has been examined and will be adopted for the rest of this study. It was considered that a number of values of discount rate should be applied, in order to obtain a sensitivity analysis for a particular problem.

The effect of including price in the capacity expansion problem is examined. The use of a constant price over time with full pay-for-use pricing was considered to be the best pricing policy. A relationship is presented which relates how a variation in price changes the level of demand. This relationship includes the price elasticity of demand which determines the amount demand will change in response to changes in price. This relationship is used to develop an expression for NPV which includes producer revenue and consumer surplus. The concept of consumer surplus is discussed extensively.

A number of sequencing techniques are discussed, although a further technique, genetic algorithms, will also be discussed and utilised in later chapters. Three methods are discussed and used in this study in order to evaluate them in relation to different capacity expansion problems. The problems to be examined are the sequencing of future reservoir projects, the sizing and sequencing of future reservoir projects and the sequencing problem with the operating cost of the projects included in the evaluation.

Not all the methods detailed in this chapter will be used for all the problems. The integer/linear programming method will be used for the sizing and sequencing problem only.

Four different models were presented to determine the yield of a multiple reservoir system. These methods utilise either optimisation or simulation and the expected yield estimates from each model is likely to be different. This is primarily because of the different ways of handling the operating rules in each method.

The remainder of the study will concentrate on applying the sequencing methods and yield methods in order to obtain a better understanding of the optimum price and capacity expansion problem.

Chapter 4

Case Study 1: Canberra Water Supply System

4.1 Introduction

The aim of this case study of the Canberra Water Supply System is to apply the methodology outlined in Chapter 3 to a real system. The case study involves the determination of the existing system yield using four yield evaluation methods for comparison. These methods have been discussed previously and are a simulation model developed for the Canberra System, ACTEW, a combined simulation and network optimisation model, WATHNET, and two optimisation methods (the yield model and the optimisation model). Once the existing system yield is determined, the yield of future projects and project sequence is examined. The yield of future alternatives is determined using the three optimisation methods. The yield estimates for the future alternatives are then used in the equivalent cost and unit cost sequencing methods to achieve a sequence of future projects. This is carried out for four population growth projections so that the effects of demand growth rate on project sequence can be demonstrated.

As part of this study, a detailed examination of the yield model is undertaken. The reason is that the yield model is an approximation of the full optimisation model and the values parameters used in the yield model must be selected so that it approximates the optimisation model. Thus a small study is undertaken to evaluate suitable values of these parameters.

Following the yield evaluation and sequencing study the values of yield obtained by the optimisation model are used in a study of the optimum pricing and sequencing on the Canberra System. A two part pricing structure is adopted for this study which consists of an annual connection fee per service (with no free allowance) and a price per kilolitre of water charged for all consumption. The price per kilolitre is determined so as to maximise the net present value of economic benefits of the water supply, while the connection fee is set so that the total revenue just covers the total cost of supply. The emphasise in this study is on the value of the constant price per unit rather than the connection fee. The purpose of this study is to investigate how the optimum price per kilolitre of water and project sequence and scheduling varies with different population growth rates, discount rates and values of price elasticity of demand. In addition, the effect of the length of planning period will also be investigated.

Another factor which is becoming more popular is the deferment of future project expansion using demand management measures. Demand management has the effect of reducing the per capita demand either by voluntary or mandatory means. Thus it is a way of increasing the efficiency of the water supply system. Some examples of demand management measures include instalment of water saving devices, water restrictions and publicity, education and legislation. For the purpose of this study the demand management measures are assumed to be voluntary and will be applied at the start of the planning period. Demand management is include in this study to investigate the effect it has on the optimum price and sequencing and scheduling of projects. The final step in this study will be to determine the price which should be charged so that no projects are required to be built within the planning period and how demand management can affect this price.

4.2 The Canberra Water Supply System

Canberra is the capital of Australia and is located approximately 237 km South-West of Sydney. It lies on a latitude of 35.18 degrees south and longitude of 149.08 degrees east. The cities of Canberra and nearby Queanbeyan are supplied with water by the Australian Capital Territory Electricity and Water (ACTEW). The two cities had a combined population of 320,000 in 1992.

The Canberra Water Supply System consists of three reservoirs on the Cotter River, namely Corin, Bendora and Cotter Reservoirs and the Googong Reservoir on the Queanbeyan River. The layout of the Canberra water supply systems reservoirs, supply mains and treatment plants is illustrated in Figures 4.1 and 4.2. The supply to Canberra is from the Stromlo Water Treatment Plant (WTP) and the Googong WTP. Stromlo is supplied by Bendora Reservoir via a gravity main and by water pumped from Cotter Reservoir. The largest of the reservoirs on the Cotter River is Corin Reservoir which is a secondary supply to Canberra via Bendora Reservoir. The Googong WTP is supplied by Googong Reservoir. The capacities of the existing reservoirs is given Table 4.1 and the particular details of the supply mains (ie. capacity, type, etc) are indicated in Table 4.2.

Table 4.1 Capacities of the Existing Reservoir

Reservoirs	Capacity (ML)
Corin	75,500
Bendora	10,700
Cotter	4,700
Googong	124,500

Table 4.2 Supply Main Characteristics

Supply Source	Capacity(ML/day)	Type
Bendora Reservoir	320 (116.8)	Gravity
Cotter Reservoir	75*(27.38)	Pumped
Stromlo WTP	400 (146.0)	Gravity
Googong WTP	190(69.35)	Pumped

* Pumping limited to 12 hours in a day.
The figures in brackets are values in GL/year.

Once the existing water supply reaches its capacity, four possible alternative supplies have been identified. The possible new options are all surface reservoirs and are described as follows :

(i) Coree Reservoir on the Cotter River between Cotter and Bendora Reservoirs with a direct supply to Stromlo WTP;
(ii) Tennent Reservoir on the Gudgenby River (South of Canberra) at Tennent supplying Canberra directly;
(iii) Riverlea Reservoir on Paddy's River at Riverlea supplying Stromlo WTP; and

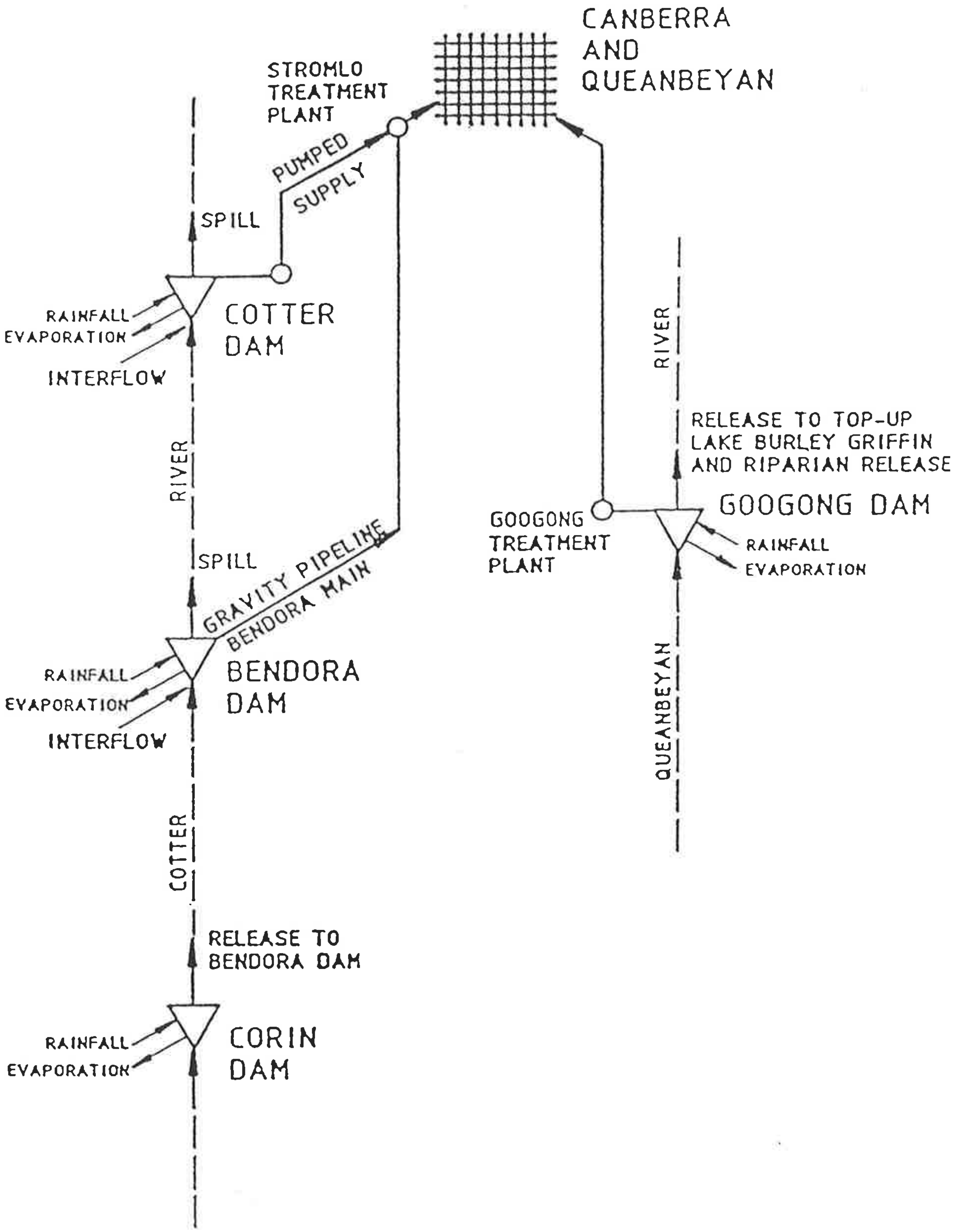

Figure 4.1 Schematic of Canberra Water Supply (Pink and Sooriyakumaran, 1988)

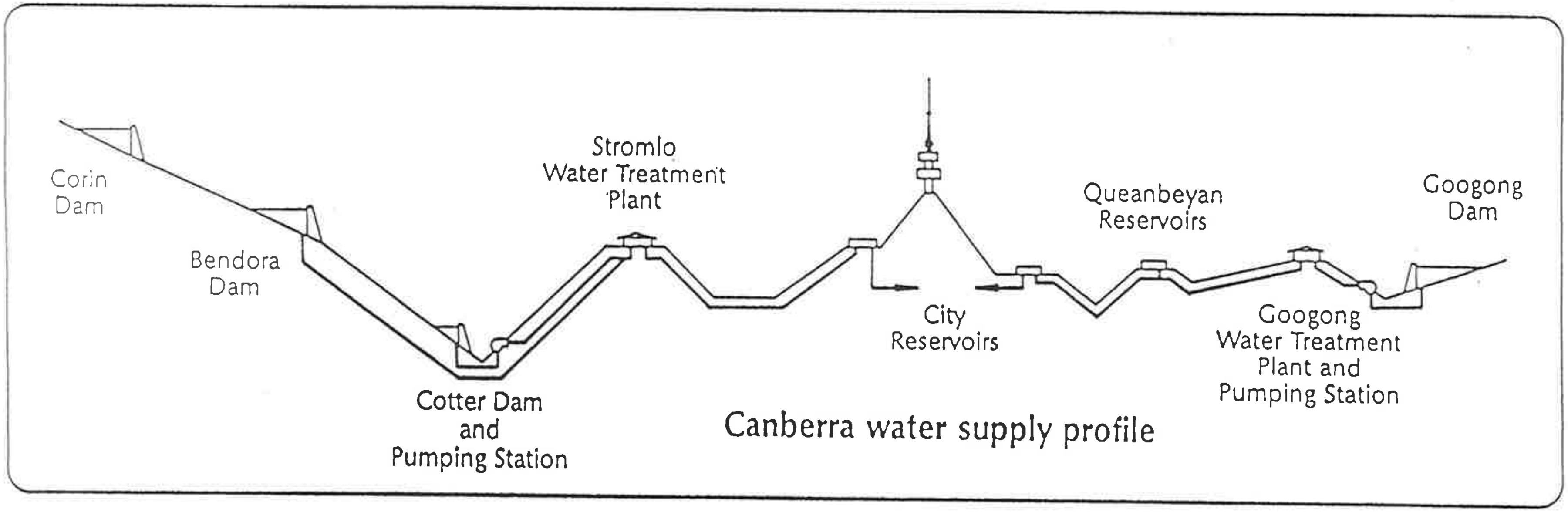

Figure 4.2 Canberra Water Supply Profile (ACTEW, 1991)

(iv) Raising the height of Cotter Dam and upgrading the supply main to Stromlo WTP.

Figure 4.3 shows the locations of these new alternatives relative to the total catchment and a schematic displaying the interaction of the new alternatives with the existing system is shown in Figure 4.4. The capacities and costs of the four possible reservoir options are given in Table 4.3.

Table 4.3 Reservoir Capacity and Cost for Future Expansion Options

Reservoir	Capacity (ML)	Cost ($ Million)
Coree	86,000	92.0
Tennent	151,000	110.0
Riverlea	83,000	148.0
Cotter	76,000	92.0*

* This is an approximate cost.

The options of raising Cotter Dam and building Coree Dam are mutually exclusive because the raising of Cotter Dam will probably flood the dam site at Coree. Thus if one of them is built, the other is no longer an option. However, for the sequencing study it is assumed that both can be built so that the effectiveness of the various sequencing methods can be examined. For the study which includes water pricing the two options will be treated as being mutually exclusive.

The assumed annual growth rates in population are 1.5%, 2.0%, 2.58% and 3.0%. The 2.0 % and 2.58 % population growth rates were low and high estimates for Canberra determined by the economic development branch of ACTEW. The 1.5% and 3.0% population growth rates were determined by BHP as being low and extra high population growths respectively for Canberra. The initial demand for water is based on a population of 320,000 and a specified consumption for Canberra and Queanbeyan. The per capita consumption assumed during a drought year is 785 litres per capita per day (lpcd) (Pink, 1991). This will be used for the sequencing of the future projects. The corresponding total initial demand is 91.7 GL per annum.

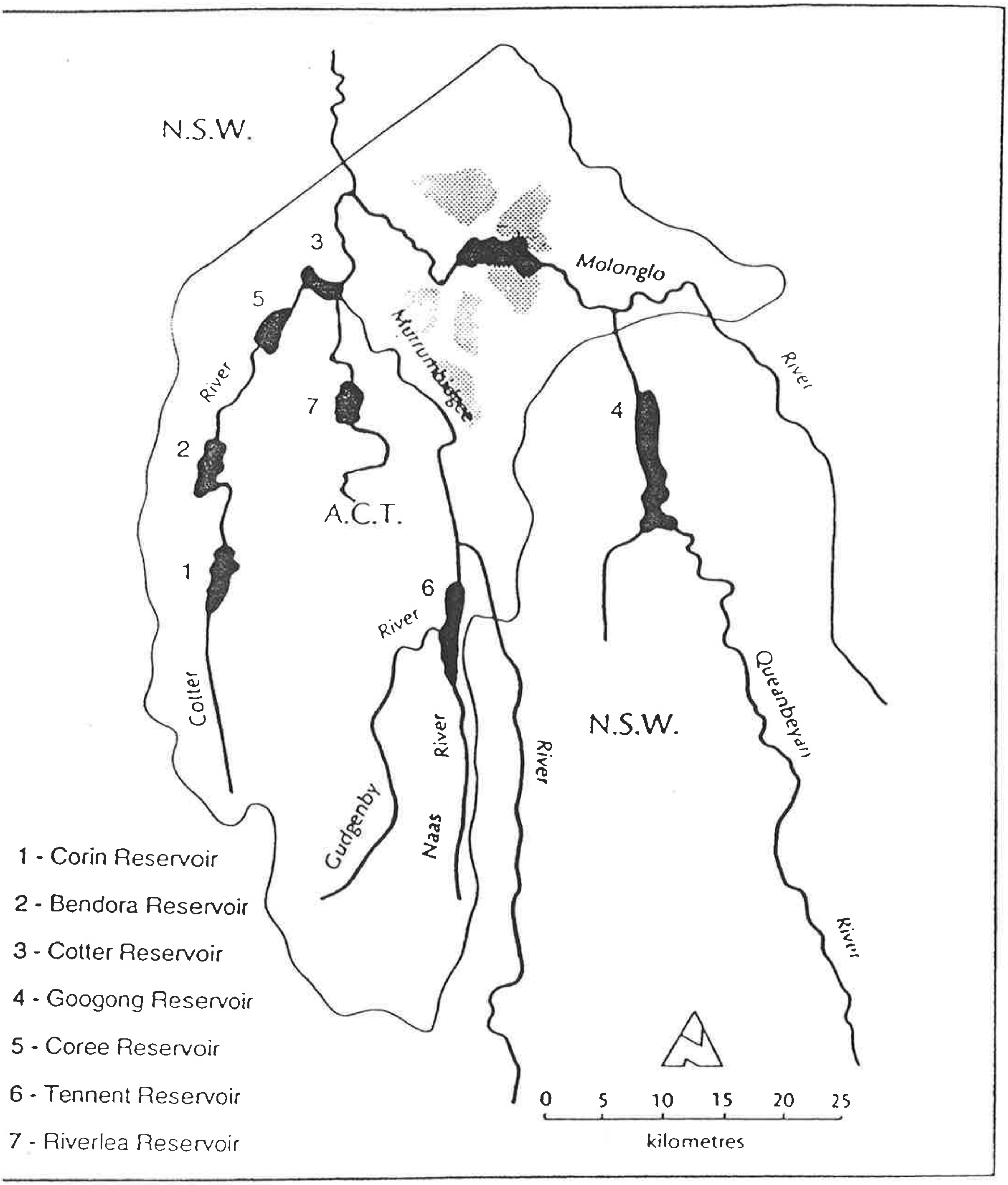

Figure 4.3 Canberra Water Supply Catchment Showing Existing and Possible Future Reservoirs (Pink and Sooriyakumaran, 1988)

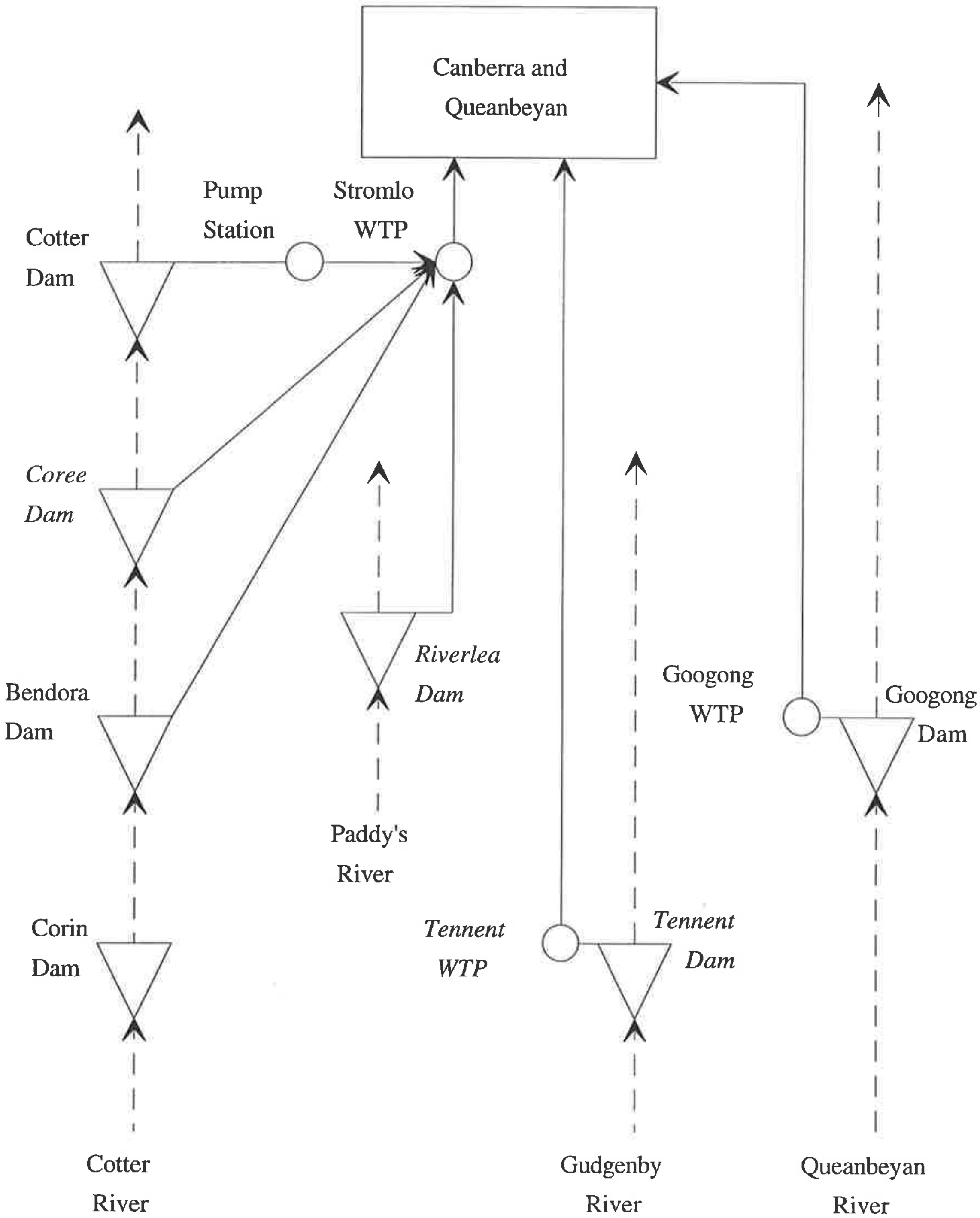

Figure 4.4 Canberra Water Supply System with all Future Reservoirs Incorporated (Proposed projects are shown in italics)

4.2.1 Data for Yield Estimation for the Canberra Water Supply System

Monthly streamflow, evaporation and rainfall data were obtained from ACT Electricity and Water (ACTEW) for the existing and proposed reservoirs.

The streamflow data obtained from ACTEW was in the form of the (reconstructed) total natural streamflow for the Cotter River at Cotter Dam and the natural streamflow at Googong Dam. The natural streamflow records for the Cotter River and the Googong River extended over the period 1912 to 1983. The Googong data could be used directly but the Cotter streamflow needed to be modified to include the effects of the upstream reservoirs of Bendora and Corin. The following approximate proportions of the total natural streamflow of the Cotter River were used in estimating the yield for the existing system:

Corin inflow = 0.4087 of the total natural streamflow of the Cotter River at Cotter Dam;
Bendora inflow = 0.2913 of the total natural streamflow of the Cotter River at Cotter Dam;
Cotter inflow = 0.3000 of the total natural streamflow of the Cotter River at Cotter Dam.

These proportions were deduced from the input data used in Pink (1991). The above proportions for the Corin and Bendora inflows remain the same when estimating the yield of future proposals. However, the Cotter inflow proportion will change if Coree Reservoir is built upstream of Cotter Reservoir. The proportion of the previous Cotter inflow which is now collected by Coree is approximately 95% and therefore only 5% of the Cotter inflow is collected by Cotter Reservoir. Therefore the proportion of total Cotter streamflow which goes into Coree is 0.285 and the proportion flowing into Cotter is 0.015. For the future alternatives of Tennent and Riverlea the monthly streamflow records provided are of various lengths. For the Tennent Reservoir the record is continuous from 1966 to 1987 and for the Riverlea Reservoir the data is continuous from 1958 to 1983.

The rainfall data was a monthly historical record of rainfall at all four of the existing reservoir sites from 1912 to 1983. The rainfall for Coree is also known for period 1912 to 1983. However for both Tennent and Riverlea the rainfall data is not continuous over a particularly long period and therefore it was decided to use precipitation figures from Cotter and Corin Reservoirs for Riverlea and Tennent Reservoirs (respectively) to achieve a reasonable length of record. The Cotter and Corin Reservoirs rainfall data is chosen as they are in approximately the same areas as Riverlea and Tennent Reservoirs and should experience similar weather patterns and therefore rainfall.

The evaporation data for the four existing reservoirs was obtained by the following method :

(i) Pan evaporation data were obtained for two sites over the period 1912-1983. The sites were: (a) at Blundell's Creek Road which falls in the proximity of the Reservoirs on the Cotter River and (b) Canberra Airport which is used for the Googong Reservoir evaporation.

(ii) These pan evaporations were multiplied by pan coefficients to achieve lake evaporation at the four reservoirs. The pan coefficients for the reservoirs are given in Table 4.4 (Pink and Sooriyakumaran, 1988).

Table 4.4 Reservoir Pan Coefficients for Evaporation

Reservoir	Jan	Feb	March	April	May	June
Corin	0.85	0.85	0.90	1.00	1.10	1.30
Bendora	0.85	0.85	0.90	1.00	1.10	1.30
Cotter	1.00	1.00	1.10	1.20	1.30	1.60
Googong	0.85	0.85	0.93	1.07	1.18	1.19
Reservoir	July	Aug	Sept	Oct	Nov	Dec
Corin	1.15	0.85	0.75	0.75	0.75	0.70
Bendora	1.15	0.85	0.75	0.75	0.75	0.70
Cotter	1.40	1.00	0.90	0.90	0.90	0.85
Googong	0.94	0.69	0.67	0.67	0.76	0.72

The evaporation figures for the future alternatives were evaluated in the same manner as for evaporation at the existing reservoirs. Thus evaporation data can be estimated for the period 1912-1983. However pan factors for the proposed Tennent, Coree and Riverlea Reservoirs are not known. Therefore on advice from ACTEW the Blundell's Creek Road pan evaporation data and the following figures for pan coefficients were used:

(1) For Coree Reservoir evaporation, the Cotter Reservoir pan factors.
(2) For Tennent Reservoir, the Bendora Reservoir pan factors.
(3) For Riverlea Reservoir, the Cotter Reservoir pan factors.

The evaluation of the actual evaporation from a reservoir is dependent on the surface area of the reservoir which in turn is reliant on the storage volume at the particular time. Thus, to estimate the evaporation, the storage volume vs surface area relationship needs to be known for each reservoir. This relationship is illustrated by Figure 3.5 in chapter 3. The surface area versus storage volume curves for the existing and future reservoirs are given in Appendix H, Figure H.1 to H.8.

A problem with including the new developments in the existing system is to find a time period for which there is a contiguous data record for all sites. For the existing system and alternatives (i) and (iv), the streamflow, evaporation and rainfall data is available from 1912 to 1983. However the Tennent Reservoir streamflow data is only continuous from 1966 to 1987 and the Riverlea Reservoir data is continuous from 1958 to 1983. In order to include all projects into a simulation or optimisation model, the period of data available must be the same for all projects and therefore the period to be utilised is 1966 to 1983. The critical year for yield assessment is 1982, as the lowest flows in the streamflow records for all reservoirs occur in this year.

4.3 Adaptation of Methodology

The procedure which is used for the sequencing of projects in this report utilises the methods for evaluating project yield discussed in Chapter 3 and the unit cost and equivalent cost sequencing method of Erlenkotter (1973). The sequencing procedure is discussed in relation to the equivalent cost sequencing method and is as follows:

(1) The yield of the existing system is evaluated;
(2) The yield of the expanded system is determined with each proposed project added individually. Hence the incremental yield of each proposed project is determined;
(3) The equivalent cost per period (α) for each new project is calculated and the project with the lowest value is sequenced first;
(4) The incremental yields of the remaining projects are evaluated as the next expansion to the system;
(5) The equivalent cost per period (α) for the remaining projects is calculated and the project with the lowest value is selected as the next expansion.

This procedure continues until either all projects are expanded or enough projects are expanded so that demand is satisfied for the entire planning period.

The formulation of the yield evaluation models as applied to the Canberra Water Supply System are shown in Appendices B, D and F. The formulation of WATHNET for the Canberra System is discussed in Appendix B. The formulation of the yield model for the Canberra System is given in Appendix D. The various models evaluate the yield of the existing system using different time periods. This is primarily due to restrictions on the version of WATHNET utilised and the version of LINGO used for the optimisation model. The period examined in the WATHNET model is 1954 to 1983 as a maximum of 360 periods can be evaluated in a single run. For the optimisation model the period of examination is restricted to 9 years of record (108 monthly periods) due to the limits of LINGO (Schrage and Cunningham, 1991). The period considered is January 1975 to December 1983 which incorporates the critical period for the Canberra Water Supply System (ie 1979 to 1983). The yield model was also solved using LINGO. The model was run for the period 1912 to 1983 and the critical year was selected by inspection to be 1982, as it had the lowest annual and monthly flows, high evaporation and high demand. In addition, a sensitivity study was undertaken for the yield model where different years and data sets were examined as input for the critical year. The results of this sensitivity study will be discussed when the existing system yield is examined.

The yield, optimisation and WATHNET models will be used for the evaluation of the yields of the four future reservoirs. With the inclusion of the future reservoirs there are various changes which need to be made to the formulations previously mentioned. The Tennent and Riverlea Reservoirs are independent of the existing system of reservoirs, but act in a similar manner to that of Googong Reservoir. Their only interaction with the existing system is via the supply to Canberra. Therefore to include the Tennent and Riverlea Reservoirs in the evaluation it is simply a matter of including the appropriate constraints in the yield and optimisation models and editing the system schematic to include both reservoirs in WATHNET. The raising of Cotter Reservoir will only require a change in the storage constraints and supply restriction of the existing system's formulation for all models. However, for the Coree Reservoir addition the process is slightly more complicated. The reason is that Coree will affect the inflow to the Cotter Reservoir. The change to the streamflow data has been discussed previously. However, there is an additional change to the water balance equations for the Cotter Reservoir for the yield and the optimisation models as no longer does the Bendora release go directly to Cotter Reservoir. Therefore the Bendora release will be inflow to the Coree Reservoir and the Coree release will be inflow to the Cotter Reservoir. The full formulation of the yield model with all reservoirs included is given in Appendix F. The associated data files for the new system formulation can be found in Appendix G. Similar changes are also made to the optimisation model.

The future reservoirs will have their own supply mains. The Cotter, Coree and Riverlea Reservoirs are assumed to supply Canberra via Mount Stromlo Treatment Plant whereas Tennent will supply Canberra directly. The identification of the supply capacities is an iterative procedure. Firstly no constraint is placed on the supply capacity and the yield is evaluated. Then restrictions are applied to the supply capacity until the minimum size of the supply main is found which will still obtain the maximum yield figure. Therefore for the WATHNET model the maximum yield of the system is determined via an iterative procedure and then the supply capacities are slowly restricted in the EDNET program until the minimum size is obtained.

The other change made with the addition of the future alternatives is the time period utilised to evaluate the yield of the future alternatives. As mentioned previously the length of continuous data available for the future alternatives is from 1966 to 1983. Therefore for the WATHNET and yield models the yield evaluation will be using this shorter period. However the optimisation model will use the 9 year period from 1974 to 1983 as used for the existing system yield evaluation.

4.3.1 Results

4.3.1.1 Existing System Yield

The first item examined in the case study, is the yield of the existing system using WATHNET, the yield model and the optimisation model. The yield of the existing system estimated by the ACT Electricity and Water (ACTEW) is 115 GL/year (Pink and Sooriyakumaran, 1988). This figure is obtained assuming there is no failures of the system. Executing WATHNET, the yield model and the optimisation model for the existing system produces the results given in Table 4.5.

Table 4.5 The Estimated Yield of the Existing System

Method	Yield (GL/year)
WATHNET	116.5
Optimisation model	120.9
Yield model	126.6

As can be seen, the WATHNET result for the yield is close to that estimated by ACTEW. A closer examination of the system behaviour was undertaken, by studying the storage and supply main plots for all reservoirs and supplies from WATHNET. These plots are given in Figures 4.5 to 4.12.

The plots show the variation in the storage volume or supply from the reservoirs over the period and also the percentage of time that the reservoir or the supply main is below a particular percentage of its capacity. The entire period of examination is not shown in the plots but just the period which contains the critical failure period. This was January 1959 (time step 1) to December 1983 (time step 300) with the critical time being April 1983 (time step 292). Over this period, it is evident that all the reservoirs remain reasonably full. Bendora Reservoir remains above 80% of its capacity for approximately 80 % of this period whereas the other reservoirs have a higher percentage of this period above 80% full. The reason for this is that Bendora Reservoir is the major supplier of water to Canberra (via Stromlo Water Treatment Plant). From these plots it is evident that Bendora supply and therefore the Stromlo supply is nearly always fully utilised, but the Cotter and Googong supplies have a high proportion of the period with no supply from them, which indicates the importance of Bendora Reservoir to the existing system. Another point from the plots is the under utilisation of the full capacity of the Stromlo supply. This is caused by the limited transfer capacities from Bendora and Cotter Reservoirs. In practice, Cotter is not used for normal supply due to the cost of pumping and water quality problems. Thus if these supplies could be increased it may be possible to more fully utilise Stromlo.

As expected the optimisation model gives a higher yield than WATHNET because it assumes optimum operations with perfect foresight of future inflows. This is optimistic compared to what can be achieved in actual operations.

The result for the yield model at first seems somewhat surprising, as it is expected that this method should produce a similar result to that of the optimisation model. However, it must be emphasised that the yield model is only an approximation to the full optimisation model with perfect forecasts.

While this may be true, it is uncertain whether the approximation will give a lower or higher yield than the optimisation model. This will depend on how well the critical year flow proportions (and therefore the within-year storage constraint) represent what actually occurs in other years.

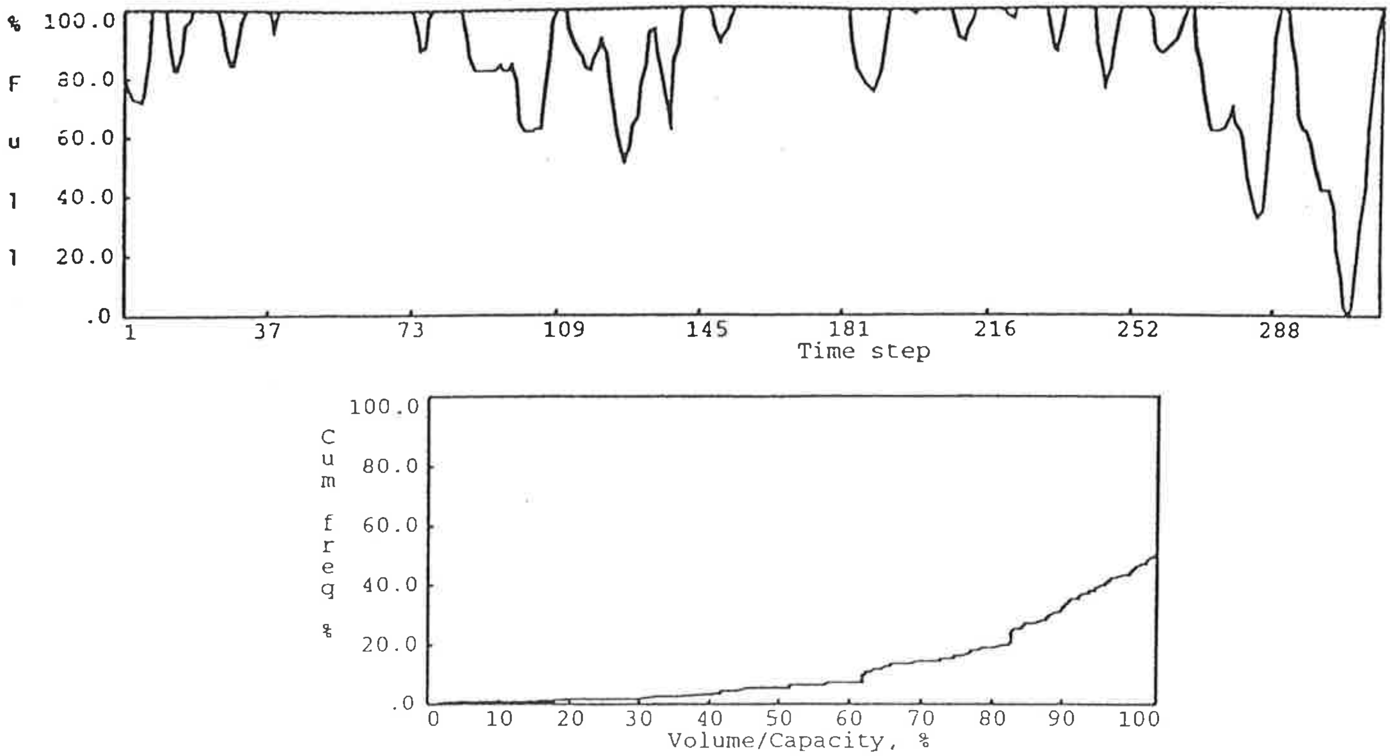

Figure 4.5 Corin Reservoir Storage (% Full / month)

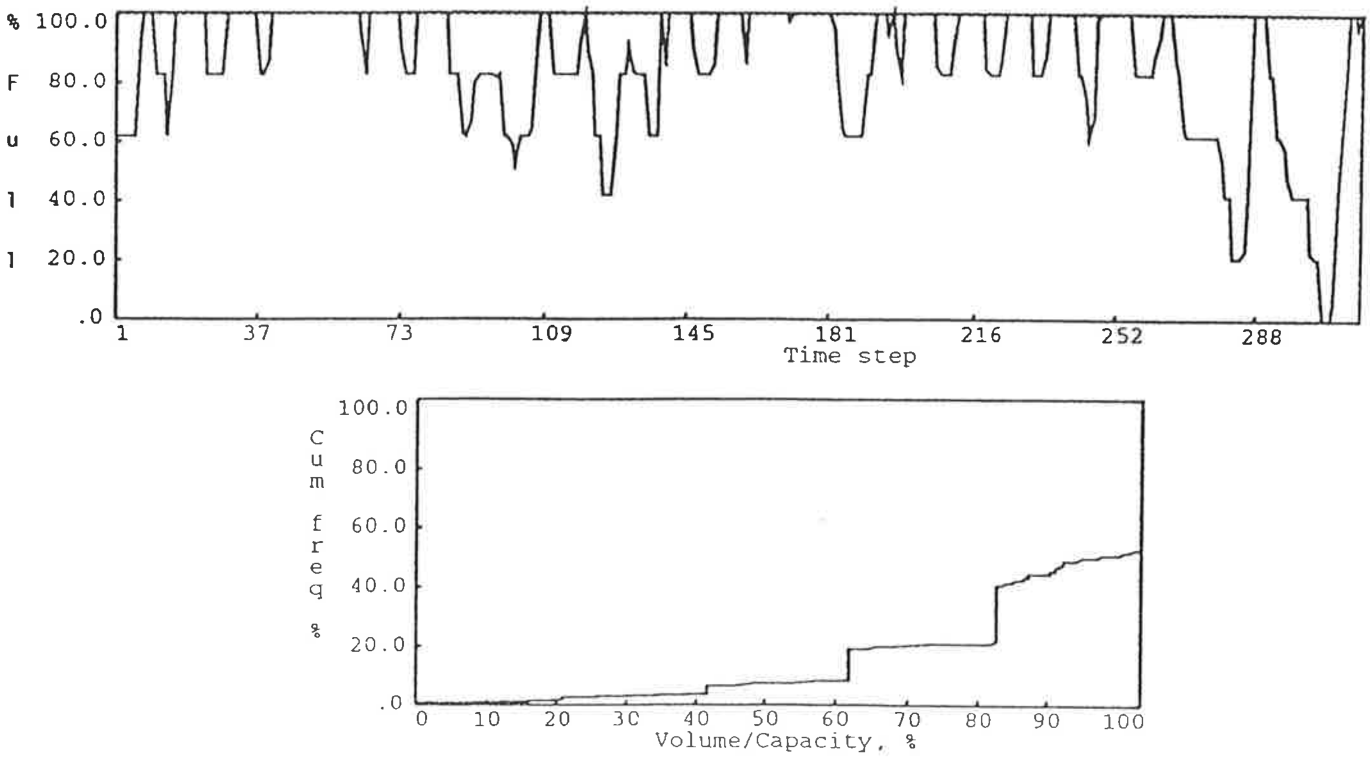

Figure 4.6 Bendora Reservoir Storage (% Full / month)

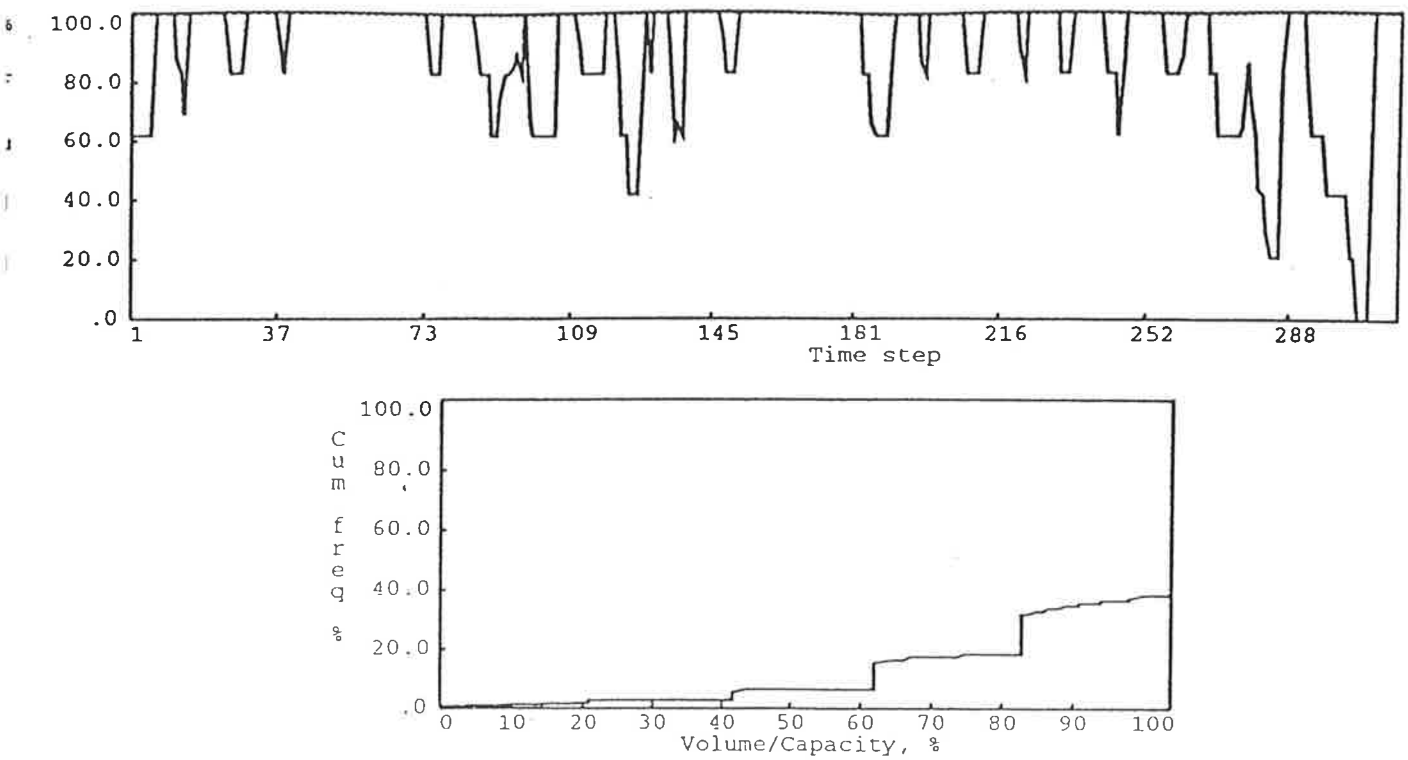

Figure 4.7 Cotter Reservoir Storage (% Full / month)

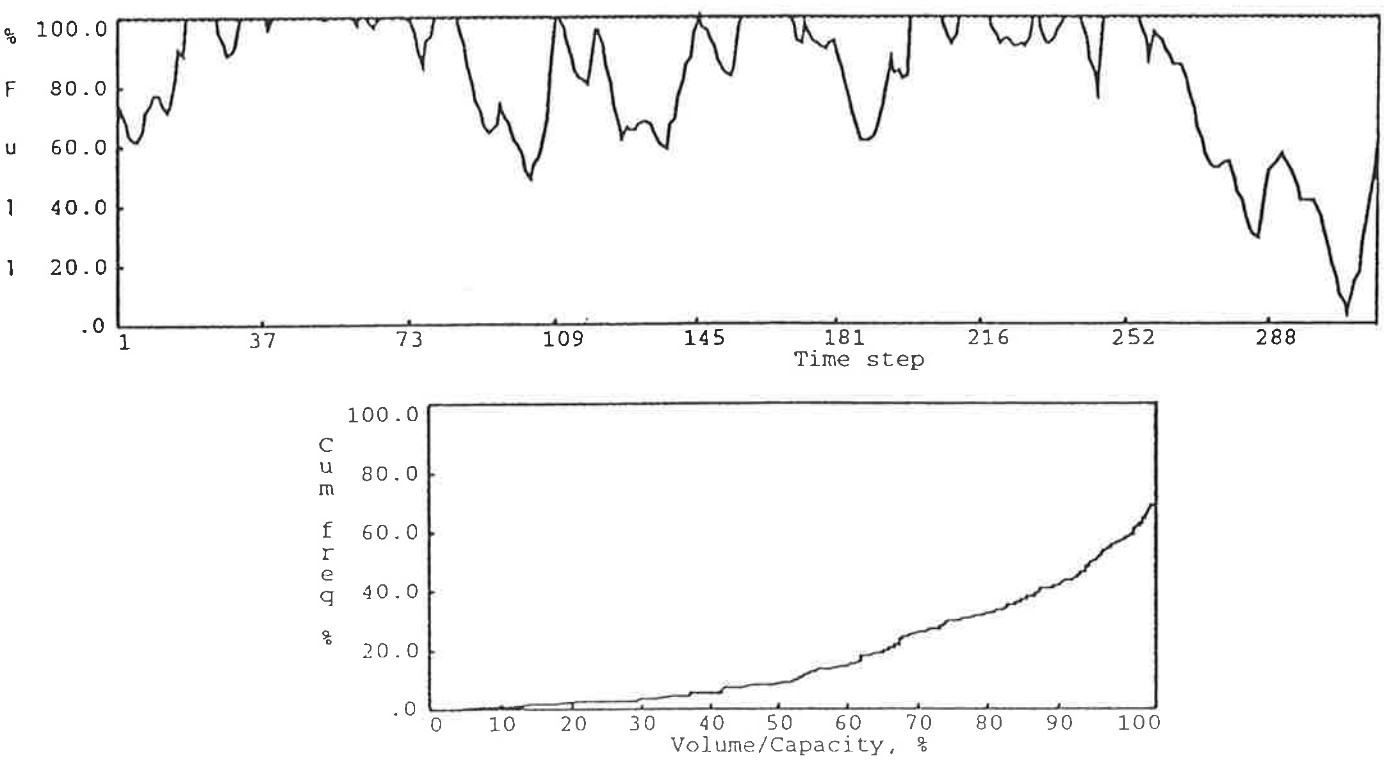

Figure 4.8 Googong Reservoir Storage (% Full / month)

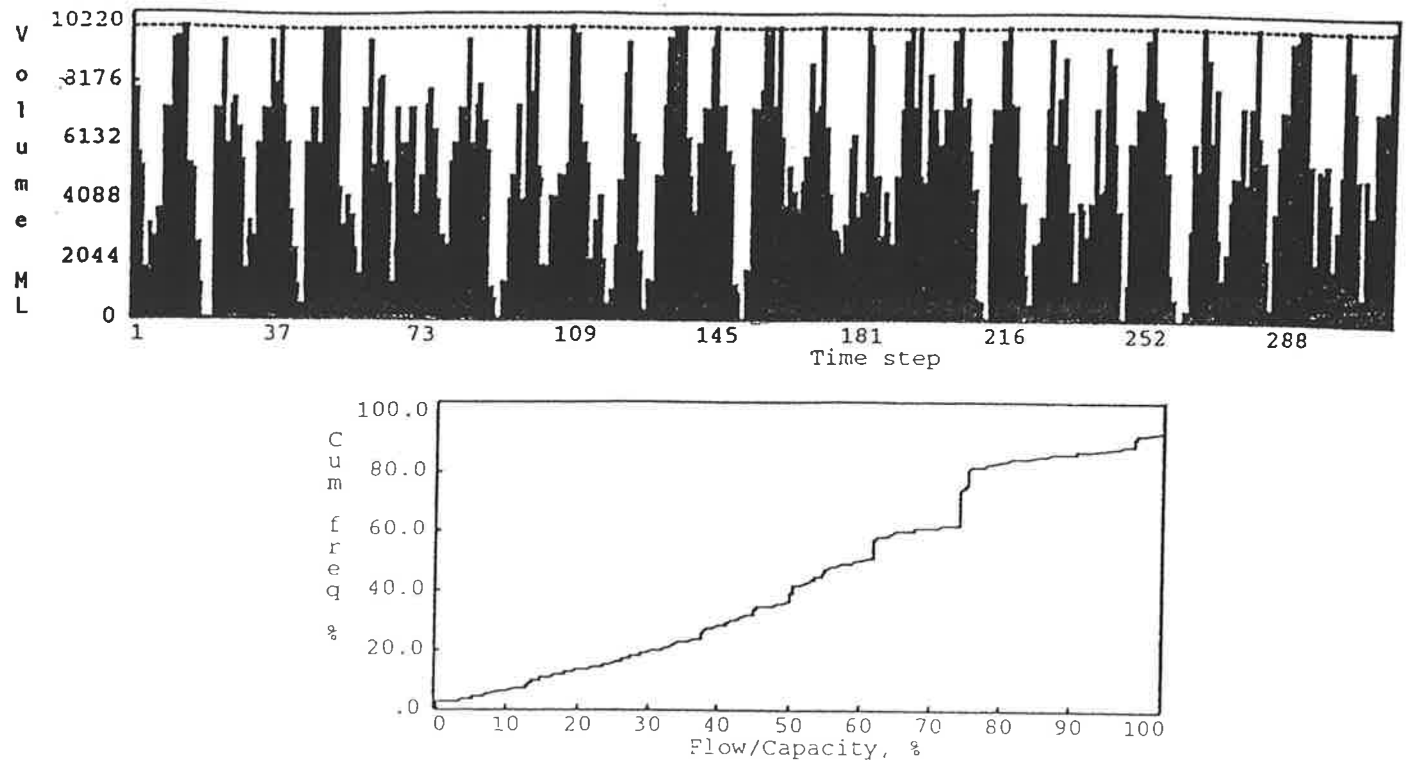

Figure 4.9 Bendora Reservoir Supply (ML / month)

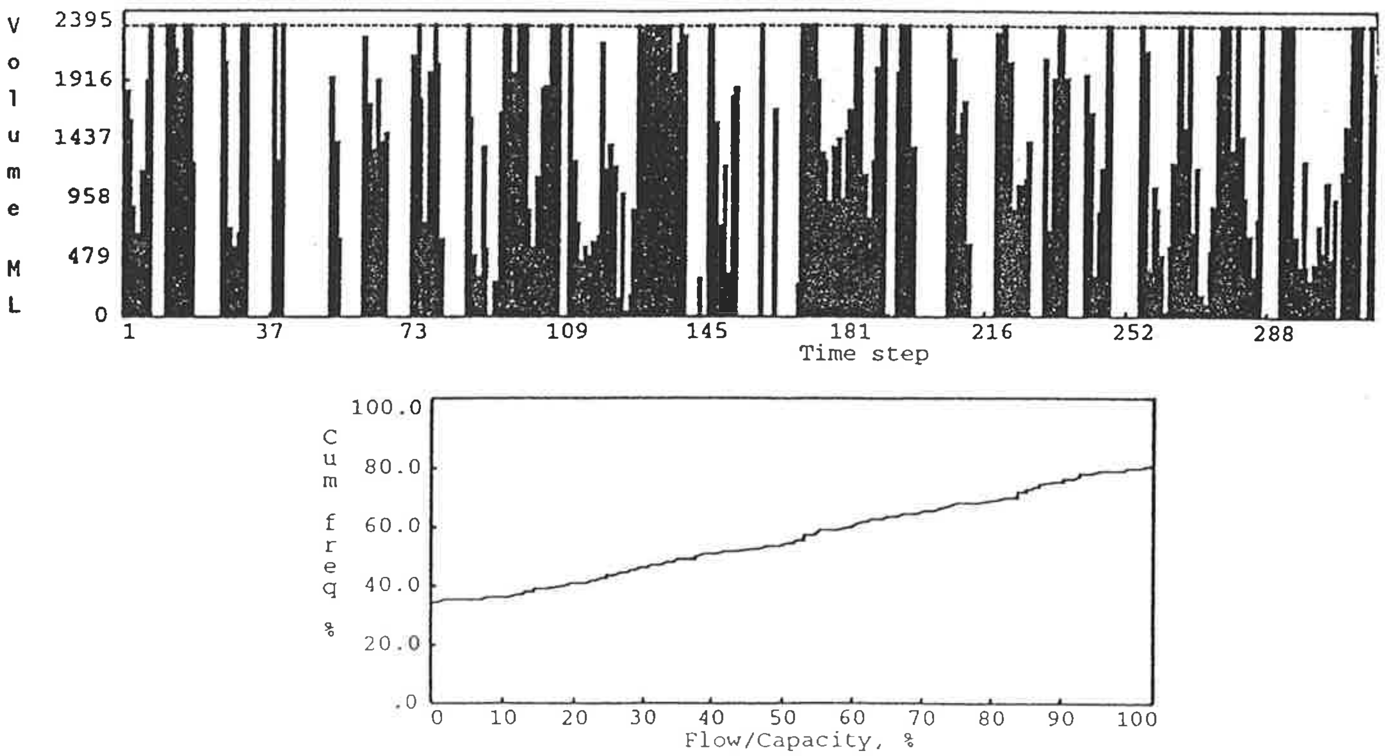

Figure 4.10 Cotter Reservoir Supply (ML / month)

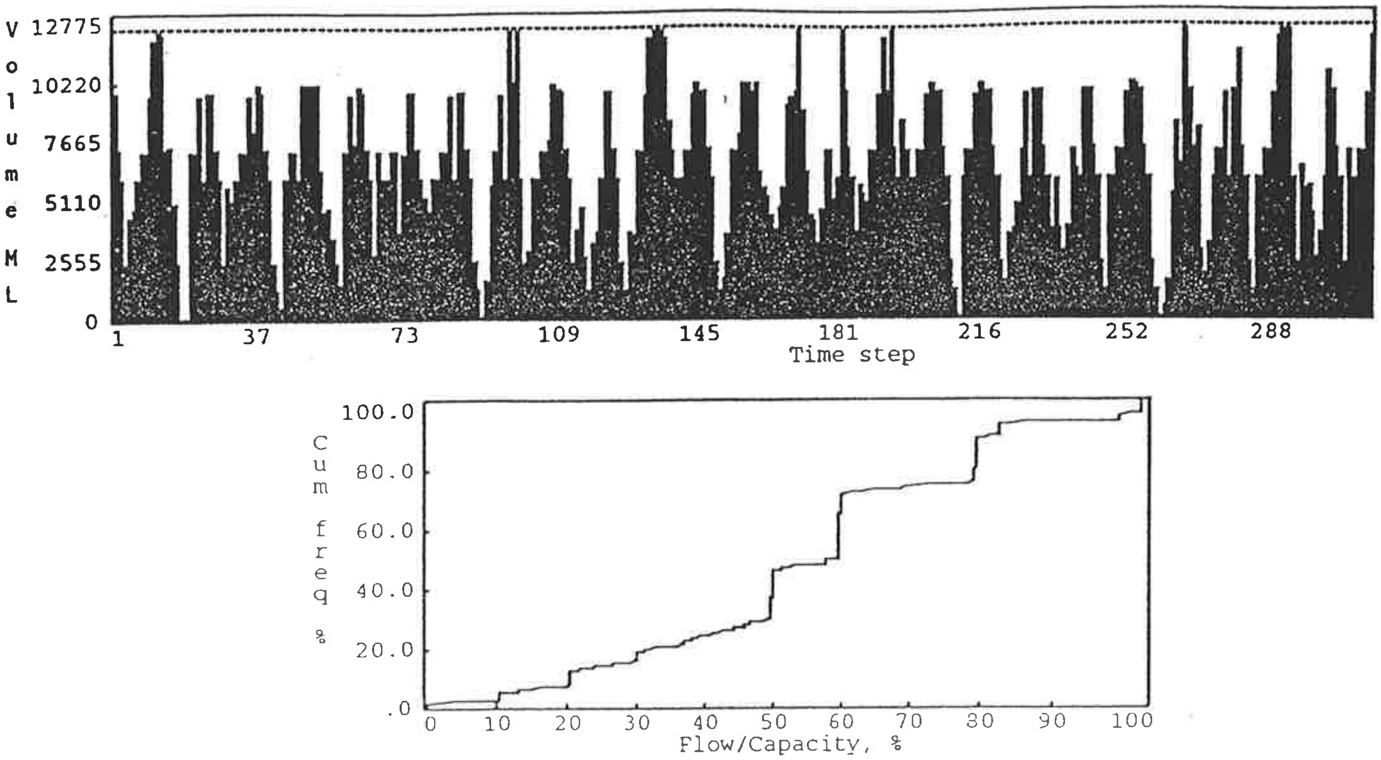

Figure 4.11 Stromlo Water Treatment Plant Supply (ML / month)

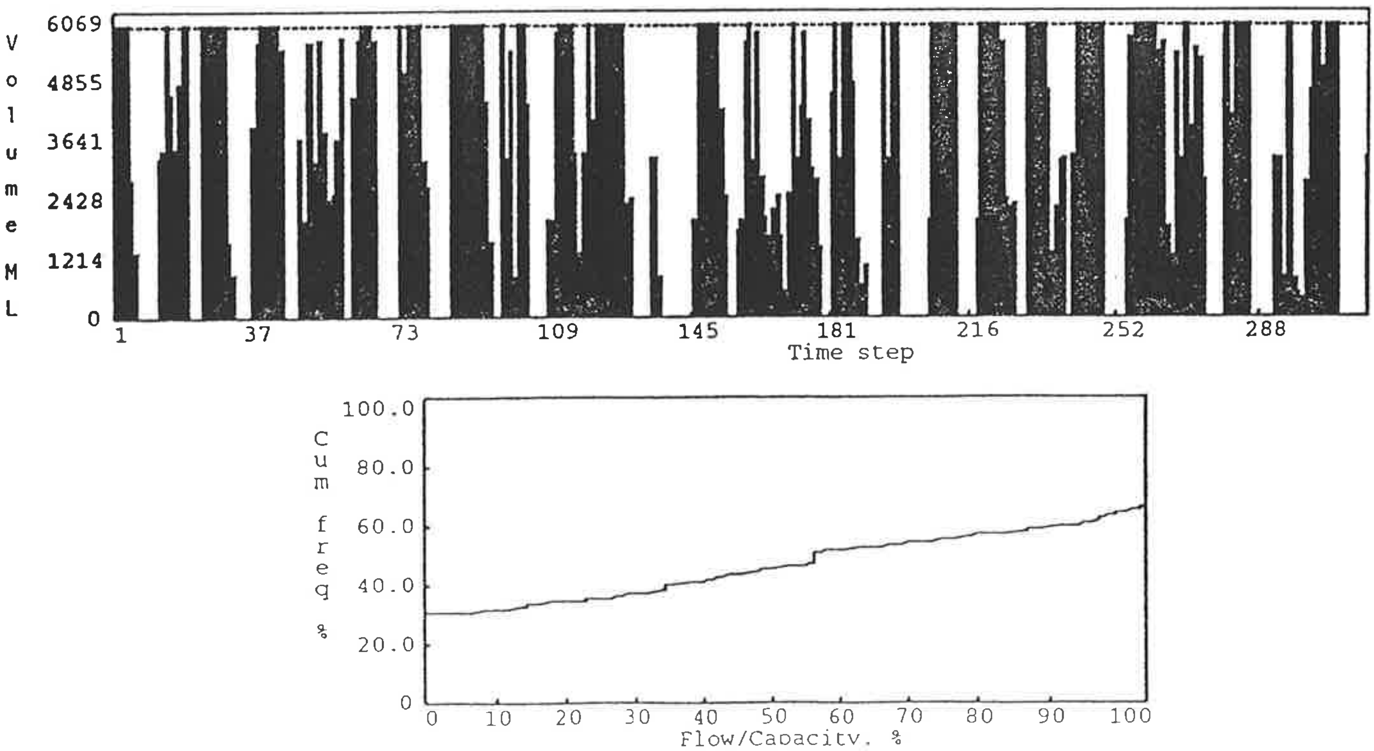

Figure 4.12 Googong Reservoir Supply (ML / month)

The selection of 1982 as the critical year in the yield model, is not quite correct, as the WATHNET model plots indicate that the low flows during 1982 result in shortfalls being experienced early in 1983. Therefore a sensitivity analysis of the critical year was performed and the results are presented in this section.

Further to these results and in an attempt to evaluate the performance of the various methods to achieve what may be expected to occur in the actual system when the operating rules are applied, a simulation model developed by ACTEW (Pink and Sooriyakumaran, 1988 and Pink, 1991) was run to evaluate the yield of the system for no shortfalls. The result of this was a yield of 108.0 GL. As expected this is lower than the other methods as it is a simulation model, but as expected WATHNET produces a better approximation of the yield than does the optimisation model or the yield model. A further improvement may be made to the WATHNET result by adding supply costs to the system, as these play a major role in the actual operation of the system. The WATHNET model will reduce the yield, in an attempt to minimise the supply cost according to the objectives discussed in Chapter 3. By including treatment and pumping costs for the Stromlo, Googong and Cotter supplies (according to Table 4.6) a reduced yield of 112.4 GL is obtained using WATHNET. This result may be more realistic, as the actual operating policies take these costs into account. A conclusion from the simulation model run and WATHNET run involving costs of supply is that it may be possible to improve the operation policy of the system in order to achieve a larger system yield in reality.

Table 4.6 Treatment and Pumping Cost for the Water Supplied to Canberra

Supply	Cost ($/ML)
Cotter	100.0*
Stromlo	7.3**
Googong	69.4**

* This figure is an arbitrary figure as the true cost of pumping water from Cotter to Stromlo was unknown.

** These cost as based on a supply from Stromlo of 56,000 ML / year and from Googong of 9,000 ML / year. Also it is worth noting that the pumping costs for Googong vary. The value given in Table 4.6 is an average figure.

4.3.2 Sensitivity Study on the Critical Year for the Yield Model

This study is undertaken to see if a better estimate of system yield can be obtained using some other values of the parameters of the yield model, β^r_m and Y^r_c. The accuracy of the yield model solution is dependent on the selection of the β^r_m values and the Y^r_c values in Equation 3.35. Usually the β^r_m values are based on the critical year or the driest year of the record. However, the accuracy of the solution will still depend on how the values in the year selected reflect the monthly flow proportions throughout the period of evaluation. From the results of the models it appears that 1983 is the critical year, however the driest year is 1982. It was therefore decided to evaluate the yield model using β^r_m values for 1982 and 1983 as well as the average monthly flow proportions for the period 1912-1983 and the average monthly flow proportions for the extended critical period 1979-1983. Corresponding values of Y^r_c were used. These values of β^r_m and Y^r_c are shown in Table 4.7 together with the estimated system yield using these values.

Table 4.7 Values of System Yield Estimated by the Yield Model

β^r_m values	Y^r_c values	Estimated System Yield (GL)
1982	1982	126.6
1982	Average 1912-1983	117.7
1983	1983	109.5
1983	Average 1912-1983	100.0
Average 1912-1983	1982	113.2
Average 1912-1983	1983	113.2
Average 1912-1983	Average 1912-1983	103.9
Average 1979-1983	1982	107.6
Average 1979-1983	1983	107.6
Average 1979-1983	Average 1979-1983	89.5

Most of these results are comparable with those obtained by the ACTEW simulation model and WATHNET. However, only the first two are approximately the same as the estimate of yield obtained using the optimisation model. It is considered better to use β^r_m and Y^r_c values which are the same (ie. 1982, 1983 or average 1912-1983) thus using the 1982 values of β^r_m and Y^r_c give the closest approximation to the optimisation model. The reason may be that the proportions of monthly flow in this year are a good approximation to actual withdrawals from the reservoir. The reason for the critical year (1983) giving a lower estimate of the yield would appear to be due to the extreme conditions which occur in this year. For instance, in the first two months of 1983 there is no flow in the Cotter River and the maximum withdrawal for supply occurs. A further reason for using a particular years Y_c^r value is that with a multiple reservoir system the yield from a particular reservoir may vary over the time period. Thus, if a average or the same value is assumed to be supplied from a particular reservoir for all periods then this will result in a reduction in the possible system yield. The reason this occurs is that there is likely to be periods when the particular reservoir can supply more than this yield, thus the system yield can be increased. This is possibly why when a particular year's yield is used the value of yield is higher than if an averaged value is used. It is interesting to note that for all yield model runs Corin, Bendora and Cotter Reservoirs have the same over-year and within-year capacities (both the Bendora and Cotter over-year capacities are at dead storage level). Googong storage capacity is the only one to vary between runs.

Therefore from these results the value of β_m^r and Y_c^r for the driest year 1982 were used for the remainder of this study for the evaluation of the yield of future reservoirs.

4.3.3 Evaluation of the Yields of Future Reservoirs

At this stage, the option of evaluating the yields of Riverlea and Tennent Reservoirs separately from the total system, over the period of record available for both was considered. These could then be added to the existing system yield to find the combined yield. This seems reasonable given that the two alternatives do not interact with the existing system with regard to regulation of streamflows, as is the case with the Coree and Cotter Reservoirs.

The results of examining the Tennent and Riverlea Reservoir expansions as individual projects and also including them as part of the current system are shown in Table 4.8.

It is quite clear from the results in the above table that there is not a great deal of difference between the results and therefore either approach would be adequate. The small difference does however indicate that the options do interact with the existing system in terms of which reservoirs are used to meet demand at any particular time. Therefore they will be evaluated in this manner. Also, when considering further expansions to the system it is appropriate to incorporate the previous expansions to the system to achieve more reliable results.

As an example of how reservoirs interact, consider the individual yield of Tennent as 53.3 GL (from the above table). It may be possible in some years to draw 120.0 GL from Tennent to meet demand. In years when the existing system can supply more than its designated yield the amount supplied by Tennent can be reduced. This then increases the yield of the existing system plus the option and explains why the yield for Tennent as part of the combined system is 56.1 GL. As can be seen, both WATHNET and the yield model utilise interaction between reservoirs to boost the total system yield when a new project is added. Therefore, for the remainder of this study, the incremental system yield of new options will be determined as they are added to the existing system.

Table 4.8 Yields of Tennent and Riverlea Reservoirs

Yield Model		
Option	Individual Yield	Increase in System Yield*
Tennent	53.3	56.1
Riverlea	29.1	30.3
WATHNET		
Option	Individual Yield	Increase in System Yield*
Tennent	49.6	58.5
Riverlea	27.5	33.0

*This is the increase in system yield when the option is included as the first expansion to the existing system.

The next step is to examine the incremental yields of all options as the first expansion to the existing system. Following this, the most appropriate option will be selected to ensure a minimum cost sequence is obtained. This option will then be added to the system and the incremental yields of the remaining three projects will be evaluated to find the next expansion. This procedure will continue until all the incremental yields of all projects are established and the projects are sequenced.

4.3.4 Evaluation of the Incremental Yield for the First Expansion

Once the existing system yield is obtained (Table 4.5), the next process is to assume that the four projects are added one at a time to the existing system and to determine the yield of the augmented system. The results obtained from this procedure are shown in Table 4.9a for WATHNET, Table 4.9b for the yield model and Table 4.9c for the optimisation model.

Table 4.9a Incremental Yields for the Four Options from WATHNET

Option	Incremental Yield (GL)	Equivalent Cost for an Annual Growth Rate of				Unit Cost ($/KL)
		1.5 %	2 %	2.58 %	3 %	
Coree	30.3	9.10	10.96	13.14	14.73	3.04
Tennent	58.5	**8.18**	**9.31**	**10.70**	**11.74**	**1.88**
Riverlea	33.0	14.00	16.74	19.98	22.35	4.48
Cotter exp.	27.1	9.69	11.76	14.19	15.95	3.40

Table 4.9b Incremental Yields for the Four Options from the Yield Model

Option	Incremental Yield (GL)	Equivalent Cost for an Annual Growth Rate of				Unit Cost ($/KL)
		1.5 %	2 %	2.58 %	3 %	
Coree	24.9	10.33	12.85	14.90	16.12	3.69
Tennent	56.1	**8.45**	**9.75**	**11.09**	**11.99**	**1.96**
Riverlea	30.3	14.91	18.23	21.13	22.91	4.88
Cotter exp.	21.5	11.28	14.19	16.43	17.72	4.28

Table 4.9c Incremental Yields for the Four Options from the Optimisation Model

Option	Incremental Yield (GL)	Equivalent Cost for an Annual Growth Rate of				Unit Cost ($/KL)
		1.5 %	2 %	2.58 %	3 %	
Coree	27.1	9.64	11.3	13.46	15.74	3.39
Tennent	59.1	**8.19**	**9.20**	**10.51**	**11.71**	**1.86**
Riverlea	31.6	14.3	16.66	19.72	22.83	4.68
Cotter exp.	23.8	10.38	12.2	14.61	17.24	3.87

The results in the above Tables show that Tennent Reservoir has the lowest equivalent cost for all growth rates and the lowest unit cost. It will, therefore, be the first project expanded in all cases. This results in the estimated yield of the expanded system being 175.0 GL using WATHNET, 182.7 GL using the yield model and 180.0 GL using the optimisation model.

4.3.5 Evaluation of the Incremental Yield for the Second Expansion

The procedure is the same as previously. The remaining three projects are each added to the new system and the results are displayed in Tables 4.10a to 4.10c for WATHNET, the yield model and the optimisation model respectively.

Table 4.10a Incremental Yields for the Three Remaining Projects Using WATHNET

Option	Incremental Yield (GL)	Equivalent Cost for an Annual Growth Rate of				Unit Cost ($/KL)
		1.5 %	2 %	2.58 %	3 %	
Coree	27.0	**12.19**	**14.65**	**18.24**	**19.00**	**3.41**
Riverlea	31.1	17.93	21.47	26.53	27.85	4.75
Cotter exp.	24.0	13.18	15.86	19.89	20.55	3.83

Table 4.10b Incremental Yields for the Three Remaining Projects Using the Yield Model

Option	Incremental Yield (GL)	Equivalent Cost for an Annual Growth Rate of				Unit Cost ($/KL)
		1.5 %	2 %	2.58 %	3 %	
Coree	26.2	**12.90**	**15.11**	**20.19**	**21.84**	**3.51**
Riverlea	30.4	18.82	22.06	28.95	31.46	4.87
Cotter exp.	22.7	14.25	16.62	22.63	24.36	4.05

Table 4.10c Incremental Yields for the Three Remaining Projects Using the Optimisation Model

Option	Incremental Yield (GL)	Equivalent Cost for an Annual Growth Rate of				Unit Cost ($/KL)
		1.5 %	2 %	2.58 %	3 %	
Coree	24.8	**13.26**	**16.93**	**19.50**	**20.65**	**3.71**
Riverlea	30.4	18.64	23.43	27.14	28.98	4.87
Cotter exp.	21.5	14.65	18.90	21.64	22.74	4.28

The results shown in the above tables indicate that the second project to be expanded will be the Coree Reservoir. The estimated total yield including the Tennent and Coree

Reservoirs is 202.0 GL using WATHNET, 208.9 GL using the yield model and 204.8 GL using the optimisation model.

The incremental yields of the projects in Tables 4.10a to 4.10c decrease from the estimates of yield for these projects in Tables 4.9a to 4.9c. The reason for this is that as the first expansion (ie Table 4.9a to 4.9c) there is more interaction between the existing system and the reservoirs. This will result in a larger estimate of the yield of a particular project.

4.3.6 Evaluation of the Incremental Yield for the Third and Fourth Expansions

With the addition of Tennent and Coree Reservoirs to the existing system, only the Riverlea expansion and the expansion of the existing Cotter Reservoir remain to be examined. The results are shown in Tables 4.11a to 4.11c.

Table 4.11a Incremental Yields for the Two Remaining Projects Using WATHNET

Option	Incremental Yield (GL)	Equivalent Cost for an Annual Growth Rate of				Unit Cost ($/KL)
		1.5 %	2 %	2.58 %	3 %	
Riverlea	29.5	**20.93**	23.84	**32.31**	32.44	**5.02**
Cotter exp.	14.9	21.96	**23.44**	35.72	**32.28**	6.17

Table 4.11b Incremental Yields for the Two Remaining Projects Using the Yield Model

Option	Incremental Yield (GL)	Equivalent Cost for an Annual Growth Rate of				Unit Cost ($/KL)
		1.5 %	2 %	2.58 %	3 %	
Riverlea	30.6	**20.46**	24.55	**30.7**	31.69	**4.84**
Cotter exp.	15.9	20.50	**24.36**	31.58	**30.43**	5.79

Table 4.11c Incremental Yields for the Two Remaining Projects Using the Optimisation Model

Option	Incremental Yield (GL)	Equivalent Cost for an Annual Growth Rate of				Unit Cost ($/KL)
		1.5 %	2 %	2.58 %	3 %	
Riverlea	29.5	19.35	**24.39**	**29.53**	**35.16**	**5.02**
Cotter exp.	14.9	**18.84**	24.82	30.27	38.14	6.17

For all three methods, it was found that for the low demand growth case, the equivalent cost values were very similar (ie. nearly the same) and when using non-linear growths, an optimum sequence is not guaranteed and therefore it was decided to calculate the present value of cost (PVC) for both sequences. The same procedure was also used for the extra low demand growth case when the equivalent cost values are similar. For the low demand growth case the PVC for both the sequences of Riverlea and Cotter Reservoirs is shown in Table 4.12.

Table 4.12 Present Value of Costs in the Ordering of Riverlea and Cotter for the Case of Low Demand Growth

Model	PVC (Riverlea/Cotter)	PVC (Cotter/Riverlea)
WATHNET	90.480	90.485
Optimisation	84.598	84.602
Yield	75.175	75.179

As can be seen the results are very similar for all yield estimation techniques and the order of these last two projects would appear to be not very critical. However as the ordering of Riverlea then Cotter expansions achieves a slightly reduced PVC then Riverlea will be expanded first. The sequencing for the other demand growth rates was also checked using the PVC, and in some cases the sequence indicated in Tables 4.11a to 4.11c did not provide the lowest PVC. However, the sequences which provide the lower PVC solution will be used for the remainder of this study.

The estimated system yield after the Riverlea expansion using WATHNET is 231.5 GL, using the yield model is 239.5 GL and using the optimisation model is 235.1 GL. In the case of a Cotter expansion first, the estimated yield using WATHNET is 216.9 GL, using the yield model is 224.8 GL and using the optimisation model is 219.9 GL.

For the unit cost method, Riverlea is the project selected for all the yield estimation techniques. The subsequent system yield after Riverlea is expanded is detailed above.

Finally, the remaining project is expanded and it is found there is a slight variation in the yield for all methods from the results shown in Tables 4.11a to 4.11c. The estimated yields found for Cotter were 15.0 GL using WATHNET, 16.2 GL using the yield model and 15.1 GL using the optimisation model and for Riverlea 29.0 GL using WATHNET, 30.8 GL using the yield model and 30.3 GL using the optimisation model. With the addition of the final expansion, the final Canberra water supply yield was estimated as 246.5 GL using WATHNET, 255.7 GL using the yield model and 250.2 GL using the optimisation model.

The time series of storage volumes and supplies for the WATHNET analysis of the total expanded system for the period 1966 to 1983, are shown in Figures 4.13 to 4.26. These plots show that for the majority of the period under consideration the reservoirs remain above 60% of their capacity. All the reservoirs experience a zero storage level in April 1983, which is the critical month in the simulation. The Stromlo treatment plant never operates at zero capacity and in fact Stromlo is at 50 % of its capacity or greater for a large percentage of the period. Of the remaining pipelines, Cotter does not supply any flow for approximately 55% of the time. While the other pipelines experience times of zero flow they are not of the same order as the Cotter supply. The percentage of the time the other pipelines have zero flow in them varies from 40% for Coree to 15% for Tennent. Of the supply mains, Googong spends the greatest time at full capacity (approximately 50%).

While the above yields were being estimated for the new projects, the size of the supply mains from the new reservoirs were also found. The capacities of the supply mains found by WATHNET are shown in Table 4.13. Values were not estimated using either the yield model or the full optimisation model due to the large amount of computer time required.

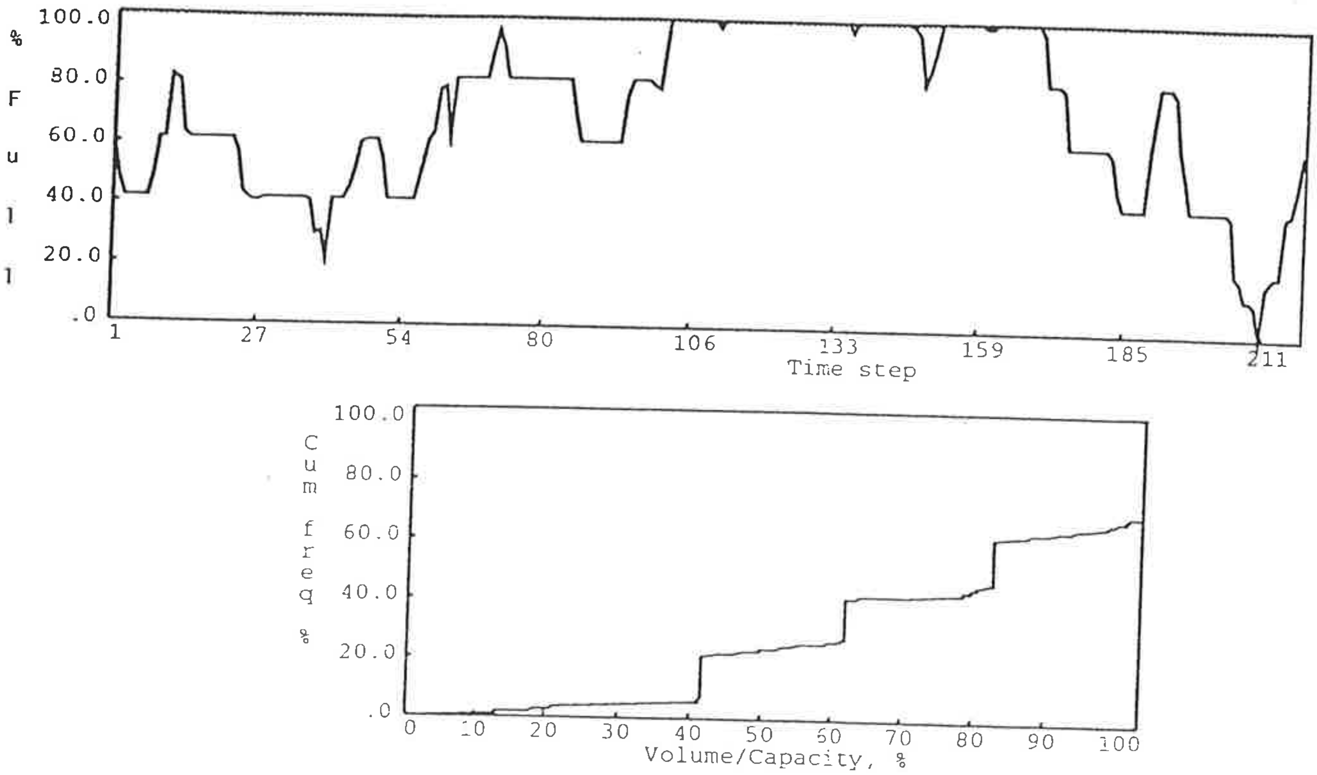

Figure 4.13 Corin Reservoir Storage after Full Expansion (% Full / month)

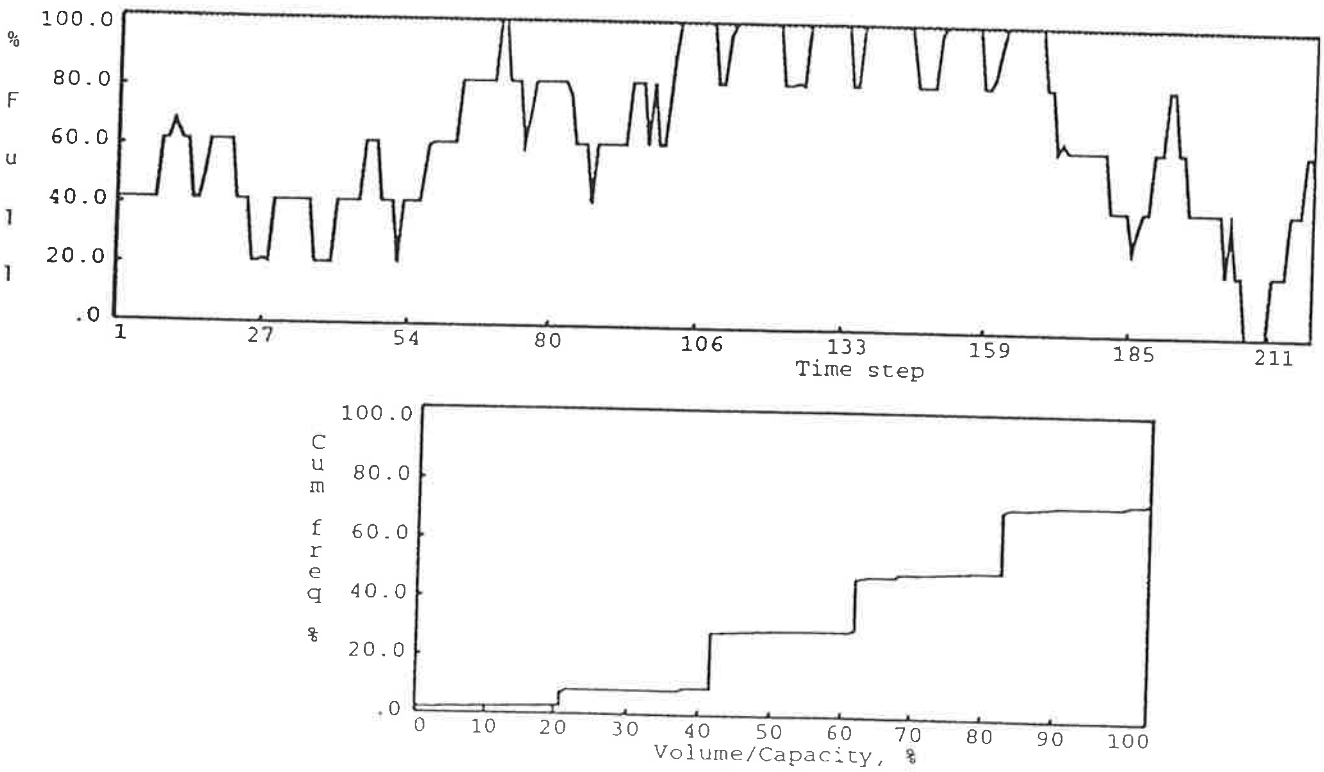

Figure 4.14 Bendora Reservoir Storage after Full Expansion (% Full / month)

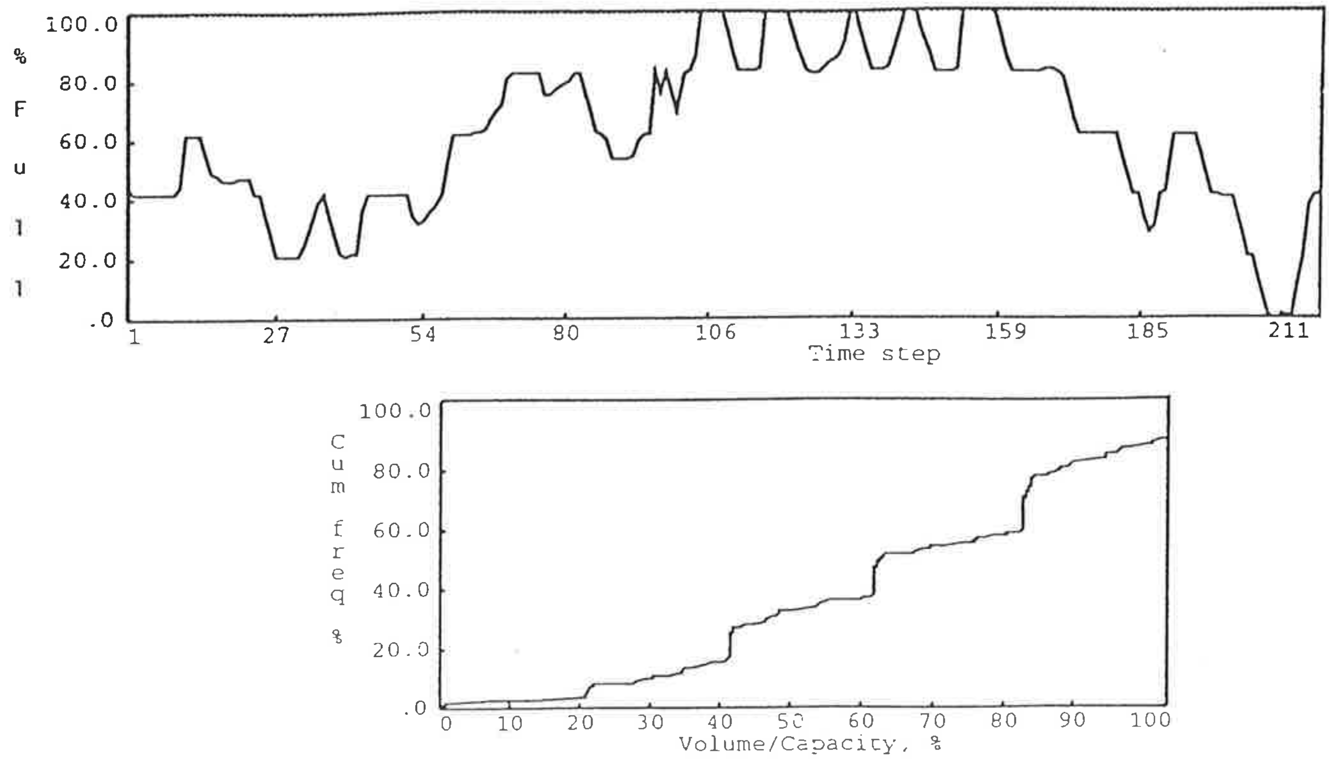

Figure 4.15 Cotter Reservoir Storage after Full Expansion (% Full / month)

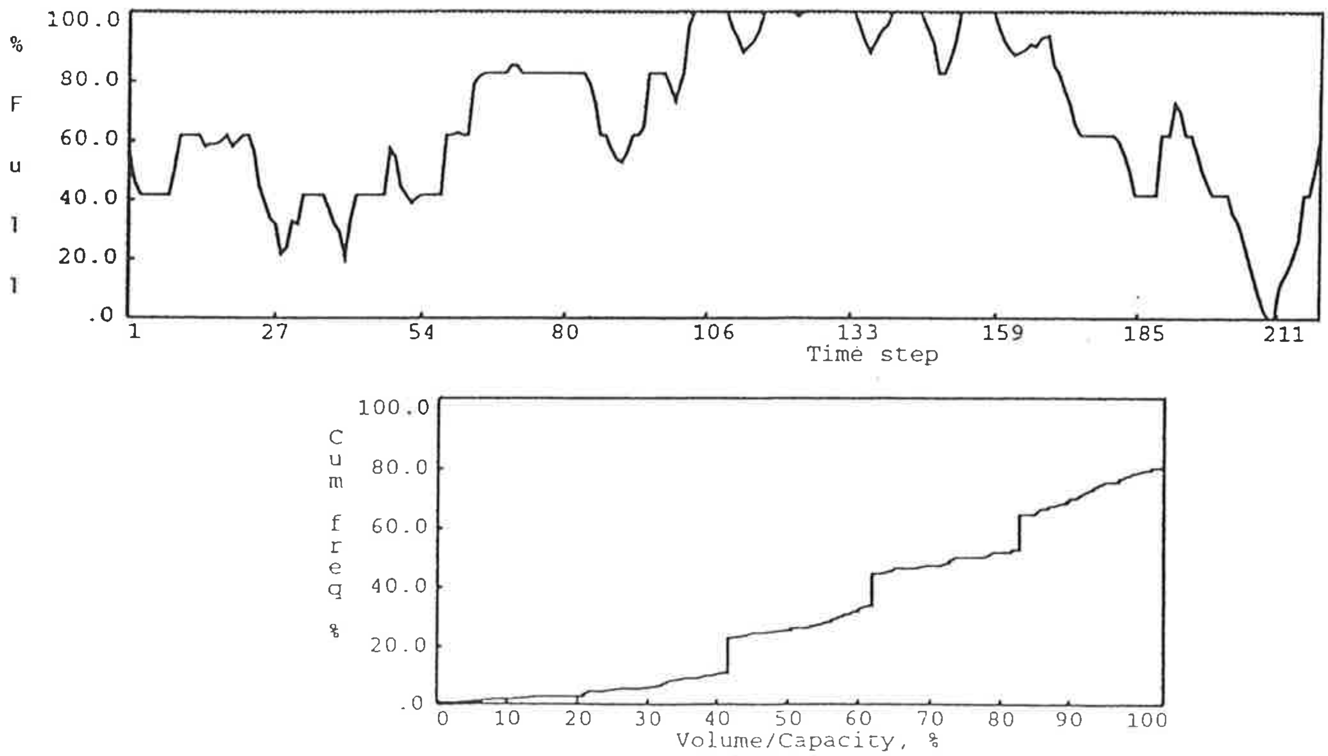

Figure 4.16 Coree Reservoir Storage (% Full / month)

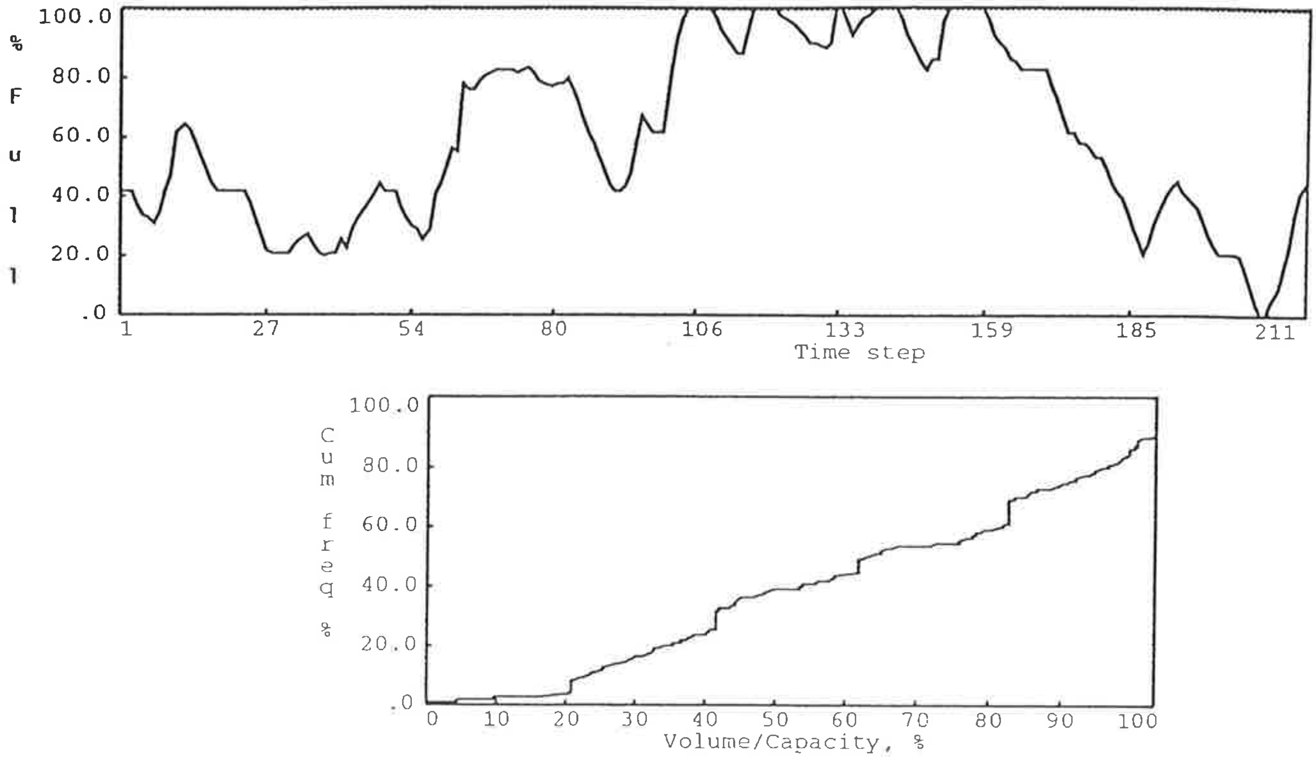

Figure 4.17 Tennent Reservoir Storage (% Full / month)

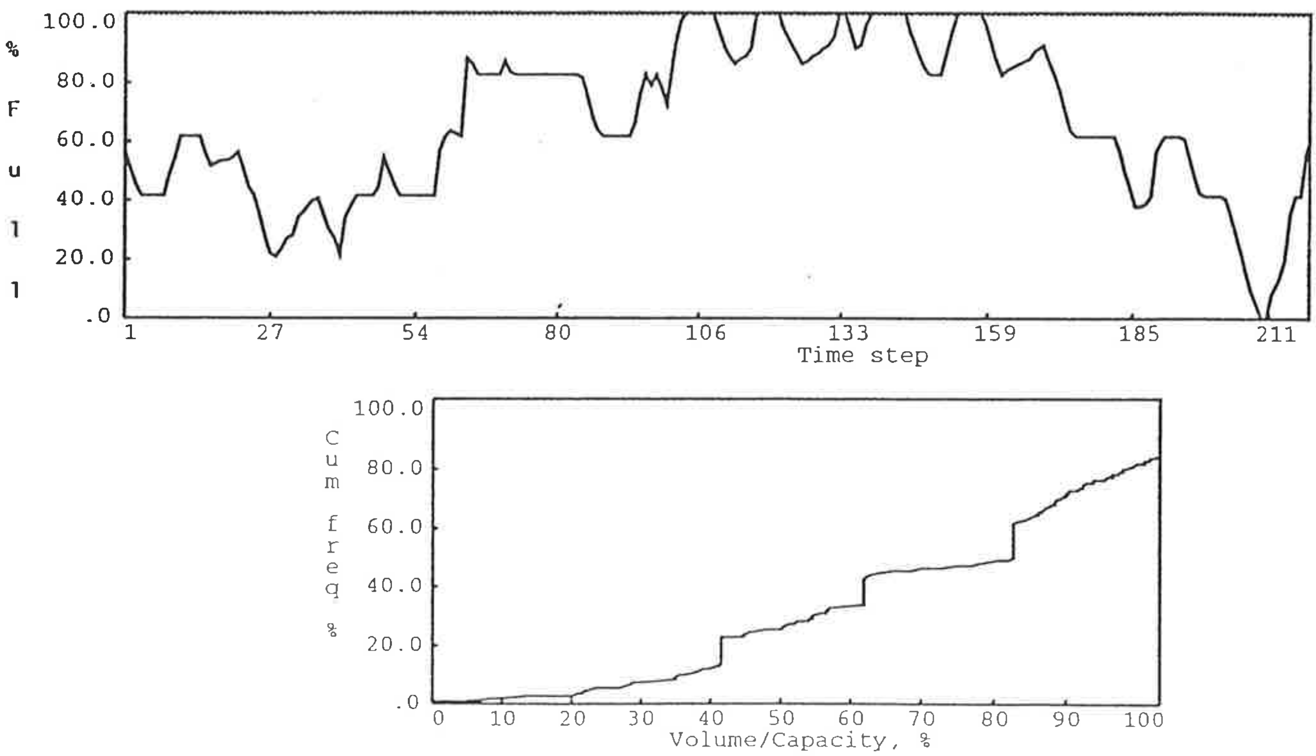

Figure 4.18 Riverlea Reservoir Storage (% Full / month)

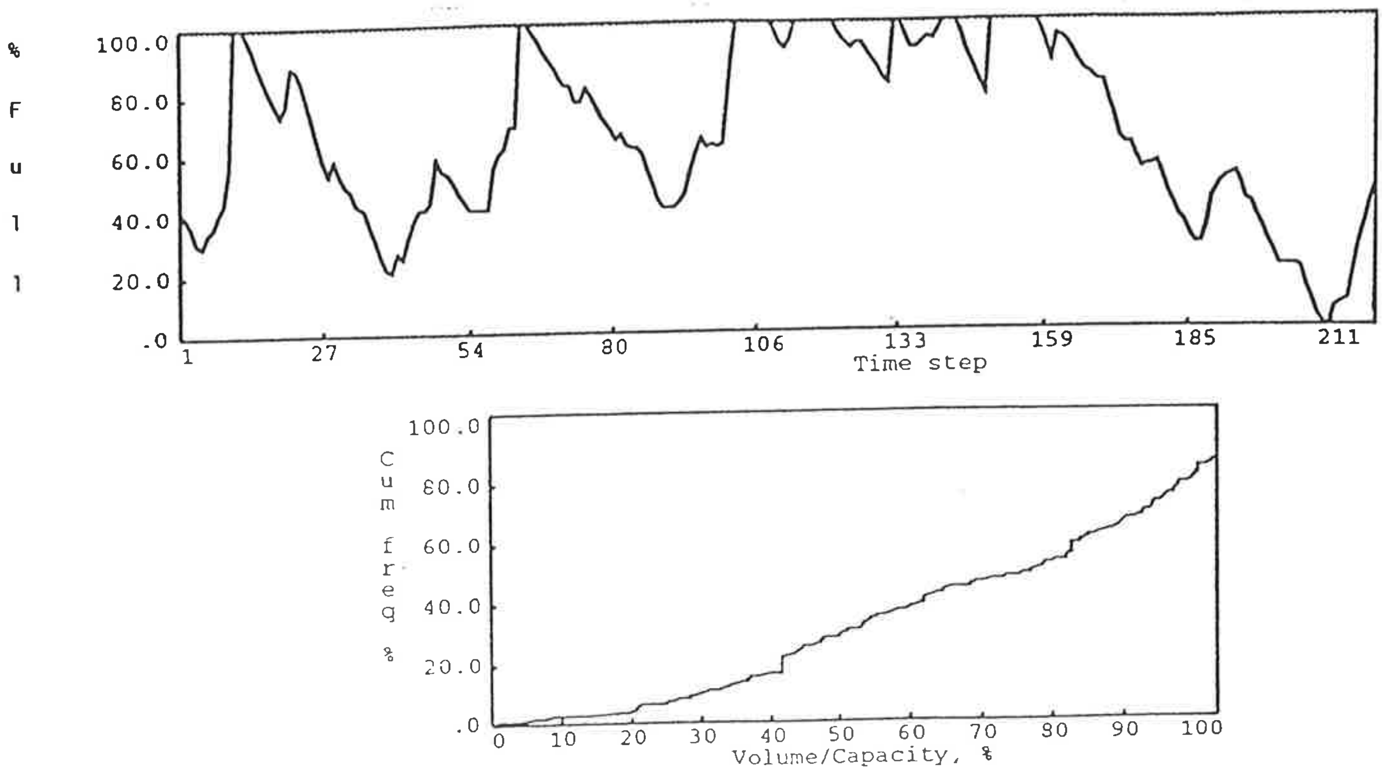

Figure 4.19 Googong Reservoir Storage after Full Expansion (% Full / month)

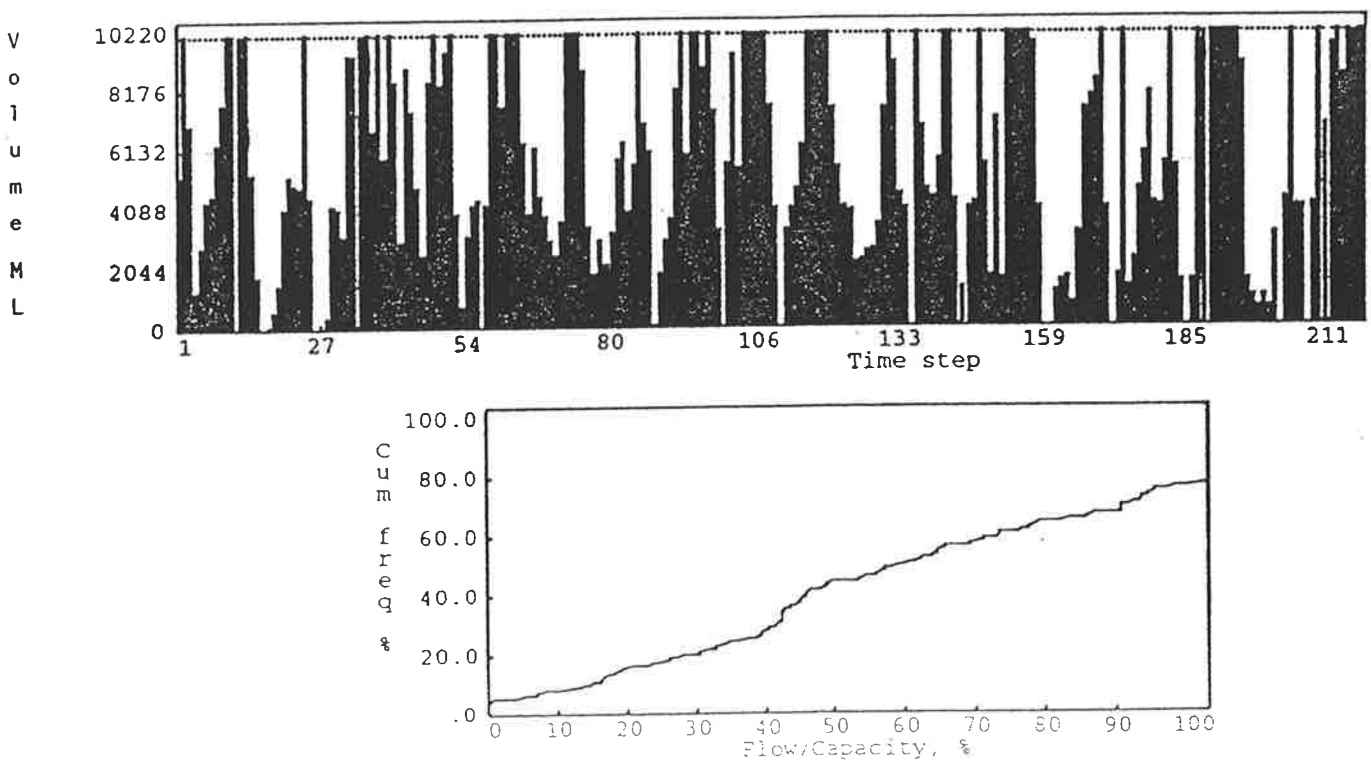

Figure 4.20 Bendora Reservoir Supply after Full Expansion (ML / month)

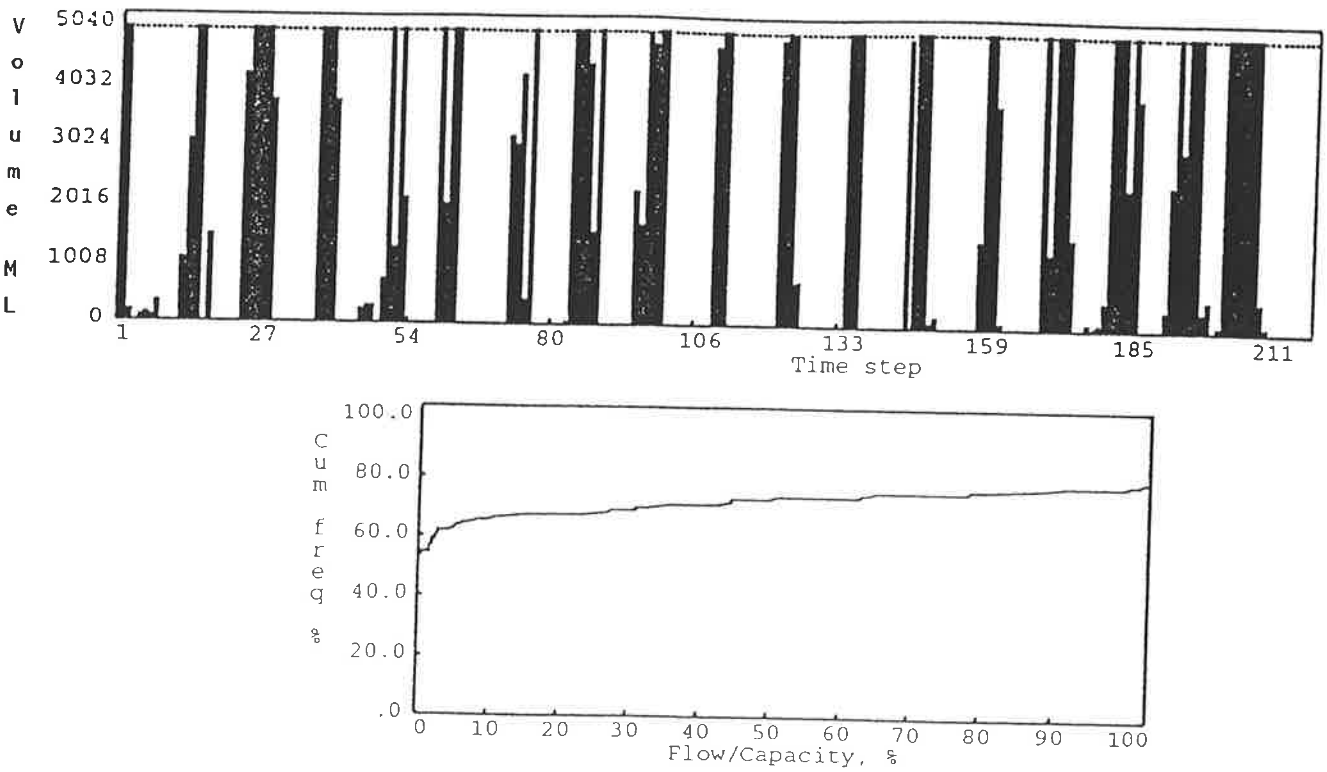

Figure 4.21 Cotter Reservoir Supply after Full Expansion (ML / month)

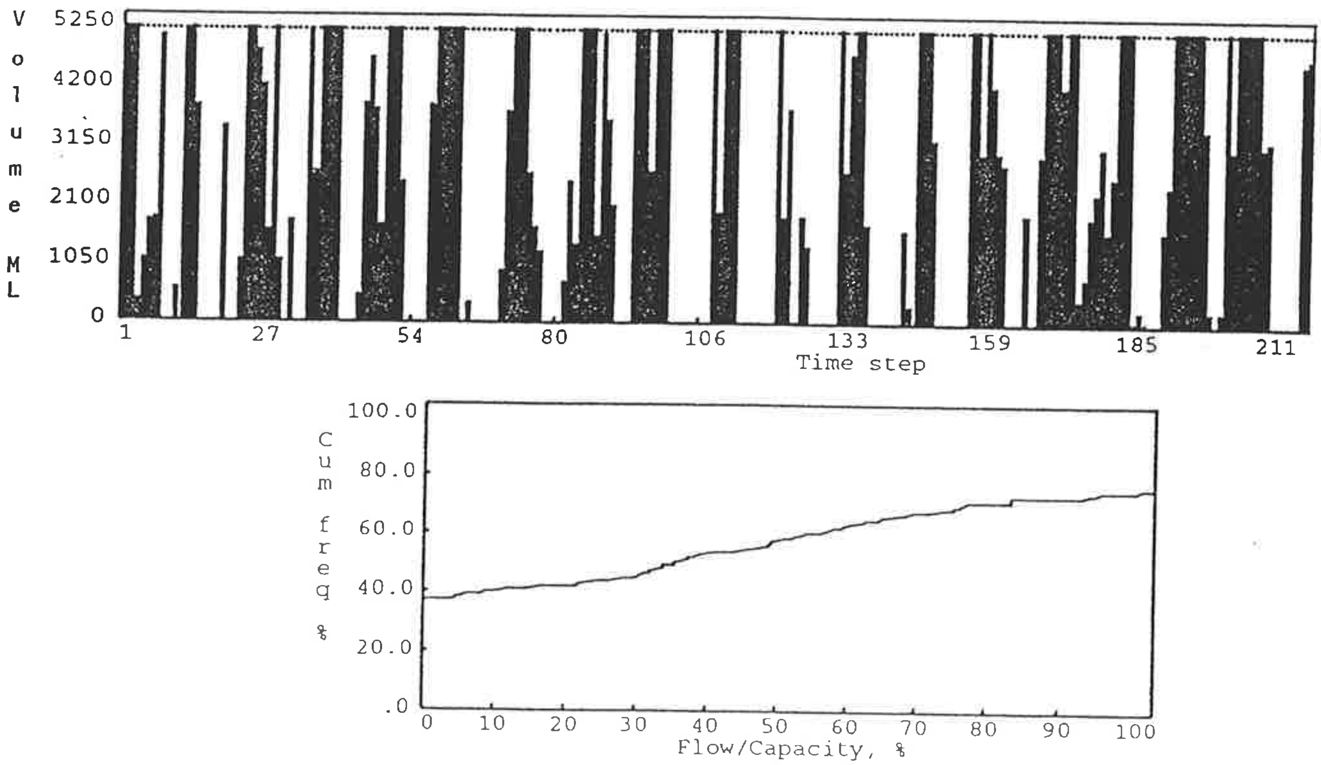

Figure 4.22 Coree Reservoir Supply (ML / month)

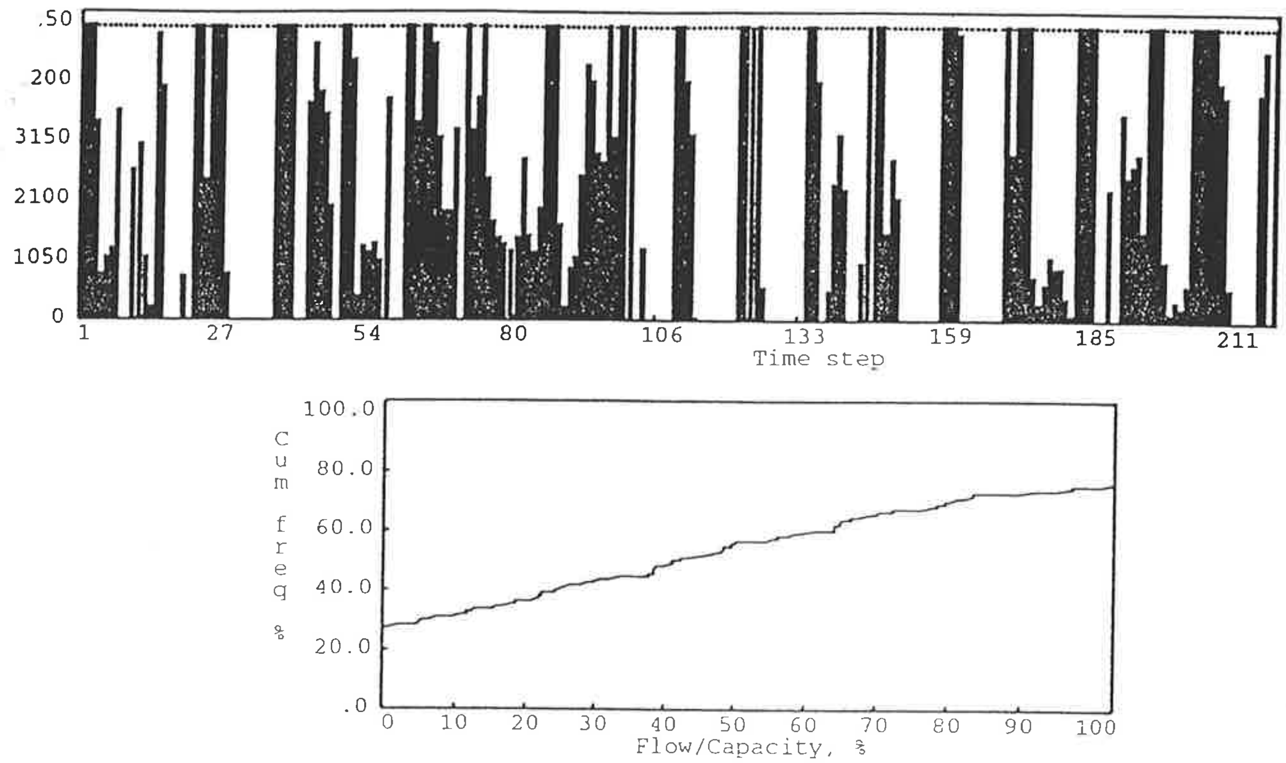

Figure 4.23 Riverlea Reservoir Supply (ML / month)

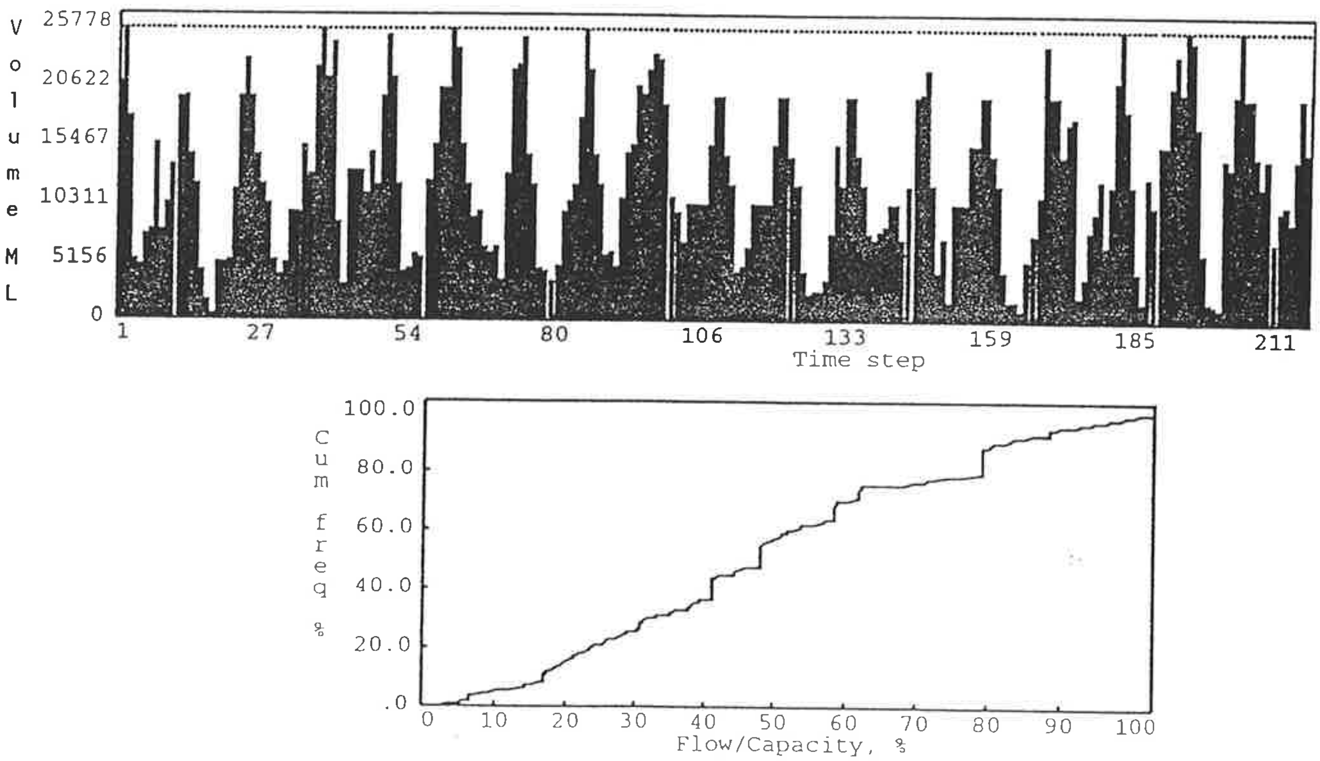

Figure 4.24 Stromlo Water Treatment Plant Supply (ML / month)

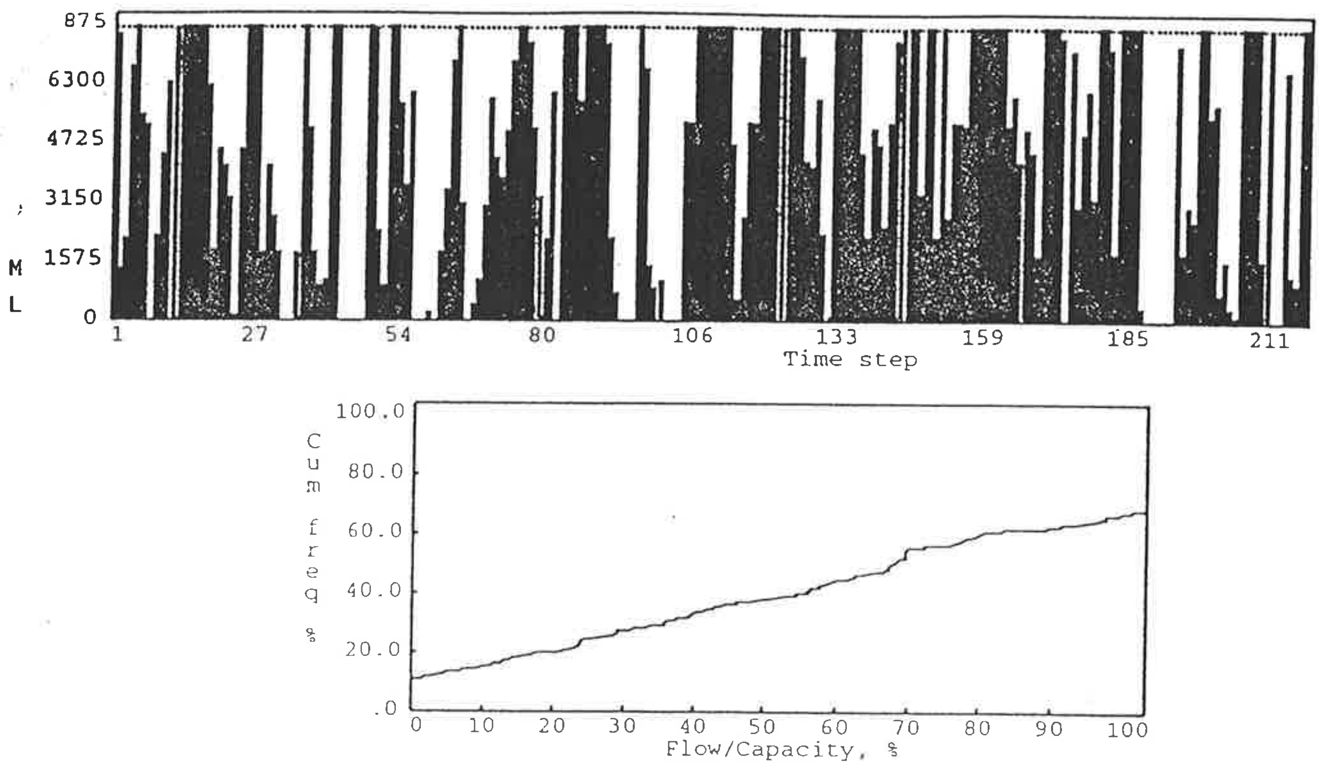

Figure 4.25 Tennent Reservoir Supply (ML / month)

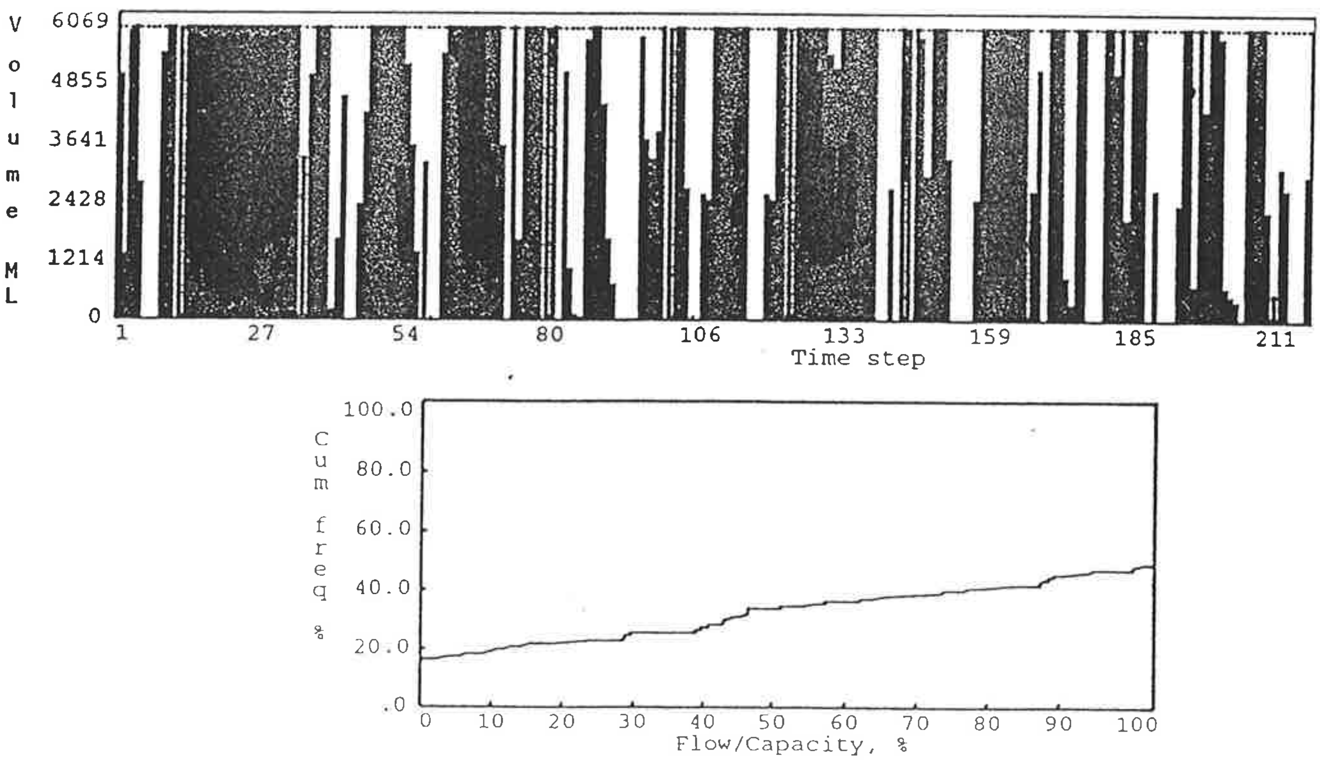

Figure 4.26 Googong Reservoir Supply after Full Expansion (ML / month)

Table 4.13 Capacity of the Supply Mains Estimated by WATHNET

Supply Mains	WATHNET (GL / month)
Coree	5.0
Tennent	7.5
Riverlea	5.0
Cotter	4.8
Stromlo	24.6*

*These figures are the capacity of Stromlo after all expansions. However it is possible to augment Stromlo in several stages depending on the project size and timing between projects.

4.3.7 Timing of the Future Expansions

After the yield and the sequence of new projects was obtained, the timing of the particular projects was examined. Using the demand projections discussed earlier for Canberra (Figure I.1) and the initial yields of the system from WATHNET, the yield model and the optimisation model (Table 4.5), the results shown in Tables 4.14, 4.15 and 4.16 were obtained for the equivalent cost sequencing method. These tables give the estimated year of expansion for each project taking 1992 as year zero. The timing and expansion schedule obtained by the unit cost method is the same as the equivalent cost methods shown in Tables 4.14 to 4.16 when the sequence is Tennent, Coree, Riverlea and Cotter. In the cases where the equivalent cost method sequences Cotter before Riverlea, the timing and expansion schedule for the unit cost sequence of Riverlea then Cotter is given in Table 4.17.

Table 4.14 WATHNET Timing and Expansion Schedule for the Equivalent Cost Sequencing Method

Expansion Options	Demand Growth Rate = 1.5 %	Demand Growth Rate = 2.0 %	Demand Growth Rate = 2.58 %	Expansion Options	Demand Growth Rate = 3.0 %
Tennent	16 (2008)	12 (2004)	9 (2001)	Tennent	8 (2000)
Coree	43 (2035)	32 (2024)	25 (2017)	Coree	21 (2013)
Riverlea	53 (2045)	39 (2031)	31 (2023)	Cotter	26 (2018)
Cotter	62 (2054)	46 (2038)	36 (2028)	Riverlea	29 (2021)
PVC ($Million)	60.04	90.48	122.15	PVC ($Million)	143.61

Table 4.15 The Yield Model Timing and Expansion Schedule for the Equivalent Cost Sequencing Method

Expansion Options	Demand Growth Rate = 1.5 %	Demand Growth Rate = 2.0 %	Expansion Options	Demand Growth Rate = 2.58 %	Demand Growth Rate = 3.0 %
Tennent	21 (2013)	16 (2008)	Tennent	12 (2004)	10 (2002)
Coree	46 (2038)	34 (2024)	Coree	27 (2019)	23 (2015)
Riverlea	55 (2047)	41 (2033)	Cotter	32 (2024)	27 (2019)
Cotter	64 (2056)	48 (2040)	Riverlea	35 (2027)	30 (2022)
PVC ($Million)	46.88	75.18	PVC ($Million)	107.26	130.35

Table 4.16 The Optimisation Model Timing and Expansion Schedule for the Equivalent Cost Sequencing Method

Expansion Options	Demand Growth Rate = 1.5 %	Demand Growth Rate = 2.0 %	Demand Growth Rate = 3.0 %	Expansion Options	Demand Growth Rate = 2.58 %
Tennent	18 (2010)	13 (2005)	9 (2001)	Tennent	10 (2002)
Coree	45 (2037)	34 (2026)	22 (2014)	Coree	26 (2018)
Riverlea	53 (2045)	40 (2032)	27 (2019)	Cotter	31 (2023)
Cotter	63 (2055)	47 (2039)	31 (2023)	Riverlea	34 (2026)
PVC ($Million)	54.31	84.60	136.44	PVC ($Million)	117.17

Table 4.17 The Timing and Expansion Schedule for the Unit Cost Sequencing Method

Expansion Options	WATHNET Demand Growth Rate = 3.0 %	Yield Model Demand Growth Rate = 2.58 %	Yield Model Demand Growth Rate = 3.0 %	Optimisation Model Demand Growth Rate = 2.58 %
Tennent	8 (2000)	12 (2004)	10 (2002)	10 (2002)
Coree	21 (2013)	27 (2019)	23 (2015)	26 (2018)
Riverlea	26 (2018)	32 (2024)	27 (2019)	31 (2023)
Cotter	31 (2023)	37 (2029)	32 (2024)	36 (2028)
PVC ($Million)	143.72	107.33	130.46	117.25

From the results in Tables 4.14 to 4.16 it is obvious that there is variation in the timing of projects. This is due to the different yield estimation methods used and the different project sequencing. The difference in the project timing using the three methods is more significant for the lower demand growth rates. This is particular true for the timing of the initial project. The timing of projects is later using the yield model yield estimates. The reason for this is that the yield estimates of the existing system yield and the future projects yields are larger for this method than the other methods. The timing of projects when using the yield and optimisation models yield estimates are comparable, with only one year difference in the majority of cases. For the different population growth rates it is apparent that as population growth increases that the timing of projects is earlier.

When comparing the present value of cost between the cases appearing in Table 4.17 (for the unit cost method) and Tables 4.14 to 4.16 it can be seen that the equivalent cost method produces a slightly better sequence in the case when Cotter is sequenced before Riverlea. The results indicate how the sequence varies with demand growth rate and therefore how this parameter should be included in the sequencing of projects. Thus, the equivalent cost method appears to be the better sequencing method even when expected the demand growth in demand is non-linear and the results of using the equivalent cost method cannot be guaranteed to be optimal.

The discount rate was selected as 6 %. Other discount rates could be examined but it was decided to take 6 % as a standard rate. However, with an increase in the discount rate it is likely that a change in sequence will occur. For instance if the discount rate was 12 %, Tennent and Coree will be interchanged in the extra low (1.5 %) demand growth case for the WATHNET results. The information for the optimisation model in Tables 4.16 is displayed graphically in Figure 4.27. Figure 4.27 represents an expansion schedule for the Canberra system.

4.4 Conclusions for the Yield Evaluation and Project Sequencing Study

The ability of the Canberra water supply system to satisfy demand now and in the future has been evaluated. The evaluation examined the yield of the existing system as well as the incremental yields of future reservoirs. With these results the projects were sequenced and the results of using three yield evaluation methods are shown in Table 4.18, 4.19 and 4.20.

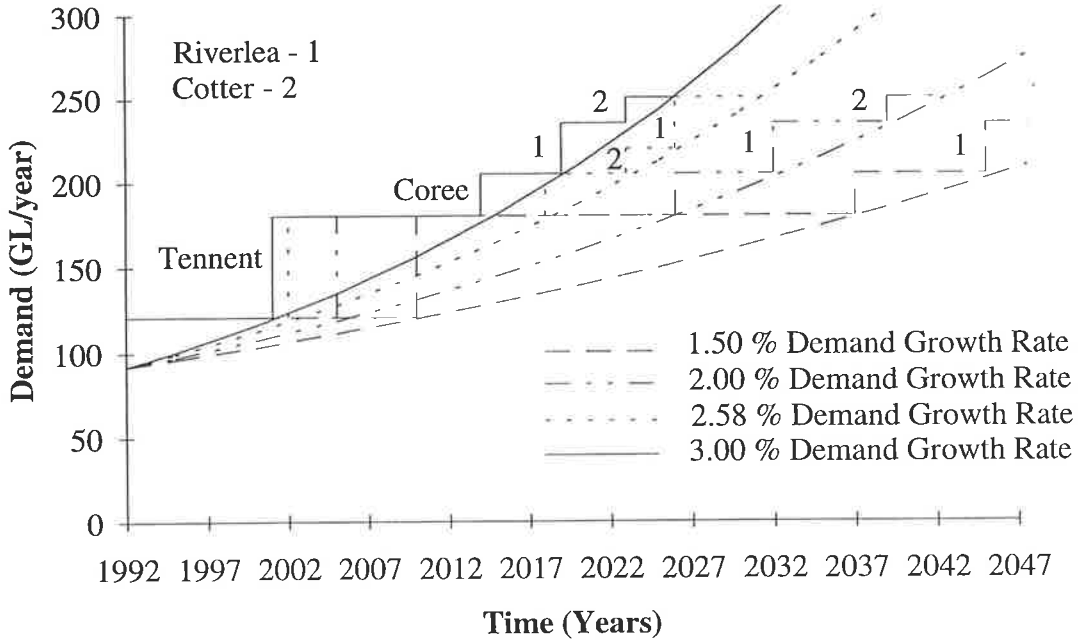

Figure 4.27 Project Expansion for the Various Demand Growth Rates for the Optimisation Model Evaluation of the Yields of Future Reservoirs

Table 4.18 Summary of Yield Evaluation and Sequencing of Future Reservoirs using WATHNET and the Equivalent Cost Sequencing Method

Reservoir Expansion	WATHNET Demand Growth Rates of 1.5 %, 2.0 % and 2.58 %		Reservoir Expansion	WATHNET Demand Growth Rate of 2.58 %	
	Incremental Yield (GL/Year)	Total Yield (GL/Year)		Incremental Yield (GL/Year)	Total Yield (GL/Year)
Existing	-	116.5	Existing	-	116.5
Tennent	58.5	175.0	Tennent	58.5	175.0
Coree	27.0	202.0	Coree	27.0	202.0
Riverlea	29.5	231.5	Cotter	14.9	216.9
Cotter	15.0	246.5	Riverlea	29.5	246.6

Table 4.19 Summary of Yield Evaluation and Sequencing of Future Reservoirs using the Yield Model and the Equivalent Cost Sequencing Method

Reservoir Expansion	Yield Model Demand Growth Rates of 1.5 % and 2.0 %		Reservoir Expansion	Yield Model Demand Growth Rates of 2.58 % and 3.0 %	
	Incremental Yield (GL/Year)	Total Yield (GL/Year)		Incremental Yield (GL/Year)	Total Yield (GL/Year)
Existing	-	126.6	Existing	-	126.6
Tennent	56.1	182.7	Tennent	56.1	182.7
Coree	26.2	208.9	Coree	26.2	208.9
Riverlea	30.6	239.5	Cotter	15.9	224.8
Cotter	16.2	255.7	Riverlea	30.9	255.7

Table 4.20 Summary of Yield Evaluation and Sequencing of Future Reservoirs using the Optimisation Model and the Equivalent Cost Sequencing Method

Reservoir Expansion	Optimisation Model Demand Growth Rates of 1.5 %, 2.0 % and 3.0 %		Reservoir Expansion	Optimisation Model Demand Growth Rates of 2.0 %	
	Incremental Yield (GL/Year)	Total Yield (GL/Year)		Incremental Yield (GL/Year)	Total Yield (GL/Year)
Existing	-	120.9	Existing	-	120.9
Tennent	59.1	180.0	Tennent	59.1	180.0
Coree	24.8	204.8	Coree	24.8	204.8
Riverlea	30.3	235.1	Cotter	15.1	219.9
Cotter	15.1	250.2	Riverlea	30.3	250.2

These results are for the equivalent cost sequencing method. For the unit cost method the same yield and sequence of projects were found for all demand growth rates. The sequence found was Tennent, Coree, Riverlea and Cotter and therefore the summary for the unit cost sequencing method will be the same as the results appearing in the left hand columns of Tables 4.18 to 4.20.

The results obtained by all three yield evaluation methods are comparable. The estimation of the yield for the existing system produces good results when compared to the 108 GL obtained by the ACTEW simulation model and the 115 GL estimated by ACTEW. The difference between these two values is because ACTEW have considered other augmentations of the existing supply system. The reason that the estimated values are higher than the ACTEW simulation model result is due to the latter's use of the actual system operating rules. It is interesting to note that when costs are placed on the supplies for the WATHNET run the yield is reduced to 112.4 GL. This result may indicate that the existing operating policies could be changed to increase the yield. The difference in the estimated yields is due to the utilisation of simulation and optimisation methods.

The variation between the yield model and the optimisation model was discussed in section 4.1 and it was concluded to be due to the within-year storage constraints in the yield model and the ability of the selected critical year reservoir inflow proportions to represent the inflow proportions in the other years of analysis. A possible way to reduce the effect of the within-year storage constraint is to increase the critical period to say two years. This may result in a more realistic evaluation of the within year storage and thus yield.

A problem experienced with the yield model and also the optimisation model, is the length of the study period. As both models use an optimisation technique they have the ability to adjust for extended high flow and drought periods. Thus a longer length of record may be needed in order to obtain a more accurate estimate of the yield. The historical flow records for the reservoirs may be higher than the long term average and thus overestimate the yield or lower than the long term average and thereby underestimate the yield. The actual effect on the water supply system is unknown due to the interaction between the projects.

The WATHNET results are expected to be more realistic than the yield model or the optimisation model results, as the simulation examines the system on a month to month basis in a similar way to the traditional operation of a reservoir system. The use of WATHNET could be expanded to evaluate restriction rules for the system.

The results obtained so far are based purely on the objective of maximising the system yield. No preference is placed on the use of any particular supply source or reservoir (ie. operating rules) as may be experienced in real world situations. Such preference may be based on water treatment cost and pumping cost or water quality considerations. Cost differences occur in the Canberra system and Table 4.6 identifies the relative costs of the various sources. Also, for this system, a restriction is placed on the water pumped from the Cotter Reservoir due to the quality of the water. For WATHNET the result of placing these constraints on the system were shown in section 4.4.1. It was found that a reduced yield was obtained. With these restrictions on supply, a set of operating rules could be obtained for the system to help meet demand while minimising the operating costs.

In the three methods of analyses of the yield, errors are evident. The linearisation of the surface area versus storage volume, the assumption regarding flow into Corin, Bendora, Coree and Cotter, rainfall over particular area's, etc. may all lead to errors in the results. The models could be extended to reduce the errors and give better results. However the additional work needed is not likely to affect the results greatly and it was considered not to be worth the extra effort. In comparison to the assumption of using the historical data to model the system to find the yield (ie. no critical year in the future is worse than one previously experienced), the simplifications seem acceptable. The technique outlined in the study could be improved by using a longer period of synthetically generated hydrologic data to estimate the system yield for a specified level of reliability.

The equivalent cost method and unit cost method were used for project sequencing in this study, with the equivalent cost method producing the slightly better results. The equivalent cost sequencing method's ability to consider changes in sequence when the demand growth rate changes was highlighted. The changes which occurred show the importance of considering the demand growth rate, as well as the project cost and yield, when sequencing projects in the future. Although a cost sequencing method, as used here, is a good method for selecting projects for future expansion, other factors, such as environmental or social concerns can also influence the sequencing of projects. It could also be argued that in certain situations the operational cost of projects may effect their sequencing and thus should also be included in the sequencing decision.

The methods used in this study appear to give good results for the yield determination. The use of the historical flows in WATHNET, the yield model and the optimisation model produced reasonably comparable results for the system. These methods, as well as the sequencing method, should be useful tools for water authorities to develop future expansion schedules and operating rules for the water supply system in question, so that the future demands of a community can be satisfied.

4.5 Inclusion of Water Price and Demand Management

The above study investigates a possible solution technique to the supply and demand problem. In this case the problem is dealt with by examining the supply side of the problem by increasing the capacity of the system at minimum cost to the water authority. An alternative method is to examine ways of controlling the demand for water. One such method is by using the water pricing. For instance, the price of water can be varied to provide for more efficient utilisation of resources. In the case where demand is approaching the capacity of the system the price can be increased so that demand is reduced. Where excess capacity is available, price may be reduced to encourage greater utilisation of the available resources. The manner in which price affects demand has been previously discussed in Chapter 3 and is illustrated by Equation 3.3 and Figure 3.2. To apply Equation 3.3 to the Canberra Water Supply System a number of modifications are necessary, which results in Equation 4.1.

$$D_n(P_n) = q_0 POP_0 (1+w)^n (1-f)\left(\frac{P_n}{P_0}\right)^{\beta} \tag{4.1}$$

where $D_n(P_n)$ is the demand in year n at price P_n, P_0 is the initial price (in year zero), P_n is the price in year n, β is the price elasticity of demand for water, POP_0 is the initial population, q_0 is the initial per capita water consumption, w is the growth rate in population relative to POP_0, n = the year (n=0,1,2,...,N) and f = the fraction reduction in demand due to demand management measures.

With the inclusion of price in a study of this kind there are associated benefits which should also be included. These benefits are incorporated within the study by including them in the objective function. Thus, the objective is no longer to minimise present value of cost but to maximise the net present value of consumer benefits (NPV). A general expression for the NPV is defined by Equation 3.6. The NPV for the Canberra Water Supply System case can be obtained by substituting Equation 3.8 into Equation 3.6. This NPV formulation will incorporate the demand function (Equation 4.1) that applies for the Canberra Case study.

The study described in the next section examines the supply and demand problem for water by investigating the supply problem (ie. scheduling of projects) as well as the demand problem (ie. pricing and demand management). The water pricing policy adopted in this study is a two part tariff as recommended in AWRC (1987). This consists of an annual connection fee per service (with no free allowance) and a price per kilolitre of water charged for all consumption. The price per kilolitre is determined so as to maximise the net present value of economic benefits of the water supply, while the connection fee is set so that the total revenue just covers the total cost of supply. The level of the connection fee will vary with demand and the water price. Values for the annual connection fee are not quoted in this case study, but a typical value is $75 per year per connection for a water price of 36 cents/KL. The price per kilolitre will be a constant in real terms over the planning period, the reasons for adopting a constant unit price are discussed in section 3.3 of Chapter 3 on pricing methodology.

4.5.1 Data Utilised for the Pricing Study on the Canberra System

For the pricing study of the Canberra water supply system only the optimisation model results for yield evaluation will be used. The reason is that it is unlikely that any extra insight into the problem will be gained by utilising all of the yield evaluation models. The yield of the existing system is assumed to be 120.9 GL/year and the yield for the future projects is given in Table 4.21.

Table 4.21 Costs and Yields of Future Expansion Projects

Expansion Project	Capital Cost ($ Million)	Yield (GL/YEAR)
1 Coree*	92.0	24.8
2 Tennent	110.0	59.1
3 Riverlea	148.0	30.3
4 Cotter*	92.0	15.1

* These projects are mutually exclusive (ie. only one may be built)

One change to the previous study is that the Coree and Cotter projects are now considered to be mutually exclusive. That is if one is built the other is not.

The assumed growth rates in population are the same as used in the previous study and the initial population, POP_0, is 320,000. The cost of operations and maintenance for the existing system is assumed to be constant and equal to 11.4 cents/KL. It is assumed that the annual operations and maintenance cost of each future alternative is 2 % of its capital cost. This annual operations and maintenance cost of each future alternative is assumed to apply from the year construction is completed to the end of the planning period.

The existing pricing structure used by ACTEW needs to be considered. In 1992 the ACTEW water rates had a fixed annual charge of $200 and a free allowance of 455 KL per connection. All consumption above 455 KL was charged at 53 cents/KL (ACTEW, 1991). ACTEW is, however, moving towards a full pay-for-use system and the free allowance was recently reduced to 350 KL and was further reduced to zero in 1994.

For this study a complete pay-for-use system with no free allowance was assumed as it is considered to be superior to an allowance based rating structure. Problems associated with an allowance based rating structure are that the effect of price on demand is difficult to model and the use of a constant price elasticity is not applicable. The initial price per kilolitre and associated demand were determined by examining the previous years revenue and water consumption. In recent years (ie. 1989-1990, 1990-1991) the percentage of revenue collected by the supply charge was approximately 2/3 with the remainder being from the use of excess water (ACTEW, 1991). On the basis of these figures the constant unit price was assumed to be $0.47/KL.

The problem with this assumption is that if a unit price of $0.47/KL was charged the actual consumption level may be lower than at present and the response to water price changes will be different from the present allowance method. However, it is a assumed that these differences will be small and that at this price the consumption will be the same as that under the actual pricing structure. The initial demand per capita, d, is 620 litres per capita per day at an equivalent price, P_0, of 47 cents/KL. This is used in determining the average annual consumption, $D_n(P_n)$, in Equation 4.1 and hence the economic benefits and costs. However, when determining whether a new increase in capacity is required, $D_n(P_n)$, is multiplied by 1.27 to allow for the increased demand in a drought year (ie. 785 litres per capita per day).

For this study a sensitivity analysis will be undertaken on the planning period, discount rate and price elasticity of demand (β) to examine what effect these parameters have on the sequence of projects and the optimum price. The standard case will be for a planning period of 30 years, discount rate of 6 % and price elasticity of demand equal to -0.3. The value of price elasticity of demand was chosen as it was within the range of -0.2 to -0.4 specified by Boland (1984) and -0.1 to -0.785 indicated by Dandy (1989).

The planning period will be varied according to the population growth rate with two other planning periods being examined per population growth rate case. The planning periods used will depend on the number of projects required for a particular population growth case. Two other values of discount rates and price elasticity will be examined in addition to the values used in the standard case. The other discount rates to be examined will be 3.0% and 12.0% while the values of price elasticity of demand to be investigated are -0.1 and -0.6. It is considered that the values chosen for discount rate and price elasticity of demand will represent the extreme cases. For the price elasticity of demand the values used are in the range suggested by Dandy (1989). It is assumed that the same value of price elasticity of demand applies to both peak and average consumption.

Demand management measures will be considered which reduce the per capita demand by a specified amount (ie. 10 % and 20%). It is assumed that a demand management measure (such as dual flush toilets, restriction on garden watering, etc.) will have an immediate effect rather than the expected lag due to implementation of the measure. The values of demand reduction investigated will be 0 %, 5 %, 10 %, 15 % and 20 % for the standard case. However, for the sensitivity studies mentioned above only the demand reduction levels of 0 %, 10 % and 20 % will be examined.

The optimum water price and sequence of projects is identified using the above assumptions and data in the following manner:

(1) Set the assumed level of reduction due to demand management measures, f.
(2) Set the water price equal to its lower bound.
(3) Calculate the predicted growth in demand using Equation 4.1.
(4) Find the optimum sequence of projects using Equations 3.13 and 3.14.
(5) Calculate the NPV (Equations 3.6 and 3.8) for this water price and sequence.
(6) Increase the water price by one unit.
When water price exceeds the upper bound, stop. Otherwise return to step 3. The water price is constrained to lie between 20 cents/KL and $ 4/KL.

Additional assumptions made are: (i) the ultimate price P_n^u is set at $ 10/KL and thus the consumer surplus is evaluated relative to a water price of $ 10/KL, and (ii) the values calculated for revenue and consumer surplus are reduced by 20 % to allow for unaccounted water.

4.6 Results

4.6.1 No Demand Management

The first section of this case study will examine the problem of optimum price and sequencing of projects with no demand management. Thus the factor f in Equation 4.1

will be equal to zero. The first case considered is the standard case mentioned above. This is when the discount rate equals 6.0 % and the price elasticity equals -0.3 for a 30 year planning period. The results are given in Table 4.22 in which PVC is the present value of capital costs ($ Million) and TE is the time in years until the demand exceeds the supply from all available projects. The project sequence indicates the project numbers undertaken (Table 4.21) while the figure in brackets is the year in which the project is built (starting from the present year of 1992).

Table 4.22 Optimum Water Price for No New Demand Management Measures and a Planning Period of 30 Years

Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
1.50 %	36	5375.37	51.57	57	2 (13)
2.00 %	39	5685.43	57.95	44	2 (11)
2.58 %	44	6058.35	82.86	36	2(10),1(25)
3.00 %	63	6343.63	76.10	34	2(12),1(25)

The results in Table 4.22 show that the number of projects which are constructed during the planning period varies depending on the growth rate. In the case of the two lowest population growth rates only Tennent is expanded. For the 2.58% and 3 % population growth rates the project sequence is Tennent and then Coree.

It was found that the optimum water price occurs when the last project implemented just satisfies demand at the end of the planning period. For instance when the population growth rate equals 3.0% a price of 62 cents requires a third project to be built to satisfy demand within the 30 year planning period. This results in a large jump in the present value of capital cost (PVC) and produces a reduction in NPV. Thus, 63 cents becomes a better price as only two projects are needed to satisfy demand during the planning period. The same occurs with the 2.58% population growth rate case. The exception in this case is with the lower population growth rates (1.5% and 2 %) where the price would need to drop substantially before another project is needed. In these cases the optimum price occurs when there is a reduction in PVC as a result of delaying the project by a single year. On inspection of the above results it appears that as the population growth rate increases so does the optimum price.

The next step is to examine the effects of varying the planning period on the optimum price and the scheduling of future projects. Table 4.23 shows the effect of varying the planning period, TP, on the optimum price and the scheduling of future projects.

Table 4.23 Effects of Planning Period on Optimum Price With No Demand Management

Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	TP (years)	Project Sequence
1.50 %	36	5375.37	51.57	57	30	2(13)
1.50 %	40	6471.52	53.86	59	50	2(15),1(42)
1.50 %	42	6743.04	58.39	60	60	2(16),1(43),3(51)
2.00 %	39	5685.43	57.95	44	30	2(11)
2.00 %	51	6110.08	45.90	48	35	2(15)
2.00 %	46	6459.51	65.02	47	40	2(13),1(33)
2.58 %	44	5461.79	61.42	36	25	2(10)
2.58 %	44	6058.35	82.86	36	30	2(10),1(25)
2.58 %	42	6555.56	112.31	35	35	2(9),1(25),3(30)
3.00 %	38	4905.03	73.16	29	20	2(7)
3.00 %	59	5681.85	57.95	34	25	2(11)
3.00 %	63	6343.63	76.10	34	30	2(12),1(25)

The values obtained for NPV in Table 4.23 cannot be compared directly, as it is expected that for a longer planning period the NPV should be larger due to the additional years of net benefits. However, in relation to the variation of optimum price with changing planning period, it is expected that if the same projects are undertaken for two different planning periods the price would be higher for the longer period. For example, for a population growth rate of 2.0 % and planning periods of 30 and 35 years only one project is expanded (Tennent). The optimum water price increases from 39 cents/KL to 51 cents/KL with the increase in planning period. Otherwise, it appears that for longer planning periods more projects are required. In general, the optimum price is obtained, so that at a lower price either another project is required or the projects built are built at earlier times, thus increasing the PVC. If the increase in PVC, results in an increased NPV, then a new optimum price is obtained.

The next step is examine the effect of discount rate on the project schedule and the optimum price. The results are shown in Table 4.24 for a 30 year planning period.

Table 4.24 Effects of Discount Rate on Optimum Price With No Demand Management

Discount Rate r (%)	Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
3.0	1.50 %	31	7741.39	81.85	54	2(10)
6.0	1.50 %	36	5375.37	51.57	57	2(13)
12.0	1.50 %	42	3145.33	17.94	60	2(16)
3.0	2.00 %	37	8283.42	81.85	43	2(10)
6.0	2.00 %	39	5685.43	57.95	44	2(11)
12.0	2.00 %	42	3264.46	28.23	45	2(12)
3.0	2.58 %	42	8930.47	128.25	35	2(9),1(25)
6.0	2.58 %	44	6058.35	82.86	36	2(10),1(25)
12.0	2.58 %	44	3411.42	40.83	36	2(10),1(25)
3.0	3.00 %	63	9430.96	121.09	34	2(12),1(25)
6.0	3.00 %	63	6343.63	76.10	34	2(12),1(25)
12.0	3.00 %	51	3520.67	48.40	32	2(10),1(23),3(28)

It appears from these results that as the discount rate increases the optimum water price also increases, as long as the same projects are expanded. This result could be expected as at a higher discount rate the delaying of a project will result in a greater reduction in PVC because of the effect of discounting. The amount of increase in the optimum price depends on the change in discount rate, the demand growth and also the incremental yield of the various projects expanded. In the majority of cases as the discount rate increases the projects that are expanded are delayed by an increase in price. The amount the projects are delayed depends on the population growth rate as well as the benefits obtained by delaying the project. For a low population growth rate the projects can be delayed more than for a high population growth rate. If the delaying of a project reduces the cost by more than a higher price reduces the benefits (ie. by a drop in revenue or consumer surplus), then the optimum price will rise.

The interesting case in Table 4.24 is the final result where an extra project is built at a lower price rather than building only two projects at a higher price. The reason for this is not immediately apparent, however closer inspection of the NPV vs Price curves for the higher population growth cases gives a possible explanation. At the higher discount rate the range of variation in the NPV is considerably lower over a significant price range. Also, when a higher discount rate is used, the changes in PVC between prices and the increase in PVC when using a lower price, is less. In this case there is an increase in the present value of benefits obtained at the lower price which are greater than the increase in present value of the systems costs, thus a lower optimum price is achieved. This can be seen by inspecting the NPV/NPVO versus Price curves shown in Figure 4.28 for the 3 % population growth case. The reason for examining the NPV/NPVO, where NPVO is the optimum value of NPV, is that it enables the three different discount rates to be compared and the manner in which projects are delayed and no longer required with different discount rates can be easily seen.

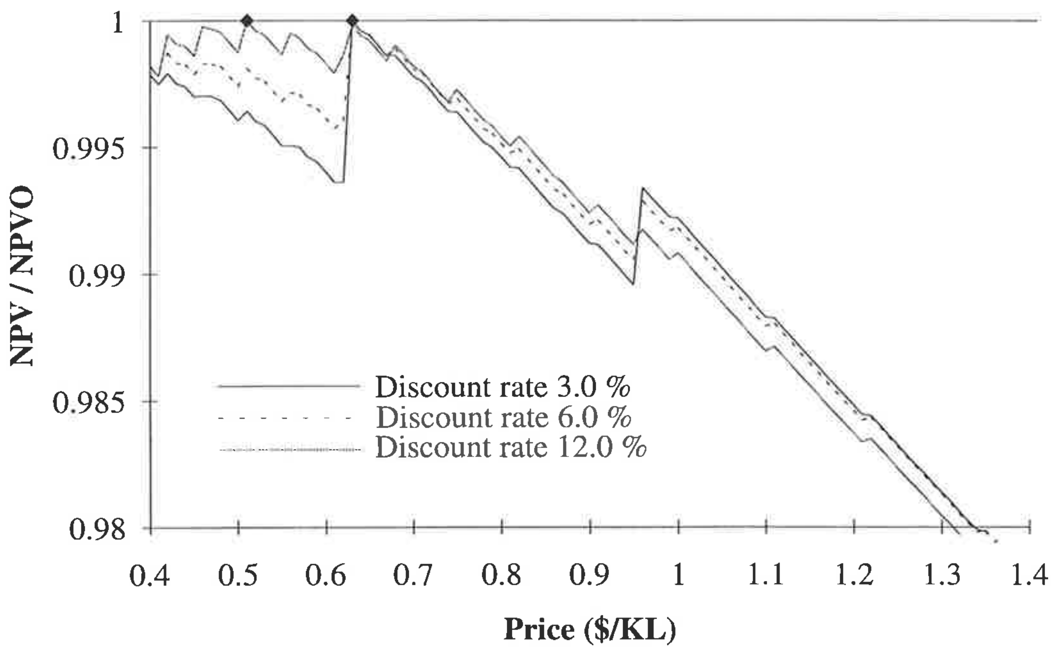

Figure 4.28 NPV/NPVO versus Price for a Population Growth of 3 %

The next step is to examine the effect of the price elasticity of demand on the project schedule and the optimum price. The results are shown in Table 4.25 for a 30 year planning period.

The effect of price elasticity appears to be complicated. However if the results are examined individually and then overall an understanding of the behaviour of optimum price and price elasticity can be obtained. From the 2.0 % and 2.58 % population growth cases it appears the price changes such that the same schedule will be found and therefore then same demand situation occurs. This is concluded as the expansion schedules are nearly identical for each value of population growth rate, regardless of the price elasticity of demand. As the magnitude of the price elasticity of demand decreases, a greater reduction in price from the initial value of 47 cents/KL is require to achieve the same demand. A similar result applies for the price elasticities of -0.3 and -0.6 for the case of 3.0 % growth rate in population. The difference is in this case that a greater price increase relative to the 47 cents/KL is required for an elasticity of -0.3 to achieve the same demand.

Table 4.25 Effects of Price Elasticity of Demand on Optimum Price With No Demand Management

Price Elasticity of Demand	Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
-0.1	1.50 %	38	8022.40	40.85	61	2(17)
-0.3	1.50 %	36	5375.37	51.57	57	2(13)
-0.6	1.50 %	40	3137.47	54.67	56	2(12)
-0.1	2.00 %	32	8490.16	54.67	45	2(12)
-0.3	2.00 %	39	5685.43	57.95	44	2(11)
-0.6	2.00 %	43	3310.93	57.95	44	2(11)
-0.1	2.58 %	38	9066.91	82.86	36	2(10),1(25)
-0.3	2.58 %	44	6058.35	82.86	36	2(10),1(25)
-0.6	2.58 %	46	3510.91	82.86	36	2(10),1(25)
-0.1	3.00 %	45	9501.91	121.33	31	2(9),1(22), 3(27)
-0.3	3.00 %	63	6343.63	76.10	34	2(12),1(25)
-0.6	3.00 %	54	3670.36	76.10	34	2(12),1(25)

This effect is shown in Figure 4.29 where squares and triangles on the price elasticity curves represent the 3 % and 2.58 % population growth rate case respectively. As can be seen the squares and triangles lie approximately on a vertical line relatively to each other. This indicates that a similar total demand is achieved at different price elasticities. In addition, the relative change in price to achieve a similar demand situation can be seen.

The above explanation indicates the reason for the majority of the results in Table 4.31 but the results of the 1.5 % population growth rate and the 3 % population growth rate for the price elasticity of -0.1 still need to be considered. The reason for the 1.5 %

population growth rate results being different is due to the slope of the NPV versus Price curve especially when the price elasticity equals -0.1. In this case the curve is very flat and the delaying of projects at various stages changes the position of the optimum price.

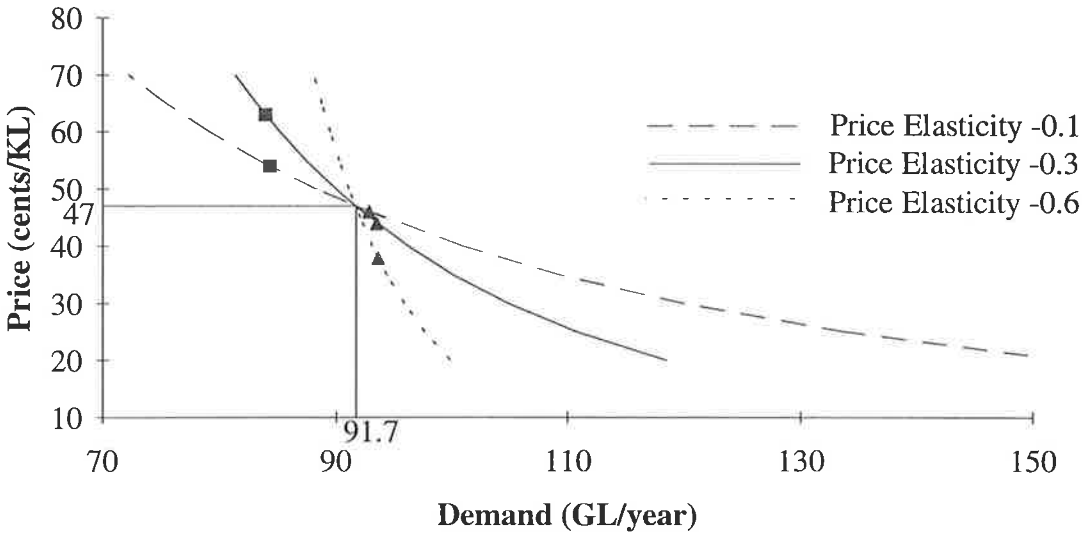

Figure 4.29 The Effect of Various Price Elasticities of Demand on the Price and Demand Relationship

For instance, the optimum price produces a NPV just greater than the NPV produced for a price of 33 cent/KL. Under slightly different conditions this lower price would become the optimum and the conclusions made previously would apply to the 1.5 % population growth rate. The reason for the result of the 3 % population growth rate when price elasticity equals -0.1 is again basically because of the slope of the NPV versus Price curve. For the same condition to occur as for the other price elasticities the price would need to be 109 cents/KL. At this price the benefits are significantly lower than that obtained at the optimum price which results in a lower NPV than the optimum NPV. To illustrate the above conclusions the NPV/NPVO versus price curves for the 1.5 % and 3 % population growth rate are shown in Figures 4.30 and 4.31.

In general it would appear if the same projects are expanded in the same order, then an increase in the price elasticity, discount rate and planning period will result in an reduced difference between the optimum price and the initial price.

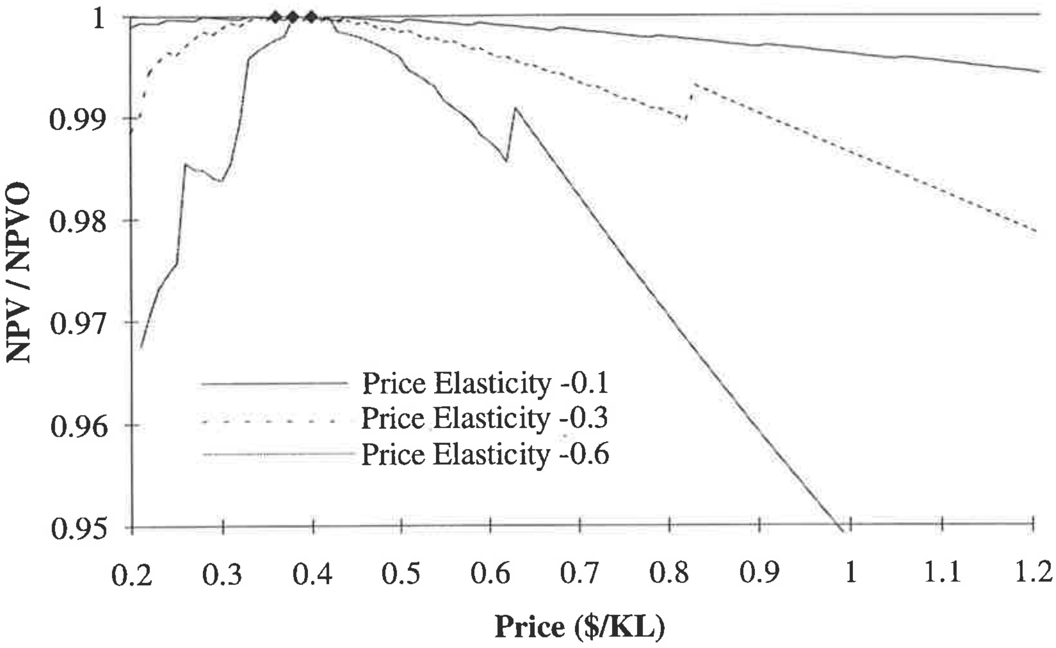

Figure 4.30 NPV/NPVO versus Price for a Population Growth of 1.5 %

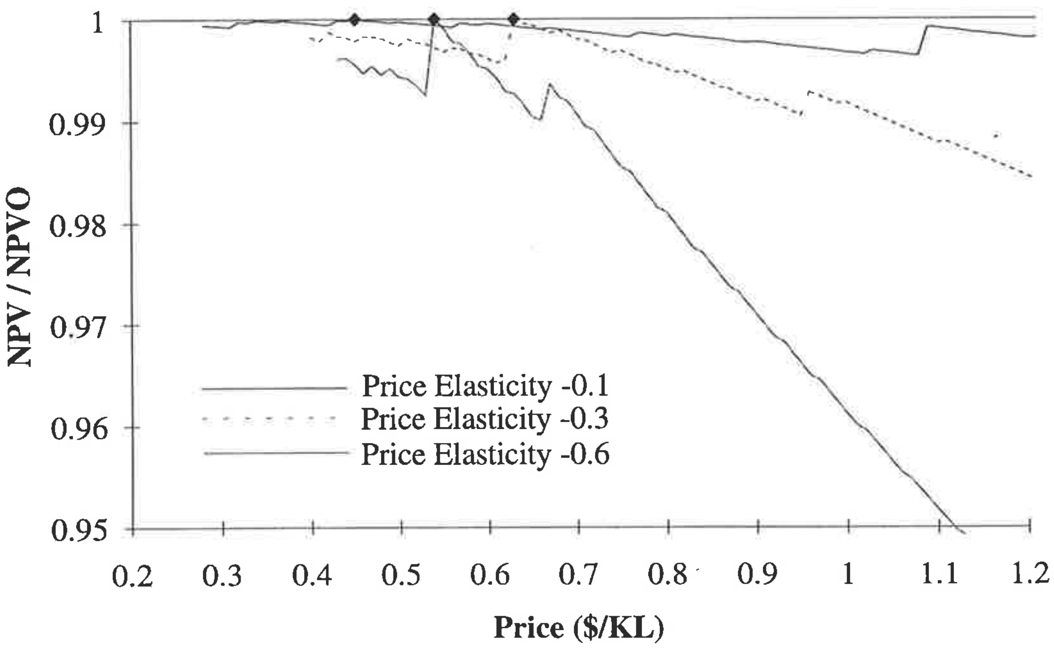

Figure 4.31 NPV/NPVO versus Price for a Population Growth of 3 %

4.6.2 Examing the Effect of Price when Including Demand Management Measures

The next step is to examine the effect that demand management measures have on the optimum price and on project sequencing and scheduling. The first demand management level to examine is a 10 % reduction in demand for the standard case used previously. The results of this case are given in Table 4.26.

Table 4.26 Optimum Price Variations for 10% Demand Management and a Planning Period of 30 Years

Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
1.50 %	34	4855.42	36.36	63	2(19)
2.00 %	34	5131.68	48.65	47	2(14)
2.58 %	45	5480.77	48.65	40	2(14)
3.00 %	44	5743.85	76.10	34	2(12),1(25)

These results should be compared with the case of no demand management (Table 4.22), which is reproduced here as Table 4.27.

Table 4.27 Optimum Water Price for No New Demand Management Measures and a Planning Period of 30 Years

Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
1.50 %	36	5375.37	51.57	57	2 (13)
2.00 %	39	5685.43	57.95	44	2 (11)
2.58 %	44	6058.35	82.86	36	2(10),1(25)
3.00 %	63	6343.63	76.10	34	2(12),1(25)

When comparing the results of Tables 4.26 and 4.27 it can be seen that for population growth rates of 1.5 %, 2.0 % and 3.0 %, the same number of projects are required. In all these cases, the optimum price with 10 % demand management is less than that with no demand management. The reason for this is that, with demand management a lower price will achieve the same level of demand, ie. demand management has an equivalent effect to a price increase. It is interesting to note that the NPV drops for all cases with demand management. This is due to a reduction in consumer surplus. Presumably there are other non-economic benefits of implementing the demand management measures. For the lowest three population growth rates the present value of costs is significantly reduced by demand management.

Table 4.28 Optimum Price Variations for 20% Demand Management and a Planning Period of 30 Years

Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
1.50 %	40	4343.75	00.00	74	-
2.00 %	30	4574.87	38.54	52	2(18)
2.58 %	32	4892.76	45.90	41	2(15)
3.00 %	46	5130.70	43.30	39	2(16)

In Table 4.28 the demand is reduced by 20 % due to demand management measures and only Tennent is required to satisfy demand for the 30 year period for the three highest population growth rates. For the 3 % population growth rate the price increases to ensure that Coree is not required. For the 1.5 % growth rate, no projects are required within the planning period. The price is increased to ensure that occurs. For the other population growth rates the prices drop from the 10 % demand management case and the same sequence are found. However, the timing of Tennent is slightly different in the 2.0 % and 2.58 % population growth case. Once again the NPV and PVC are reduced by increased demand management.

It would appear from the results of Tables 4.26 to 4.28 that as the demand is reduced through demand management, the price will decrease if the same projects are sequenced. When a demand reduction results in a project no longer being required the price tends to increase. The trend experienced in regard to price and demand management for values of 5, 10, 15 and 20 % are represented graphically in Figure 4.32.

The next step is to see how various discount rates and price elasticities effect the optimum price when demand management is present. Unlike the previous study without demand management it was consider unnecessary to examine the effects of varying the planning period with regard to demand management levels as the effects of planning period on sequencing and optimum price has already been examined for the case of no demand management. Table 4.29 shows the effects of variations in the discount rate on the optimum price and project sequence with 10 % reduction in demand due to demand management.

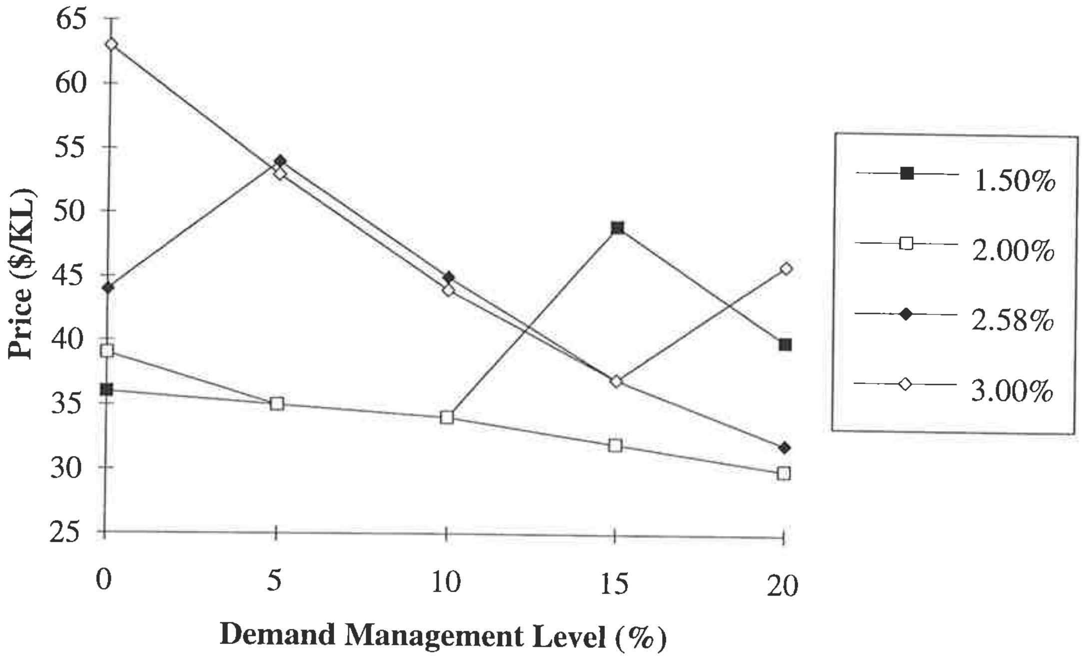

Figure 4.32 Variation in Optimum Price with Different Levels of Demand Management

The conclusions that can be drawn from the results in Table 4.29 are similar to those made previously for the no demand management case when discount rate is examined (Table 4.24). That is as the discount rate increases the optimum water price will either increase or remain the same, as long as the same projects are expanded. It appears at the higher population growth rates there is unlikely to be a change in optimum price if the same projects are built. The unusual result in Table 4.29 is that of the 1.5 % population growth and the 3 % discount rate. It is unusual as there is a price rise rather than a decrease. The reason is that at the higher price no project is required and at a 3 % discount rate this corresponds to a significant decrease in PVC. The decrease is greater than the reduced benefits at the higher price (ie. as price increases the benefits decrease mainly due to the a reduction in consumer surplus which is greater than the increased revenue raised) thus resulting in a new optimum price. This process is not repeated for the higher discount rates as the reductions in PVC due to delaying projects reduces as the discount rate grows. So at higher prices for the higher discount rates, the drop in PVC is not significant enough to overcome the drop in benefits and therefore result in a new optimum price. It is possible however, that at this higher price the NPV for the higher discount rates will be close to the optimum NPV. In addition, at lower discount rates the NPV versus Price curve tends to be more irregular (ie. bumpy) resulting in the possibility of more variable solutions being obtained at lower discount rates.

Table 4.29 Effects of Discount Rate on Optimum Price with 10% Demand Management

Discount Rate r (%)	Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
3.0	1.50 %	59	6987.83	00.00	74	-
6.0	1.50 %	34	4855.42	36.36	63	2(19)
12.0	1.50 %	34	2843.25	12.77	63	2(19)
3.0	2.00 %	26	7472.76	81.85	43	2(10)
6.0	2.00 %	34	5131.68	48.65	47	2(14)
12.0	2.00 %	38	2951.26	17.94	49	2(16)
3.0	2.58 %	45	8079.44	72.72	40	2(14)
6.0	2.58 %	45	5480.77	48.65	40	2(14)
12.0	2.58 %	45	3085.29	22.51	40	2(14)
3.0	3.00 %	44	8538.08	121.09	34	2(12),1(25)
6.0	3.00 %	44	5743.85	76.10	34	2(12),1(25)
12.0	3.00 %	44	3188.34	33.65	34	2(12),1(25)

The results for the 1.5 % population growth and 3 % discount rate case are compared to the same case in Table 4.30 where there is no demand management, it can be seen that the reduction in demand leads to the exclusion of a project in the sequence. The reduction in demand results in a number of changes. Firstly the demand level at the same price is different thus the annual benefits and cost will both be reduced and also the project timing will be changed resulting in a lower PVC. Thus depending on the level of demand reduction the sequence of projects will most likely change, however this is also dependent on the other parameters in the model.

The next step is to consider the case of a 20 % reduction in demand due to demand management. The results of this are shown in Table 4.30.

Table 4.30 Effects of Discount Rate on Optimum Price With 20% Demand Management

Discount Rate r (%)	Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
3.0	1.50 %	40	6257.70	00.00	74	-
6.0	1.50 %	40	4343.75	00.00	74	-
12.0	1.50 %	28	2536.35	8.12	67	2(23)
3.0	2.00 %	24	6653.28	70.61	48	2(15)
6.0	2.00 %	30	4574.87	38.54	52	2(18)
12.0	2.00 %	30	2632.84	14.30	52	2(18)
3.0	2.58 %	32	7210.23	70.61	41	2(15)
6.0	2.58 %	32	4892.76	45.90	41	2(15)
12.0	2.58 %	32	2755.80	20.10	41	2(15)
3.0	3.00 %	46	7629.47	68.55	39	2(16)
6.0	3.00 %	46	5130.70	43.30	39	2(16)
12.0	3.00 %	39	2846.61	23.95	37	2(15),1(28)

The results in Table 4.30 are similar to those of Table 4.29. The same conclusions regarding optimum price and discount rate can be made and the occurrence of the optimum price increasing when a project is removed from the sequence is reinforced for lower discount rates. The explanation given for the result in Table 4.29 for the 1.5 % population growth and 3 % discount rate also applies to the cases of 1.5 % and 3 % population growth rate and 3 % and 6 % discount rate in Table 4.30.

The next step is to look at the effects of variations in price elasticity and demand management on the optimum price and project sequence and schedule. The results are given in Table 4.31.

The results in Table 4.31 demonstrate that as the price elasticity increases the optimum price increases. For the higher population growth cases, this occurrence results in the same sequence and timing of projects. For the lower population growth rates this does not occur however the projects are scheduled sooner for higher values of price elasticity.

When compared with the case of no demand management (Table 4.25) there is a exclusion of one project from the sequence for the 2.58 % population growth cases and the 3% population growth rate with a price elasticity of -0.1. The optimum price tends to increase in these cases. For the same project sequence the optimum price is reduced when the demand management level is increased.

Table 4.31 Effects of Varying Price Elasticity of Demand on Optimum Price With 10% Demand Management

Price Elasticity of Demand	Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
-0.1	1.50 %	32	7234.74	28.80	67	2(23)
-0.3	1.50 %	34	4855.42	36.36	63	2(19)
-0.6	1.50 %	37	2843.83	43.30	60	2(16)
-0.1	2.00 %	30	7654.00	40.85	50	2(17)
-0.3	2.00 %	34	5131.68	48.65	47	2(14)
-0.6	2.00 %	37	3001.68	54.67	45	2(12)
-0.1	2.58 %	41	8188.60	48.65	40	2(14)
-0.3	2.58 %	45	5480.77	48.65	40	2(14)
-0.6	2.58 %	46	3190.21	48.65	40	2(14)
-0.1	3.00 %	38	8594.33	76.10	34	2(12),1(25)
-0.3	3.00 %	44	5743.85	76.10	34	2(12),1(25)
-0.6	3.00 %	46	3330.26	76.10	34	2(12),1(25)

The final step for this study is to examine the effect increasing the demand management level to 20 %. The results of this are given in Table 4.32.

Similar conclusions can be made here as for the results given in Table 4.31. Two interesting facets of the results of Table 4.32 are that no projects are required for the 1.5 % population growth rate cases and that two optimum prices are found for the 3 % population growth case for a price elasticity of -0.6. Otherwise, the results are similar to those previously seen and discussed. The reason for two optimum prices is that the drop in PVC at the higher price is substantial enough to account for the reduction in benefits and cost encountered when moving from the lower price to the higher price. The fact that two optimum prices occur is purely coincidental.

It is now useful to examine the effect of demand management on the optimum price and the sequencing and scheduling of projects. For this comparison the results of the general case will be examined. This is where the discount rate equals 6 % and price elasticity equals -0.3. The results are tabulated in Tables 4.26, 4.27 and 4.28 but are shown together for an easier comparison in Table 4.33.

Table 4.32 Effects of Varying Price Elasticity of Demand on Optimum Price With 20% Demand Management

Price Elasticity of Demand	Population Growth Rate	Optimum Price (cents/KL)	NPV ($ Million)	PVC ($ Million)	TE (years)	Project Sequence
-0.1	1.50 %	28	6461.11	00.00	74	-
-0.3	1.50 %	40	4855.42	00.00	74	-
-0.6	1.50 %	44	2549.48	00.00	75	-
-0.1	2.00 %	25	6814.15	30.53	55	2(22)
-0.3	2.00 %	30	5131.68	38.54	52	2(18)
-0.6	2.00 %	34	2683.37	45.90	49	2(15)
-0.1	2.58 %	25	7291.16	40.85	43	2(17)
-0.3	2.58 %	32	5480.77	45.90	41	2(15)
-0.6	2.58 %	38	2860.33	48.65	40	2(14)
-0.1	3.00 %	43	7664.66	43.30	39	2(16)
-0.3	3.00 %	46	5743.85	43.30	39	2(16)
-0.6	3.00 %	39	2984.61	71.80	35	2(13),1(26)
		47	2984.61	43.30	39	2(16)

It is apparent from Table 4.33 that as the demand management level increases the optimum price drops, if the same sequence of projects occurs. Furthermore, if the same sequence of projects does occur it appears that the projects are scheduled later in the planning period. Also, as the demand management level increases it seems the likelihood of a project being excluded from a project sequence increases and the optimum price will rise. This price rise however is more evident if the Figure 4.29 previously displayed where all the levels of demand management are illustrated (ie. 0, 5, 10, 15 and 20 %). Thus it appears the behaviour experienced in the optimum price will depend on the level of demand management as well as the population growth case being investigated.

One further aspect of this study is to investigate the water price at which no projects are required during the 30 year planning period. This was determined only for the price elasticities of -0.3 and -0.6 as it is considered that an unrealistically high price would be required for a price elasticity of -0.1 In the case of no demand management the results of this study are shown in Table 4.34. For comparison the previously determined optimum price is included in the Table and the present value of profit in each case.

Table 4.33 Optimum Price Variations for Various levels of Demand Management with a Planning Period of 30 Years

Demand Management	Optimum Price (cents/KL)	Population Growth Rate	NPV ($Million)	PVC ($Million)	TE	Project Sequence
0 %	36	1.50 %	5375.37	51.57	57	2 (13)
0 %	39	2.00 %	5685.43	57.95	44	2 (11)
0 %	44	2.58 %	6058.35	82.86	36	2(10),1(25)
0 %	63	3.00 %	6343.63	76.10	34	2(12),1(25)
10 %	34	1.50 %	4855.42	36.35	63	2(19)
10 %	34	2.00 %	5131.68	48.65	47	2(14)
10 %	45	2.58 %	5480.77	48.65	40	2(14)
10 %	44	3.00 %	5743.85	76.10	34	2(12),1(25)
20 %	40	1.50 %	4343.75	0.00	74	-
20 %	30	2.00 %	4574.87	38.54	52	2(18)
20 %	32	2.58 %	4892.76	45.90	41	2(15)
20 %	46	3.00 %	5130.70	43.30	39	2(16)

As can be seen, the price that needs to be charged increases as the growth rate in demand increases. In addition, the difference between this price and optimum price is smaller for the higher price elasticity. It can be seen that the charging of the higher price (ie. so no projects are needed) results in a reduction in NPV. This reduction is small in percentage terms, but increases for higher values of growth rate. The reduction in the NPV is the net effect of a reduced operating cost, a reduced present value of capital costs and a reduction in consumer surplus. At the same time there is a substantial jump in revenue for the water authority. The net effect of this is illustrated by the profit figures in Table 4.34. This profit is the present value of revenue raised minus the present value of system costs. The system costs only include operating costs and the present value of the capital cost of new projects. It does not include interest payments on borrowing prior to 1992. As can be seen there is a substantial increase in profit when no project is built in the first 30 years. For this reason a private water authority would prefer to charge the higher price and receive a higher return on capital. In addition, such a price will work as a conservation tool. It could be argued by the authority therefore that this is a fair price and as long as consumers are willing to pay for water at this rate then it is justifiable. However, it can be seen that there is still a healthy profit to the water authority at the optimum price level. It should be borne in mind that the optimum price gives the maximum net benefits to the whole community not just the water authority.

Table 4.34 Price to be Charged to Ensure that No Project is Required for 30 years

Population Growth Rate	Price Elasticity	Price ($/KL)	NPV ($ Million)	Present Value of Profit ($ Million)	Optimum Price ($/KL)	Optimum NPV ($ Million)	Present Value of Profit ($ Million)
1.5 %	-0.3	0.83	5338.25	585.11	0.36	5375.37	175.45
	-0.6	0.63	3108.83	412.75	0.40	3137.47	219.82
2.0 %	-0.3	1.36	5542.47	946.90	0.39	5685.43	209.12
	-0.6	0.80	3226.66	511.17	0.43	3310.93	253.52
2.58 %	-0.3	2.39	5723.07	1581.75	0.44	6058.35	249.11
	-0.6	1.06	3357.22	645.67	0.46	3510.91	269.95
3.0 %	-0.3	3.60	5785.04	2265.40	0.63	6343.63	449.08
	-0.6	1.30	3446.21	758.68	0.54	3670.36	351.62

It was also shown that the use of demand management can reduce the price of water in order to delay the first project beyond the thirty year planning period. A 10 % demand management level was utilised for this purpose and the results are shown in Table 4.35

As can be seen by comparing Tables 4.34 and 4.35 the price which needs to be charged drops when demand management is utilised. This is expected as the demand is lower and so a lower price rise is required to achieve the same total demand.

From these results it appears that for the low population growth rates a small increase in price from the current value of 47 cents/KL can achieve the objective of deferring all projects for 30 years. However, for the higher growth rates the price increase to achieve this is substantial and it is likely this will not be accepted by consumers. As was the case with no demand management there is a substantial increase in profit to the water authority when charging the higher price. But due to the demand reduction (through demand management and lower prices) the profit is lower for both pricing scenarios than for the no demand management case. This would make this scheme more acceptable to the consumer but less desirable to the water authority.

Table 4.35 Price to be Charged to Ensure that No Project is Required for 30 years with 10 % Reduction Due to Demand Management

Population Growth Rate	Price Elasticity	Price ($/KL)	NPV ($ Million)	Profit ($ Million)	Optimum Price ($/KL)	Optimum NPV ($ Million)	Profit ($ Million)
1.5 %	-0.3	0.59	4850.57	379.73	0.34	4855.42	123.70
	-0.6	0.53	2834.19	327.54	0.37	2843.83	97.41
2.0 %	-0.3	0.96	5065.51	635.25	0.34	5131.68	151.05
	-0.6	0.67	2950.30	410.53	0.37	3001.68	186.33
2.58 %	-0.3	1.69	5280.63	1087.59	0.45	5480.77	262.94
	-0.6	0.89	3079.52	525.78	0.46	3190.21	273.34
3.0 %	-0.3	2.53	5396.21	1565.03	0.44	5743.85	239.84
	-0.6	1.10	3167.08	624.38	0.46	3330.26	259.58

Therefore, from the results in Table 4.34 and 4.35, it would be better to use some sort of demand management measure coupled with a smaller price rise to achieve the same outcome. This type of strategy would be more attractive to the community.

4.7 Conclusions for the Pricing and Demand Management Study

In conclusion, the effects of demand management on project sequencing and optimum price were examined. It was found that demand management led to the delay of future projects, which in some cases resulted in no project being required during the planning period. While the effect of demand management is one of conservation the expected NPV for a particular situation is reduced by demand management. The results of this study indicate that in the majority of the cases, as demand management increases the optimum price will tend to fall if the same projects are expanded under similar conditions. The explanation for this is as follows. When demand management is implemented in a system the demand will decline. Therefore at the previous optimum price before demand management the projects expanded are no longer being fully utilised. Thus the price will fall in such a manner so a new optimum price is obtained at a level that is just short of requiring a further project to be needed. For example, if a new optimum is found at $0.30/KL at a price of $0.29/KL another project will need to be constructed. It may be argued that as the consumer surplus plays such a major role and in effect the physical measurement of this value is unrealistic then it should be neglected. However, if the consumer surplus were to be ignored, the objective would basically become the maximisation of net profit for the water authority. The water authority would then act as a monopolist and set a very high price which would result in a loss in benefits to the whole community. The optimum price will generally be established just above a price that requires the construction of an extra project to satisfy demand. If demand management results in a project no longer being needed it was found that the optimum price would rise to a price that fully uses the implemented projects. When investigating both pricing and demand management together, with the demand management acting to conserve water, under certain conditions the pricing will tend to offset some of the effect of demand management as a conservation tool. As mention this will rely on certain conditions that are controlled by the values of discount rate, population growth rate, planning period, individual project yields and the total system yield.

It was also found that in the majority of cases the optimum price varied when there was a change in either discount rate or population growth rate or price elasticity or planning period. The amount the optimum price changed for a change in any of the above variables seems to be dependent on the other variables mentioned. This can also be said for the variation of the optimum price with a variation in the level of demand management. The actual effect on the price is not entirely dependent on the level of demand management but also on the various other factors mentioned here. For the sensitivity analysis of the discount rate it is found that if the same conditions apply (ie. the same projects expanded) then as the discount rate increases the difference between the optimum price and the initial price will remain the same or decrease. Whether the optimum price remains the same or increases is dependent on the other factors in the calculation (ie. price elasticity, population growth, planning period, etc.). Similarly for the sensitivity analysis on the price elasticity if the same conditions apply with respect to the number of projects constructed then as price elasticity increases the difference between the optimum price and the initial price remained constant or decreased. As for the amount the optimum price would vary (if any), this was dependent on other factors as was the case for the discount rate. However, it can be said that the closer the optimum price is to the initial price of 47 cents/KL, the more likely the change in the optimum price will be either small or non existent for any of the parameters tested. The reason this is the case for the price elasticity of demand is in the calculation of the demand. The demand in any year or for any price is calculated using Equation 4.1. In this calculation the expression, $\left(\frac{P_n}{P_0}\right)^{\beta}$ occurs. Now if the same sequencing and scheduling of projects is to occur with an increase in price elasticity the difference between the new price and P_0 will be less in order to give the same demand. Therefore with the same sequencing and scheduling of projects for an increase in price elasticity, the price P_n will approach P_0 . With the price elasticity values used in this study, the price approached the initial price but did not actually reach or go past the initial price.

The last result examined was that of the selection of a planning period. The results in Table 4.23 are inconclusive. It is expected that as the planning period increases the optimum price would tend to rise. However, this is not always the case. As expected as the planning period increases the value of NPV also increases. However, although no general conclusion can be made about the variation of the optimum price with a change in the planning period, some important points can be made. Unless the change in planning period is only relatively small and/or the yield of the future projects is large, a change in the number of projects is likely to occur with a change in planning period. Also the length of the planning period selected is of great importance when trying to find an optimum expansion schedule. This fact is illustrated in Table 4.23. The problem experienced here is the sequence is selected based on an infinite period and therefore if a cheaper alternative, which can satisfy demand for the planning period is available, it may become a optimum solution for that planning period. For instance, in the study above, if only one project is expanded then Tennent Reservoir was selected and the optimum price is such that at a lower price an extra project is required. However, at a higher price, Coree Reservoir will be able to satisfy demand just as well as Tennent but at a lower cost. So if the reduction in PVC of building Coree instead of Tennent at a higher price is greater than the loss in benefits at that price then a new optimum price will occur. On recalculating the cases where the results indicate only one reservoir is sequenced, for the 1.5 % population growth rate the building of Coree tends to be a better decision as the losses of benefits of an increased price are lower for this case. For the remainder of the population growth cases the results shown in this study are the optimum results except for the case of 20 % demand management and the 2.0 % population growth. Here the population growth rate becomes similar to the 1.5 % population growth case due to the reduction in demand and the Coree Reservoir is a slightly better sequence. The only exception to the cases mentioned are for the 1.5 % population growth and discount rate equal to 3.0 % case and for the case of 2.0 % population growth, price elasticity equal to -0.6 and a demand management level of 20 %. In these cases the Tennent expansion will produce the higher NPV.

This problem of selecting a suitable planning period then reverts back to the managers of the water supply system. The selection of a suitable period is difficult. In any study the usual method is to assume all factors are constant over the set planning period and then formulate a plan based on these factors for the planning period. However, it is more than likely that many of the assumed constant factors, such as discount rate or demand growth rate or climatic conditions, will vary significantly over the planning period. For instance, in today's economic and environmental climate more people are aware of the need to conserve water and therefore there is likely to be a reduction in the consumption per head of population. Therefore, even if the planning period consider was only short, the aims and objectives of a study using this planning period will be substantially changed due to changes in various factors. Another difficulty at this time is the rate of advancement of technology. Technology may produce an alternative water supply (ie. desalination of seawater, or recycling waste water for human consumption) which has a lower O&M cost of existing supplies or implementation of future alternatives. Thus if a planning period was considered which required the construction of a new water resource project, such as a new dam and during the planning period a new alternative far more efficient than the newly constructed project or even any existing water resource was developed, then the newly constructed project or existing resource would be inefficient and most likely become obsolete. Added to this is the long term environmental effects on existing reservoirs (ie. pollution which may result in a reduced yield or even decommissioning of a reservoir), then the selection of a suitable planning period becomes very difficult.

In regard to the sequencing method used for the pricing and demand management study, it is considered that neither the equivalent cost or unit cost method could guarantee the optimum solution when pricing and a finite planning period are examined. Both methods work on the premise that the sequence found is for the condition of all projects being built. However, for this study not all projects are required for the finite planning period, thus on occasions a better sequence and schedule of projects can exist other than that determined by the equivalent cost or unit cost method. Such a situation was elaborated on before when Coree is expanded instead of Tennent and is the only project required to satisfy demand for the planning period. When this occurred, the price increased so demand was reduced and the smaller Coree could satisfy demand for the period at a lower cost than Tennent. However, this situation is only specific for that planning period and if a considerably longer planning period is chosen where more the one reservoir is built, then the optimum sequence will be Tennent, Coree and Riverlea. It is possible that Coree could be sequenced before Tennent however, this would only be under different circumstances than examined in this study (ie different discount rate and population growth rate). Thus for the above reasons, the aim of the pricing and demand management study was not intended to be the examination of the sequencing of projects but was directed at the change in optimum price with various parameter sets, the scheduling of projects and highlighting the difficulty when selecting a suitable planning period when pricing and demand management are considered.

Finally, it can be seen from this study that the use of demand management can help delay future water resource projects and extend the life of a water supply system. However, the effects of various factors such as discount rate, population growth rate and price elasticity, on the sequencing and scheduling of future projects as well as the optimum price is unclear. It should be evident that the various factors mentioned and examined in this study will combine to have some effect on the optimum price and capacity expansion of a water supply system.

Chapter 5

Genetic Algorithm Methodology

5.1 Introduction

The purpose of this chapter is to introduce the relatively new optimisation method of genetic algorithms (GA). It examines the history and theory of genetic algorithms and the reasons for the use of the method in this study. GAs involve a search procedure based on the mechanics of natural selection and genetics. They use a coded string and the processes of reproduction, crossover and mutation to produce better strings. Their advantages over other optimisation methods are; that they work with the coding of a parameter set, not the parameters themselves; they search a population of points rather than a single point; they use payoff information, not derivatives or other auxiliary knowledge; and they use probabilistic transition rules not deterministic rules (Goldberg, 1989).

GAs have been successfully applied to many different problems which indicates the flexibility of the method. Of particular interest is the variation in GA theory when examining water resources problems and combinatorial problems and how this relates to the problems being investigated in this study. The application of GA to the sequencing problems will be discussed, and specifically the parameters and models to be used in the case studies of Chapters 6, 7 and 8.

5.2 Literature Survey

5.2.1 The Theory of the Traditional Genetic Algorithm

The present theory of genetic algorithms is relatively new having been developed from work on evolutionary processes in the 1950's. The GA theory was introduced by Holland (1975) and is comprehensively explained by Goldberg (1989) which will serve as the major reference text.

Goldberg (1989) describes the GA as a search procedure based on the mechanics of natural selection and genetics. The GA differs from the traditional approaches in a number of ways including: (1) the GA works with the coding of a parameter set, not the parameters themselves, (2) the GA searches a population of points rather than a single point, (3) the GA uses payoff information, not derivatives or other auxiliary knowledge and (4) the GA uses probabilistic transition rules not deterministic rules (Goldberg, 1989).

The simple GA as discussed by Goldberg (1989) works with a coded string of bits (a chromosome). These bits are assigned binary values, (0 or 1). The string is then decoded and the fitness of the string is calculated. The fitness of a string is the measure of its worth (Simpson et al., 1994). For example, in a cost minimisation problem, the fitness will be greater when the cost is reduced. The GA uses a population of strings to achieve a solution. All strings in the population have their fitness evaluated and this is used to select suitable parents for the next population. A population of strings is called a generation and the GA will continue to produce new generations up to a specified limit. The new population is produced from the previous population by using the operators of reproduction, crossover and mutation.

The traditional reproduction operator discussed by Goldberg (1989) is termed roulette wheel selection or proportionate selection. This uses string fitness to select suitable parents for the next generation. The general procedure for selecting new parents string using roulette wheel selection is analogous to the simple action of spinning a roulette wheel, hence the name. Firstly, each string is assigned a fraction of the roulette wheel so that the wheel is full. The size of each segment of the roulette wheel is not the same but is associated to the fitness of the string, with higher fitness strings having larger segments. Thus, when the roulette wheel is spun there is more chance of the higher fitness strings being selected. The wheel is then spun and a parent is selected. This continues until enough parents are selected to produce a new generation. The process follows the Darwinian theory of survival of the fittest (ie. the fitter the string the more likely it will be reproduced).

Following the selection of the parent strings the crossover and mutation operators are employed. Crossover is a primary mechanism in the genetic algorithm search. It is simply a partial exchange of corresponding segments of the two parent strings to produce two offspring (Simpson et al., 1994). It occurs with a specified probability, p_c. The process of crossover can be explain by considering the following strings:

1 1 1 1 1 1

and

0 0 0 0 0 0

If crossover occurs after bit 3 then the following two new strings will be produced:

1 1 1 0 0 0

and

0 0 0 1 1 1

Mutation is then used to maintain any important information in the string which may be lost in the other processes. The mutation operator occasionally changes the bit value of a single bit to the opposite value (ie. 0 to 1 or 1 to 0). This process can be illustrated by examining the following strings:

1 1 1 1 1 1

and

1 1 1 0 1 1

Here bit 4 has been mutated by simply changing the 1 to a 0. The mutation operator is considered a secondary mechanism in the GA process. This is reflected by the probability of mutation (p_m) being set considerably lower than the probability of crossover (p_c).

The various steps within the GA process are as follows:

(1) With the use of a random seed an initial population of strings is generated (generation 0)
(2) Each string in the population has its fitness evaluated
(3) The fitness is then used to select two parents for the next population of strings
(4) The two parent strings are tested to see if crossover will occur using the value of p_c. If crossover occurs, segments of the parent strings are exchanged
(5) Each individual bit is also tested using the value of p_m, to see if mutation of that bit will occur. If mutation occurs then the bit value is changed.
(6) After this process two offspring of the parent strings will have been generated for the new population
(7) Steps 3 to 6 are repeated until enough strings are generated to fill the new population (generation 1)
(8) Steps 3 to 7 define the creation of a new generation and these series of steps are repeated until a specified number of generations have been reached.

A simple example is used by Goldberg (1989) to illustrate how the GA works and to explain the reasons why it works. At this stage the theory of schemata is introduced to help explain the GA process. Schemata represent the common features of strings which result in a particular output. For instance consider the four generated strings and their associated fitness shown in Table 5.1 (Goldberg, 1989).

Table 5.1 Some Sample Strings and their Associated Fitnesses

String	Fitness
01101	169
11000	576
01000	64
10011	361

For these strings an example of schema would be 1*0**, where the stars may represent either a 1 or a 0. This particular schema represents 8 different strings which include strings 2 and 4 and is expected to have a high fitness. The chances of these schemata being retained generation to generation is particularly good as it has a short defining length and therefore is unlikely to be destroyed by crossover. The defining length is the length between fixed bits (ie. 0 or 1). Goldberg (1989) discusses the theory behind schemata in more detail and explains the building block hypothesis utilising schemata.

Goldberg (1989) then applies this theory to the simple problem of finding the maximum value for the simple polynomial function x^{10} between the values of 0 and 2^{30}. A 30-bit binary string is utilised for the example. Although it is obvious that the maximum value is when x = 31, the example highlights the process of using strings of higher fitness as parent strings and how with this process the GA can produce near-optimal solutions in a short time. Goldberg (1989) also examines the previous work by Hollstien (1971) and DeJong (1975) on function optimisation as well as listing the various problems the GA has been used to solve. These problem are in the fields of engineering, biology, physical and social sciences to name a few. With the different problems examined it is sometimes necessary to alter the characteristics of the basic GA. In particular, the coding scheme, selection procedure, crossover and mutation operators have been changed to suit the particular problem being examined. Such changes to coding scheme and crossover operators are discussed by Goldberg (1989), however due to the type of problem involved these will be detailed later.

Discussed below are some studies which examine variations in the GA parameters and structure in an effort to improve the GA process. These studies examine the GA in general rather than its application to a specific problem.

Coding Scheme

The first change to be examined is that of the coding scheme. The use of graý coding has been used as an alternative to binary coding (Caruana and Schaffer, 1988). Gray coding uses the same binary variables (ie. 0 or 1) as binary coding. However in gray coding, there is only a one bit change between adjacent strings whereas with binary coding there may be a number of changes in bits between adjacent strings. For instance, using binary coding the strings 011 and 100 represent adjacent strings and using gray coding the same adjacent strings are represented by the codings 010 and 110. In this case, there needs to be only one change to the bits for the gray coding but three changes to the bits for the binary coding, to move to an adjacent string coding. Caruana and Schaffer (1988) examine a gray coding scheme as the binary coding scheme finds it difficult to climb Hamming cliffs evident in particular functions. Figure 5.1 illustrates a function which includes a Hamming cliff.

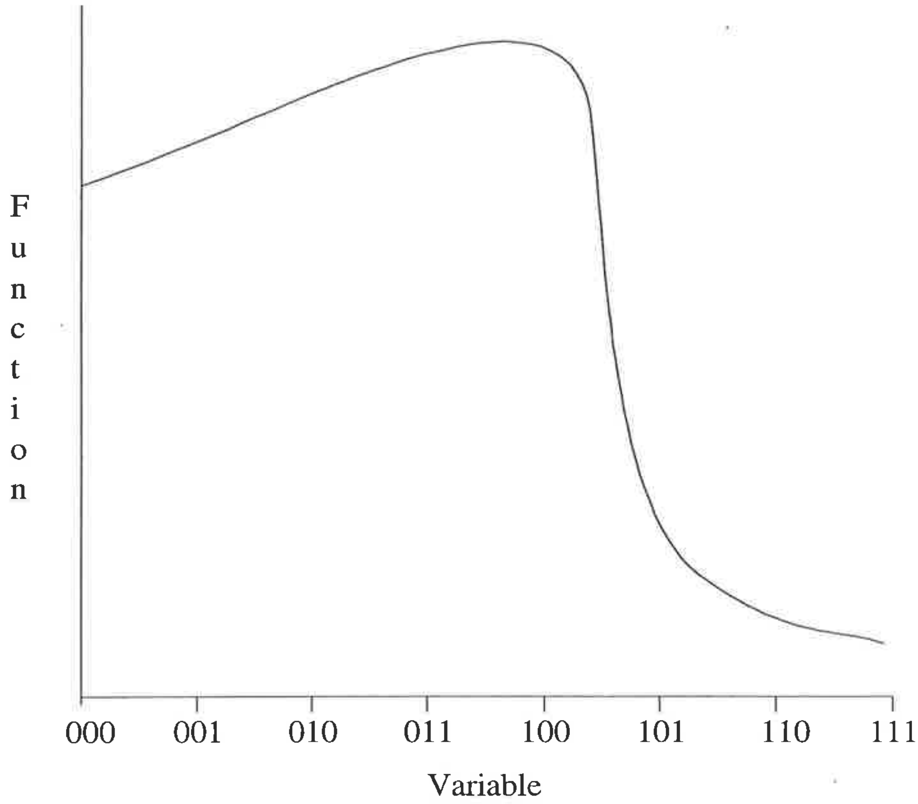

Figure 5.1 A Three Bit Function with a Hamming Cliff (Goldberg, 1990)

Thus with a Hamming cliff, at the points 001, 010, 011 mutation or crossover will not result in the optimum value 100 being found. The existence of Hamming cliffs enables the binary coded function only to find a local optimum. This does not occur if gray coding is utilised. Caruana and Schaffer (1988) apply the gray coding GA to 5 functions used by DeJong (1975) and an extra function with no known analytical solution. On all occasions the gray coding outperformed the binary coding giving a better result or a result of similar accuracy. The success of the gray code is thought to be because of its ability to preserve the domain and the correlation between the domain and range of a function better than binary coding (Caruana and Schaffer, 1988).

Murphy et al. (1993) examined the use of gray coding for a pipe optimisation problem. In their example, the change to gray coding reduced the distance between adjacent decision variable coded substrings to one bit rather than upto 4 bits found with binary coding. In this case the gray coding seemed to improve the solution obtained for the New York city tunnel problem however it was included with various other changes to the GA so no conclusive statement can be made regarding the effectiveness of the gray coding. Hollstien (1971) conclude that bit-wise complimentary mutation would cause less disruption to the solution when using gray coding as there is only one-bit distance between adjacent integers (Murphy et al., 1993). Thus gray coding may be a preferred coding to binary coding.

Another coding scheme option investigated is real coding. Real coding in this case refers to using integer numbers (ie. 0, 1, 2, 3, etc) where the integer value will represent a particular option. For instance, in a sizing problem the number 3 may represent size 3 whereas using binary coding size 3 would be represented by the coding 10. The main reason to change to real coding would seem to be due to the type of problem under investigation, as it is acknowledged that the success of the GA depends on the cardinality of the coding used.

The cardinality of a coding scheme is the possible range of values which can occur in a string. For example, binary and gray coding have a cardinality of 2, as a bit position can take the value of 0 or 1. In the case of real coding, if the variables are integer values from 0 to 8, then the cardinality of this coding scheme is 9.

Goldberg (1990) felt that the lower the cardinality the better the GA. However, there has been success with real coding on practical examples (Simpson and Goldberg, 1994) which contradicts the conclusion of cardinality. Goldberg (1990) examined the theory of genetic algorithms and cardinality of alphabets, specifically aimed at explaining the success of the high cardinality alphabet of real coding. It was concluded that the success of the real coding GAs was due to the initial alphabet of high cardinality being quickly reduced to a virtual alphabet of lower cardinality. However, the problem of "blocking" arises when using real coded GAs. The phenomena of "blocking" occurs when a GA climbs a local optimum which blocks the process from finding the global optimum behind the local optimum. The global optimum is not searched as it is effectively blocked by the lower peak and only a near-optimal solution will be found. Goldberg (1990) expected problems of quadratic or higher order to experience blocking and therefore this may restrict the success of real coding to small problems. Alternatively, for larger problems the user should investigate ways of overcoming blocking if real coding is used. On the practical side, real coding was used by Simpson and Goldberg (1994) on a pipe optimisation problem along with binary and gray coding. They found there was no benefit from using a particular coding if there was adequate mixing within the GA process. Davis (1985), Davis and Coombe (1987) and Coombe and Davis (1987) have also applied types of real coding to the job scheduling and the communication network problems.

Selection Scheme

Additional work has been done on the type of scheme used to select new parents from the old population. As explained early, the traditional method was proportionate or roulette wheel selection. The problem with this procedure is that there is no guarantee that either the highest fitness string will be selected to be a parent for the new generation or the lower fitness strings will not be selected as a parent. As discussed previously (Goldberg, 1989), the success of the GA is due to using higher fitness strings to create the new generation. Therefore, if the selection scheme could guarantee that the best strings are represented in the parent set then this should provide a better GA process.

Goldberg and Deb (1992) examined various selection schemes for GA in order to evaluate their merit. The selection schemes examined were proportionate selection, ranking selection, tournament selection and GENITOR (Whitley, 1989). Ranking selection is the sorting of the population from best to worst, assigning the number of copies each individual should receive according to an assignment function and then performing the proportionate selection using the assignments. The tournament selection is when two or more individuals are selected from the population and the one with the highest fitness goes into the new population. The GENITOR selection process, developed and described by Whitley (1989), will be discussed later in this chapter. Rather than applying the various selection techniques to a particular example, Goldberg and Deb (1992) investigated how these selection techniques converge to a population dominated by one individual. The study ignores crossover and mutation and compares the growth ratio of strings of the best class in the population, the takeover time of the individual and the time complexity of the various selection schemes. The time complexity is defined as the number of evaluations needed to produce a new population. As expected, the proportionate selection was the slowest of the methods tested. The binary tournament selection performs better than linear ranking. The GENITOR process and tournament selection with large tournament sizes (ie. 2 or more) produce similar results with regard to growth rates and performed better than the other methods.

In order, to increase the effectiveness of the proportionate selection operator it is possible to introduce fitness scaling. Fitness scaling is when the fitness is adjusted so that differences in fitness between individuals string is increased, making it more likely that a higher fitness string will be selected as a parent for the new generation (Goldberg, 1989). The purpose behind this is, to maintain diversity in early generations, and then to tighten the search by increasing the scaling, so that higher fitness strings in the later generations are favoured for selection as parents (Murphy et al., 1993). A simply scaling method is to raise the fitness function to a power, as a higher value will increase more than a lower value and therefore a greater difference between string fitness will be created. Initially the fitnesses of strings varies considerably, so the scaling is low. As the number of evaluations increase and the fitnesses of the strings become closer, the scale will increase so that differences between string fitnesses will be amplified and the higher fitness strings will have more chance of being selected as the parent strings (Murphy et al., 1993). Murphy et al. (1993) utilise increasing power scaling for a pipe optimisation problem. Increasing power scaling is where the power to which the fitness is raised, is increased as the number of generations increases. This ensures that there is a greater difference in the string fitnesses in the later generations.

The tournament size for the tournament selection procedure was investigated by Simpson and Goldberg (1994) for the pipe optimisation problem. In this case, tournament selection outperforms proportionate selection and a 5 member tournament produced the optimal solution in the least amount of evaluations over ten runs. A 20 member tournament was also tested however, on one out of the ten runs a non-optimal solution was found, although it took just over half the number of evaluations of the 5 member tournament to obtain the minimum cost solution. These cases are performed without mutation being applied.

Crossover and Mutation Procedures

Crossover and mutation procedures can also be varied. Changes in crossover procedures have been investigated but are mainly restricted to particular cases rather than being applied to the general GA theory. Examples are pipe optimisation (Simpson and Goldberg, 1994) and combinatorial problems. The change of crossover procedure for the combinatorial problems will be presented later. In the case of the pipe optimisation problem one-point, two-point and uniform crossover are investigated. The one-point crossover is the traditional crossover as illustrated previously. Two-point crossover involves randomly selecting two cut points in the strings and then swapping the bit patterns between the two cut points between the two strings. Uniform crossover is when for each bit position on the first child, a parent is selected with probability p_X. The bit from the parent which is not selected then goes to the second child (Simpson and Goldberg, 1994). It was found that the crossover operator made little difference to the result as long as adequate mixing occurs.

As far as the mutation operator is concerned one change found with this operator is to either a swap function or a inversion procedure (Spillman, 1993). The "swap" function replaces a bit in a string with another bit in the string and "inversion" randomly selects a continuous number of bits positions and then reverses the value of each bit position. In addition, Simpson and Goldberg (1994) and Murphy et al. (1993) use an adjacency mutation in a pipe network optimisation problem. Davis and Coombs (1987) use a similar operator to adjacency mutation (called "creep") for the design of communication networks. In these cases the size of an element in the problem is mutated to the next size bigger or smaller.

Value of Parameters

Apart from investigating changes to procedures there has been some examination on the appropriate value of parameters to use in GA. Goldberg (1985) investigated the optimum population size for genetic algorithms (GA) as there was little correlation between theoretical and experimental results. The theory is developed using schemata and assuming a binary coded string. A formula is developed which ensures a population size will guarantee that at least one of all possible schemata is available. The empirical formula results are compared with experimental results of DeJong (1975) and Grefenstette (1984) for a string length of 30. The experimental results indicate that the optimal average population size is 90 while the empirical formula predicts a population size of 106. Although the results are close, the study highlights the need for more comparisons between experimental results and theoretical predictions (Goldberg, 1985).

A typical population size range was suggested by Goldberg and Kuo (1987) as being between 35 and 200, although it would seem that the population size is dependent on a number of factors. Simpson and Goldberg (1994) present a formula for determining population size based on the cardinality of the coding, string length, difficulty of the problem and the standard deviation and error for a single trial. The estimates obtained using such formula's are dependent on the errors expected to occur, with a range found from 6206 to 477,107 for different error estimates. In addition, a minimum population size of 106 was estimated assuming the problem was uniformly scaled and linear. The string length for this case was 24 bits and the estimates are assuming a binary coded string. Simpson and Goldberg (1994) investigated larger population sizes (ie, 100, 500 and 1000) for a 8 and 24 bit string. It was found that for larger population sizes, higher fitness results were obtained, but the number of evaluations increased. Murphy et al. (1993) also investigated different population sizes for a 84 bit string. In this case, population sizes of 100, 200 and 500 were used however no conclusions were made on the effect of population size and solution obtained. Other studies (Goldberg and Kuo, 1987; Murphy and Simpson, 1992; Dandy et al., 1993 and Simpson et al., 1994) have adopted a population size of 100 even though the problems examined are different and the string lengths vary (ie 10 to 40 bits in a string).

Other parameter values have been examined and standard ranges identified. For instance Goldberg and Kuo (1990) estimated the probability of mutation (p_m) should be greater than 0.1/n but less than 5/n, where n = population size. Goldberg and Kuo (1987) use a population of 100 and adopted a p_m of 0.01. Goldberg and Koza (1990) indicate a different range of greater than 1/n but less than 1/lchrom, where lchrom = string length. This restricts mutation from occurring more than once within a string. A typical value used in the pipe optimisation problems investigated is 0.01 but values range from 0.0 (Simpson and Goldberg, 1994) to 0.02 (Murphy and Simpson, 1992 and Simpson and Goldberg, 1994).

As far as probability of crossover (p_c) is concerned, it is suggested by past studies (DeJong, 1975; Grefenstette, 1986 and Goldberg, 1989) that the GA will perform well if a high value of p_c is used. The suggested range for the value of p_c is generally between 0.5 and 1.0.

As mentioned the simple GA can be altered to try to improve its performance for specific cases. As the studies which follow examine the water resources sequencing problem, the discussion on the variation of the GA for these problems will be examined in two parts. Firstly, those studies which are applied to water resources problems will be presented. This will be followed by a discussion on the changes to the basic GA for combinatorial problems. The reason combinatorial problems are examined is that problems of scheduling (examined in Chapter 6, 7 and 8) are combinatorial problems within the water resources field.

5.2.2 GAs Applied to Water Resources Problems

The application of GAs to water resources is limited to finding an optimum solution to the pipe network problem. The GA has not been applied previously to the sequencing of reservoirs as investigated in this research. Therefore, the following discussion will mainly apply to the pipe network optimisation problem.

The basic pipe network optimisation problem involves determining that the sizes of pipes in a network in order to deliver required volumes of water at specified pressures at various locations in the network. If the problem was only to find the pipe sizes so that a specified volume of water is delivered, then a simple GA could be used. The string could be simply coded to represent the pipes in the network and the fitness would be the reciprocal of the total cost (Murphy and Simpson, 1992). However, if pressure constraints are introduced, it is possible that particular pipes sizes may cause pressure to drop below allowable levels and the string would be infeasible. Rather than neglecting this string, a penalty can be applied to the string for the pressure violation so that it can remain in the GA process. Such a method is used in Murphy and Simpson (1992), Dandy et al. (1993), Murphy et al. (1993), Simpson and Goldberg (1994) and Simpson et al. (1994). This is done because slightly infeasible results may be close to the optimum solution and therefore to neglect these results may slow the GA process down. In addition, the GA will tend to perform better if it can approach the optimum solution from both the feasible and infeasible sides rather than just the feasible side. Smith and Tate (1993) argue that the better solution (ie. closer to the optimal solution) are likely to be in the infeasible solution space rather than the feasible solution space. Therefore, it is beneficial to keep these infeasible solutions in the GA process rather than disregarding them.

Smith and Tate (1993) apply a penalty function that places a dynamic penalty on solutions depending on the distance they are from the best existing feasible solution. The GA is then used to solve the unequal area layout problem (investigated previously by Armour and Buffa, 1963). The unequal area layout problem as defined by Smith and Tate (1993) is as follows. There is a rectangular area with dimensions H by W, and a collection of n "apartments" of specified area, whose total area is HW. To each ordered pair of departments (j,k) is associated a traffic flow F(j,k). The objective is to partition the region into one sector departments, of appropriate area, so as to minimise the sum of F(j,k)×(the distance between the centroids of apartments j and k in a particular partition). It was found that the use of a penalty function combined with the inclusion of the infeasible solution space produced superior results to that of a unpenalised run and a run examining feasible solutions only, for the highly constrained problem.

The pipe optimisation problem described above was examined by Murphy and Simpson (1992). A simple GA similar to that presented in Goldberg (1989) was used to solve the Gessler problem (Gessler 1985) which has a total solution space of over 3 million possible combinations. The differences between the GA used by Murphy and Simpson (1992) and that appearing in Goldberg (1989), is the use of a different random number generator (Barnard and Skillcorn, 1989) and the inclusion of a penalty cost in the fitness of a string. The GA applied to this problem has a 3-bit binary string representing the possible pipe sizes for each pipe and therefore a 24-bit string represents the 8 pipe problem. For each 24-bit string, a complete network hydraulic simulation was undertaken to identify pressure heads at the different nodes. Where pressures fall below the minimum allowable values, penalty costs are applied. A Newton-Raphson network solver is utilised to determine the pressures with in the pipe network. The GA result is compared to those obtained by the enumeration technique and also against a random walk. The GA was found to be robust and greatly superior to a random walk. The GA found optimal and near-optimal results after searching only a small fraction of the complete search space. The GA is considered to be efficient in finding near-optimal solutions for a highly discontinuous function as it climbs numerous peaks at the same time rather than climbing a single peak to obtain a local optimum. This occurs with some other optimisation techniques.

The above study is extended by Dandy et al. (1993) by including linear programming and non-linear programming as comparative techniques to the GA as well as replacing the complete enumeration with a partial enumeration. Comparison is made using the 10 pipe problem of Loubser and Gessler (1990). The coding is changed from binary to real coding and with the change in problem the string size is reduced from 24 bits to 10 bits. It was concluded that the genetic algorithm performed the best but because it is a stochastic process an optimal solution can not be guaranteed. The other methods examined not only produced higher cost solutions but had other associated difficulties.

The GA used in the above studies was then modified by Murphy et al. (1993) to develop an improved GA. The new method differs from the traditional simple GA with the changing of the binary coding to gray coding, using an adjacency mutation operator in addition to bit mutation and scaling of the fitness function. The improved GA was compared to the traditional GA for a problem examining the primary water distribution system of the City of New York. This problem has been previously studied using a number of other methods and so the two GA methods can be compared with other optimisation methods. Of the GA methods, the improved GA produces the bower cost solution. Of the previous studies, the results of Fujiwara and Khang (1990) appear to give the least cost solution. However, it was shown that the solution obtained actually violates minimum pressure constraints in the system and so the result is considered infeasible. The lowest cost result which is hydraulically feasible is that produced by the improved GA.

The Gessler problem is used by Simpson and Goldberg (1994) to examine various parameters of the GA. Various coding schemes, crossover and mutation operators, population size and different selection procedures were investigated. The coding schemes examined were binary, gray and real coding with no appreciable variation in the performance of the GA between schemes. The population size was predicted theoretically using previously developed equations. The predictions for the problem under examination were considerably higher than what was expected. A lower bound of population of 106 was found using a formula developed by Goldberg et al. (1992). The study then tested population sizes of 100, 200 and 1000 with the last producing the optimum solution on all occasions used. Tournament selection with a size of tournament of 5 was found to perform the best of those investigated. One point, two point and uniform crossover were used, but no advantage was found from using any of these operators. Finally, the mutation operators of random and adjacency mutation (mutates the pipe sub-string to the next adjacent size) were examined and both types of mutation improved the results. The authors noted that studies using larger strings do not achieve improved results with mutation. Simpson and Goldberg (1994) considered that determining an appropriate selection scheme and population size was important in producing an effective GA . However, the selection of coding schemes and crossover operators seemed to make little difference to the effectiveness of the GA, especially if adequate mixing occurs. The use of mutation may improve GA results depending on the string length.

Simpson et al. (1994) use the Gessler problem to compared the results obtained by the GA, complete enumeration and non-linear programming methods. Although complete enumeration obtains the optimum solution it takes considerably longer to run and for larger problems it is infeasible to use this method because of computation time. Non-linear optimisation provided the optimal solution in the least time. However, the solution required rounding of the pipe sizes after the model run and a cost function had to be fitted to the costing of the pipes before the model could be used. The GA produced the optimal solution in 3 out of 10 runs. Although the GA takes longer than the non-linear programming model, it does not have the associated problems. In addition, the GA produces many alternative solutions which are near optimal, whereas the non-linear programming method produces only one solution. This is important as one of the other solutions may be preferred because of non-quantifiable measures which exist.

Another problem investigated using GAs is that of pipeline pumping operation optimisation (Goldberg and Kuo, 1987). This determines which pumps are to be operated to deliver a specified flow rate while minimising the total power utilised. Only a simple GA was utilised to solve this problem. The GA obtained a near-optimal solution which was only slightly inferior to the optimum results obtained by an integer programming model. Given that the GA uses probabilistic rules rather than deterministic ones and the small fraction of the total solution space examined by the GA, then the GA performance was exceptional. Goldberg and Kuo (1987) present a useful comparison to demonstrate the efficiency of the GA process. The problem examined was compared to searching only 15 people out of the worlds 4.5 billion in order to find the best person.

A similar problem to the pipe optimisation problem is the design of a communication network. This problem is examined in joint papers by Davis and Coombs (Davis and Coombs 1987 and Coombs and Davis 1987). The first paper investigates the theoretical considerations of the problem including the practical aspects and constraints. The theory moves away from the traditional bit string to a string that consists of a series of link speeds. The coding of the string is a type of real coding. A new operator is also developed called "creep" that is particular useful for this problem using the new string coding. The creep operator will creep up or down a number of available link speeds. This is similar to the adjacency mutation used by Simpson and Goldberg (1994) and Murphy et al. (1993) for pipe network optimisation. Also the crossover operator cuts the parent string in two places to form a new string. Even with these changes it is demonstrated by Davis and Coombs(1987) that the general principles of genetic algorithm theory are not violated.

Coombs and Davis (1987) also present two additional operators specific to solving the communication network design problem. These are the 'Ice age constraint' and 'LaMarck' operator. The 'Ice age constraint' limits the amount of times the complete nodal simulation occurs as the simulation is the time consuming part of the technique. This operator restricts the performing of the simulation to every n generations. The LaMarck operator can adjust the speed of a series of links or add more ports to the system, in order to reduce the occurrence of any backups or satisfy increased demand on the system. The performance of the GA was compared to a greedy cyclic algorithm with the GA producing the better results although it took more time to run. Finally, the GA was run using a post optimisation procedure that leads to improvements in the system design in a reduced time.

The next section examines how the genetic algorithm has been applied to the combinatorial problem.

5.2.3 Genetic Algorithms Applied to Combinatorial Problems

The water resources sequencing problem being investigated here is a typical combinatorial problem. Although, this particular problem has not previously been investigated using GA theory. However, combinatorial problems such as the travelling salesperson problem (TSP), job scheduling problem and vehicle routing problem have been examined previously. The classical combinatorial problem is that of the TSP and this is the one examined in most previous studies. The TSP attempts to find the minimum cost path for a travelling salesperson to visit a specified number of cities, with every city being visited only once.

The main emphasis when solving the combinatorial problems seems to be aimed at the crossover operator. The reason is that the use of normal crossover in an order problem may result in illegal solutions being obtained. When normal crossover is used in the TSP, a number of cities may occur more than once in a string while some cities may not occur. This will be illegal as a city representation should appear once and only once within a string. A number of studies have examined different crossover operators. Goldberg and Lingle (1985) develop a crossover procedure called partially mapped crossover (PMX) to solve the travelling salesperson problem. PMX crossover selects randomly two positions in the parent strings where all bits between the two positions are to undergo crossover. Then the bits that are now the same as the crossed over bits are swapped with those bit positions that are missing from the particular string. For example, if we consider the parent strings as follows:-

A = 9 8 4 | 5 6 7 | 1 3 2 10

B = 8 7 1 | 2 3 10 | 9 5 4 6

The marks (|) represent randomly selected positions. From here the bits between the marks 5 6 7 (for string A) are swapped with 2 3 10 (for string B) as the first part of the procedure. Then the bits outside the string that correspond to those within the string are exchanged ie. 5 for 2, 7 for 10 and 3 for 6. Thus the resulting strings are:-

A' = 9 8 4 | 2 3 10 | 1 6 5 7

B' = 8 10 1 | 5 6 7 | 9 2 4 6

The theory of PMX crossover is examined with relevance to its effect on allele (bit value) and schemata theory. Goldberg and Lingle (1985) concluded that PMX crossover allows the same implicit parallelism to occur in both orderings and alleles as witnessed with allele information alone. When PMX crossover was tested using a 10 city problem (Karg and Thomson, 1964) an optimal and near-optimal solution was found for the two runs performed. However, the problem is only examined with 20 generations.

PMX crossover was then compared to order crossover (Davis 1985) and cycle crossover (CX) by Oliver et al. (1987). Order crossover (OX) random selects two cut points in two parent strings. The section between the two cut points in the first parent is copied to the offspring. The remaining elements in the offspring are filled with elements not occurring in the crossover section. This is done by using the order the elements are found in the second parent after the second cut point. An example of order crossover is as follows (Oliver et al., 1987):

Parent A :- *h k c e f d* | *b l a* | *i g j*

Parent B :- *a b c d e f* | *g h i* | *j k l*

Offspring :- *d e f g h i* | *b l a* | *j k c*

Cycle crossover (CX) works on the basic principles that (i) every bit position of the offspring has a value found in the corresponding bit position of one of the parents and (ii) the offspring must be a permutation (Oliver et al., 1985). Two explain the process of cycle crossover, consider the following parents:

Parent A :- *h k c e f d b l a i g j*

Parent B :- *a b c d e f g h i j k l*

Using the first principle, either *h* or *a* is selected as the value in position one of the offspring. Assume *h* is chosen. Then, using the second principle, the position of *a* cannot be chosen from parent B since that position is occupied by *h* and therefore the position of *a* is chosen from parent A. As *a* in parent A is above *i* in parent B then the position of *i* also must be selected from parent A. This argument leads to the positions of *h, a, i, j* and *l* being selected from parent A. This process is said to have formed a cycle hence the name cycle crossover. This cycle continues until all positions in the offspring are occupied. Thus, for the example discussed, if the remaining positions for the offspring are selected from parent B, the following offspring is produced :

Offspring :- *h b c d e f g l a i k j*

It was found that OX performed better for the TSP where compact schema is important. The OX operator was the tested against other methods where it was discovered that for two runs using different parameter values, OX produced a result within 0.25 % of the optimum both times. This was better than a neural process (Hopfield and Tank 1985) but not as good as a heuristic technique (Lin and Kernighan 1973) which produced the optimum tour. Oliver et al. (1987) concluded that OX is best in cases where schemata compactness is important, PMX where it is less important and CX when compactness of schemata is irrelevant.

The TSP was also used by Grefenstette et al. (1985) to develop an heuristic crossover operator. Before the heuristic was developed, Grefenstette et al. (1985) tried three other crossover operators namely, ordinal, adjacency and subtour chunks, but all performed poorly. The poor performance was attributed to high disruption to the strings and little representation of the parents in the offspring. As a result of the failure of the methods a hyperplane analysis of the problem was undertaken, which resulted in the heuristic operator. When this was tested on a 50, 100 and 200 city problem with a probability of crossover of 50 % the operator significantly outperformed a random search. Further, if selection of suitable parents is applied in conjunction with the operator, the solutions are near optimal.

For the crossover operators developed by Goldberg and Lingle (1985), Grefenstette et al. (1985) and Davis (1985), it was observed by Whitley et al. (1993) that the performance of such operators depends on their ability to preserve the parents in the offspring. Whitley et al. (1993) then developed the genetic edge recombination (GENITOR) operator. GENITOR uses an edge map to construct an offspring that inherits as much information as possible from the parent structure. Basically, GENITOR selects the initial bit as the one with the most edges or connections to the other bits in the parent strings. Then the next bit to be selected is the bit with the least amount of edges which is also connected to the previous bit. This continues until all bits are represented in the string. GENITOR was utilised to solve a 30, 50 and 75 city TSP and was found to give slightly better results than previously discovered. The operator is also applied to the job scheduling problem and outperforms a greedy operator for a particular example. However, the GENITOR operator does not achieve the optimum result, although it converges close to the optimum. Whitley et al. (1993) conclude that the edge recombination operator lends itself to combinatorial problems where cost information on the entire sequence is utilised and that such an operator is superior to the simple genetic algorithm for this type of problem.

Homaifar et al. (1993) also developed a new GA operator which utilises matrix crossover and two point inversion to solve the TSP. The method uses a binary string of length n, which is converted into an n by n matrix. A value of 1 in a matrix position represents a tour between two cities whereas a 0 indicates no tour. This matrix then undergoes crossover between two points. If this process produces an illegal tour (two 1's in the same row) then, one of the 1s is taken from this row and placed in a vacant row until all rows are filled and the tour is legal. Another potential problem is two cycles within the tour. These are removed by simply cutting and connecting the cycles so that the maximum number edges within the parent strings are preserved in the offspring. The inversion operator is used as a hill climber. If the offspring produced has a greater fitness, then it replaces the parent, but if it does not then the parent is retained. This method is used to solve a TSP with 25, 30, 42, 50, 75, 100, 105 and 318 cities.

Homaifar et al. (1993) also uses the PMX, CX, OX and edge recombination (Whitley et al., 1989) operators and the TABU search method (Glover 1990 and Knox 1989) for the same problems so that the results can be compared. It was found that the matrix crossover with 2-point inversion outperformed the other GAs for 30, 50, 75 city TSP and is competitive with the TABU search for the TSP examined. In the cases examined the matrix method gave the optimal or near optimal solutions (ie. the definition of optimum in this case being the best solution obtained by previous methods).

The operators of edge recombination (Whitley 1990), cycle crossover (Davis 1985) and PMX crossover (Goldberg and Lingle, 1985) are also used by Blanton Jr. and Wainwright (1993) for the multiple vehicle routing problem (MVR). They are compared to a new family of crossover operators developed by Blanton Jr. and Wainwright (1993) termed Merge crossover, which are designed specifically for MVR problems. The new operators vary from the traditional crossover operators by using global information rather than chromosome specific information. The global information is coded in the form of a global precedence vector. This indicates where genes should be placed relative to other genes in a global sense. For this problem each gene represents a customer and an associated time window. The shorter the service time, the higher the gene in the global precedence vector. The global precedence vector can also be obtained by using other criteria such as distance and capacity. For instances the distance precedence vector works on the minimum distance from a particular gene to the next two possible genes (This type of precedence vector is similar to some genetic algorithm operators used to solve the TSP). Blanton Jr. and Wainwright (1993) establish a number of new crossover operators which use a combination of the time, distance and capacity global precedence vectors. The operator's performance is tested with a 15, 30, 75 and 99 customer problem with the number of vehicles per problem being varied. It was found that the merge crossover operators outperformed the other methods on all occasions. For the larger problems with 75 and 99 customers, the other three operators failed to find a feasible solution. The merge crossover operator always found a feasible solution defined as when all customers are serviced in the appropriate time.

An extended vehicle routing problem was also investigated by Thangiah et al. (1993). In this case time deadlines are imposed to further constrain the vehicle routing problem. Thangiah et al. (1993) presented a two part solution method termed the genetic sectoring heuristic where a genetic algorithm clusters the customers within the problem and a local optimisation technique then routes the vehicles in the clusters. This method involves using a 5 bit binary string which represents angle offset and determines in which clusters the customers are present. Once the best cluster is found, a process called the cheapest-insertion method is used to route each cluster independently. The cheapest-insertion cost is evaluated based on distance travelled plus a penalty for tardiness of the vehicles and overloading of the vehicles. The local optimisation method is then used to improve the routes by moving and exchanging customers within and between the clusters. The cheapest-insertion method is again utilised. The genetic sectoring heuristic is compared with a greedy time orientated sweep heuristic for a 200 customer problem. The customers are grouped in five sets based on time serviced. Five problems are addressed where the percentage of customers within the five sets is varied. These five problems are examined for five different cluster cases ranging from no clusters to 4 clusters. Thangiah et al. (1993) found that the genetic algorithm produced feasible solutions for all the cases examined and outperforms the greedy heuristic when the customers are uniformly distributed and/or time deadlines are tight. However, the greedy heuristic outperforms the genetic algorithm for tightly clustered customers and long deadlines, but there were two occasions when it failed to find a feasible solution.

Finally, Davis (1985b) introduces both new coding and new operators to solve the job shop scheduling problem. This problem experiences the same difficulty as the TSP with illegal strings being produced using the traditional GA operators. The coding is a word coding that allows a particular machine a choice of five possible actions (ie. 60, contract1, contract2, wait, and idle). The new operators are a scramble and a run idle operator and were developed as a result of trying to solve the problem deterministically. The scramble operator scrambles the members of the preference list. The run idle operator is performed on machines waiting for more than an hour and with a frequency based on the percentage of time a station is waiting divided by the total time of the simulation. In addition, a penalty cost is applied on schedules failing to achieve the desired levels of production which results in these schedules being costly and therefore undesirable.

The next stage in discussing GAs is to examine the problem of water resources sequencing and to develop a suitable GA methodology to solve the problem.

5.3 Adaptation of Genetic Algorithm Theory to Solve the Water Resources Sequencing Problem

Before the traditional GA theory is adapted to solve the water resources sequencing problem an explanation should be given to why the GA is applied to this problem. It has been discussed in past research (Grefenstette et al., 1985) that combinatorial problems such as TSP are NP hard. The definition of NP hard is that the search space increases exponentially when the number of variables being examined increases. Water resources sequencing problem will fall into this classification. Generally, with NP-hard problems, a solution is found by using heuristic procedures. Other procedures such as dynamic and linear programming experience problems with computation time and size for moderate to large problems. For the water resources problem heuristic methods such as equivalent cost and unit cost are used to obtain the minimum cost solution for this problem. These methods have been discussed in Chapter 3 and 4 with the equivalent cost method providing the better results. However, the equivalent cost method will not provide an optimum solution for the case of non-linear demand. Therefore a method is required which will solve the water resources sequencing problems given difficult cases such as non-linear demand growth. The traditional GA has been successfully adapted previously to similar problems (eg. TSP) and it is expected that it can be adapted for the problems presented in this study.

As noted, combinatorial problems require some alteration to the traditional GA in order to obtain an efficient solution algorithm. The same problems experienced with the TSP and the other problems illustrated above will be experienced with the water resources sequencing problem. The major problem is the production of illegal strings through normally mutation and one-point crossover. Therefore, different crossover and mutation operators will need to be used to stop illegal tours from being produced. The reason an illegal string is produced using normal mutation and crossover is discussed below.

Real coding will be used to illustrate the problem of illegal strings. When using real coding, the integer values will represent the project number and the bit positions will represent the sequencing order of project. So for string (1) shown below, the project sequence would be 1, 2, 3, 4, 5 and 6. For the discussion of why the normal crossover and mutation operators, may lead to illegal strings, consider the following strings.

(1) 1 2 3 4 5 6 and (2) 6 5 4 3 2 1

In the problem it is required that a number is represented once and once only within a string. Now consider crossover occurring between bits 3 and 4. The resulting strings are:

(3) 1 2 3 3 2 1 and (4) 6 5 4 4 5 6

The strings produced are not legal because 3 of the numbers do not occur in either of the strings. If traditional mutation occurs to bit 3 of the first string (1), and the 3 is mutated to a 4 the following string is produced.

1 2 4 4 5 6

This is an illegal tour as the number 4 occurs twice within the string and the number 3 does not occur. These problems have been addressed by previous studies with new crossover and mutation procedures defined. One such crossover procedure is PMX crossover (Goldberg and Lingle, 1985). The operation of this has been discussed in section 5.2.3. This procedure will be used in the case studies in Chapters 6, 7 and 8.

In addition, a swap operator (Spillman, 1993) will be used to replace the mutation operator as this will ensure a legal tour is produced. It works in the following manner. If the first string (1) is again used and bits 2 and 4 are selected to be swapped, the new string will become:

1 4 3 2 5 6

which is a legal string. This is an example of a random swap operator. In addition, an adjacent bit swap operator will also be examined. This is when adjacent bits either prior to or following the selected bit are swapped with that bit. For example if bit 2 is selected as the bit to swap then it will be swapped with either bit 3 or bit 1. If the swap occurs between bits 2 and 3 of the first string (1) above, the resulting string will be:

1 3 2 4 5 6

Another possible change to the traditional GA is to alter the coding, such as using real coding instead of the traditional binary coding. The strings shown above are classified as real coded strings. Another coding structure has been developed using real numbers between 0 and 1, such as 0.987, 0.34, 0.065. This coding structure will be referred to as continuous coding, with the previous definition of real coding being continued. The way in which this new coding structure works is as follows. The following string is an example of a continuous coded string.

0.982 0.567 0.001 0.986 0.332 0.653

The sequence of projects this produces will be determined by the relative magnitude (from largest to smallest) of the real number for a particular bit position. Thus the bit position represents the project number. Thus, as 0.986 is the largest value and is found in bit position 4, then project 4 is the first sequenced. By this method, project 1 will be the second project sequenced, as the first bit has the second largest value (eg. 0.982). Therefore, the sequence of projects for this string will be 4, 1, 6, 2, 5 and 3. An additional advantage of this coding structure, is the traditional crossover and mutation operators can be utilised without an illegal string being produced. In the case where a real number occurs within the same string more than once then the first occurrence of the real number will be taken as the first of the two projects sequenced. For example, consider the following string :

0.982 0.567 0.982 0.986 0.332 0.653

In this case the sequence will be 4, 1, 3, 6, 2 and 5 even though bits 1 and 3 have the same value. The possibility of the same real number occurring twice within a string is very low as the real number is generated to 6 decimal places and theoretically the same number will be generated on average once in every million numbers generated. The mutation operator will be the same as the traditional mutation operator in this case, with the exception that a 0 or 1 are not swapped but a new real number is randomly generated and it replaces the selected real number to be mutated.

The main advantage of changing from binary coding to continuous and real coding is as follows. When using a binary coding the project number and project order information must be contained within the string. Therefore, either the bit position represents the order and then the value of the bit will represent the project number or the opposite will be true. So for a four project problem, a representative coding for the project sequence 4, 2, 1 and 3 will be :

11 (4) 01 (2) 00 (1) 10 (3)

if the bit position represents the order and the bit value represents the project number. This is fairly straight forward. However, if the problem was a 10 project sequencing problem then, a four bit binary number will be required to account for all projects and 10 of these four bit binary numbers will be needed to represent all the projects to be sequenced. This is not unreasonable, however at 17 projects a five bit binary number is required and the string length will be 85 bits long. So as the size of problem increases so does the string size. The increasing string size is not the real problem, but rather the previous problem of producing illegal strings through crossover and mutation. The change in crossover and mutation procedures must also be included so a legal solution will always be produced. The problem with this is that the number of bits to be evaluated by crossover and mutation will be increasingly changing, depending on the size of problem being investigated. For instance when crossover is applied to the 10 project problem, crossover must apply to the four bits which represent the projects and only after every four bits. For the 17 project problem the 5 bits per project must be considered when crossover is undertaken. However, the changing of the string composition with problem size will further complicate the use of binary coding for the sequencing problem. Therefore, it is easier and more efficient to use continuous or real coding than binary coding,

The above problem is not the only difficulty associated with using binary or gray coding. In fact the problem described can be overcome with some effort if the other forms of coding were found not to be successful. Another problem associated with binary coding is that there will be an excess number of binary strings created. For example, for a 17 project problem, 5 bits are required to represent the 17 projects. However, 5 bits will represent as many as 31 projects. So for the 17 project problem it is possible that the string produced may contain projects 18 to 31, which do not exist. However, if this occurs, an illegal string will be produced. To ensure this does not occur, a check of the strings produced in the GA process would be required. When illegal strings occur, adjustments to the string are required to produce a legal string. This is not a problem experienced with continuous or real coding, which is another benefit in using these types of coding schemes.

It could argued that as the TSP and water resources sequencing problem are similar then why develop a new operator and coding when it would be easier to use real coding and PMX crossover, as Goldberg and Lingle (1985) have done successfully for the TSP. The answer to this is that the TSP and sequencing problem are sufficiently different to warrant an investigation of the performance of PMX crossover and real coding against some other GA parameters and operators. In addition, the use of the traditional crossover and mutation routines is seen as an advantage in solving the sequencing problem.

The differences which exist between the TSP and the sequencing problem are evident when both problems are examined. The TSP is defined as finding the shortest distance (ie minimum cost) for a salesperson to travel from town A through all towns in their tour back to town A. The fitness of a string is not based on the global positioning of a town but what town precedes the town, as the important information is the distance from one town to the next. However the selection of the next town is not affected by the towns preceding the town the salesperson is at. In the sequencing problem where time is important, as is the cost and yield of a project, the global positioning of a reservoir is very important. Consider a four bit string example, A, B, C and D. In the TSP if the tour ABCD is evaluated then what is calculated in the distance from A to B, B to C, C to D and D to A. The value of the string is not dependent on D's relationship to B or C to A. In the sequencing problem for the same sequence, the evaluation of reservoir C is dependent on all preceding reservoirs as they affect the timing of the reservoir C and therefore the present value of cost. To highlight this further the evaluation of travelling B to C or C to B for that matter, in the TSP, is the same no matter when it occurs in the string (ie. ABCD, ADBC, BCAD, CADB). However, for reservoir sequencing the value of the sequence BC changes all the time depending on what projects precede it. For example the sequence ADBC may produce a smaller value of present value of costs for BC than BCAD or ABCD.

Another difference between the two problems, is that in the TSP problem the tour (or string) is cyclic. That is the evaluation of the string is complete when the salesperson returns to the first city in the tour (ie. the tour is actually ABCDA). This is not considered in the sequencing problem. Also, in the sequencing problem the value of the string does not remain the same if a set of bits are reversed. Because discount rate and timing are included in the sequencing problem a different value of present value of cost will be obtained if the sequencing order is reversed. Therefore, it could be considered that the TSP is less complex than the sequencing problem and the latter should be a good test of the ability of the GA to solve such combinatorial problems.

Another variation to the traditional GA is the replacing of the selection operator. As mentioned above the traditional selection procedure is a proportionate or roulette wheel selection. In addition to this procedure, tournament selection will also be examined. The proportionate selection will also use a constant scaling factor of 3 so the fitness is x^{-3}, where x is the present value of cost for the project sequence. The tournament selection operator has been discussed previously and will be used because of the encouraging results obtained by Goldberg and Deb (1992) and Simpson and Goldberg (1994).

Two forms of tournament selection are examined. The first randomly selects a set number of strings, n, from the population, with the fittest string becoming the parent string. The strings are then replaced in the population and the next parent selected by the same process. This continues until enough parent strings are selected to produce the next generation. The second tournament selection process (Goldberg and Deb, 1992) shuffles the population of strings and then a specified number of strings, n, are drawn from population. The highest fitness string is then selected as the parent string. The strings are placed in a discard pile and the process continues until all the strings have been drawn. This will give a proportion of the parent strings for the next generation. This proportion is equal to the population size divided by n,. The full population of strings is then reshuffled and the process repeated. This procedure will be repeated n times, until enough parent strings have been selected to produce the next generation. This process is analogous to the dealing and shuffling of a pack of cards.

The two tournament selection procedures are the same except the first samples the population with replacement while the second tournament selection samples without replacement.

5.3.1 Application of Genetic Algorithms to the Water Resources Sequencing Problem

The various alterations to the GA for the case studies in Chapters 6, 7 and 8 are combined to form a number of different GAs. Combining the various operators and selection processes result in 18 genetic algorithm models. The first six use proportionate selection (Models P1 to P6), with the remaining models using the tournament selection processes. The following is a brief description of the models.

P1: Continuous coding, random mutation of bits and traditional crossover
P2: Continuous coding, adjacent swapping of bits and traditional crossover
P3: Continuous coding, random bit swapping and traditional crossover
P4: Real coding, no mutation and PMX crossover
P5: Real coding, adjacent swapping of bits and PMX crossover
P6: Real coding, random bit swapping and PMX crossover

For tournament selection without replacement and with replacement, the Models will be referred to as T1 to T6 and R1 to R6 respectively. In addition, Models T1 to T6 will use two members for the tournament while for Models R1 to R6 four members are used.

A brief discussion is needed regarding the swap mutation for Models P2, P3, P5 and P6. In these cases the mutation with Models P2 and P5 involves swapping adjacent bits and with Models P3 and P6 swapping two bits randomly. The same applies for the Models T1 to T6 and R1 to R6. For the adjacent swap, on 50 % of the occasions the adjacent bit preceding the selected bit is swapped and on the remaining occasions the selected bit will be swapped with the next bit in the string. In addition, these swap operators are applied to a string using a string evaluation and a bit evaluation. Bit evaluation tests every bit and then if a swap occurs will swap the selected bits. String mutation checks whether mutation will occur within a string and then swaps two bits within the string. With string mutation there is no possibility of two swaps occurring in one string. However, in the bit mutation there is a slight possibility this may occur. The difference when comparing the probability of mutation rates is the string mutation rate will be higher as less evaluations of mutation will be made. For instance, if the p_m is equal to 0.05, for a population size of 100 there will be on average 5 swaps per generation. For the bit mutation for a string of length n, this will result in 5n swaps. Thus, a comparative bit mutation rate would be 0.05/n for this case.

All the GA models which are examined are programmed in PASCAL and run using the package Borland Turbo Pascal version 7.0. In addition, the random number generation required in the GA formulation is available within the package used and is not that used by Goldberg (1989).

5.3.1.1 Evaluation of the Various Genetic Algorithm Operators

The next step is to test which of the operators are the best using a simple sequencing problem with no sizing. Demand will be assumed to be linear so that the equivalent cost method can be used to find an optimal solution. The test problem will have 10 possible projects. The 10 projects selected are part of the South East Queensland system which is the case study examined in Chapter 6. The demand growth rate is set at 10 GL/year. The discount rate is set at 5 % and the time period is such that all projects are required to be sequenced. The yield of the existing system is assumed to be zero. The yields of the individual problems are given in this problem. It is assumed that they have been determined using a suitable method. The costs and yields of the projects are illustrated in Table 5.2.

Table 5.2 Project Costs and Yields

Project Number	Cost ($Million)	Yield (GL)
1	123.0	98.60
2	127.0	42.40
3	134.0	64.40
4	309.0	110.1
5	99.0	61.50
6	61.0	48.69
7	104.0	54.27
8	126.0	44.60
9	225.0	59.00
10	72.0	29.38

From applying the equivalent cost sequencing method to the projects in Table 5.2, the optimum sequence of projects is shown in Table 5.3.

Table 5.3 Optimum Project Sequencing

Project Sequence									
6	1	5	7	3	10	8	2	4	9

The present value of costs (PVC) for this sequence is $396.55 million.

The following values of GA parameters were used in this study. The population size for this problem will be taken as 100, as it is a typical value applied to large problems (see Section 5.2.1). The number of generations will be set equal to 200. Ideally, the number of generations used should be determined after initial runs are performed as the value selected may not allow the best solution to be obtained. However, for this case it is expected that the value of 200 should ensure enough evaluations are made to obtain an optimal solution. The probability of crossover (p_c) and mutation/swap (p_m) for string mutation are 0.9 and 0.1 respectively. The probability of mutation for the string mutation would be equivalent to a probability of mutation of 0.01 for bit by bit mutation for this example. These values are chosen based on past studies outlined in Section 5.2.1. The seed for the various runs was continually changed to avoid similar starting populations. Two runs were performed for each different GA model. The results for the proportionate selection models are shown in Table 5.4.

Table 5.4 Results of Models P1 to P6

MODEL	P1		P2		P3	
RUN	1	2	1	2	1	2
PVC	396.55	397.01	396.68	396.88	396.55	396.55
Evalns	9090	11880	3960	12060	14130	6300
MODEL	P4		P5		P6	
RUN	1	2	1	2	1	2
PVC	396.55	397.33	396.55	396.56	396.55	396.55
Evalns	6840	3870	16650	7650	10710	14310

The value of PVC is Table 5.4 is the minimum PVC found and the term "Evalns" is the number of evaluations required to achieve the minimum PVC. Model P2 failed to find the optimum, however it produced near optimum solutions. Model P1 obtained the optimum in one of two runs. P3 produced better results than Models P1 and P2 as it produced the optimum well within 100 generations and then did not to deviate far from that optimum. Model P4 produced the optimum result in one of two runs performed. However, for the second run a near optimum solution was obtained and then no convergence occurred (ie. solution is approximately 0.25% higher than the optimum). Models P5 and P6 produced the optimum solution in both the runs examined. The optimum was found well within 200 generations and the solutions tended to continue to converge to the optimum solution unlike some of the previous models.

The next step is to test the models which used tournament selection as a basis for selection. The first tournament selection to discuss is that without replacement. The results of using this selection procedure are shown in Table 5.5.

All the models produced an optimum result. For all the models except Model T1, the optimum was found within the first 25 generations and once the optimum was found there was no deviation from it. In the case of Model T1 the optimum was achieved within the first 50 generations however, once it was obtained the result fluctuated between the optimum and values within approximately 0.25 % of the optimum.

Table 5.5 Results of Models T1 to T6

MODEL	T1		T2		T3	
RUN	1	2	1	2	1	2
PVC	396.55	396.55	396.55	396.55	396.55	396.55
Evalns	2700	2790	1440	2070	1530	1350
MODEL	T4		T5		T6	
RUN	1	2	1	2	1	2
PVC	396.55	396.55	396.55	396.55	396.55	396.55
Evalns	1440	1440	1620	1260	1260	1890

The final models to examine are those using tournament selection with replacement. These results are shown in Table 5.6.

Table 5.6 Results of Models R1 to R6

MODEL	R1		R2		R3	
RUN	1	2	1	2	1	2
PVC	396.55	396.55	396.55	397.33	396.55	396.55
Evalns	630	1170	810	810	900	2160
MODEL	R4		R5		R6	
RUN	1	2	1	2	1	2
PVC	396.84	396.55	396.55	396.55	396.55	396.55
Evalns	450	540	990	990	1170	1170

For tournament selection with replacement, the optimum was obtained for all the models. However, Models R2 and R4 produced one near optimum solution in one of their two runs. It is interesting to note though, that when Model R4 produced the near optimum result, the average population fitness was the same as the maximum population fitness, indicating that all the population has the same fitness value. This is the reason the optimum was not produced, as crossover occurs between identical strings which results in no change in the strings.

This would advocate the used for a mutation operator in conjunction with the PMX crossover (eg Models R5 and R6). This would lead to changes in strings once a particular local optimum occurs. If the changed string produces a lower fitness, tournament selection will almost certainly guarantee the string drops out. However, if mutation produces a fitter string then the use of tournament selection will increase the likelihood the better string is used. This process will continue until the optimum is obtained. This is the process that occurs in Models R5 and R6.

For those models which produced the optimum solution the optimum was found within 15 generations with the best models appearing to be Models R3 and R5. These results suggest any of the models apart from Models R2 and R4, could be used with confidence in finding the optimum solution.

The reason for the near optimum produced by Model R2 is because real numbers within strings are swapped and when crossover occurs the same real number occurs more than once in a string. In this case the first number will be decoded as occurring first in the sequence. Thus, if the optimum is actually the reverse, the optimum will be difficult to obtain if not impossible (ie. only chance is through further crossover or mutation). As an example consider the following string:-

0.8 0.5 0.9 0.4 0.6 0.5

The order will be decoded as 3 1 5 2 6 4 whereas the optimum may be 3 1 5 6 2 4 which if the values of 2 and 6 do not change then the optimum will never be achieved.

The same problem may also occur with the Model R3 and for the same operators when using tournament selection without replacement (eg. Models T2 and T3).

In comparing the various selection processes it is clear that the tournament selection methods are superior to proportionate selection. However, the results of the two tournament selection methods are very similar. It was decided that tournament selection without replacement is the better of the two for the following reasons. Firstly, this method allows a greater diversity in the fitness of strings within a population to be maintained. The method ensured that the fittest strings survived to become the parents of the next generation without them becoming dominant in the next generation. Although, tournament selection with replacement did the same, the fittest string tended to become dominant and diversity was lost. This was shown in the results of Model R4 where all the strings in the population had the same fitness. Although this lack of diversity did not cause any major concerns in this case, for more difficult problems it may result in a solution which is far from the optimum.

In addition, tournament selection without replacement will ensure the highest fitness string is always represented twice as a parent string. However, tournament selection with replacement, cannot ensure that the highest fitness string is represented as a parent string, as it may not be randomly selected in the selection process. Alternatively, the method may select the highest fitness string on all occasions resulting in the previously discussed lack of diversity in the population occurring. Thus with tournament selection without replacement, there is some guarantee of representation of strings in the new population. This cannot be stated for the tournament selection with replacement.

Following these results, it was decided that only models using the tournament selection without replacement will be used in the case studies. The problem outlined with Model R2 and which may occur with Model R3, will preclude both Models T2 and T3 from further analysis. In addition, the Model T4 will not be included in the study because of the problems discovered with Model R4 in this exercise. Therefore the models to be used further are Models T1, T5 and T6.

The next step was to examine the use of bit mutation evaluation and string mutation, to observe if any major differences occur in the results. The Models considered are T5 and T6. As mentioned the results of Model T4 indicate that the PMX crossover will produce near optimal or optimal results by itself, but on the occasions it does not produce an optimal result the use of a mutation operator may provide the information needed to find the optimal solution. This is illustrated by comparing the results of Models T4, T5 and T6. As PMX crossover produces near optimal results without mutation, only a low mutation rate needs to be used when it is introduced. For string mutation, a mutation probability of 0.1 was used, so on average 10 strings per generation will change. For the bit by bit mutation a probability of 0.1 was used.

The outcome was that Model T5 produced similar results, no matter which mutation operator was used. For the bit by bit mutation operator, for Model T6, the results were disappointing because the probability of mutation was considered too high. This does not explain why the Model T5 produced such good results for this mutation operator. The mutation rate was reduced to 0.05 for the bit by bit evaluation, to examine the effect of the mutation probability. All the results were optimal and there was no real difference between the results of either mutation operator. This test of mutation has shown that Model T6 is more sensitive to the mutation rate and if the mutation rate is too high, mutation may disrupt the convergence process.

It is also expected that the probability of mutation will need to be higher when using string mutation because it will go through fewer evaluations per generation than bit by bit mutation. For example, in this problem, string mutation will make 100 evaluations (eg population size) of whether to mutate or not to mutate, whereas bit by bit mutation will make 1000 evaluations (population size×string length). If on average, approximately 50 mutations are desired within a generation, then the probability of mutation using string and bit mutation, would need to be 50 % and 5 % respectively. Therefore, for the two mutation criteria to perform to a similar degree (eg. perform the same amount of mutations), the bit by bit mutation requires a lower probability of mutation.

The results show the use of a mutation operator in conjunction with PMX crossover is appropriate. However, the mutation rate needs to be kept low so that it does not interfere with the PMX crossover operator, which produces good if not optimal solutions by itself.

5.4 Conclusions

It is evident from previous studies that GAs provide an efficient and flexible method for solving many different problems. The ability of the GAs to optimise functions is well documented and their benefits over traditional optimisation methods have been discussed (Goldberg, 1989). The efficiency and flexibility of the GA to model the water resources sequencing problem has been illustrated. This conclusion is justified, if the percentage of the actual number of evaluations compared to the total possible evaluations for complete enumeration are examined. For the simple problem examined, there are 10 ! or 3,628,800 possible combinations of projects. The GA Model, T1 (which performs the least efficiently of the three models ultimately selected for further use) obtained the optimum solution within 4500 evaluations. Thus the optimum is obtained after only examining 0.124 % of the possible search space. This percentage is halved if the results of the T5 and T6 Models are examined.

Examining the water resources sequencing problem using GA involves a number of changes in the traditional GA operators. The most significant of these is the changing of the GA coding from a binary coding to a continuous and a real coding. The variation in coding is not expected to alter the success of the GA process, as past studies have successfully utilised different coding schemes for some practical problems. Other coding schemes which have been used are binary, gray and real coding. Traditionally it was considered that codings with low cardinality alphabets (ie. binary and gray coding) will perform better than those which have high cardinality alphabets (ie. continuous and real coding). The theory of virtual alphabets is presented by Goldberg (1990) in an effort to explain the success achieved by continuous or real coding. The theory states that although the initial cardinality of the continuous or real coding alphabet is high, after a number of generations the cardinality of the alphabet will be lowered and therefore the performance will be better than expected. Other studies (Simpson and Goldberg, 1994) have shown that the coding scheme used is not of particular importance as long as adequate mixing occurs.

Adequate mixing will occur within the GA process if the appropriate operators are selected. In this study different crossover, mutation and selection operators were utilised. The traditional operators used were one-point crossover, bit mutation and proportionate selection. Other operators which were found to be useful were PMX crossover (Goldberg and Lingle, 1985), swap mutation and tournament selection. All these operators are used for the remainder of the studies in Chapters 6 and 7 except for proportionate selection. This was found to be considerably slower than tournament selection in obtaining convergence to a solution. In addition, tournament selection produced higher fitness solutions. A further reason why tournament selection is used is it always selects the best solution as a parent for the next generation and the worst solution will be ignored. This is not the case with proportionate selection even if fitness scaling is used.

PMX crossover (Goldberg and Lingle, 1985) was developed to apply GAs to the TSP which is a combinatorial problem similar to the water resources sequencing problem. Because of differences between the two problems, a mutation operator was required to assist PMX crossover, so an optimum solution was obtained. The mutation operator selected was a swap operator which swaps two bits within a string. The traditional bit mutation could not be applied when using PMX crossover as an illegal string would be produced because PMX crossover is only used with the real coding scheme.

A number of different GA models resulted from the various operators discussed above. For the simple example examined in this study, three GA models performed better than the others and will be used for the remaining studies. The best GA models found were:

1) T1 - continuous coding, one-point crossover, bit mutation and tournament selection
2) T5 - real coding, PMX crossover, adjacent swap mutation and tournament selection
3) T6 - real coding, PMX crossover, random swap mutation and tournament selection

These models will be tested further in Chapters 6, 7 and 8 to find the best GA model for each case study. In addition, the parameter values such as probability of mutation and crossover will also be investigated to obtain the best possible combination of GA parameter values. The parameter values used in the example in this chapter were, a population size of 100, p_c of 0.9 and p_m of 0.1 for string mutation and 0.05 for bit mutation. Investigation of the case studies will include evaluating the relative merits of string or bit mutation and identifying the best value of p_m to use.

The results so far of the selected GA models are encouraging. With the flexibility and efficiency demonstrated by the GA to solve various problems, it is considered that the GA will be able to successfully model the more complicated case studies to follow.

Chapter 6

Case Study 2 : The South-East Queensland System

6.1 Introduction

The case study described in this chapter allows the methodologies of Chapters 3 and 5 to be compared and an assessment made on how appropriate they are in solving water resources sequencing problems. The South-East Queensland System is an extension of the work completed on the Canberra Water Supply System in Chapter 4 which examined simply the sequencing of water resources projects. The South-East Queensland problem has a much larger number of future water resource options available and so a more difficult problem can be examined. When examining the sizing of a water resource project an additional scenario will be investigated. This is the possibility of increasing the size of projects once they are built. This process will be referred to as the upsizing of projects. This is examined as there is likely to be economic and perhaps environmental benefits involved with upsizing projects. The economic benefits are achieved through the discounting of costs while the environmental benefits will be obtained when a project is upsized rather than building another major dam. The use of upsizing of projects is not new however, as water authorities have in the past increased the heights of dams to increase the storage capacity of reservoirs. However, the decision to upsize a dam usually occurs some time in the future rather than at the initial planning stage of the dam. Thus it is the intention of this study to indicate the economic benefits of incorporating the upsizing of projects at the planning stage.

Another factor which is becoming increasingly popular is the effect of demand management on the sequencing of projects. This was studied in the Canberra case study and is also examined here. In this case the demand management is built into the future demand forecasts for the region and its effect on the size of a project can also be examined. The final study which will be undertaken is an investigation of the effect of price on the size and sequencing of projects. This will be applied in the same way as price was included in the Canberra case study. Thus, the same changes which were involved with including price in the Canberra case study are applied to this case.

A further investigation on the sensitivity of demand growth rate, discount rate and planning period will also be carried out in this case study. For the South-East Queensland system three demand forecasts have been made for the period 1990 to 2090 (Lane, 1991). In addition, to examine the effect of discount rate, various rates will be applied to the different cases. With the inclusion of the possibility of upsizing of projects an examination of the effect of the upsizing cost on the frequency of upsizing and ultimate size of projects sequenced will also be undertaken. The reason for this is that when a project is built, a substantial portion of the overall cost is the set up cost. Thus to assume that when a project is upsized that the upsizing cost will simply be the incremental cost will not be true as there will be a set up cost involved with the upsizing. Therefore, three upsizing costs were used to examine the effect of upsizing cost on the size and sequence of projects.

As mentioned the methodologies of Chapters 3 and 5 will be used for this case study. Of particular interest is the performance of the GA method in solving the problem being investigated. In particular, whether it will provide a better solution than that of the heuristic and integer/linear programming (ILP) methods. The heuristic methods utilised are the equivalent cost (EC) and unit cost (UC) methods discussed in Chapter 3. The reason for applying the GA to the sequencing problem is that the other methods used have various difficulties with different sequencing problems. It has already been shown in Chapter 4 that the unit cost method can not guarantee an optimal sequence. The reasons for this is that the discount rate and demand growth rate effect the sequencing of projects and the unit cost method does not consider these variables in the sequencing of projects. On the other hand it was seen in Chapter 4 that the equivalent cost method produced the best sequences and in fact an optimal sequence when the growth in demand is linear. However, the equivalent cost method will only provide a good solution when the demand is non-linear. In addition, in this study the factor of project size is incorporated and it is not known whether the equivalent cost method can effectively solve the size and sequencing problem.

In the case of the heuristic methods, an optimal solution cannot be guaranteed under all conditions, although the time taken to compute a sequence is small. However, the opposite is true for the ILP method where an optimal solution will always be produced for the problem specified, but it will take a considerable time even for a small problem. In fact, the computer time to produce the optimal sequence is the constricting factor in using ILP. Thus, discrete time periods and a smaller planning period are used to reduce the computation time. The number of time periods used in the investigation is 8 and each has a duration of 5 years. Thus, the demand is satisfied at the start of every 5 year interval, rather than at yearly intervals. If a greater number of periods were to be used, in an effort to provide more accurate results, the computer time required could be considerable (ie. months). In addition, the existing system yield is considerable and will satisfy demand for the 15 year period from 1990 to 2005 for the highest demand forecast and longer for the other demand forecasts. The ILP model will assume the initial year as the year 2005 rather than the year 1990, to account for the existing system yield. Thus the ILP model will investigate the 40 (8 by 5) year planning period following the year 2005. This results in a total planning period length of 55 years.

A method is required which can provide an optimal or near optimal solution while successfully incorporating the factors of discount rate, demand growth rate, planning period and sizing and upsizing of projects to the problem under investigation in a reasonable computation time. It is expected that the GA method may be successful in achieving this aim. The reasons are that the GA has been successfully applied to similar combinatorial problems, such as the travelling salesman problem and is expected to be considerably faster than the ILP method. Although, it will not be as quick in computation time as the heuristic methods it is expected to produce better results. Not only is it expected to produce better results it is expected that it will provide a number of good solutions for each problem, a point discussed in Chapter 5. As part of this study a number of variations to the GA will be examined with the best GA model being used for the size and sequencing problem. These variations have been discussed in Chapter 5 and will be discussed further in this chapter.

Another benefit of using a methodology such as the GA to size and sequencing water resource projects is that the size and sequencing decision are made in conjunction with each other. In the past the traditional approach to this problem is to size a reservoir based on system reliability and cost but not based on the size of other reservoirs which may be developed in the future. The sequence of reservoirs is then determined based on some economic criteria (eg. the unit cost of projects has been used in the past) as well as other factors. So in economic terms the lowest PVC solution may not be obtained as the decisions to what size to build the projects and the sequence are made separately. A true optimum solution requires the decisions on size and sequence to be made together.

The purpose of this chapter is to examine the sizing and sequencing problem and the various factors which influence this decision and to illustrate how the GA method can be successfully applied to solve this problem.

6.2 The South-East Queensland System

The South-East Queensland System covers an area of 24750 square kilometres with a population of approximately 1.76 million.

In South-East Queensland in order to supply the future demand of the region there are 16 proposed reservoir sites, 15 of these sites have three possible sizes. There are three demand growth rates indicated for the region which span the 100 year period of 1990 to 2090. The purpose of this study is to use the unit cost and the equivalent cost per period sequencing methods and the ILP technique detailed in Chapter 3 and the GA method outlined in Chapter 5 to obtain an optimal sequence for the South-East Queensland region.

The data used for this study are shown in Tables 6.1 and 6.2. The yields of individual projects were calculated using historical streamflow data (Lane, 1991) and it is assumed that the reservoir does not empty during the period of analysis. The costs in Table 6.1 include land acquisition, relocation of infrastructure and the capital cost of the reservoir.

For simplicity from herein when referring to a project the project number will appear first followed by the project size. For example project 8 size 2 will appear as 8/2. To simplify the problem the number of projects examined by the various methods is reduced to 9. This is thought not to affect the results, as the seven projects not used were found to be inferior in regard to cost and yield based on preliminary results of both the equivalent cost and unit cost methods. In addition, by inspection the projects had higher cost for lower yields than many of the alternatives examined. Those projects not examined further were projects 2, 3, 11, 12, 14, 15 and 16. Of these projects, only 2, 14 and 16 would have any chance of being sequenced. However they would only be sequenced as the last project, as these projects could provide a cheaper alternative that just satisfies demand during the planning period and therefore reduces the present value of costs.

Table 6.1 Project Cost and Yield for the South East Queensland Region (Water Resources Commission, 1991)

Project	Project Size	Cost ($Million)	Yield (GL/year)	Project	Project Size	Cost ($Million)	Yield (GL/year)
1	1	107.0	79.71	9	1	83.0	37.58
Kenilworth	2	123.0	98.60	Glendower	2	94.0	45.60
	3	139.0	105.5		3	104.0	54.27
2	1	63.0	9.875	10	1	97.0	27.29
Zillmans	2	72.0	12.22	Bega Hills	2	110.0	37.13
Crossing	3	80.0	13.68		3	126.0	44.60
3	1	164.0	9.230	11	1	184.0	43.00
Green-	2	182.0	14.71		2	225.0	59.00
wood	3	228.0	15.69		3	277.0	65.00
4	1	114.0	31.30	12	1	230.0	48.30
Peachester	2	120.0	36.40	Army	2	238.0	52.30
	3	127.0	42.40	Camp	3	249.0	54.60
5	1	83.0	7.000	13			
Linville	2	109.0	26.20	Hinze Dam	1	72.0	29.38
	3	134.0	64.40	Stage (3)			
6	1	309.0	110.1	14	1	74.0	12.86
Cedar	2	327.0	116.4	Neran-	2	101.0	15.72
Grove	3	350.0	122.3	wood	3	140.0	16.91
7	1	60.0	23.20	15	1	134.0	24.01
Tilleys	2	99.0	61.50	Ingleside	2	152.0	32.81
Bridge	3	119.0	70.05		3	177.0	35.21
8	1	54.0	23.53	16	1	80.0	16.05
Braford	2	61.0	48.70	Craigs	2	100.0	19.12
Hills	3	88.0	61.34	Crossing	3	124.0	20.46

Table 6.2 Demand Growth Projections (GL/Year) for the Period 1990 to 2090 for the South East Queensland region (Water Resources Commission, 1991)

Demand Forecast	1990	2010	2030	2050	2070	2090
1	337.70	440.00	547.10	614.60	661.80	706.40
2	337.70	550.00	683.90	768.20	827.30	883.00
3	337.70	473.80	612.40	728.10	814.40	895.90

Demand forecasts 1 and 2 are both based on mid range population growth. However, Demand forecast 1 has a lower estimate of demand because it includes a 20 % reduction in demand due to the implementation of demand management measures. Demand forecast 3 is calculated based on a high population growth. The period investigated in this study is the 100 year period 1990-2090 for the unit cost, equivalent cost and the GA methods and a forty year period from 2005 to 2045 for the ILP method. A discrete 5 year time interval is used for this last method. The growth in demand is assumed to be linear between the periods shown in Table 6.2. The demand growth rates to be used for each period are shown in Table 6.3.

Table 6.3 Demand Growth Rates (GL/Year) for the Three Demand Forecasts for the Period 1990 to 2090

Demand Forecast	Demand Growth rate (GL/year)				
	Period 1990-2010	Period 2010-2030	Period 2030-2050	Period 2050-2070	Period 2070-2090
1	5.12	5.36	3.38	2.36	2.23
2	10.62	6.70	4.22	2.96	2.79
3	6.80	6.94	5.80	4.30	4.20

For the purposes of this study the system yield in 1990 is assumed to equal 500 GL/year and the current demand will be assumed to be 337.7 GL/year (Water Resources Commission, 1991). The actual system yield is estimated to be 674 GL/year for no historical failures and 751 GL/year assuming a 1% probable monthly failure rate (PMFR). These yield estimates were not used in this study as only a small number of projects would be required for the 100 year planning period. Therefore, with only a few projects needed to satisfy demand for the planning period, it is unlikely significant conclusions regarding sizing and sequencing of projects would be obtained.

The discount rate will be varied to examine the effect it has on the sequencing of projects. The values to be used are 2.5, 5.0 and 10.0 %.

6.3 Models Utilised for the South-East Queensland Case Study

The models used in this study have been defined and discussed in Chapters 3 and 5. The models are unit cost sequencing, equivalent cost sequencing, ILP and the genetic algorithm. These models will be applied to the South-East Queensland problem so that the size and sequencing of projects can be obtained. For this study when examining the sizing question two situations will be examined These situations are where no upsizing of projects is allowed and where upsizing of projects is allowed. The term upsizing is defined in Chapter 3. In this case it is possible to upsize a project at a site twice as there are three possible sizes for a reservoir at a particular site. Therefore, the no upsizing case occurs when once a project is built at a particular site then no further development at that site can occur. The upsizing case allows for increasing the size of a project at a particular site until the maximum size for that site is reached. For the upsizing case, there is a cost associated with the upsizing of projects. This cost is considered to be dependent on the incremental cost associated with the increase in size of a project. A number of different costs are examined. The various costs for upsizing examined were 100 %, 120 % and 150 % of the incremental cost. The yield of larger projects will also change with the building of a smaller project. The yield of a larger project will simply be the incremental yield of that project (ie. the difference in yield between the two sizes of project).

For the unit cost and equivalent cost methods, after a project at a particular site is built, the larger projects at that site will have their incremental yields and incremental costs determined as discussed above. The alteration to the yield and cost of projects will then change the unit cost and equivalent cost for the projects in question, which will change the sequencing of the projects. The same applies for the ILP and the genetic algorithm methods. For the genetic algorithm method, three different GAs have been identified which could be used for this study. However, rather than using all three methods, a sensitivity analysis will be performed on the three GA models and the model parameters to identify the best GA model for the situations to be examined. The results of this sensitivity analysis are illustrated in Appendices J and K.

The three GA models used in the sensitivity analysis were Models T1, T5 and T6 from Chapter 5. The sensitivity analysis of the GA models involved trying to identify the best mutation rate and mutation operator to use for the study of the South-East Queensland System. Two mutation operators were examined. These were bit and string mutation which are detailed in Chapter 5. A number of different values of probability of mutation were examined for each operator. The various operators examined were applied to a number of cases which exist in the South-East Queensland case study. Thus, the results of these cases should provide an indication of which is the best GA model, mutation operator and rate to use.

The results of this sensitivity analysis indicate that Model T1 was the best model. This GA model uses continuous coding and the standard crossover and mutation operators. For the various cases of upsizing and no upsizing the best results were found for a mutation rate of 3 %. However, for the upsizing case a mutation rate of 1 % also performed well.

Once the mutation operator and rate were examined a small study on the parameter values of the probability of crossover and the random seed was performed. This was undertaken to investigate the effect these parameters on the GA performance. Also as a result of the sensitivity analysis and this parametric study a new coding was developed for the no upsizing case. However, the parametric study will be discussed first.

The study of varying the probability of crossover produced a similar result to that when the mutation rate was varied. At high probability, the strings in a generation would change rapidly and the chance of losing the best solution in the generation was increased. However, for the lower crossover probabilities some strings did not vary which resulted in a slower convergence to a solution. Thus, it was decided that a relatively high probability of crossover of 0.9 would be used in the remainder of this study so there is adequate mixing in the GA process.

The random seed was tested several times to see whether the random number sequence (RNS) influenced the solution. It was found that on all occasions the same result was obtained and the RNS had no effect. For one particular case, 9 different seeds (ie. 0.1, 0.2, 0.3, ..., 0.9) were used and the same solution was obtained. The case in question was demand forecast 3 and a discount rate of 5 %. However, it was decided that the seed should be varied in all cases so that it can be shown that the RNS will not affect the results. In the model utilised further in this study, three runs will be undertaken and each run will have a different seed.

The results of the sensitivity analysis which indicate that the Model T1 be used in the study, lead to the development of a new coding and new model. The model uses a continuous coding however its values range between 1.0000 to 3.9999. The real number represents the size and project order and the positioning in the string represents the project number. The size of the project is given by the number to the left of the decimal point and the project order is determined by the number to the right of the decimal point. The project order is the same as described in Chapter 5 for Model T1. To help explain this technique consider the following string:

3.298, **1**.876, **2**.421, **2**.567

This string will be decoded as 2/1, 4/2, 3/2 and 1/3, where 2/1 represents project 2 at size 1. The benefit of this string is that it does not require as many bits to describe the same problem as previously. However, this still is only beneficial in the no upsizing case, as for the upsizing case such a string would be harder to decipher than that previously developed. This model was also used on the problem of no upsizing. The parameters used for this model were a population size of 80, 100 generations and probability of mutation and crossover were 8% and 90 % respectively. The results obtained when using this coding were the same as Model T1, although on some occasions (4 out of 27 runs) a slightly higher PVC was obtained. The generation of the bit value was achieved by randomly generating an integer between 1 and 3 and a real number between 0.0000 and 0.9999 and adding the two values together.

The last point to discuss is that regarding the decoding of the string for the size and sequencing problem. As can be appreciated a smaller project at a site cannot come after a larger project at the same site. Thus, if this occurs the bit associated with the smaller project will not be read and therefore its value will not have any bearing on the evaluation of the string fitness. In the case of only one size being built at a site (ie. no upsizing allowed) once a project is built at that site all subsequent projects are ignored and their bit value does not contribute to the string fitness evaluation. One problem which this causes is associated with the mutation rate. Under normal condition the mutation of a bit will affect the string fitness however, in the problems examined here, mutation may not affect the string fitness. To overcome this the mutation rate needs to be slightly larger than that specified for a string where all bits contribute to the fitness evaluation. What effectively happens is that there is an effective length of the string, l_e, which is less than lchrom, the actual string length, and therefore p_m will be more likely to be equal to or less than $1/l_e$ rather than 1/lchrom. The result is that a larger value of p_m

than would be determined using the theoretical range specified in the literature will provide better results.

Therefore, for the South-East Queensland case study the GA used will be Model T1 with a population size of 100, probability of crossover and mutation of 90 % and 3 % respectively and 200 generations will utilised, which should provide enough evaluations to find a good solution. These GA parameters will apply for both the no upsizing and upsizing cases.

6.4 Results

6.4.1 No Project Upsizing Allowed

Now that the study has been described and the various models defined, the first section to be investigated for the South-East Queensland problem is when upsizing of reservoirs is not possible. The results are displayed so that the various methods are compared directly. The results for demand forecast 1 for the three discount rates used, for the various methods are shown in Tables 6.4 to 6.6. The PVC in the following tables is in $ million, with the times of 55 and 100 years referring to the planning period used for that case.

Table 6.4 Results for the Various Models for a Discount Rate of 2.5 % and Demand Forecast 1

Method	Project Sequencing and Timing					PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2			
	Timing	31	55	73		89.22	57.21
Equivalent Cost	Project	1/2	8/2	7/2			
	Timing	31	55	73		89.22	57.21
GA (100 years)	Project	1/2	8/2	7/2			
	Timing	31	56	73		89.22	57.21
ILP (55 years)	Project	1/2					
	Timing	30				-	58.64
GA (55 years)	Project	1/2					
	Timing	31				-	57.21

Table 6.5 Results for the Various Models for a Discount Rate of 5 % and Demand Forecast 1

Method	Project Sequencing and Timing					PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2			
	Timing	31	55	73		34.08	27.10
Equivalent Cost	Project	8/2	1/1	7/2	9/1		
	Timing	31	40	65	92	33.60	28.60
GA (100 years)	Project	8/2	1/1	7/2	9/1		
	Timing	31	40	65	92	33.60	28.60
ILP (55 years)	Project	8/2	7/2				
	Timing	30	40			-	28.18
GA (55 years)	Project	1/2					
	Timing	31				-	27.10

Table 6.6 Results for the Various Models for a Discount Rate of 10 % and Demand Forecast 1

Method	Project Sequencing and Timing						PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2				
	Timing	31	55	73			6.83	6.41
Equivalent Cost	Project	8/2	1/1	7/1	13/1	9/1		
	Timing	31	40	65	75	88	5.74	5.54
GA (100 years)	Project	8/2	1/1	7/1	13/1	9/1		
	Timing	31	35	65	75	88	5.74	5.54
ILP (55 years)	Project	8/2	7/2					
	Timing	30	40				-	5.68
GA (55 years)	Project	8/2	7/2					
	Timing	31	40				-	5.37

The timing value in the Tables represents the number of years of demand growth from the initial year (1990) before the project is required. For example, for the unit cost sequences in the above tables, the value of 31 years indicates that the existing system yield will supply demand for 31 years. Alternatively, the timing value could be written to indicate the year in which the project needs to be built. For the example mentioned, the existing system yield will supply demand for a full 31 years but during the 32nd year, project 1/2 is required so that demand is satisfied for the remainder of that year. Thus, project 1/2 will actually be built at the start of year 32 and project 8/2 will be built at the start of year 56. The reason for showing the timing value with regard to the number of years demand is supplied before a project is required, is that this is what is used to calculate the PVC. So discounting of project cost is assumed to occur at the end of a year. Thus following this reasoning, the project 8/2 for the unit cost sequence will not be included in the PVC for the 55 year planning period, as project 1/2 will satisfy demand past the end of the 55th year. Therefore, projects which are sequences before the year 55, will be included in the calculation of the PVC for the 55 year planning period (projects left of the bold line in the tables).

The ILP method sequence is only for a 55 year planning period. The 100 year planning period is not examined, as extremely long run times are experienced for the smaller planning period for the ILP method. Thus, a longer planning period will increase the time required to obtain a solution. For comparative reasons, the PVC for a 55 year planning period for the unit cost, the equivalent cost and the GA sequences, is also calculated, based on the sequence obtained for the 100 year planning period. As mentioned above, projects which are sequenced prior to the year 55 in the Tables, are included in the calculation of PVC. In addition, the GA model is also run for the 55 year planning period which is the solution given in last two rows of the tables. This is done as the shorter planning period is likely to affect the project sequence, especially the last project sequenced.

For demand forecast 1, for the 100 year planning period, the equivalent cost and GA methods produce the lowest cost solution for all discount rates. For the 2.5 % discount rate, the unit cost method also produces the same result. However, as discount rate increases the unit cost method produces a higher PVC sequence. The actual sequence of the equivalent cost and GA method change when discount rate is changed, while the unit cost sequence does not.

For the 55 year planning period, the sequences produced by all methods are the same for the discount rate of 2.5 % . However, due to discrete time periods in the ILP model the PVC is slightly higher as project 1/2 is expanded at year 30 rather than year 31. For the 5 % discount rate, the unit cost method and the GA run for the 55 year planning period, produced the lowest PVC solution. In this case, the GA model produced two different sequences for the different planning periods. This highlights a problems which may be experienced with selecting a suitable planning periods. A further result to discuss for this case is the difference between the ILP and the GA sequence. On calculating the PVC for the ILP model for a continuous time period, it is found that the sequence produced by the GA and the unit cost method, produces a lower PVC. However, when the GA and unit cost sequences are calculated based on discrete time periods, the ILP sequence produces the lower PVC. This indicates that the use of discrete or continuous time periods can affect the sequences obtained. The most realistic time period to use is the continuous time period. Thus using discrete time period should be avoided where possible because of the above results and provides an argument against ILP for the problem under examination.

For the 10 % discount rate, the best sequence was produced by the GA run for the 55 year planning period and the ILP model. In this case the use of discrete and continuous time periods does not seem to effect the sequencing of projects. With the increase in discount rate the unit cost sequence has gone from the best to the worst as it does not consider the change in discount rate. The sequences produced by the GA model for the different planning periods are different. This indicates that while a sequence may be optimal for one planning period, it may not be necessarily be the optimum sequence for another planning period.

A brief note regarding the ILP model needs to be made at this stage. As mentioned previously, the ILP method is a time consuming process. As a result the discrete time periods and a smaller planning period than the 100 years used for the other methods are utilised to reduce the computation time for the ILP model. However, even with these simplifications the method still takes considerable computer time to run. In an effort to improve this computation time the number of projects examined by the method was reduced to only four. The projects included in the model were projects 1, 7, 8 and 9. This simplification is not expected to lead to sub optimum results. The reason for this conclusion is that with the smaller planning period, even at the highest demand forecast, only three of these projects will be required. In addition, based on the cost estimates and yield values for these projects, those projects not examined appear inferior to the projects examined. The only case in which the sequence produced by the ILP model using just these four projects, may be non optimal, for the planning period being investigate, is if a better project exists which just satisfies demand at the end of the period. However, on inspection of the various cases and the other projects cost and yields this situation does not appear to be a possibility. If the planning period was slightly longer however, this situation may arise. Thus the projects of 1, 7, 8 and 9 will be the only projects involved in the sequencing of projects when using the ILP method.

The above results indicate that the discount rate will affect the sequence of projects. As the discount rate increases the sequence changes for the equivalent cost, ILP and GA methods. The unit cost method sequence does not change as the selection of projects by this method is independent of discount rate. The result was the unit cost method produces higher PVC than the other methods. Thus the ability of the other methods to incorporate the discount rate in the sequence of projects leads to better results than if the discount rate is ignored when sequencing projects. It appears that as discount rate increases, smaller less costly projects are sequenced before larger, more costly projects. This is concluded as project 8/2 is sequenced before project 1 at the higher discount rates and additionally at the 10 % discount rate project 7/1 is sequenced rather than project 7/2 as occurs for the 2.5 and 5 % discount rate cases. This results in the likelihood that more projects of smaller size will be sequenced as the discount rate increases (ie. Table 6.6). The reason for this is that using smaller projects results in a lower PVC and using more smaller projects is an advantage as the scheduling of future projects is delayed. Therefore, the discounting of the projects cost is increased. Therefore the result is a lower PVC.

The next set of results to examine are for the case of demand forecast 2. These results for the various methods and discount rates are displayed in Tables 6.7 to 6.9.

Table 6.7 Results for the Various Models for a Discount Rate of 2.5 % and Demand Forecast 2

Method	Project Sequencing and Timing								PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1		
	Timing	15	27	34	45	58	79	90	268.95	193.24
Equivalent Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	10/3		
	Timing	15	27	34	45	58	79	90	249.12	193.24
GA (100 years)	Project	1/2	8/2	7/2	9/3	13/1	5/3	10/1		
	Timing	15	27	34	45	58	68	90	245.94	193.24
ILP (55 years)	Project	1/2	7/2	8/2	9/2					
	Timing	15	25	35	45				-	194.97
GA (55 years)	Project	1/2	8/2	7/2	9/2					
	Timing	15	27	34	45				-	189.95

Table 6.8 Results for the Various Models for a Discount Rate of 5 % and Demand Forecast 2

Method	Project Sequencing and Timing								PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1		
	Timing	15	27	34	45	58	79	90	119.19	105.92
Equivalent Cost	Project	1/2	8/2	7/2	9/3	13/1	5/3	10/2		
	Timing	15	27	34	45	58	68	90	116.39	105.92
GA (100 years)	Project	1/2	8/2	7/2	9/3	13/1	5/3	10/1		
	Timing	15	27	34	45	58	68	90	116.23	105.92
ILP (55 years)	Project	1/2	7/2	8/2	9/2					
	Timing	15	25	35	45				-	109.92
GA (55 years)	Project	1/2	8/2	7/2	9/2					
	Timing	15	27	34	45				-	104.81

Table 6.9 Results for the Various Models for a Discount Rate of 10 % and Demand Forecast 2

Method	Project Sequencing and Timing									PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1			
	Timing	15	27	34	45	58	79	90		40.03	39.40
Equivalent Cost	Project	8/2	1/1	7/2	9/1	13/1	5/3	10/2	4/3		
	Timing	15	19	31	41	50	57	77	91	40.22	39.54
GA (100 years)	Project	1/2	8/2	7/2	9/3	13/1	5/3	10/1			
	Timing	15	27	34	45	58	68	90		39.91	39.40
ILP (55 years)	Project	1/2	8/2	7/2	9/2						
	Timing	15	25	30	45					-	42.04
GA (55 years)	Project	1/2	8/2	7/2	9/2						
	Timing	15	27	34	45					-	39.26

In the above cases the GA method provided the lowest PVC solution on all occasions. For the 100 year planning period the GA produces similar sequences to the unit cost and equivalent cost methods. The differences are that for the 2.5 % discount rate the GA sequences project 5 before project 13, the unit cost sequences the more expensive project 6 and the GA uses a small size of project 10 as the last project sequenced. These results alone indicate the problem experienced with the unit and equivalent cost methods when sequencing for a finite planning period. The project sequence for the AG and equivalent cost methods are nearly the same for the 5 and 10 % discount rates. The difference is the use of different sizes of projects in the sequences produced and also for the 10% discount rate the equivalent cost method sequences project 8 prior to project 1. The differences between the equivalent cost and GA methods indicates that there is no guarantee the former method will produce an optimum sequence when a finite planning period and non-linear growth over that planning period are used.

When the PVC for the unit cost, equivalent cost and GA method sequences are calculated for a 55 year planning period it was found the sequence produced by the ILP method provides the optimum solution given the utilisation of a discrete time period. However, for a continuous time scale the sequence given by the ILP method will not provide the lowest PVC for the 55 year planning period and for the discount rates of 2.5 and 5 %. Alternatively neither does any of the other methods. The other methods do not achieve the lowest PVC solution as they are either sequencing over a infinite planning period (ie. unit and equivalent cost methods) or the result shown is for the 100 year planning period (ie. GA method). These situations lead to a larger project being sequenced than is necessary for the 55 year planning period.

For the GA for the 55 year planning period, a different sequence is produced to that of the ILP method for the 2.5 and 5 % discount rate cases. The solution found produces a lower PVC than the ILP solution for a continuous time scale. However. the reverse is true if a discrete time scale is assumed. This result, as well as the ILP result illustrate the difficult in selecting a suitable planning period so that it does not interfere with the sequence produced. For example, for the 55 year planning period project 9/2 is sequenced by the GA and ILP methods. This project will just satisfy the demand requirements for the 55 year planning period. However, the unit cost and equivalent cost methods sequences 9/3 instead. This project will also satisfy demand but at a higher cost and therefore a higher PVC results. So therefore the selection of the planning period can alter the sequences obtained. In addition, this problem with planning period selection has a more dramatic effect on the equivalent and unit cost methods. The reason is that these methods sequence projects based on the principle that all projects will be sequenced eventually. However, when examining a specified planning period this may not be the case. Thus what will tend to happen is that both methods may sequence projects that are not the best options for satisfying demand as far as producing the lowest PVC for that planning period. This is indicated by the sequencing of project 9/3 for the 55 and 100 year planning periods rather than selecting 9/2 instead of 9/3 for the 55 year planning period. This problem will not be experienced by the GA or the ILP method as both methods account for the planning period when sequencing projects.

This issue of using a finite period may be the reason why the unit cost method provides a lower PVC than the equivalent cost method for a 10 % discount rate. This is an unusual result as it is generally expected that the equivalent cost method should provide lower PVC sequences than the unit cost method. The reason for this assertion is that it has been shown that the discount rate and demand growth rate will play a part in the sequencing projects and the equivalent cost method considers both these factors. Therefore, it is expected that if a longer planning period is used, the equivalent cost method would give a lower PVC solution than the unit cost method.

As far as the discount rate is concerned there was no change in sequence for the GA results. However, there is a change to the sequences obtained using the equivalent cost and ILP methods. The result of the ILP method indicates the discount rate will have an effect on the optimum sequence of projects as the ILP method will produce the optimum sequence when using discrete time periods. This can not be concluded for the sequences produced by the equivalent cost method as they are not optimal. In fact for the 10 % discount rate, the sequence produced has a higher PVC than that of the unit cost sequence. However, it is evident that the discount rate will effect the sequence produced by the equivalent cost method.

In regard to the equivalent cost sequencing method it appears that as the discount rate increases more projects with lower cost and smaller size are preferred in the sequencing of projects. This is the same as previously experienced in the results for demand forecast 1.

The final set of results for the no upsizing of projects case is for demand forecast 3. The results for the three different discount rates and the various models are displayed in Tables 6.10 to 6.12.

Table 6.10 Results for the Various Models for a Discount Rate of 2.5 % and Demand Forecast 3

Method	Project Sequencing and Timing								PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1		
	Timing	23	38	46	56	68	83	90	219.21	125.37
Equivalent Cost	Project	8/2	1/2	7/2	9/3	5/3	13/1	10/3		
	Timing	23	30	46	56	68	83	90	199.02	125.00
GA (100 years)	Project	8/2	1/2	7/2	9/3	5/3	13/1	10/3		
	Timing	23	30	46	56	68	83	90	199.02	125.00
ILP (55 years)	Project	8/2	1/2	7/2						
	Timing	20	30	45					-	128.45
GA (55 years)	Project	8/2	1/2	7/2						
	Timing	23	30	46					-	125.00

Table 6.11 Results for the Various Models for a Discount Rate of 5 % and Demand Forecast 3

Method	Project Sequencing and Timing								PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1		
	Timing	23	38	46	56	68	83	90	76.80	60.09
Equivalent Cost	Project	8/2	1/2	7/2	9/3	13/1	5/3	10/3		
	Timing	23	30	46	56	68	74	90	73.37	58.81
GA (100 years)	Project	8/2	1/2	7/2	9/3	5/3	13/1	10/3		
	Timing	23	30	46	56	68	83	90	73.25	58.81
ILP (55 years)	Project	8/2	1/2	7/2						
	Timing	20	30	45					-	62.47
GA (55 years)	Project	8/2	1/2	7/2						
	Timing	23	30	46					-	58.81

Table 6.12 Results for the Various Models for a Discount Rate of 10 % and Demand Forecast 3

Method	Project Sequencing and Timing									PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1			
	Timing	23	38	46	56	68	83	90		17.39	16.60
Equivalent Cost	Project	8/2	1/1	7/2	9/3	13/1	5/3	10/2	4/3		
	Timing	23	30	42	53	63	70	85	94	15.82	15.42
GA (100 years)	Project	8/2	1/1	7/2	9/3	13/1	5/3	10/2	4/1		
	Timing	23	30	42	53	63	70	85	94	15.81	15.42
ILP (55 years)	Project	8/2	1/2	7/2							
	Timing	20	30	45						-	17.47
GA (55 years)	Project	8/2	1/2	7/2							
	Timing	23	30	46						-	15.10

The GA method again produced the lowest PVC sequence for the 100 year planning period for the cases illustrated in Tables 6.10 to 6.12. The equivalent cost method produced the next lowest PVC sequences and in the case of 2.5 % discount rate produced the same sequence as the GA method. For the high discount rate cases the equivalent cost sequence had a slightly higher PVC. For the 5 % discount rate case, two projects are reversed in the order of projects which results in the higher PVC. This is a result of using the equivalent cost method for non-linear demand growths, where the method cannot guarantee an optimum solution. However, for the 10 % discount rate case the difference between the equivalent cost and GA sequence is a result of using a finite planning period. This problem was mentioned previously and here it can be seen that the equivalent cost method sequences 4/3 at year 94, whereas the GA sequences 4/1 which satisfies demand at a lower cost. In all cases the unit cost sequence produced a higher PVC than the other methods.

In regard to the ILP method and a 55 year planning period, the equivalent cost and GA sequence for the 2.5 % and 5 % cases are the same as the ILP sequence. However, the PVC for the ILP is higher due to using discrete time periods. For the 10 % discount rate case, the equivalent cost and GA sequence shown, gives a higher PVC for a 55 year planning period than the sequences obtained by ILP model no matter if a continuous or discrete time period is used. For the GA run using a 55 year planning period, the sequence obtained is the same as for that found for the ILP method, for all discount rates. This sequence provides a lower PVC for the 55 year planning period, than the sequence obtained by the GA for the 100 year planning period and a 10 % discount rate. This indicates the importance of selecting a suitable planning period when examining the sequencing problem, as a different project sequence may provide the lowest PVC for a particular planning period.

With regard to changing sequence with variations in the discount rate, the same conclusions as were previous made apply to these cases. The results of the GA and equivalent cost methods indicate that as the discount rate increases smaller projects are more likely to be sequenced. For instance, as discount rate increases from 5 to 10 % for the GA method, projects 13/1 and 5/3 are reversed, with the smaller project 13/1 appearing first in the sequence and projects 1/2 and 10/3 are replaced by the smaller projects 1/1 and 10/2 at the higher discount rate. This last occurrence also occurs in the equivalent cost sequence when going from a discount rates of 5 % to 10 %.

A further observation can be made with regard to the alteration of the sequence for various demand growth rates. If the unit cost method sequence is disregarded as it does not considered demand growth rate then there is a definite change in sequence for different demand growth rates. A general conclusion is difficult to make as the three demand growths are non-linear and cannot be defined as low, high or otherwise. If anything, demand forecast 1 could be considered to be a low estimate however, demand forecasts 2 and 3 are hard to separate into different categories. In addition, if the first 60 years are considered then demand forecast 2 would be a high demand growth and demand forecast 3 would be a medium demand growth. Using these categories however, the projects sequenced would be {1, 8} for the GA method for the low and high demand growth cases and {8, 1} for the medium demand growth for a discount rate of 2.5 %. This pattern changes for the discount rates of 5 and 10 % where projects {8, 1} are sequenced for the low and medium demand growth cases and the reverse is true for the high demand growth case. What can be said though is that the sequence of projects does depend on both the discount rate and demand growth rate and to use a sequencing procedure which does not included these variables in the decision process (ie. unit cost method) will, in general, provide inferior results. The variation of sequence with demand growth rate appears also to depend on the project's cost and yield being utilised. This is concluded because of the results found when a discount rate of 2.5 % was used for the various demand forecasts.

With regard to the sequence produced, the equivalent cost, genetic algorithm and ILP methods, sequence the same first project on all occasions. Whereas the unit cost method always sequences the same project first regardless of the demand growth or discount rate. The first project is either 1/2 or 8/2 depending on the discount rate and demand growth rate. All of the methods sequence projects 1, 7, 8 and 9 as the first four projects with the order varying with sequencing method and the discount rate and demand growth rate. The only exception to this is for demand forecast 1 and a discount rate of 10 % for the GA and equivalent cost methods. In this case project 13/1 appears before project 9/1 in the sequence. It is likely that projects 1 and 8 will be the first projects followed by project 7 and then project 9.

The results found for this study favour the use of genetic algorithm for this problem. In all cases, it produced the lowest PVC and although it cannot be certain that these are optimal results, it is considered that the results are optimal or near optimal. Other reasons for the favouring the genetic algorithm technique are that it does not have the problems associated with the finite planning period of the equivalent cost and unit cost methods or the limitation placed on the ILP formulation of fixed 5 year time periods. Also it is likely the best solutions will be obtained when discount rate, demand growth rate, planning period and project yield and cost are incorporated within the sequencing decision, as they are in the GA method. The method not only produces the lowest PVC result but on an examination of the solution path will produce many solutions which are close to the lowest PVC obtained. Although the genetic algorithm is considerably more complex and requires more time to obtain a solution than the equivalent cost and unit cost methods, the production of many near-optimal results by the genetic algorithm is considered equally as important if not more important than the time to run the models. To clarify this last statement the equivalent cost and unit cost methods took approximately 1 to 2 seconds to run, the ILP method took from 40 minutes to 40 hours (depending on the demand forecast) and the genetic algorithm took approximately 200 seconds to produce a solution. The unit cost, the equivalent cost and the ILP methods were run on a DECstation 5000/240 computer and the GA was run on a personal computer (80486 with a clock speed of 33 MHz). The extra time taken by the genetic algorithm is not considered to be excessive considering the results it obtains.

Of the other methods used, the equivalent cost method is considered the better method. In fact if a water authority was after only an approximate sequence then the equivalent cost method would be a better method to use than the GA. The reason is its simplicity and the fact that it obtains sequences which are close to the optimum value of PVC (eg. within 1.28 % for the cases examined). In the case when the PVC obtained is not the optimum, the sequence produced by the equivalent cost method is similar to the optimum sequence. In addition, if the demand growth rate is linear the equivalent cost method will produce the optimum sequence. Thus, the equivalent cost method is more likely to be used in engineering practice.

It must be also mentioned that throughout this thesis the future demand are assumed to be known precisely. When forecasting demand various assumptions and approximations are made to achieve what is considered to be a reliable forecast. However, it is unlikely that the actual demand growth will follow any one of the forecasts. Thus, using three demand forecasts, enables the sensitivity of the optimum sequence to change in the demand forecast to be examined. In practice, although planning may occur over a 30-100 year planning horizon, the water authority is only interested in the implementation of the first project. After this, the water authority should reassess the situation at regular intervals (eg. every 5 to 10 years).

Before the upsizing case is examined, another small study was undertaken to examine the benefits of considering the sizing and sequencing problem, as a single problem. This was achieved by using the unit cost method to select the best sizes of projects and then using the equivalent cost method to sequence the projects. This was performed using the three demand forecasts and the discount rates of 5 and 10 % for the 100 year planning period. The results are shown in Tables 6.13 and 6.14 for the 5 and 10 % discount rate respectively and are compared with the corresponding solutions found using the equivalent cost method.

Table 6.13 Results of Using a Hybrid Method for the Sizing and Sequencing of Projects for a 5 % Discount Rate

Demand Forecast	Method	Project Sequencing and Timing								PVC (100 years)
1	Hybrid	Project	1/2	8/2	7/2					
	Method	Timing	31	55	73					33.72
1	Equivalent	Project	1/2	8/2	7/2					
	Cost	Timing	31	55	73					33.72
2	Hybrid	Project	1/2	8/2	7/2	9/3	13/1	5/3	10/3	
	Method	Timing	15	27	34	45	58	68	90	116.59
2	Equivalent	Project	1/2	8/2	7/2	9/3	13/1	5/3	10/2	
	Cost	Timing	15	27	34	45	58	68	90	116.39
3	Hybrid	Project	8/2	1/2	7/2	9/3	13/1	5/3	10/3	
	Method	Timing	23	30	46	56	68	74	90	73.37
3	Equivalent	Project	8/2	1/2	7/2	9/3	13/1	5/3	10/3	
	Cost	Timing	23	30	46	56	68	74	90	73.37

Table 6.14 Results of Using a Hybrid Method for the Sizing and Sequencing of Projects for a 10 % Discount Rate

Demand Forecast	Method	Project Sequencing and Timing									PVC (100 years)
1	Hybrid Method	Project	8/2	7/2	13/1	9/3	1/2				
		Timing	31	40	58	70	94				5.80
1	Equivalent Cost	Project	8/2	1/1	7/1	13/1	9/1				
		Timing	31	40	65	75	88				5.74
2	Hybrid Method	Project	8/2	1/2	7/2	9/3	13/1	5/3	10/3		
		Timing	15	19	31	41	50	57	77		40.53
2	Equivalent Cost	Project	8/2	1/1	7/2	9/1	13/1	5/3	10/2	4/3	
		Timing	15	19	31	41	50	57	77	91	40.22
3	Hybrid Method	Project	8/2	1/2	7/2	9/3	13/1	5/3	10/3		
		Timing	23	30	46	56	68	74	90		15.85
3	Equivalent Cost	Project	8/2	1/1	7/2	9/3	13/1	5/3	10/2	4/3	
		Timing	23	30	42	53	63	70	85	94	15.82

As can be seen in Tables 6.13 and 6.14 the examination of the sizing and sequencing problem as separate problems can result in inferior sequences and higher PVC solutions. Although the differences are rather small for this example. This is most evident with the results in Table 6.14 where the equivalent cost produces a lower PVC sequence for all the demand forecasts. In these cases, the main change between sequences is due to larger projects being sequenced by the hybrid method. However, for the demand forecast 1 there is also a considerable variation in the sequence produced by both methods. Thus, it is clear the determination of the sizing and sequencing of projects should be considered in conjunction with each other rather than as separate problems.

The next section examines the possibility of allowing a project at a particular site to be increased in size at a later time, for a particular cost. This is termed project upsizing and there is expected to be some benefit through a reduction in PVC from allowing this to happen, provided the upsizing cost is not too prohibitive.

6.4.2 Project Upsizing Allowed

As previously discussed in Chapter 3 the benefits in upsizing existing projects is through reducing the PVC which may be incurred if the project is initially built to the larger sizes. Associated with the upsizing of a project is an upsizing cost. The actual value of this cost will vary from situation to situation with the type of existing dam structure being an important factor in the upsizing cost. For this study three upsizing costs will be investigated to provide an understanding on the possibility of upsizing at various costs. The three costs have been previously defined and are 100 %, 120 % and 150 % of the difference in initial cost between the two dam sizes.

The different upsizing cost cases are examined using the unit cost and equivalent cost methods. For the unit cost method the projects are sequenced based on their unit cost. This method is discussed in Chapter 3. Thus, the best size of a particular project is sequenced, based on its unit cost. If larger sizes of the projects exist, then the yields and costs of these projects are adjusted and the larger sizes of the projects are sequenced. The same occurs for the equivalent cost method, however as this method uses the demand growth rate and discount rate, the projects are sequenced one at a time. So the amount of time the projects will satisfy demand is calculated and their equivalent cost determined. The project with the lowest equivalent cost is the project which is sequenced. The yield and cost of any larger sizes of the sequenced project are then adjusted. The time the remaining projects will satisfy demand is calculated, their equivalent cost is determined and the next project is sequenced. Both processes continue until enough projects are sequenced so the demand is satisfied for the planning period being examined.

The first results to examine are for the demand forecast 1 and a discount rate of 2.5 %. Tables 6.15 to 6.17 compare the models used for this case and the variation in sequence as upsizing cost increases.

The benefits associated with upsizing can be seen in Tables 6.15 to 6.17 when the results of the unit cost and equivalent cost methods are compared to the GA methods results. In the three cases the same projects are sequenced to the same size over the 100 year planning period. However, the GA method upsizes all projects whereas the other methods upsize no projects. The result is a lower PVC when using upsizing. The benefits of upsizing are more when the upsizing cost is lower which can be seen if the results of Tables 6.15 and 6.17 are compared.

Table 6.15 Project Sequence for Demand Forecast 1, Discount Rate of 2.5 % and Upsizing Cost Equal to the Incremental Cost

Method	Project Sequencing and Timing							PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2					
	Timing	31	55	73				89.22	57.21
Equivalent Cost	Project	1/2	8/2	7/2					
	Timing	31	55	73				89.22	57.21
GA (100 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2		
	Timing	31	49	55	63	73	83	84.82	54.84
ILP (55 years)	Project	1/1	1/2						
	Timing	30	45					-	56.28
GA (55 years)	Project	1/1	1/2						
	Timing	31	49					-	54.84

Table 6.16 Project Sequence for Demand Forecast 1, Discount Rate of 2.5 % and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing							PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2					
	Timing	31	55	73				89.22	57.21
Equivalent Cost	Project	1/2	8/2	7/2					
	Timing	31	55	73				89.22	57.21
GA (100 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2		
	Timing	31	49	55	63	73	83	87.07	55.37
ILP (55 years)	Project	1/1	1/2						
	Timing	30	45					-	57.33
GA (55 years)	Project	1/1	1/2						
	Timing	31	49					-	55.37

Table 6.17 Project Sequence for Demand Forecast 1, Discount Rate of 2.5 % and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing							PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2					
	Timing	31	55	73				89.22	57.21
Equivalent Cost	Project	1/2	8/2	7/2					
	Timing	31	55	73				89.22	57.21
GA (100 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2		
	Timing	31	49	55	63	73	83	88.93	56.92
ILP (55 years)	Project	1/2							
	Timing	30						-	58.64
GA (55 years)	Project	1/1	1/2						
	Timing	31	49					-	56.92

For the 55 year planning period and comparing all the methods again it was apparent that using upsizing would provide the lower PVC solution. However, the ILP result for the largest upsizing cost would indicate that upsizing does not lower the PVC. But this result of no upsizing is brought about by the discrete time periods within the ILP method and if the PVC is calculated for the GA sequence which still upsizes project 1 a lower PVC solution is found for the continuous time scale. If the discrete time scale is used then the lowest PVC is when no upsizing occurs.

On all occasions the GA method provides the lowest PVC sequence. This is mainly due to the GA method making use of upsizing to lower the PVC. The methods of equivalent cost and unit cost were not developed to specifically consider the possibility of upsizing and they do not favour upsizing in this case. The GA and ILP methods however are more flexible and examine more of the solution space and incorporate upsizing of projects. Thus it would seem that heuristics like the unit cost and equivalent cost methods are not suitable for solving the upsizing problem and a method which is more flexible and examines more of the solution space should be used for this case. However, the unit cost and equivalent cost methods do provide the same sequence of projects as the other methods. Therefore, if the possibility of upsizing is examined for the sequence produced by these methods then this may provide a lower PVC solution.

The next step is to increase the discount rate and examine if the upsizing of projects is altered when upsizing cost increases. Thus the case of demand forecast 1 and discount rate 5 % is examined in Tables 6.18 to 6.20.

Table 6.18 Project Sequence for Demand Forecast 1, Discount Rate of 5 % and Upsizing Cost Equal to the Incremental Cost

Method	Project Sequencing and Timing							PVC (100 years)	PVC (55 years)
Unit	Project	1/2	8/2	7/2					
Cost	Timing	31	55	73				34.08	27.10
Equivalent	Project	8/2	1/1	1/2	8/3	1/3	7/2		
Cost	Timing	31	40	65	73	79	82	32.23	28.60
GA	Project	8/1	8/2	1/1	1/2	7/1	7/2		
(100 years)	Timing	31	35	40	65	73	83	31.42	28.37
ILP	Project	1/1	1/2						
(55 years)	Timing	30	45					-	26.54
GA	Project	1/1	1/2						
(55 years)	Timing	31	49					-	25.04

Table 6.19 Project Sequence for Demand Forecast 1, Discount Rate of 5 % and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing							PVC (100 years)	PVC (55 years)
Unit	Project	1/2	8/2	7/2					
Cost	Timing	31	55	73				34.08	27.10
Equivalent	Project	8/2	1/1	1/2	7/2				
Cost	Timing	31	40	65	73			32.26	28.60
GA	Project	1/1	1/2	8/1	8/2	7/1	7/2		
(100 years)	Timing	31	49	55	63	73	83	31.93	25.34
ILP	Project	1/1	1/2						
(55 years)	Timing	30	45					-	26.89
GA	Project	1/1	1/2						
(55 years)	Timing	31	49					-	25.34

Table 6.20 Project Sequence for Demand Forecast 1, Discount Rate of 5 % and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing						PVC (100 years)	PVC (55 years)
Unit	Project	1/2	8/2	7/2				
Cost	Timing	31	55	73			34.08	27.10
Equivalent	Project	8/2	1/1	1/2	7/2			
Cost	Timing	31	40	65	73		32.46	28.60
GA	Project	8/2	1/1	1/2	7/1	7/2		
(100 years)	Timing	31	40	65	73	83	32.37	28.60
ILP	Project	1/1	1/2					
(55 years)	Timing	30	45				-	27.43
GA	Project	1/1	1/2					
(55 years)	Timing	31	49				-	25.78

The GA produces the lowest PVC for the 100 years for the results in Tables 6.18 to 6.20. These results indicate that the increase in upsizing cost will effect the sequence of projects. This is seen for the equivalent cost method for a increase in upsizing cost from 100 % to 120 % of the incremental cost and for both increases in upsizing cost for the GA method. The other two methods produce the same sequence no matter the upsizing cost. For the equivalent cost result it appears that, as upsizing cost increases, projects are less likely to be upsized. In the case of the GA results the increase in upsizing cost firstly varies the sequence and also reduces the number of projects upsized. Another possibility for the GA method is that the solution obtained is not optimal. However, on checking the other possible sequences which could be optimal, the solution shown above produced the lowest PVC. Therefore, the change in cost when upsizing cost increases, will affect the sequence of projects and the number of projects upsized.

When comparing the other methods to the ILP method for a 55 year planning period, the ILP produces the solution with the lowest PVC. Therefore it produces better results for the 55 year planning period than the unit and equivalent cost methods. However, the unit cost method produces the same sequence although it fails to upsize the project in question, thus producing a slightly inferior sequence. If the sequence for the GA method given above are used to calculate the PVC for a 55 year planning period then when upsizing cost equals 120 % of incremental cost the same sequence as the ILP method is produced. On the other occasions the sequence produced will give a higher value of PVC than the ILP sequence for the same situation for continuous and discrete time scales. When the GA method is used to calculate the sequence for the 55 year planning period it produces the same result as the ILP model. This result indicates the problem with using finite planning periods as the sequence of projects which is optimal for one planning period may not be optimal for another planning period.

For demand forecast 1 the final situation to examine is for a discount rate of 10 %. The results of this case are shown in Tables 6.21, 6.22 and 6.23 for the various upsizing cost cases.

The GA method produces the lowest PVC solution for all upsizing costs. In addition, as the upsizing cost is increased to 150 % of the incremental cost the projects are less likely to be upsized or upsizing occurs later in the sequencing of projects. Of the other methods only the ILP method sequence changes when upsizing cost increases. In this case projects 7/1 and 7/2 are replaced by projects 9/1 and 9/3. The GA method sequences more projects than the equivalent cost method. The reason for this is that at a high discount rate the GA uses smaller less costly projects which at a higher discount rate results in the PVC of projects being lower. The major change is the replacing of project 1 with projects 9, 13 or 10 and the expansion of project 7 to size 3. The result of the GA model for the 150 % upsizing cost case indicates that the GA cannot guarantee an optimum solution as it is obvious that project 13/1 is a better option than project 10/2 as the last project. The reason is that project 13/1 is a lower cost project than 10/2 but will also satisfy demand for the remainder of the 100 year planning period. In fact as a result of further runs with the GA, the project sequence 8/3, 7/3 and 10/2 may be replaced with 13/1, 7/3 and 8/3 to lower the PVC to 5.562. This non-optimal solution was identified after examining the GA runs and the various solutions obtained in the process of achieving the result shown and from a knowledge of the various projects cost and yields. Thus although the GA method may not obtain the optimal solution directly, examination of the GA results may allow for some improvement to be made to the lowest PVC solution found.

If the equivalent cost, unit cost and GA methods solutions above are used to calculate the PVC for a 55 year planning period then it is found that for discrete time (ie. ILP), the ILP method produces the lowest PVC result for all upsizing cost cases. On the other hand the GA sequence shown above to satisfy demand for the 55 year planning period provides the lowest PVC for a continuous time scale when the upsizing cost is equal to 150 % of the incremental cost. On the other occasions the project sequence shown for the GA and the other methods does not produce a lower PVC than the ILP method for either the continuous or discrete time scale. For the GA for the 55 year planning period, the same sequences as produced by the ILP method are obtained for the 100 and 120 % upsizing cost cases. On the other occasion the sequence is the same as obtained by the GA for the 100 year planning period. These results indicate how the use of a discrete time periods can result in non-optimal results for a continuous time horizon. In addition, the results indicate how a finite planning period can produce a sequence which may not be in the optimal sequence for a longer planning period.

Table 6.21 Project Sequence for Demand Forecast 1, Discount Rate of 10 % and Upsizing Cost Equal to the Incremental Cost

Method	Project Sequencing and Timing											PVC (100 years)	PVC (55 years)
Unit	Project	1/2	8/2	7/2									
Cost	Timing	31	55	73								6.83	6.40
Equivalent	Project	8/2	8/3	1/1	1/2	1/3	7/1	7/2					
Cost	Timing	31	40	44	71	79	82	92				5.45	5.39
GA	Project	8/1	8/2	8/3	7/1	7/2	7/3	9/1	9/2	9/3	13/1		
(100 years)	Timing	31	35	40	44	51	63	66	83	86	90	5.09	4.87
ILP	Project	8/1	8/2	7/1	7/2								
(55 years)	Timing	30	35	40	45							-	5.20
GA	Project	8/1	8/2	7/1	7/2								
(55 years)	Timing	31	35	40	47							-	4.80

Table 6.22 Project Sequence for Demand Forecast 1, Discount Rate of 10 % and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing											PVC (100 years)	PVC (55 years)
Unit	Project	1/2	8/2	7/2									
Cost	Timing	31	55	73								6.83	6.40
Equivalent	Project	8/2	8/3	1/1	1/2	1/3	7/1	7/2					
Cost	Timing	31	40	44	71	79	82	92				5.57	5.51
GA	Project	8/1	8/2	8/3	7/1	7/2	7/3	9/1	9/2	9/3	13/1		
(100 years)	Timing	31	35	40	44	51	63	66	83	86	90	5.33	5.10
ILP	Project	8/1	8/2	7/1	7/2								
(55 years)	Timing	30	35	40	45							-	5.36
GA	Project	8/1	8/2	7/1	7/2								
(55 years)	Timing	31	35	40	47							-	4.97

Table 6.23 Project Sequence for Demand Forecast 1, Discount Rate of 10 % and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing										PVC (100 years)	PVC (55 years)
Unit	Project	1/2	8/2	7/2								
Cost	Timing	31	55	73							6.83	6.40
Equivalent	Project	8/2	8/3	1/1	1/2	1/3	7/1	7/2				
Cost	Timing	31	40	44	71	79	82	92			5.77	5.69
GA	Project	8/2	7/1	7/2	9/1	9/2	9/3	8/3	7/3	10/2		
(100 years)	Timing	31	40	47	58	73	77	81	86	90	5.57	5.16
ILP	Project	8/1	8/2	9/1	9/3							
(55 years)	Timing	30	35	40	50						-	5.57
GA	Project	8/2	7/1	7/2								
(55 years)	Timing	31	40	47							-	5.16

As far as the change in discount rate is concerned as discount rate increases more upsizing occurs even at higher upsizing costs and in the extreme large projects are not sequenced but are replaced by a number of smaller, less costly projects. For instance for the ILP method the sequence involves just project 1 for the 2.5 and 5 % discount rates, but for the 10 % discount rate, project 1 is not sequenced but project 8 is sequenced with either project 7 or 9 depending on the upsizing cost. For the GA method at a 10 % discount rate project 1 is replaced by project 9 and either project 13 or 10, depending on the upsizing cost, and the upsizing of projects 7 and 8 to their maximum size. If it is considered that project 1 is more expensive than the projects which replace it, then this would indicate at high discount rates that it is better to sequence more smaller projects rather than one or two large projects. The possible reason is that there will be a greater discounting of cost when using a number of smaller projects rather than the larger projects. So even though the cumulative cost of the smaller projects may exceed that of the larger projects, the higher discounting of smaller costs will make a better solution. For example consider the upsizing cost case when it equals 100 % of incremental cost. In this case project 1 is built to 1/2 which costs \$123 million. For the projects which replaces project 1 for a 10 % discount rate the cumulative cost is \$223 million. So even though the extra projects cost \$100 million more, the discounting is such that this sequence produces the lowest PVC for a 10 % discount rate.

One factor which must be considered when examining the upsizing of projects is if it is always practical to upsize projects. While on a cost basis, upsizing may reduce the PVC, if the time between the upsizing of a project is small then it may not be considered practicable to upsize the project but rather build it to the larger size directly. For example, at a low upsizing cost, the GA builds every project at one stage at a time. This reduces the PVC but in some cases the building of stages of a project are close together, eg Table 6.18 where project 8 is upsized 4 years after it is initial built. Thus in reality if such a case occurs, it may be more practicable to build project 8/2 initially.

The next step is to examine the case of demand forecast 2. The three discount rates of 2.5, 5 and 10 % are again used in this study. However, only the results of using the discount rate of 5 % will be shown in this chapter. The results for the 2.5 and 10 % discount rates cases are shown in Appendix L, Tables L.1 to L.6. The results of using a discount rate of 5 % for demand forecast 2 are illustrated in Tables 6.24 to 6.26.

For the results in Tables 6.24 to 6.26 the GA produces the lowest PVC sequence for the 100 year continuous time scale. As has been the case previously the GA utilises more upsizing of projects which results in a lower PVC. In addition, the GA considers the finite period which the unit cost and equivalent cost methods do not. In the cases examined the finite planning period of 100 years does not effect the equivalent cost method as it has done in previous cases. The major differences in this case is the upsizing of projects and the different sequences produced.

For the 55 year planning period the ILP method produces the lowest PVC sequence given the discrete time periods utilised for this method. The sequence produced by the ILP method varies from those found using the other methods. This is thought to due to using the discrete time periods, especially when the order of projects 7 and 8 are reversed. Other variations in the sequences are due to the sequences produced being applied to a 100 year planning period rather than the 55 year planning period. Thus in some cases better options are available to satisfy demand for the smaller planning period. For this reason the GA was rerun for a 55 year planning period.

The same sequences as found above were again produced by the GA for the 55 year planning period except for the case when upsizing cost is equal to incremental cost. For this case projects 1/3 and 9/1 are replace by project 13/1 to produce a lower PVC for the smaller planning period. The major difference between the ILP sequence and the GA and equivalent cost sequences is that sequence of project 1/3 for various upsizing cost levels. The ILP method sequences project 1/3 to delay larger projects for the higher upsizing costs but the other methods do not. However, when upsizing cost equals incremental cost project 1/3 is sequence by the other methods to delay larger projects whereas project 1/3 does not appear in the ILP solution for this case.

The above results again indicate that the use of discrete timing and a specified finite period may alter the solution in such a way that for a continuous time scale and different planning period the solution obtained may not provide the lowest PVC.

As upsizing cost increased the results of Tables 6.24 to 6.26 indicates that the amount of upsizing decreased and when projects were upsized it tended to be later in the sequence of projects. This can be illustrated by examining the GA and equivalent cost results for the extremes in upsizing cost. For the GA results the projects 7, 8 are no longer upsized from size 1 to size 2 at a higher upsizing cost and projects 13/1, 5/3 and 9/3 appear before the upsizing of project 1, 7 and 8 to their maximum size (ie. 1/3, 7/3 and 8/3). For the equivalent cost case the amount of upsizing does not decrease however the case mentioned above involving the delaying of the upsizing of projects 1, 7 and 8 does occur.

For the ILP method not only is there less upsizing with increased upsizing cost but there is an alteration to the sequence of projects. In the lowest upsizing cost case project 7 is the second project sequenced following the upsizing of project 1 from 1/1 to 1/2. In the highest upsizing cost case projects 1/2, 8/2 and 1/3 precede the sequencing of project 7/2. This results in a delay in the sequencing of project 7 by 10 years. As this does not occur with the other methods it is considered this results is caused by the use of discrete time periods in the ILP model.

The above results and conclusion are substantiated by the solutions obtained when the discount rates of 2.5 and 10 % were used. These results are shown in Tables L.1 to L.6 in Appendix L. The effect on the sizing and sequencing of projects of using a finite planning period and a discrete time period (ie. ILP method) were again seen. In fact the change in sequence for the GA and ILP method shown in Table 6.24, where projects 8 and 7 are reversed in the order for the two methods, is also experienced for all cases using a discount rate of 2.5 %. This highlights the problem of using discrete time periods to sequence projects. In addition, the number of projects upsized and where the upsized projects occur in the sequence was shown to be dependent on the upsizing cost. This is the same conclusion as obtained for the 5 % discount rate.

Table 6.24 Project Sequence for Demand Forecast 2, Discount Rate of 5 % and Upsizing Cost Equal to the Incremental Cost

Method	Project Sequencing and Timing																	PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	8/3	1/3	7/3										
	Timing	15	27	34	45	58	79	84	86									115.91	105.92
Equivalent Cost	Project	1/2	8/2	7/2	8/3	1/3	9/3	7/3	13/1	5/3									
	Timing	15	27	34	45	48	50	64	67	77								114.71	107.96
GA (100 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2	1/3	8/3	9/1	9/2	9/3	7/3	5/1	5/2	5/3	13/1		
	Timing	15	24	27	30	34	37	45	47	50	59	61	64	67	70	76	89	109.66	102.09
ILP (55 years)	Project	1/1	1/2	7/1	7/2	8/2	9/1	9/2											
	Timing	15	20	25	30	35	45	50										-	105.45
GA (55 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2	8/3	13/1										
	Timing	15	24	27	30	34	37	45	48									-	100.27

Table 6.25 Project Sequence for Demand Forecast 2, Discount Rate of 5 % and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing														PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	8/3	1/3	7/3						
	Timing	15	27	34	45	58	79	90	95	97					116.16	105.92
Equivalent Cost	Project	1/2	8/2	7/2	9/3	8/3	1/3	7/3	13/1	5/3						
	Timing	15	27	34	45	58	62	64	67	77					115.69	105.92
GA (100 years)	Project	1/1	1/2	8/2	7/2	9/1	9/2	9/3	7/3	8/3	13/1	5/2	5/3	1/3		
	Timing	15	24	27	34	45	54	56	58	61	65	75	84	98	113.13	102.79
ILP (55 years)	Project	1/1	1/2	8/1	8/2	1/3	7/2	9/1								
	Timing	15	20	25	30	30	35	45							-	108.23
GA (55 years)	Project	1/1	1/2	8/2	7/2	9/1	9/2									
	Timing	15	24	27	34	45	54								-	102.79

Table 6.26 Project Sequence for Demand Forecast 2, Discount Rate of 5 % and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing													PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1							
	Timing	15	27	34	45	58	79	90						119.19	105.92
Equivalent Cost	Project	1/2	8/2	7/2	9/3	13/1	5/3	8/3	1/3	7/3					
	Timing	15	27	34	45	58	68	90	94	97				116.04	105.92
GA (100 years)	Project	1/1	1/2	8/2	7/2	9/1	9/2	9/3	13/1	5/3	7/3	8/3	1/3		
	Timing	15	24	27	34	45	54	56	58	68	90	93	98	115.60	104.52
ILP (55 years)	Project	1/2	8/2	1/3	7/2	9/1									
	Timing	15	25	30	35	45								-	109.92
GA (55 years)	Project	1/1	1/2	8/2	7/2	9/1	9/2								
	Timing	15	24	27	34	45	54							-	104.52

In regard to the change in sequence for various discount rates there will not be any alteration in the unit cost sequence as discount rate is not a decision variable in the sequencing method. For the other methods it appears that as discount rate increases the amount of upsizing of projects also increases. Also, it seems that upsizing will tend to occur earlier in the sequence at higher discount rate. In addition, smaller less expensive projects will be sequenced before larger projects particularly later in the sequence (ie 13/1 before 5/3) when discount rate increases. These last two situations lead to the larger more costly projects being scheduled later in the planning period, a results of which is higher discounting of the project costs and a lower PVC. The last two observations in essence are similar as the upsizing of projects is cheaper than building a new project as is the sequencing of smaller projects before larger projects. The upsizing of more projects earlier in the sequence occurs to a lesser degree when upsizing cost is large (ie equal to 150 % of incremental cost). That is the upsizing of projects is delayed more than when a lower upsizing cost is used.

The final demand case to examine is that of demand forecast 3. The results of using a discount rate of 5 % are shown in Tables 6.27 to 6.29. The discount rates of 2.5 and 10 % were also examined. These results are shown in Appendix L, Tables L.7 to L.12.

As was the case for the previous results the GA method produces the lowest PVC solution for the 100 year planning period. However, the GA result can be seen not to be optimal particularly for the cases of upsizing cost equal to 100 % and 120 % of the incremental cost. This is concluded as project 8 does not start with size 1 for the GA sequence but does for the ILP sequence. In addition, the projects should be upsized to a maximum when the upsizing cost equals incremental cost to obtain the lowest PVC solution.

The equivalent cost method produces the next lowest PVC solution, however as has been the case previously the difference in the sequences found by the equivalent cost and unit cost methods to that of the GA method is that the latter uses more upsizing of projects. In addition, there is a slight variation in the sequence of projects between the equivalent cost and GA method. The variation is the reversal of projects 5/3 and 13/1 in the sequences. It is considered that the GA sequence is the closer to the optimum sequence and the different ordering of projects 13/1 and 5/3 reflects the equivalent cost method not being able to guarantee an optimal solution when using a non-linear demand growth.

Table 6.27 Project Sequence for Demand Forecast 3, Discount Rate of 5 % and Upsizing Cost Equal to the Incremental Cost

Method		Project Sequencing and Timing																	PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	8/3	1/3	7/3	13/1	6/1									
	Timing	23	38	46	56	68	83	86	87	89	96								76.50	60.09
Equivalent Cost	Project	8/2	1/2	7/2	9/3	8/3	1/3	7/3	13/1	5/3	10/3									
	Timing	23	30	46	56	68	71	72	74	81	96								73.34	58.81
GA (100 years)	Project	8/2	1/1	1/2	7/1	7/2	7/3	9/1	9/2	9/3	5/1	5/2	5/3	10/1	10/2	10/3	8/3	1/3		
	Timing	23	30	42	46	50	56	58	66	68	70	71	76	85	91	93	95	98	69.85	56.44
ILP (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2													
	Timing	20	25	30	40	45	50												-	59.53
GA (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2													
	Timing	23	27	30	42	46	50												-	56.04

Table 6.28 Project Sequence for Demand Forecast 3, Discount Rate of 5 % and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing															PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	8/3	1/3	7/3	6/1						
	Timing	23	38	46	56	68	83	90	93	94	96					76.67	60.09
Equivalent Cost	Project	8/2	1/2	7/2	9/3	8/3	13/1	1/3	7/3	5/3	10/3						
	Timing	23	30	46	56	68	71	77	79	81	96					73.70	58.81
GA (100 years)	Project	8/2	1/1	1/2	7/1	7/2	9/1	9/2	9/3	5/2	5/3	13/1	10/1	10/2	10/3		
	Timing	23	30	42	46	50	56	64	66	68	74	83	90	96	98	71.52	57.53
ILP (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2										
	Timing	20	25	30	40	45	50									-	61.08
GA (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2										
	Timing	23	27	30	42	46	50									-	57.50

Table 6.29 Project Sequence for Demand Forecast 3, Discount Rate of 5 % and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing										PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1				
	Timing	23	38	46	56	68	83	90			76.80	60.09
Equivalent Cost	Project	8/2	1/2	7/2	9/3	13/1	5/3	8/3	1/3	10/3		
	Timing	23	30	46	56	68	74	90	93	94	73.86	58.81
GA (100 years)	Project	8/2	1/1	1/2	7/2	9/2	9/3	5/3	13/1	10/3		
	Timing	23	30	42	46	56	66	68	83	90	72.59	58.20
ILP (55 years)	Project	8/2	1/1	1/2	7/2							
	Timing	20	30	40	45						-	62.18
GA (55 years)	Project	8/2	1/1	1/2	7/2							
	Timing	23	30	42	46						-	58.20

In the case of the 55 year planning period the ILP and the GA methods produce the same sequence of projects for all upsizing cases. Thus the sequence obtained is considered to be optimal sequence for both a discrete and continuous time scale. These results highlight the non-optimality of the GA sequence obtained for the 100 year planning period as project 8 is initially built to size 2 rather being upsized to size 2 for the lower upsizing cost cases.

In regard to increased upsizing cost again it is seen that as the upsizing cost increases there is less upsizing of projects. This is evident for all methods, but is particularly highlighted by the ILP and GA method which generally account for upsizing to a greater extent than the other methods. A good example of the reduction in upsizing with increased upsizing cost occurs when the upsizing cost increases from 100 % to 120 % of the incremental cost for the GA method. In this situation not only is project 5 upsized more at the lower upsizing cost but project 1, 7 and 8 are upsized to size 3 and replace project 13/1 in the sequence at the lower upsizing cost.

The results of using the discount rates of 2.5 and 10 % substantiate the results obtained for the 5 % discount rate. This includes the effect a finite planning period has on the sequence of projects particularly when using the equivalent cost or the unit cost methods. However, while for the other demand forecast cases, the use of a discrete time period in the ILP method effected the sequences obtained, this was not seen in this demand forecast case. However, what was seen for a 10 % discount rate and the largest upsizing cost was that the discrete time period effected the upsizing of projects. In this case the use of a discrete time period produced more upsizing of projects. This result was found by comparing the solutions of the ILP and GA methods.

The next discussion is in regard to the sequence change when discount rate changes for the demand forecast 3. As discount rate increased it appears there is more upsizing of projects and the upsizing of projects occurs earlier in the sequence. In particular for the GA method projects 1/3, 7/3 and 8/3 seem to occur earlier in the sequence when discount rate is high. This is thought to be because the smaller less costly projects delay the larger cost projects enough that at a high discount rate the cost is discounted greater which results in a lower PVC. This conclusion is more evident when upsizing cost is at its lowest. In fact when the upsizing cost is equal to 150 % of the incremental cost and the discount rate is 2.5 % (ie. Table L.9) there is no upsizing of projects. Thus the effects of discount rate and upsizing cost can combine to alter the amount of upsizing and when it occurs in the sequence. In addition, it was seen in the GA sequences that when the discount rate changed the sequence of projects changed. In particular at a 10 % discount rate project 13 preceded project 5 in the sequence but at the lower discount rates the opposite occurred no matter the level of upsizing cost. This also occurred in the equivalent cost methods results, however the reversal of the projects occurs at the 5 % discount rate and not the 10 % discount rate as was the case for the GA method results. Thus at the 5 % discount rate the equivalent cost and GA methods sequences conflict each other with regard to the ordering of projects 5 and 13.

The next variable to examine is the effect that the various levels of demand growth rates have on the sequence of projects and the upsizing of projects. Again if the unit cost results are disregarded in this discussion as the method does not consider the demand growth rate, there is a change in sequence when demand growth changes. As was the case with the no upsizing problem a general trend cannot be established between project sequencing and the change in demand growth rate. For instance for the GA method, in the case of demand forecast 2 where the initial growth rate is 10.62 GL/year project 1 is sequenced before project 8. But on the other side for demand forecast 2, (which has a lower growth rate) project 8 is sequenced before project 1. However, this conclusion seems to be contradicted by the results from using demand forecast 1 which has the lowest demand growth. Here the first project sequenced varies between project 1 and project 8. The explanation for this could be one of two things. Firstly, at the lower demand growth rate, discount rate, upsizing cost and the other factors play a more significant role in the sequence of projects. Or secondly some of the results are not the true optimum. The second theory is tested by calculating the PVC of the sequence with the reverse ordering of project 1 and 8. The result of which shows the sequence presented are close to optimal. Thus the first conclusion would seem to be the reason for the variation in sequence. Thus, what can be concluded is that the demand growth rate, discount rate and upsizing cost all effect the sequencing of projects and a method which includes these variables should be utilised when sequencing and scheduling projects.

In regard to the sequence of projects it can be seen that projects 1 and 8 are the most likely projects to be sequenced first. In addition, project 7 would seem likely to be the next project sequenced followed by project 9 and projects 5 and 13. The order of the last two projects has been discussed previously with the discount rate having an effect on the likely order. As far as the order of projects 1 and 8 goes this depends on the value of demand growth rate, discount rate and to a lesser extent the upsizing cost. The only dilemma is the amount of upsizing and the respective sizes of the projects. The upsizing of the projects sequenced is also dependent on the factors mentioned above. However, the higher the discount rate or lower the demand growth rate and lower the upsizing cost the more likely the amount of upsizing will increase.

As was the case with the no upsizing case, a hybrid method was used to determine the sizing and sequencing of projects. Again the unit cost method is used to size the projects and the equivalent cost method sequences the projects. For demand forecasts 2 and 3, the discount rates of 5 and 10 % were examined for an upsizing cost of 120 % of the incremental cost. The upsizing cost of 150 % of the incremental cost was also examined for the two demand forecast and a discount rate of 5 %. The cases using a discount rate of 5 % and for demand forecast 2 and 3 are shown in Table 6.30 and 6.31 respectively, while the results of using a 10 % discount rate are given in Table 6.32. The equivalent cost solutions are also indicated in these tables, so a comparison can be made of solutions obtained for the sizing and sequencing of projects when a hybrid method is used rather than a single method.

It can be seen in Tables 6.30, 6.31 and 6.32 that the use of a hybrid method for sizing and sequencing projects can results in an inferior solution than if a single method is used for the same purpose. This is not evident for a 5 % discount rate case, however for the 10 % discount rate the sequence produced by the hybrid method is not as good as that produced by the equivalent cost method for both demand forecasts. The reason in this case is the equivalent cost method utilises more upsizing of projects, particularly project 1. Otherwise, the sequences produced by both methods are similar.

Table 6.30 Results of Using a Hybrid Method for the Sizing and Sequencing of Projects for a 5 % Discount Rate and for Demand Forecast 2

Upsizing Cost	Method	Project Sequencing and Timing										PVC (100 years)
120 %	Hybrid Method	Project	1/2	8/2	7/2	9/3	8/3	1/3	7/3	13/1	5/3	
		Timing	15	27	34	45	58	62	64	67	77	115.69
120 %	Equivalent Cost	Project	1/2	8/2	7/2	9/3	8/3	1/3	7/3	13/1	5/3	
		Timing	15	27	34	45	58	62	64	67	77	115.69
150 %	Hybrid Method	Project	1/2	8/2	7/2	9/3	13/1	5/3	8/3	1/3	7/3	
		Timing	15	27	34	45	58	68	90	94	97	116.04
150 %	Equivalent Cost	Project	1/2	8/2	7/2	9/3	13/1	5/3	8/3	1/3	7/3	
		Timing	15	27	34	45	58	68	90	94	97	116.04

Table 6.31 Results of Using a Hybrid Method for the Sizing and Sequencing of Projects for a 5 % Discount Rate and for Demand Forecast 3

Upsizing Cost	Method	Project Sequencing and Timing											PVC (100 years)
120 %	Hybrid Method	Project	8/2	1/2	7/2	9/3	8/3	1/3	13/1	5/3	7/3	10/3	
		Timing	23	30	46	56	68	71	72	79	94	96	73.75
120 %	Equivalent Cost	Project	8/2	1/2	7/2	9/3	8/3	13/1	1/3	7/3	5/3	10/3	
		Timing	23	30	46	56	68	71	77	79	81	96	73.70
150 %	Hybrid Method	Project	8/2	1/2	7/2	9/3	13/1	5/3	8/3	1/3	10/3		
		Timing	23	30	46	56	68	74	90	93	94		73.86
150 %	Equivalent Cost	Project	8/2	1/2	7/2	9/3	13/1	5/3	8/3	1/3	10/3		
		Timing	23	30	46	56	68	74	90	93	94		73.86

Table 6.32 Results of Using a Hybrid Method for the Sizing and Sequencing of Projects for a 10 % Discount Rate and for an Upsizing Cost Equal to 120 % of the Incremental Cost

Demand Forecast	Method	Project Sequencing and Timing												PVC (100 years)
2	Hybrid Method	Project	8/2	1/2	7/2	8/3	1/3	7/3	9/3	13/1	5/3			
		Timing	15	19	34	45	48	50	52	67	77			40.38
2	Equivalent Cost	Project	8/2	1/1	1/2	7/2	8/3	1/3	7/3	9/2	9/3	13/1	5/3	
		Timing	15	19	31	34	45	48	50	52	64	67	77	38.72
3	Hybrid Method	Project	8/2	1/2	7/2	9/3	8/3	1/3	7/3	13/1	5/3	10/3		
		Timing	23	30	46	56	68	71	72	74	81	96		15.83
3	Equivalent Cost	Project	8/2	1/1	1/2	7/2	9/3	8/3	1/3	7/3	13/1	5/3	10/2	
		Timing	23	30	42	46	56	68	71	72	74	81	96	15.26

Finally, the benefits of upsizing can be seen by comparing the PVC from the no upsizing case and the upsizing case. In all cases and methods the upsizing of projects leads to a lower PVC. When, the upsizing cost is at its highest the upsizing sequences have limited upsizing of projects. In these cases the difference in the PVC between the upsizing and no upsizing cases is only small. In fact for the case of demand forecast 3, discount rate of 2.5 % and upsizing cost equal to 150 % of the incremental cost the sequences and PVC are the same between the two scenarios.

6.5 Conclusions

What can be concluded from the study performed is that the GA will provide a very good solution under any conditions. In the case of sequencing fixed sized projects with no upsizing in linear time, the equivalent cost method will produce an optimum solution. It appears to be the best for this case as the GA will take more time and is a more complex method. In the case of non-linear demand the equivalent cost method could be used however, it cannot be guaranteed an optimum will be produced. Thus if an approximation is adequate the equivalent cost would be sufficient, however the GA and ILP methods are likely to produce better results. Of these the GA method is faster and can sequence in continuous time. For the sizing and sequencing problem where project upsizing is allowed the most suitable method appears to be the GA. Although it is more complex than the equivalent cost and the unit cost methods the results obtained are better. It uses continuous timing for project building unlike the ILP method and is also considerably quicker in producing a result. The GA takes approximately 3 minutes to run on a personal computer (eg. 80486 machine with a clock speed of 33 MHz). If the ILP method was more efficient in regard to time for computation and utilised a continuous time scale then it would be a suitable method to use as it will guarantee an optimum solution. The use of integers in the ILP model is the reason the method requires so much computation time.

The GA also obtains the best sequence for a set period whereas the equivalent cost and unit cost methods sequence projects based on an infinite time horizon. In addition, this study has shown that the equivalent and unit cost methods utilise the upsizing of projects to a lesser extent than the GA method. The result of which is a higher PVC than obtained by the GA method. A further and probably a significant advantage of GA is that it produces a number of good solutions for the problem. This can give the water resources planner a better understanding of the problem. In addition, it is thought that multiple objectives can also be modelled with the GA leading to better management and planning scenarios. Therefore, it is concluded that the GA is a more useful and adaptable tool than any of the other methods investigated here.

A conclusion regarding the effect of demand management can also be made from the results of this study. This is possible as demand forecasts 1 and 2 are the similar but demand forecast 1 includes 20 % demand management. It can be seen that demand management has a major effect on the number of projects expanded and upsized and therefore on the PVC. The result is a substantial reduction in the PVC. In addition, the sequencing of fewer projects has a positive environmental impact as less dams built will have a reduced impact on the environment.

The study also showed the benefits achievable if upsizing of projects is allowed. The benefit was achieved through the delaying of higher cost alternatives which results in a lower PVC. The magnitude of the benefit however depends on the other factors involved in the problem. These factors include project yield and cost including the magnitude of upsizing cost, discount rate, demand growth rate and also the planning period. All of these factors affect the sizing and sequencing decision and if a reasonable planning schedule is to be produced these factors should be considered.

It was also seen in this study the problems with using multiple methods to size and sequence projects. In the cases examined here the sequence of projects tended to be similar between methods which evaluate the sizing and sequencing of projects separately and simultaneously. However, the sizing of projects produced when a hybrid approach was used resulted in the inferior solutions. In addition the method which examines the problems simultaneously utilised more upsizing of projects when upsizing was allowed. Thus, methods which solve of the sizing and sequencing problem simultaneously, will produce the better solutions.

In conclusion this study has introduced many new concepts and illustrated the complexities involved in the planning of future reservoirs. The study demonstrates a new method for solving the sizing and sequencing problem called genetic algorithms. This method produced lower PVC solutions to all the problems than the other methods considered. The solutions produced for the no upsizing case are thought to be optimal because of a number of runs achieving the same results. This however, cannot be said for the upsizing case where on nearly all occasions the results of the GA were different but still lower than produced by the other methods. In addition, the GA and ILP method can be adapted to consider multiple objectives rather than just minimisation of cost. This can be achieved as the evaluation is of a fitness function rather than just an economic value like other methods. Therefore if suitable weights can be determined between objectives, the GA can be used to find a good solution based on these objectives.

6.6 Pricing, Sizing and Sequencing of Projects

With the examination of the size and sequencing problem completed, the next stage is to examine the effect of price on the size and sequence of projects. The methodology used is similar to that in Chapter 4 for the Canberra Water Supply System case study. In this study the methods used to evaluate the size and sequence of projects are the unit cost, equivalent cost and the GA. The ILP method is not used for this case because of the need to approximate non-linear demand functions which would increase the amount of computer time dramatically. When using the sequencing methods of unit cost and equivalent cost, the same iterative methodology as used in Chapter 4 will be applied. Briefly, the price starts off at its lower bound and the size and sequence of projects is determined for that price using the sequencing methods discussed. The price is then increased by one unit and the process repeated until its upper bound is reached. The NPV for each price and sequence is determined using the methodology in Chapter 3. The maximum NPV is simply found by inspection of the range of price used and the NPV calculated.

This methodology does not apply for the GA method. The GA method incorporates price into the string with the last bit being an integer bit. The integer bit can take a value in the ranges of price defined. The following string is an example of the coding used for this problem:

0.937, 0.901, 0.076, 0.567, 0.812, 0.432, 26

The real numbers of the string are ordered from highest to lowest and these will represent the order of the project and the bit position represents the project number. For instance the project sequence for this string is 1, 2, 5, 4, 6, 3. The fitness of this string is then evaluated by calculating the present value of capital cost (PVC) and the present value of maintenance cost (PVMC) of this sequence of projects for the time period considered. These costs are then subtracted from the benefits associated with a price of 26 cents/KL, which is the seventh bit in the above string, to get the NPV (ie. Equation 3.6). The price plays a role in the calculation of the PVC and PVMC as it will affect demand in accordance with Equation 3.3. Equation 3.3 is the general expression for the demand/price relationship. The specific demand/price relationship used for this study is shown in Equation 6.1.

$$D_n(P_n) = (q_0 POP_0 + wn)\left(\frac{P_n}{P_0}\right)^{\beta} \tag{6.1}$$

where $D_n(P_n)$ is the demand in year n at price P_n, P_0 is the initial price (in year zero), P_n is the price in year n, β is the price elasticity of demand for water, POP_0 is the initial population, q_0 is the initial per capita water consumption, w is the growth rate in demand (GL/year) and n = the year (n=0,1,2,...,N).

The same operators as were applied in the sizing and sequencing for the GA in the early study in this chapter also apply for the pricing study. However, the mutation of the bit which sets the price will only change the bit to another integer within the price range assumed. The population size is 100, the number of generations examined is 200 and the probability of mutation and crossover are 3 % and 90 % respectively.

For the pricing study the same current system yield and demand as used previously is utilised here. The current system yield is assumed to equal 500 GL/year and the current demand will be assumed to be 337.7 GL/year (ie assuming 1990 is the current year). The initial price at which 337.7 GL/year is consumed was difficult to calculate for the area concerned. The primary difficulties were with many different pricing structures within the South-East Queensland study area, varying levels of demand for each area and the level of metered population per area. As it is not the primary concern of this study to recommend a particular price at which to charge for water an approximate initial price of 45 cents/KL was adopted. This price is the charge for water consumed above 350 KL in the city of Brisbane. Given that the population of Brisbane is approximately half of the study area population and the other areas having generally higher charges for water, then this price was considered a reasonable approximation.

A number of other assumptions have to be made so that the study can continue. Firstly, an assumption of the current system operating and maintenance cost had to be made. The majority of the operating and maintenance cost for a multiple reservoir system is in water treatment and pumping cost. It is unknown how much treatment and pumping are required to supply water to the region in question. However, in a previous study on the Canberra system a operation and maintenance cost of 11.4 cents/KL was suggested. So without any specific knowledge on such a cost for the South-East Queensland region the operating and maintenance cost is assumed to be approximately 10 cents/KL.

In addition to this cost there will be an annual cost for the maintenance for future reservoirs. It is considered by people in the field of water resources planning, that for new reservoirs approximately 1 % of the initial capital cost is a good approximation of the likely annual maintenance cost. The operating cost however is unknown and without any further data it will be considered that the 10 cents/KL will apply to the system operating cost after new projects are added. This assumption is not unreasonable if it is considered that the cost of operating new supplies is unlikely to be significantly greater than that of the existing system and taking into account the amount of water from a new supply when compared to the entire supply, the difference in operating cost is likely to be only small for the entire system after a new project is added.

There will be an assumption made in regard to the value of price elasticity of demand. From previous research on pricing effects on demand, the value of price elasticity for demand ranges between -0.1 to -0.75 (Dandy, 1989). The majority of the studies suggest a smaller range of -0.20 to -0.40 can be used. For this study the value of -0.3 will be used as it is in the likely range of price elasticities found previously and it is considered to be a good estimate. In addition, the price elasticity is assumed to be constant in time and at different price levels.

The demand forecasts utilised previously in this chapter will also be applied in this study. However, due to the change in demand when price is altered it was decided that the 100 year planning period would not be examined. The reason is that for the demand forecast 2 and 3 the demand growth is such that for a low price the projects used in the study may not satisfy demand for the entire 100 year planning period. Thus, a 50 year planning period was utilised so that the demand would be satisfied for the entire planning period.

In addition to these assumptions, the assumption of allowing upsizing of existing projects will be examined. As was the case in the earlier study in this chapter, a penalty level will be applied to the upsizing cost to see if this affects upsizing of projects. The various levels to be examined are upsizing cost equal to 100, 120 and 150 % of the incremental cost of upsizing. Also the case of no upsizing of projects will also be examined.

The discount rate is assumed to be 5 %. This value is the same as that utilised in a report on the South-East Queensland system (Water Resources Commission, 1991). No sensitivity analysis is performed on this variable for this study, although it is considered and has been shown in this chapter and previous chapters that the discount rate will affect the size and sequence of projects.

It will also be assumed that not all the yield is actually supplied to the consumer. In this study, it will be assume that 15 % of the water supplied will be lost and will not reach the consumer. This systems loss will not effect the sizing, sequencing or timing decisions but will reduce the value of consumer surplus and revenue for a particular price.

With regard to the examination of optimum price only a small range of price is considered. The range used for the various method in this study is from a lower bound of 10 cents/KL to a upper bound of 80 cents/KL. The limits placed on the value of price is not expected to effect the optimum price obtained, as prices outside this range are likely to produce a substantially lower value of NPV. Also the assumed ultimate price (P_n^u) used in the NPV calculation for this study is \$10/KL. This is the same as used for the Canberra case study in Chapter 4.

Before the methodology is discussed a brief explanation is required on the pricing structure assumed and utilised in this study. The pricing structure assumed is the same as that used for the Canberra water supply case study (ie. Chapter 4) and is a two part structure made up of a fixed charge and a per unit usage charge. The fixed charge should cover the costs that do not directly affect the per unit price estimation. Such costs are interest cost on borrowed capital or replacement cost of existing infrastructure. The following study is not aimed at evaluating this fixed charge as the information to determine this cost is not available. However, the establishment of the fixed cost per household could include equity issues by considering the property value, income level or the size of the household as suitable criteria for the magnitude of the charge. This study however, will concentrate on the per unit usage charge. The aim of this price is to give the consumer a good indication of the true cost of water. In the past, water authorities have used allowance based structures to charge for water. In these systems the consumer receives a certain of amount of water for a fixed charge and all water usage above the allowance is charged a unit price. The problem with this is that consumers who do not use their allowance under normal conditions may be tempted to waste water as it costs them nothing more to use the full allowance. Thus the pricing system considered in this study encourages water conservation and is easier to analyse than block rate structures.

6.7 Results

6.7.1 No Project Upsizing Allowed

With the above information the three models were run for the South-East Queensland System. The results for the no upsizing case are shown in Tables 6.33, 6.34 and 6.35 which apply for demand forecasts 1, 2 and 3 respectively.

Table 6.33 No Upsizing Case with Demand Forecast 1

Method	Project Sequencing and Timing							Price ($/KL)	Adjusted NPV	PVC
Unit	Project	1/2	8/2	7/2	9/3					
Cost	Timing	9	24	31	40			19	690.03	134.79
Equivalent	Project	8/2	1/2	7/2	9/3					
Cost	Timing	10	18	32	42			20	694.59	122.73
Genetic	Project	8/2	1/2	7/2	13/1					
Algorithm	Timing	11	19	34	44			21	696.91	111.60

Before the above results are discussed a brief explanation is needed regarding the value of NPV. When the NPV values are compared from the various methods there is little difference between them. However it must be noted that the consumer surplus contributes the majority of the NPV shown. For instance for the GA method the consumer surplus is $34072.38 million. As shown in Figure 3.2, much of this consumer surplus is for the part of the demand curve which applies to very high prices and is essentially a constant in this study. Thus all NPV values shown have $34,000 million subtracted for ease of comparison. Also the values of NPV and PVC are in $ million.

Another value of comparison maybe the profit to the water authority. This is found when the consumer surplus is subtracted from NPV. The difficulty with showing the profit figure is that a water authority could maximise profit by pricing and supplying water as a monopolist, ie. reduce supply and increase price. This would not be in the best interest of the community as a whole.

As can be seen in Table 6.33 the genetic algorithm provides the best solution. However, this is thought to be due to the fact the genetic algorithm considers the finite period of 50 years rather than an improvement in general sequence evaluation. The reason this provides the best solution is the unit cost and equivalent cost methods assume an infinite period and thus no regard is given to the end of the period. It can be seen that some savings can be made. This particular problem also affects the genetic algorithm for the pricing problem. The reason can be explained by considering the result above. Here for a price of 21 cents/KL, project 13/1 will just satisfy demand for the 50 year period. If price is reduced to 20 cents/KL another project is required as demand is greater. Due to the extra project there is a substantial jump in PVC and a significant reduction in NPV and therefore the optimum price is indicated as 21 cents/KL. It so happens that at a price of 20 cents/KL project 9/1 will just satisfy demand. However, if project 9/1 replaces project 13/1 in the above sequence at 21 cents/KL the NPV will drop as project 9/1 is more expensive. Thus at 20 cents/KL there is a significant reduction in PVC rather than the previous jump when 13/1 was sequenced and the optimum price is found for the new sequence at 20 cents/KL. It turns out that this solution gives a greater value of NPV than the one shown in Table 6.33 however, the likelihood of the genetic algorithm finding this solution is low as both the sequence and price need to change within one step. Even if say the sequence changes but price does not, the sequence at that price will have a lower NPV as illustrated in this discussion and it is likely that the string may not be considered for the next generation. On the other hand, if the price changes for the previously optimal solution at one price, at the new price the sequence may no longer be optimal and therefore that string and price may not make it to the next generation due to the selection process of the GA.

To understand the problem it may be necessary to discuss the obtainment of optimum price. Generally, if the PVC for all prices was considered to be zero the NPV vs price curve would be of the inverse parabola form. This curve is fairly flat however, and the difference in NPV between the optimum point and points to either side is only small. The optimum price tends to be just greater than the operational or short-run marginal cost of supply. This will vary depending on a number of factors such as price elasticity, demand and discount rate. The slope or steepness of the curve is also dependent on these factors. In particular as price elasticity increases the steepness of the curve increases as the variation in demand between prices is greater. The point to be made here is that around the optimum price level the difference between prices is such that the actual PVC will play a significant role in the actual optimum price. Consider the result in Table 6.33. The optimum prices for the genetic algorithm and the unit cost sequence occur when the projects sequenced just satisfy demand for the planning period. A further decrease in price will require another project to satisfy demand for the remaining years. Thus, there is a substantial jump in PVC which may lower the NPV below the optimum depending on the price. However, as the variation in NPV from one price to another is relatively small when PVC is not considered, a substantial change in the PVC will result in a higher NPV for the higher price due to lower demand. If this occurs around the optimum point on the NPV versus price curve, then the optimum price will be when there is a significant change in PVC. With this in mind, it can then be argued, that the equivalent cost method should produce the optimum sequence and price if the demand is linear and a good approximation if it is not. This last statement should be true if a planning period is selected such that the finite period has no effect on the optimum sequence of projects.

Another situation does arise in the achievement of optimum price and that is when the price change is enough to change demand so that a project or a series of projects are delayed. This results in a lower PVC and depending on price elasticity, demand and discount rate the optimum price may be achieved with this variation. This is the situation which arises for the result of the equivalent cost method in Table 6.33. Thus it could be asked why this does not occur with the unit cost method. The reason is simply that due to the initial sequence change, the change in price and therefore demand do not result in the same PVC reductions. Thus the optimum price is obtained when the projects sequenced just satisfy demand for the planning period. Thus, it can be concluded that project yield and cost will affect the optimum price determination when considering discrete timing.

The next stage is to examine the effects on optimum price and sequence when using demand forecast 2. These results are shown in Table 6.34.

Table 6.34 shows that the equivalent cost and genetic algorithm produce the same sequence and price. After obtaining the results in Table 6.33, a closer examination was carried out on the results in Table 6.34, to see if any sequence change results in a higher value of NPV. It was found that on this occasion that the above result is the best found. Even, the unit cost method predicts the same price and the sequence is the same except the first two projects are reversed in the order. These results along with Table 6.33 results would indicate the sequence 8/2, 1/2, 7/2, 9/3, 5/3, 13/1 is the best sequence. So if the planning period is such that the problems with sequencing projects that occurred with demand forecast 1 do not appear, then it is likely the genetic algorithm will find the optimum result. From the results in Table 6.34, this can also be said for the equivalent cost method, however it has been shown in previous studies that this is not always the case when non-linear demand is used. These results indicate that the unit cost method failure to consider demand growth and discount rate leads to inferior results when compared to the other methods used here. This is substantiated by the results found in previous studies.

Table 6.34 No Upsizing Case with Demand Forecast 2

Method	Project Sequencing and Timing							Price ($/KL)	Adjusted NPV	PVC
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1			
	Timing	8	16	19	27	34	44	26	4323.19	212.15
Equivalent Cost	Project	8/2	1/2	7/2	9/3	5/3	13/1			
	Timing	8	12	19	27	34	44	26	4324.89	210.73
Genetic Algorithm	Project	8/2	1/2	7/2	9/3	5/3	13/1			
	Timing	8	12	19	27	34	44	26	4324.89	210.73

The final step is to utilise demand forecast 3 in the obtainment of an optimum price and sequence. The results of which are shown in Table 6.35.

Table 6.35 No Upsizing Case with Demand Forecast 3

Method	Project Sequencing and Timing							Price ($/KL)	Adjusted NPV	PVC
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3				
	Timing	10	22	28	35	42		23	2998.38	157.74
Equivalent Cost	Project	8/2	1/2	7/2	9/3	5/3				
	Timing	10	16	28	35	42		23	3001.46	155.17
Genetic Algorithm	Project	8/2	1/2	7/2	9/3	5/3				
	Timing	10	16	28	35	42		23	3001.46	155.17

As was the case in Table 6.34 the equivalent cost and genetic algorithm give the same price and sequence. In addition, the only change between those and the unit cost method is the initial two project sequence. The optimum price occurs when the last project just satisfies demand for the period so when price drops by 1 cent/KL another project is required. These results substantiate the conclusions made from Table 6.34 regarding the appropriateness of using the equivalent cost and genetic algorithm method for obtaining the optimum price and sequence.

It can be seen from these results that as demand increases it is more likely the optimum price will be higher. There was also enough evidence to show the price elasticity and discount rate can also influence the selection of optimum price. In addition the determination of optimum price will be affected by project yield and cost. This was illustrated with the results of the unit cost method and the results found when using demand forecast 1.

The next section is concerned with the results of allowing upsizing of projects to occur.

6.7.2 Project Upsizing Allowed

In this section the upsizing question in regard to price and size and sequence is examined. As mentioned previously, the study will examine three levels of upsizing cost, namely 100 %, 120% and 150 % of the incremental cost. Again, as was the case in the previous section the three demand growth rates were investigated. Also, discount rate and price elasticity will be the same as used in the previous section.

The results of utilising the three upsizing costs for the three methods are shown in Tables 6.36, 6.37 and 6.38 for demand forecast 1.

As can be seen in Table 6.36 the genetic algorithm produces the best solution. The reason is that it allows the projects sequenced to be fully augmented or upsized. However, with the other methods projects 1, 7 and 8 are initially built to size 2 rather than to size 1 first and then to size 2. For the equivalent cost method the optimum price is found when at a lower price another project is required and at a higher price the last project is dropped off. However, the reduction in cost of dropping the project is more than offset by the reduction in benefits at the higher price. Thus, 21 cents/KL is the optimum price found. For the unit cost method, at 18 cents/KL a further project is required whereas it is not until 24 cents/KL that the last project is not required. Thus for this method 19 cents/KL is optimal. On the other hand, the genetic algorithm is slightly different due to reasons discussed in the previous section. As mentioned, at different price levels different sequences will be optimal, mainly due to the last project sequenced. That is, at a higher price, if a lower cost project is available then with the lower demand this project may become optimal as it lowers PVC enough to increase the NPV. This will only occur if the benefits from the higher price are not greater than the reduction in PVC. The genetic algorithm tends to identify the optimum price quite quickly and then concentrates on finding the best sequence at that price. However, as mentioned previously with the change of optimal sequence between price this can cause problems with the genetic algorithm solution process.

Table 6.36 Optimum Price and Sequence for Demand Forecast 1 and Upsizing Cost Equal to 100 % of Incremental Cost

Method	Project Sequencing and Timing										Price ($/KL)	Adjusted NPV	PVC
Unit Cost	Project	1/2	8/2	7/2	9/3								
	Timing	9	24	31	40						19	690.03	134.79
Equivalent Cost	Project	8/2	1/2	7/2	8/3	1/3	7/3						
	Timing	11	19	34	44	47	49				21	698.92	109.79
Genetic Algorithm	Project	8/1	8/2	1/1	1/2	7/1	7/2	1/3	8/3	7/3			
	Timing	11	15	19	31	34	37	44	46	49	21	704.42	105.21

It can be concluded from these results that if upsizing cost is equal to incremental cost then all projects should start at their lowest size and then be upsized in order to obtain a lower PVC and higher NPV. Also the sequences produced by the equivalent cost and genetic algorithm method give a better sequence of projects. Thus, project 8 should be built before project 1 according to these results.

The result of increasing the upsizing cost to 120 % of the incremental cost for demand forecast 1 is shown in Table 6.37.

Again the GA provides the best solution. The GA method utilises the upsizing of projects to obtain a lower PVC and thus higher NPV. The first four projects for the unit cost and equivalent cost methods are the same except the latter method gives the best sequence of those projects. As was the case in the previous Tables the 50 year planning period plays a role in forming the optimum sequence and price. This factor distorts the results to an extent but only when examining the question of the last project to build. The GA method will provide the best solution for a finite period as it takes this into account. The interesting result in the above table is that of the price found for the unit cost and equivalent cost methods. Here almost identical sequences occur and it would be expected that the price would be the same. If the price was the same, the revenue, consumer surplus and operational cost would be the same and difference in NPV will be due to the difference in PVC. What happens above is that for the unit cost solution at 18 cents/KL another project is required, thus at 19 cents/KL there is a drop in PVC and therefore an increase in NPV. Now for the equivalent cost solution the same applies. However, a further increase in price delays the projects enough to produce a significant drop in PVC so much so that the NPV increases from the previous price. This further increase though will not provide the same benefits for the unit cost sequence and its optimum price will remain at 19 cents/KL.

Table 6.37 Optimum Price and Sequence for Demand Forecast 1 and Upsizing Cost Equal to 120 % of Incremental Cost

Method	Project Sequencing and Timing									Price ($/KL)	Adjusted NPV	PVC
Unit Cost	Project	1/2	8/2	7/2	9/3							
	Timing	9	24	31	40					19	690.03	134.79
Equivalent Cost	Project	8/2	1/2	7/2	9/3							
	Timing	10	18	32	42					20	694.59	122.73
Genetic Algorithm	Project	8/1	8/2	1/1	1/2	7/2	1/3	8/3	7/3			
	Timing	11	15	19	31	34	44	46	49	21	700.28	108.91

In regard to the change in upsizing cost, compared to the results of Table 6.36 there is less upsizing for increased cost. This is can be seen in the equivalent cost result where for the lower upsizing cost only three projects were used and all were upsized to their maximum size however, at the higher cost rather than upsizing the three projects a larger new project is built. This change also alters the price, with price going from 21 cents/KL to 20 cents/KL. A change also occurs in the GA result where project 7 is initial built to size 2 for the higher upsizing cost rather than being built to size 1 and then upsized to size 2. The unit cost sequence and price did not change.

The final study to examine for demand forecast 1, is the case of upsizing cost equal to 150 % of the incremental cost. The results of this case are shown in Table 6.38.

The GA gives the best result again and is the only solution where upsizing occurs. The sequences are similar for all the methods solutions with the same projects involved. The differences though are in the GA solution where there is upsizing of project 1 and a smaller size of project 9 is used and in the unit cost solution where project 1 is sequenced first and project 8 is next rather than the reverse. The GA solution illustrates the end of period effect mentioned earlier as project 9/1 is utilised to satisfy demand to the end of the period, whereas project 9/3 is sequenced for the other two methods as they consider the infinite planning period. The price difference shown in Table 6.38 is the same as what occurs in the Table 6.37 results and the reason for the price variation is discussed above.

Table 6.38 Optimum Price and Sequence for Demand Forecast 1 and Upsizing Cost Equal to 150 % of Incremental Cost

Method	Project Sequencing and Timing							Price ($/KL)	Adjusted NPV	PVC
Unit Cost	Project	1/2	8/2	7/2	9/3					
	Timing	9	24	31	40			19	690.03	134.79
Equivalent Cost	Project	8/2	1/2	7/2	9/3					
	Timing	10	18	32	42			20	694.59	122.73
Genetic Algorithm	Project	8/2	1/1	1/2	7/2	9/1				
	Timing	10	18	29	32	42		20	698.59	119.21

In regard to increased upsizing cost, the only difference occurs for the GA model where the number of projects upsized is reduced and project 9/1 replaces projects 1/3, 7/3 and 8/3. With this change in sequence the price decreases to 20 cents/KL. At 19 cents/KL for this sequence another project is required which results in a lower NPV.

The next step is to examine the results of using demand forecast 2 for the various upsizing costs. The results of this are shown in Tables 6.39, 6.40 and 6.41.

Again, the results show that the GA produces the best result and that the more upsizing the higher the NPV. The only problem with this conclusion is that in the GA result, project 5 should be augmented from size 1 to 2 rather than straight to size 2. A check was then carried out on the sequence with project 5 upsized from size 1 to 2 and it was found that the further upsizing produced a higher NPV. The value of NPV found for this increase in upsizing was $4337.87 million which is a slight increase over that found.

Table 6.39 Optimum Price and Sequence for Demand Forecast 2 and Upsizing Cost Equal to 100 % of the Incremental Cost

Method	Project Sequencing and Timing															Price ($/KL)	Adjusted NPV	PVC
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	8/3	1/3	7/3	13/1								
	Timing	7	14	18	25	32	40	42	44	45						24	4324.77	234.44
Equivalent Cost	Project	8/2	1/2	7/2	8/3	9/3	5/3	1/3	7/3	13/1								
	Timing	7	11	18	25	27	33	42	44	45						24	4328.38	231.43
Genetic Algorithm	Project	8/1	8/2	1/1	1/2	7/1	7/2	9/1	9/2	9/3	5/2	5/3	8/3	7/3	13/1			
	Timing	7	9	11	17	18	20	25	30	31	32	35	40	42	44	24	4337.56	223.55

Thus, the GA did not identify the optimal solution in this case, but found a near optimal solution in regard to NPV. However, the only reason that the extra upsizing of project 5 was checked was due to the results of the GA runs, where the full upsizing of project 5 was found to improve solutions when it occurred. Thus, although the GA cannot guarantee optimal solutions, if the results are studied in more detail, the optimum or a more optimum solution may be obtained. It is considered however, that the price obtained in the GA will be the optimum price for the problem examined.

All the methods produced the same price and the best sequences were produced by the GA and the equivalent cost method.

The upsizing cost is increased to 120 % of the incremental cost to examine the effect this has on the optimum price and sequence for demand forecast 2. These results are shown in Table 6.40.

Table 6.40 Optimum Price and Sequence for Demand Forecast 2 and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing												Price ($/KL)	Adjusted NPV	PVC
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1								
	Timing	8	16	19	27	34	44						26	4323.19	212.15
Equivalent Cost	Project	8/2	1/2	7/2	9/3	5/3	8/3	13/1	1/3	7/3					
	Timing	7	11	18	25	32	40	42	48	49			24	4326.53	233.16
Genetic Algorithm	Project	8/2	1/1	7/2	1/2	9/1	9/2	9/3	5/3	7/3	13/1	8/3			
	Timing	7	11	17	23	25	30	31	32	40	42	47	24	4330.54	229.64

The GA again produces the best results with the equivalent cost method providing a better solution than the unit cost method. In this case there is also a change between the price obtained for the unit and equivalent cost methods. The reason for this would seem to be due to different sequences being produced by the two methods. The unit cost in this case sequences only initial projects and there is no upsizing while the equivalent cost method utilises upsizing of projects to find a better NPV.

With regard to change in upsizing cost there is less upsizing when the cost increases. For the unit cost method the sequence goes from upsizing projects 1, 7 and 8 to not utilising them but increasing the price so that project 13/1 just satisfies demand for the period. In the equivalent cost solutions the price remains the same and the amount of upsizing does not change however, the upsizing of projects 1, 7 and 8 occurs later in the sequence. A similar observation can be made for the GA result, although project 1/3 does not occur in either sequence and project 5, 7 and 8 are initially built to a greater size than the minimum size when upsizing cost increases. It would appear from these results and the Table 6.39 results that when the upsizing of projects 1, 7 and 8 to their maximum size occurs then the price will be lower (24 compared to 26 cents/KL) than if the projects are not upsized.

It was seen in the results of Tables 6.39 and 6.40 that an increase in upsizing cost affected the size and sequencing of projects. Thus the upsizing cost is increased to 150 % of the incremental cost, the results of which are given in Table 6.41.

Table 6.41 Optimum Price and Sequence for Demand Forecast 2 and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing								Price ($/KL)	Adjusted NPV	PVC
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1				
	Timing	8	16	19	27	34	44		26	4323.19	212.15
Equivalent Cost	Project	8/2	1/2	7/2	9/3	5/3	13/1				
	Timing	8	12	19	27	34	44		26	4324.89	210.73
Genetic Algorithm	Project	8/2	1/2	7/2	9/3	5/3	13/1				
	Timing	8	12	19	27	34	44		26	4324.89	210.73

In this case the GA and the equivalent cost method produce the best solution. None of the solutions include upsizing of projects and the sequence are basically the same except for the initial sequencing of the unit cost method. However, after the initial projects the sequence is the same for the remaining projects. Therefore this initial difference in the unit cost method is the reason for its inferior solution.

In regard to upsizing change, the unit cost solution does not change from the previous upsizing cost as there was no upsizing at either level. For the other methods, the increase in upsizing cost results in there being no upsizing of projects compared to considerable upsizing with the lower upsizing cost. With the reduction in projects upsized there is also a price increase from 24 cents/KL to 26 cents/KL. For the above sequence produced at a price of 25 cents/KL another project would be required and with the increased upsizing cost the resultant increase in PVC would reduce the NPV.

The final section examines the results of using demand forecast 3 for the various upsizing costs. The results of this are shown in Tables 6.42, 6.43 and 6.44. The results of the setting the upsizing cost equal to incremental cost are shown in Table 6.42.

Table 6.42 Optimum Price and Sequence for Demand Forecast 3 and Upsizing Cost Equal to 100 % of the Incremental Cost

Method	Project Sequencing and Timing														Price ($/KL)	Adjusted NPV	PVC
Unit	Project	1/2	8/2	7/2	9/3	5/3											
Cost	Timing	10	22	28	35	42									23	2998.38	157.74
Equivalent	Project	8/2	1/2	7/2	8/3	9/3	5/3	1/3	7/3								
Cost	Timing	8	13	24	31	33	39	48	48						20	2999.02	187.40
Genetic	Project	8/1	8/2	1/1	1/2	7/1	7/2	9/1	9/2	9/3	1/3	5/1	5/2	5/3			
Algorithm	Timing	9	12	15	24	27	29	34	38	39	40	41	42	45	22	3008.95	159.33

The same conclusions as made in the previous Tables can be found with the results in Table 6.42 for this upsizing cost case. The more upsizing, the higher the NPV and the GA produces the optimum solution. The big difference however, is that prices obtained by the methods are all different. This is due to the sequences produced by the various methods and how they are effected by a drop in price. For instance, the equivalent cost sequence at 19 cents/KL will require a further project, which increases the cost to an extent that NPV will fall. At the prices of 21 and 22 cents/KL there are changes in the sequence due to the change in demand. The change in demand affects the time a project will last which in turn affects the equivalent cost of the project. At 21 cents/KL the projects 1/3, 5/3, 7/3 change in order so that project 5/3 is the last project sequenced and at this price it is still required. If the sequence found for the 20 cents/KL price was maintained for the 21 and 22 cents/KL prices then project 7/3 would not be required at the 21 cents/KL price and at 22 cents/KL project 1/3 would not be required. In fact at the price of 22 cents/KL, a better result is produced with a NPV of 3000.82 being found. However, in addition to the change in sequence of the projects just mentioned, there is also a swapping of projects 8/3 and 9/3 in the order at a price of 22 cents/KL. After, these changes the sequence does not change until 26 cents/KL when project 5/3 is no longer required, but this change does not produce a better result. For the unit cost solution the price of 23 cents/KL is optimum because at 22 cents/KL another project is required which will increase cost more than benefits increase and the price needs to rise to 26 cents/KL before project 5/3 will not be required and by this stage the decrease in cost will not offset the decrease in benefits.

The next step is to increase the upsizing cost to 120 % of the incremental cost. These results are given in Table 6.43.

Table 6.43 Optimum Price and Sequence for Demand Forecast 3 and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing										Price ($/KL)	Adjusted NPV	PVC
Unit	Project	1/2	8/2	7/2	9/3	5/3							
Cost	Timing	10	22	28	35	42					23	2998.38	157.74
Equivalent	Project	8/2	1/2	7/2	9/3	5/3							
Cost	Timing	10	16	28	35	42					23	3001.46	155.17
Genetic	Project	8/2	1/1	1/2	7/2	9/3	7/3	13/1	8/3	1/3			
Algorithm	Timing	10	16	25	28	35	42	43	47	49	23	3004.12	153.20

The same trend as previously found is shown in Table 6.43 with the GA producing the best result. The unit cost and equivalent cost methods produce similar sequences with the only variation being the swapping of projects 8/2 and 1/2. This is a similar result to that found in Table 6.37. Neither the unit cost nor the equivalent cost have any projects upsized in the sequences produced whereas the GA upsizes projects 1, 7 and 8 to produce the better result. In all the above cases 23 cents/KL is optimal as at 22 cents/KL another project is required and any further increase in price will not affect the PVC enough to create a higher NPV.

For a change in upsizing cost the unit cost results stay the same with no upsizing occurring. The equivalent cost results change the most with increased upsizing. At the lower upsizing cost level projects 1, 7 and 8 are upsized while with a higher upsizing cost no projects are upsized. With this change there is substantial increase in price obtained. For the increased upsizing cost the price jumps from 20 cents/KL to 23 cents/KL. This is primarily the result of the sequence change and the subsequent change in PVC with an increased upsizing cost. The GA result also changes significantly with a price increase of 1 cent/KL from 22 cents/KL to 23 cents/KL for an increased upsizing cost. Project 5 is no longer used for the higher upsizing cost case with it being replaced by projects 13/1, 7/3 and 8/3. This replacement of project 5 by these projects is made possible by the increase in price (ie. reduction in demand). In addition to this there is generally less upsizing of projects as project 9 is built to its maximum size and projects 7 and 8 are built to their middle size rather than the smallest size and then upsizing them. However, as mentioned, projects 7/2 and 8/2 are upsized to 7/3 and 8/3 respectively, but in total there is less upsizing.

The final case to examine is when the upsizing cost equals 150 % of the incremental cost for demand forecast 3. The results of this case are given in Table 6.44.

Table 6.44 Optimum Price and Sequence for Demand Forecast 3 and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing								Price ($/KL)	Adjusted NPV	PVC
Unit	Project	1/2	8/2	7/2	9/3	5/3					
Cost	Timing	10	22	28	35	42			23	2998.38	157.74
Equivalent	Project	8/2	1/2	7/2	9/3	5/3					
Cost	Timing	10	16	28	35	42			23	3001.46	155.17
Genetic	Project	8/2	1/1	1/2	7/2	9/3	5/3				
Algorithm	Timing	10	16	25	28	35	42		23	3001.89	154.93

As was the case in the previous Tables the GA result again produces the best solution. The GA solution is the only one which includes upsizing and this upsizing is the only difference in sequence between the GA and equivalent cost solutions. The unit cost solution is similar to the other method solution except for the initial sequence of projects 1 and 8. This is the same result as has appeared previously.

The only solution to change with increased upsizing cost for this case is the GA solution. In this particular situation with the increase in upsizing cost there is a reduction in the amount of upsizing of projects in the solution.

The next stage is to discuss the general conclusion from increasing upsizing cost and the effects it has on sequence and price. It has been shown that as upsizing cost increases that the number of projects upsized either decreases or the projects upsized are delayed in the sequence depending on the magnitude of upsizing cost. For the GA method as upsizing cost increased the NPV decreased. However, this was not the case for the equivalent cost solutions using the demand forecast 3. In this case with the initial increase in upsizing cost the NPV increased from the previous upsizing cost. Associated with the change was an increase in price from 20 cents/KL to 23 cents/KL and at the higher price there was no upsizing of projects. This would seem to indicate that there is no benefit in using upsizing, however from the results of the GA method this would indicate the above case was an exception. What can be concluded from these results, is that there is a benefit with upsizing when the cost is reasonable, but if upsizing is taken to the extreme some of the benefit may be lost (ie. if all projects are upsized to their maximum level when better cost alternatives are present). Thus, when upsizing cost equals incremental cost, the upsizing of projects should be at a maximum and with higher upsizing cost the upsizing of projects is less likely to occur. The decision on the upsizing of the projects is dependent on the cost and yield of the projects as well as the demand forecast expected.

When the upsizing cost was increased to a stage where the upsizing of projects was reduced to zero or a minimum (ie one or two) there was also a change in price. For demand forecast 1 the change in price was a decrease and for the other demand forecasts the change in price was an increase. The change also was the same for all methods, either going from 21 to 20 cents/KL or going from 24 to 26 cents/KL or from 20 to 23 cents/KL. The only explanation for this may be that projects 1/3, 7/3 and 8/3 were the projects upsized at the lower upsizing cost and with the increase in upsizing cost these projects drop from the solution. In the demand forecast 1 case these projects are replaced by a larger project 9 and the price drops, whereas in the other demand forecast cases the projects are not replaced and the price must rise so the remaining projects satisfy demand. It would appear that the whether the price rises or falls depends on the demand forecast and the available projects remaining to be built.

A comparison can be also made between the results of the not allowing upsizing case and allowing upsizing case. For the GA method the case with upsizing allowed, produces the higher value of NPV compared to the no upsizing case in all but one situation. This is when the upsizing cost equals 150 % of incremental cost and the demand forecast 2 is used. In this particular case the sequence and price produced are the same for the upsizing and no upsizing cases. As you would expect the sequence produced has no upsizing of projects involved. This would clearly indicate benefits in considering and using upsizing of projects. For the equivalent cost method for demand forecasts 1 and 3 at an upsizing cost equal to 120 % of the incremental cost there was no upsizing in the solution for the upsizing case. The sequence produced was the same for the no upsizing problem. For the demand forecast 2 this does not occur until the upsizing cost is 150 % of the incremental cost. The same occurs for the unit cost method although for demand forecasts 1 and 3 it occurs when upsizing cost equals 100 % of the incremental cost and at 120 % for demand forecast 2. The only case where the no upsizing case provides a better result than the upsizing case is for the equivalent cost method for demand forecast

3 and an upsizing cost equal to 100 % of the incremental cost. This particular situation was highlighted previously.

6.8 Conclusions from the Pricing, Sequencing and Sizing Study

The results of this study illustrate that upsizing of projects can be beneficial in financial terms when considered in the planning of a water resource system. If it was found that upsizing of a project could occur at a cost close to its incremental cost and sufficient extra yield would become available then it would be appropriate to utilise upsizing.

With regard to the methods utilised it was found the GA produced the superior results for this study. However, for the no upsizing case if the end of period problem with the equivalent cost method was not present, the equivalent cost method would have produced the same sequence of projects for all demand forecasts. As it was, it produced the same sequence for demand forecasts 2 and 3 but sequenced project 9/3 as the last project for the demand forecast 1 case, which resulted in a different price for this case when compared to the GA result. However, the performance of the equivalent cost method was lower when considering the upsizing case, although in both problems it performs better than the unit cost method. The unit cost method was the inferior model for the problems examined in this study.

In regard to the pricing study, it was found that the price obtained is considerably less than that assumed to be the initial price. It is also greater than the expected short-run marginal cost of supply, which is expected to be approximately between 12 to 15 cents/KL. This expectation is based on the operational cost of 10 cents/KL and the present value of maintenance cost for the future reservoir over the 50 year planning period. This price of water could be considered to be lower than expected and thus produce a higher consumption of water than would otherwise be desirable. However, from an economic perspective water is considered to be a "good" which should be utilised to its full extent. Thus the optimum price in the study was usually found when the water in the system was being fully utilised over the planning period.

The price obtained in this study is considered one part of a two part tariff system for residential water pricing. This price is the price per KL used for every KL used. The second part of the tariff structure would be a fixed charge cost which is commonly called an "access charge". This access charge will account for those cost which do not effect the demand based on the analysis performed. Those costs expected to be incorporated in this price are the cost not effected by demand, such as replacement of existing infrastructure (ie pipes, weirs, etc) or interest cost if applicable. For equity reasons this cost may be determined based on property value or income levels or some other evaluation criteria. This cost should be a constant charge with no allowance of water associated with it, so that the tariff system is primarily a user pay system which will give the correct signals to consumers in regard to the cost of water.

In conclusion it was found that the GA method produced the best results for the upsizing and no upsizing cases. However, the equivalent cost method could be used when upsizing is not to be considered. Upsizing was shown to be of benefit in regard to increased NPV when considered and thus if it is possible to do so it is recommended that upsizing be a serious consideration in water resources planning. The study developed techniques to find the optimum price and sequence of water resource projects. The price found would seem to be marginally higher than the short-run cost of supply but considerably lower than the average price. Such a price encourages usage of the systems water and it may be argued that this will act against conservation. However, the benefit of this pricing structure is that it maximises the consumer benefits, while satisfying the cost recovery requirement of the water authority and gives the consumer the correct signals to the true cost of water.

The final section to examine is that of planning and management of a reservoir system. Lane (1991) presents a report on the results of a study into the planning and management of the South-East Queensland system. The economic criteria used for sizing and sequencing of possible water resource, is the unit cost of the resource. In addition, environmental, social and hydrological factors were included in the capacity expansion decision. As mentioned, demand management has been considered as part of the demand forecasts, although the study list the most effective demand management techniques. The estimate of reduction in demand following implementation of these measures is approximately 20 %. Such a reduction is thought to defer system augmentation from between 10 to 40 years depending if high or medium demand is considered. The demand forecast used in the study were medium growth with no demand management and with 20 % demand management and high demand growth with 20 % demand management. The report outlines the best expansion schedule to satisfy all demand scenarios and the various objectives until the year 2090. It includes a discussion on the environmental and social aspects of the problem and stresses the need for public consultation so particular plans are public acceptable and to reduce the negative reaction of affected consumers.

Chapter 7

Case Study 3 : The Perth Water Supply System

7.1 Introduction

In Chapters 4 and 6 the methodology of Chapters 3 and 5 has been used to solve the water resources capacity expansion problem. The two problems examined have been different in that the Canberra case study (Chapter 4) examined the simple sequencing of fixed sized projects and the South-East Queensland study (Chapter 6) examined the size and sequencing of projects. The two studies are similar in that they both use the capital costs of the projects as the economic evaluation measure for the sequence of projects determined. Another cost which may be important is the operational cost of a project. A project may have a lower capital cost but if its operational cost is high it may be less desirable to sequence this project before other projects with lower operational costs. Operational costs are particularly important for groundwater schemes.

A problem with including the operational cost in the sequencing of future projects is that it may not be known with sufficient accuracy. For the case study of the Perth Water Supply System described in this chapter, detailed estimates of both operational and capital cost as well as project yield have been obtained from the Western Australian Water Authority (WAWA)(Stokes, 1993). Thus this case study will examine the effect of including the operating cost in the evaluation of a project sequence. Therefore the aim of sequencing is to obtain the lowest present value of total cost (PVTC) sequence which includes the present value of operating cost (PVOC) and the present value of capital cost (PVC).

The methods utilised to obtain this lowest PVTC sequence are detailed in Chapters 3 and 5. The methods are the unit cost method, two variations of the equivalent cost method and the GA. The unit cost method used in this study is an improvement on that previously used in Chapters 4 and 6. The unit cost method used incorporates the discount rate and the operating cost of a project as well as the projects capital cost and yield (Equation 3.11). This is the method utilised by the WAWA to sequence future projects and is detailed in Stokes and Stone (1993). The equivalent cost method utilised in previous chapters is used here as well as a modified equivalent cost method. The modified method includes the operating cost of a project within the sequencing procedure. The purpose of using the traditional equivalent cost method is to enable a comparison of the PVTC between a method which sequences based on capital cost only and one which includes operating cost as well as capital cost. The other method to be used is the GA method described in Chapter 5. Thus the ability of the GA to include the operating cost and capital cost in the sequencing decision will be examined.

The Perth water supply system was chosen as a case study because of the availability of capital and operating cost data. The factors included in the study are the cost and yield of the various sources and three likely demand growth scenarios. The costs of a project include capital, conveyance and operating cost. The conveyance cost is the cost of building additional pipelines and pump stations to transfer water to the actual demand centre. The effect of including the conveyance cost on the sequencing of projects will also be investigated.

The results of this study will indicate the relative importance of capital and operational cost in the planning decision.

7.2 The Perth Water Supply System

The Perth Water Supply System has a number of new water supply alternatives. These consist of surface water resources, groundwater resources and other alternative supplies. The Water Authority of Western Australia (WAWA) have grouped these resources into six categories based on cost, available technology and information. Descriptions of the six categories are given by Wykes and Majer (1993) and are as follows:-

1) Medium term:- likely to be viable to the year 2010 (unit cost <60 cents/KL)
2) Research and development
3) Long-Term:- expensive at present time (60 cents/KL< unit cost <100 cents/KL)
4) Very long-term:- too expensive now(100 cents/KL< unit cost <300 cents/KL)
5) Non-feasible:- expensive and/or environmentally unacceptable (unit cost>300 cents/KL)
6) Private supply

The unit costs were determined by WAWA using a method which incorporates project yield, capital and operating cost and the discount rate. A discussion of this method is presented in Chapter 3.

In this study only the projects in category 1 will be considered. The reason is that it is unlikely that all these projects will be needed in the planning period and projects in the other categories are going to be less desirable than those in category 1. In category 1 there are 9 projects whose costs and yields are given in Table 7.1. These cost and yield values are taken from Stokes (1993).

In addition to using the traditional reservoirs and groundwater schemes as future water resources alternatives the Perth Water Supply System also uses pipeheads and pumpbacks. A pipehead is a small dam only large enough to allow the water flowing in the river to be diverted into a pipe. The water is supplied to consumers in the same way as water from a dam (Mauger, 1989). A pumpback uses the same type of small dam on a river as a pipehead, to divert the streamflow, but instead of delivering the water for immediate use, the water is pumped though a pipeline into a major reservoir (Mauger, 1989).

As noted above, four of these projects require additional cost for connection to the existing system. This is termed a conveyance cost. The conveyance cost is expressed in cents/KL and consists of the capital cost of pipelines and pump stations and the operating cost to pump the water to the existing supply network. The actual break-down of the conveyance cost was not available so an assumption was made on the relative proportions of the operating and capital cost in the total conveyance cost. It was assumed that the present value of operating cost would be 36 % of the present value of capital cost. The 36 % figure was based on data supplied by Ng (1993). Table 7.2 shows the four projects with the conveyance cost included into the capital and operating costs

The demand growth rates used in this study were taken from Stokes and Stone (1993) and are shown in Table 7.3.

Table 7.1 Perth Water Supply System Costs and Yields of Projects

Project	Description	Annual Yield (GL)	Capital Cost ($Million)	Annual Operating Cost ($Million/year)
1**	Gnangara Mound GW	75.7	183.8	15.6
2**	North-West Corridor GW	60.9	119.8	13.5
3	Jandakot Mound GW	5.0	15.5	1.1
4	Serpentine GW	17.3	60.3	5.2
5	Jane and Susannah PH	12.8	49.5	2.8
6	Serpentine-Dandalup PH	25.4	66.9	3.2
7**	Harvey Dam / Wellesley PB	51.0	91.7	8.8
8	Mundaring / Canning Dams	21.0	90.4	0.7
9**	Irrigation Water	66.9*	85.4	2.0

GW-groundwater, PH-pipehead, PB-pumpback

* - The figure 66.9 GL is a maximum possible yield if all available irrigation water is diverted.

** - These projects have an associated conveyance cost as well as the costs shown in the Table. The conveyance cost is the cost of connecting the resource to the existing supply system.

The growth rate in demand is assumed to be linear as there was no information available on this. In addition, it is assumed that the yield of the existing system is the same as the demand and therefore a new resource is needed immediately. The discount rate for the study is 6 % which is the same as that used by the WAWA and the planning period considered is 19 years.

Finally, the utilisation of projects in regard to operating cost needs to be discussed. For this study it is assumed that once a project is expanded the operating cost per year for that project will be incurred for the remainder of the years until the end of the planning period. This is regardless of the utilisation of the project, thus if it is only being utilised to 50 % of its capacity the same operating cost per year will be incurred as if it was being fully utilised.

Table 7.2 Inclusion of Conveyance Costs for the Appropriate Projects

Project	Capital Cost ($ Million)	Annual Operating Cost ($ Million/year)
Gnangara Mound GW	190.1	17.88
North-West Corridor GW	126.1	16.49
Harvey Dam / Wellesley PB	118.0	18.27
Irrigation Water	122.0	15.20

Table 7.3 Three Likely Demand Scenarios from 1991 to 2010

Demand Growth Rate Scenarios	Demand (GL/Year)		Growth Rate (GL/Year)
	1991	2010	
(1) Minimum Growth	251	335	4.42
(2) Most Likely Growth	251	369	6.21
(3) Maximum Growth	251	414	8.58

7.3 Methodology

The methodology used in this study is detailed in Chapter 3 and Chapter 5. The sequencing methods included the unit cost method (UC) defined by Equation 3.11, the equivalent cost per period method without operating cost included (EC1) and with operating cost included (EC2) which are illustrated by Equations 3.13 and 3.15 in Chapter 3 respectively and the genetic algorithm method as discussed in Chapter 5. No further explanation is required for the unit cost or equivalent cost methods. However, a discussion is required for the GA to define the model and the parameter values utilised.

7.3.1 Genetic Algorithms

In Chapter 6 the results of Chapter 5 and a small sensitivity analysis of the GA Models T1, T5 and T6 for the problem considered indicated Model T1 was the best to use. However, with the change of problem it is considered that Models T5 or T6 will perform either better or to the same level as Model T1. Although an extensive sensitivity analysis was not performed for this study, the problem to be examined is similar to the 10 project problem examined in Chapter 5. As a result of the Chapter 5 analysis it was concluded that Models T1, T5 and T6 should undergo further analysis for the specific problem of sizing and sequencing as it was sufficiently different to that used in Chapter 5. However, like the example used in Chapter 5, the case study here is a straight forward sequencing problem. Therefore the results of the Chapter 5 example will be used to determine the best model to use out of the three indicated. In Chapter 5 it was concluded that all models produced the lowest PVC result although Model T1 converged at a slower rate than Models T5 and T6. For the problem examined, Model T1 found the solution after examining only 0.124 % of the possible search space. If the results of Models T5 and T6 are examined this percentage is halved. In addition, with Model T1 when the lowest PVC solution was obtained, that solution was not always maintained in the following generations. In fact it was found that the optimum solution for the remaining generations fluctuated between the optimum and values within approximately 0.25 % of the optimum. However, for both Models T5 and T6 the lowest PVC solution was always present in the following generations. For these reasons the decision of which model to use is reduced to either the Model T5 or Model T6. It was decided to use Model T6 with string mutation for this case study based on the conclusions and results of Chapters 5 and 6 and the above discussion. The use of string mutation was considered to be the better mutation operator due to its benefits over bit mutation described in previous chapters.

The model parameters which will be used with Model T6 for this study are a population of 100, probability of crossover and mutation of 90 % and 10 % respectively and 200 generations. As a brief reminder Model T6 uses real coding and a random swap mutation operator. When using a real coding structure, the bit position represents the position of a project in a sequence and the integer value of the bit represents the project number. The GA Model will be run three times per case and the minimum PVC solution from the three runs will be presented. It is considered that if on all three occasions the same result is produced then the result will be close to the optimum.

A final note must be made before the case study is undertaken. It is considered that the Model T5 will perform to a similar level as Model T6 and in fact the two models are used in conjunction for this study, however Model T6 has the more predominant usage. Thus on occasions both models are used to investigate if the best solution is being obtained. On these occasions it was found that both models produced the same results and had equivalent performance. A further analysis of the Models T1, T5 and T6 for this problem is performed in Chapter 8 to examine the best model for the sequencing of water resources.

7.4 Results

7.4.1 Base Case

The models were run for the various demand growth scenarios. In addition to these the case where conveyance cost was not included was also examined. This was carried out to ascertain whether the inclusion of conveyance cost is important in the planning decision. The results of not including the conveyance cost are shown in Tables 7.1 to 7.3 and the results when the conveyance cost is included are given in Tables 7.4 to 7.6. For the following discussion the description PVCC represent present value of capital cost, PVOC the present value of operating cost and PVTC is the present value of total cost.

From these results it was found that the GA produced the solution with the lowest PVTC in all cases. This is thought to be because of its ability to consider the PVCC and PVOC more directly than the other methods. Another problem with the other methods is that the sequence determined is for the case when all projects are required. However, in this study there is a finite planning period. The result of this is that the other methods may sequence a much larger project at the end of the planning period than is actual required to satisfy the demand for the remainder of the period. In fact a smaller, less expensive, project could satisfy demand for the remainder of the period which will result in a lower PVTC. This problem has also been experienced in the previous case studies.

Table 7.4 Sequence of Projects with No Conveyance Cost for Minimum Demand Growth

Sequencing Method	Project Sequence						PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	9	7						
	Timing	0	15				123.66	35.04	158.70
EC1	Project	9	7						
	Timing	0	15				123.66	35.04	158.70
EC2	Project	9	8						
	Timing	0	15				123.12	23.33	146.45
GA	Project	9	3	5					
	Timing	0	15	16			111.35	26.85	138.21

Table 7.5 Sequence of Projects with No Conveyance Cost for Most Likely Demand Growth

Sequencing Method	Project Sequence						PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	9	7	6					
	Timing	0	10	18			160.04	56.80	216.84
EC1	Project	9	7	2					
	Timing	0	10	18			178.58	60.20	238.78
EC2	Project	9	6	8	7				
	Timing	0	10	14	18		194.87	38.68	233.55
GA	Project	9	3	7					
	Timing	0	10	11			142.36	55.28	197.64

Table 7.6 Sequence of Projects with No Conveyance Cost for Maximum Demand Growth

Sequencing Method	Project Sequence						PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	9	7	6	8				
	Timing	0	7	13	16		213.34	79.50	292.83
EC1	Project	9	7	2					
	Timing	0	7	13			202.55	102.51	305.06
EC2	Project	9	6	8	7				
	Timing	0	7	10	13		223.36	63.11	286.47
GA	Project	9	8	6	7				
	Timing	0	7	10	13		225.87	58.66	284.53

Table 7.7 Sequence of Projects with Conveyance Cost Included for Minimum Demand Growth

Sequencing Method	Project Sequence						PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	6	8	9					
	Timing	0	5	10			202.58	98.30	300.87
EC1	Project	9	2						
	Timing	0	15				174.62	193.45	368.45
EC2	Project	8	6	3	5	9			
	Timing	0	4	10	11	14	232.08	74.09	306.17
GA	Project	6	9						
	Timing	0	5				158.07	141.28	299.35

Table 7.8 Sequence of Projects with Conveyance Cost Included for Most Likely Demand Growth

Sequencing Method	Project Sequence						PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	6	8	9	1				
	Timing	0	4	7	18		286.24	131.75	417.99
EC1	Project	9	2						
	Timing	0	10				192.41	232.23	424.65
EC2	Project	6	8	3	9				
	Timing	0	4	7	8		225.36	122.44	347.80
GA	Project	6	8	3	9				
	Timing	0	4	7	8		225.36	122.44	347.80

Table 7.9 Sequence of Projects with Conveyance Cost Included for Maximum Demand Growth

Sequencing Method	Project Sequence							PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	6	8	9	1					
	Timing	0	2	5	13			327.65	189.03	516.68
EC1	Project	9	2	7						
	Timing	0	7	14				258.06	295.59	553.64
EC2	Project	6	8	3	9	5	2			
	Timing	0	2	5	5	13	15	325.93	185.75	511.68
GA	Project	8	6	9	2					
	Timing	0	2	5	13			300.23	181.24	481.47

In the cases when conveyance cost is included (Tables 7.7 to 7.9) it is found that the GA gives the lowest cost solution and for the most likely demand growth the EC2 method achieves the same solution as the GA. The EC2 produces a lower cost solution than the UC method for the maximum demand growth but a higher PVTC for the minimum demand growth case. The Model EC1 produces a higher PVTC than the EC2 and UC Models for all demand growth rate cases. The savings in PVTC by using the GA method compared to the UC method range from 0.5 % for the minimum demand growth rate case to 16.8 % for the most likely demand growth rate case. The savings for the maximum demand growth rate case lies between these values.

As demand grows the sequence of projects should change and it is likely that more projects and larger projects will be sequenced. A conclusion which can be made from the change in sequence of projects for different demand growths, as well as the results of the different models, is the relative importance of PVCC and PVOC in regard to the value of PVTC. For the lower demand growth rates the results of the GA Model indicates that the significance of PVCC is greater than PVOC for lowering PVTC. The reason for this conclusion is that the GA Model produces a higher PVOC than the EC2 and UC Models. However, as the demand growth rate increases the GA produces lower values of PVOC than the other methods. In the case of the GA Model the sequence changes in an interesting way for the case of maximum demand growth. At the maximum demand growth the four projects implemented are actually ordered from lowest to highest operating cost. However, for the most likely demand growth the order of projects is different. The result is the lowest possible value for PVOC and a higher value for PVCC than the minimum that can be achieved for this case. Thus, the lowering of PVOC at the expense of increasing PVCC results in a lower PVTC. Thus it appears that PVCC is of greater importance than PVOC to the value of PVTC for low demand growth, but the relative importance of PVOC to lowering the value of PVTC grows as demand growth increases. To ignore either the capital cost or operating cost in the planning decision would result in only average solutions. This is seen in the EC1 Model results where only capital cost is used and the minimum PVTC is not achieved in any of the cases examined by this method. As the GA results show, the best results (ie. lowest PVTC) are found when both capital and operational cost are included in the decision making process and tradeoffs are made between the lowering of PVCC and PVOC.

The inclusion of conveyance cost is found to be of great importance as not only does it contribute substantially to the PVTC, but it changes the capital and operation cost of the projects involved sufficiently to warrant a delaying of the projects. This is indicated by projects 9 and 7 appearing early in the order for the no conveyance cost case and then being delayed when conveyance costs are introduced. The projects that precede projects 9 and 7 are those which do not require any conveyance structures to be built to meet the demand.

From this study of the Perth system, it appears the best projects to build first are Serpentine-Dandalup PipeHead (6), Raising Mundaring and Canning Dams (8), Irrigation Water (9), North-West Corridor groundwater (2) and Jandakot Mound groundwater (3). The order of these projects is dependent on the demand growth rate assumed. In addition, the result of this study may be affected by the actual volume which can be supplied from project 9, the irrigation water relocation scheme. A further analysis of this will be presented later in this study. If there is a considerable drop from the 66.9 GL/year expected, then project 9 may no longer be a suitable future project. Finally, if we assume the most likely demand scenario and demand growth is linear, then the sequence of projects to satisfy demand to the year 2010 will 6, 8, 3 and 9, provided the assumption regarding operating policy is reasonable.

As demonstrated, the selection of the best project sequence is dependent on both PVCC and PVOC. It is unlikely that the sequence with the lowest PVCC for all projects (ie. the solution found by Model EC1) will result in the lowest PVTC nor will the sequence producing the lowest PVOC. However, it appears that for low growth rates in demand it is more important to reduce PVCC in order to reduce PVTC. As the demand growth rate increases and operating cost starts to contribute more to the PVTC then the subsequent importance of operating cost increases. However, the relative importance of both is relative to the situation being examined and at no stage should either be ignored in the planning decision. Some of the factors effecting the relative importance of both costs are the project yield and cost, planning period, discount rate, demand growth rate and operating policy of the system. Thus the best solutions are obtained when both capital cost and operational cost are considered, as well as the other factors mentioned, and tradeoffs are made between the PVCC and the PVOC to lower the PVTC.

The effect the discount rate has on the sequencing of projects in this case was also examined. The discount rates of 3 and 9 % will be examined for the most likely demand growth rate with conveyance cost included. The results of this study are shown in Tables 7.10 and 7.11.

In Tables 7.10 and 7.11 it can be seen that the discount rate effects the sequencing of projects. In both tables the GA and EC2 method produced the lowest PVTC result. In these cases the UC method performance was not as good as previously seen. The change in sequence obtained with a increase in discount rate is the initial projects 6 and 8 are reversed in their order. For the higher discount rate the lower capital cost project 6 is sequenced first. This is because at a high discount rate the initial cost is more important as cost which are delayed are very small in present value terms. Thus building a lower cost project initially may result in a lower PVTC. By this reasoning the PVOC will tend to be lower for higher discount rates and projects with higher operating costs may become more favourable at higher discount rates, particularly if their capital cost is low.

Table 7.10 Sequence of Projects with Conveyance Cost Included for Most Likely Demand Growth and a Discount Rate of 3 %

Sequencing Method	Project Sequence						PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	8	6	9	1				
	Timing	0	3	7	18		362.48	180.03	542.51
EC1	Project	9	2						
	Timing	0	10				215.83	313.26	529.09
EC2	Project	8	6	3	9				
	Timing	0	3	7	8		260.53	166.74	427.27
GA	Project	8	6	3	9				
	Timing	0	3	7	8		260.53	166.74	427.27

Table 7.11 Sequence of Projects with Conveyance Cost Included for Most Likely Demand Growth and a Discount Rate of 9 %

Sequencing Method	Project Sequence						PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	6	9	8	2				
	Timing	0	4	14	18		207.11	119.46	326.57
EC1	Project	9	2						
	Timing	0	10				175.27	177.80	353.07
EC2	Project	6	8	3	9				
	Timing	0	4	7	8		200.65	88.86	289.51
GA	Project	6	8	3	9				
	Timing	0	4	7	8		200.65	88.86	289.51

The GA Model finds the best results as it considers capital and operating cost and operating policy simultaneously. The other models do not do this and also suffer from the deficiency that they apply to an infinite planning horizon. They may therefore schedule an unnecessarily large project towards the end of the (finite) planning period. The conveyance cost was found to be an important factor in project sequencing as was the percentage that the operating cost contributes to the conveyance cost. However, a more detailed analysis of the composition of the conveyance cost of individual projects would be beneficial to produce more accurate results. The reason is that in this study all projects are assumed to have the same proportion of operating cost to capital cost for the conveyance cost, whereas this is unlikely to be the case in the real system. The proportions will depend on project location, demand location and the topography separating the two locations.

7.4.2 Effect of Subdividing Projects

This study is a variation on the initial study in which a number of projects are split into smaller projects based on conveyance cost and yield of the projects. Currently all the projects are made up of many smaller projects. Within the current project groups there are some which require conveyance structures to supply demand and others which do not. For instance consider the Gnangara Mound groundwater scheme. This scheme consists of six smaller projects of which two require conveyance structures. When the Gnangara scheme is considered as one scheme the conveyance costs are assumed to apply to all projects. This gives the perception of a higher operating and capital cost for the other projects in the group which do not require conveyance structures. In reality however, a considerable volume of water can be supplied before the conveyance structures are required and therefore the cost of these structures can be delayed to a later time. Thus in this study those projects requiring conveyance structures are grouped together, if the conveyance costs are approximately the same and the individual yields are under 10 GL/year. In the case where a scheme consists of projects with no conveyance cost and all having yields smaller than 10 GL/year then all the projects are grouped as one (ie. Serpentine-Dandalup pipehead project). Other projects are split if there is no reliance on another project or the operating costs are such that there is a distinct advantage in operating one project separately from another. The gains which can be obtained from this process are a reduction in the PVCC as the same total capital cost will still apply but it is incurred over a greater time and therefore is more heavily discounted. There is also likely to be a reduction in PVOC as those projects with no conveyance cost will have lower operating cost and capital cost and if they are built then a lower PVOC may occur. The result of splitting the nine original projects is the production of a 15 project system whose costs and yields are shown in Table 7.12. The costs shown in this Table do include the conveyance costs.

Table 7.12 Extended Perth Water Supply System Projects Cost and Yield

Initial Scheme	Project Number	Project Description	Annual Yield (GL)	Capital Cost ($Million)	Annual Operating Cost ($Million/year)
Gnangara Mound Ground Water (GW)	1	Mirr/Lex/Muc	22.5	61.9	5.0
	2	Pinjar 2 & 3	26.6	52.1	4.6
	3	Yeal/ Barragoon	26.6	76.1	8.28
North-West Corridor GW	4	Whitfords	14.0	27.4	3.16
	5	Eglington	18.0	39.6	5.88
	6	Yanchep	10.9	23.3	3.23
	7	Quinns	18.0	35.8	4.22
Jandakot Mound GW	8	Jandakot Mound GW	5.0	15.5	1.1
Serpentine GW	9	Serpentine GW	17.3	60.3	5.2
Jane and Susannah PH	10	Jane and Susannah PH	12.8	49.5	2.8
Serpentine-Dandalup PH	11	Serpentine-Dandalup PH	25.4	66.9	3.2
Harvey Dam / Wellesley PB	12	Harvey Dam / Wellesley PB	51.0	118.0	18.27
Mundaring / Canning Dams	13	Mundaring / Canning Dams	21.0	90.4	0.7
Irrigation Water	14	Waroona D/ Sam B/Log B	27.9	46.1	4.70
	15	Stirling Dam	39.0	75.9	10.5

The splitting of the projects also enables the yield of project 9, to be examined in more detail. As can be seen from Table 7.12 the original project 9 is split into two projects. One consists of 3 smaller projects and the other of a single large project. This is done as the large project contributes a larger proportion of the capital and operation cost of the original project 9 and has a much larger conveyance cost than the three smaller projects. This splitting also allows the study to consider drawing smaller increments from the irrigation water scheme.

In the above Table the original project description is given and the subsequent new projects are shown adjacent to the description. A brief description is needed for Gnangara Mound groundwater and the irrigation water scheme. As is seen, Gnangara Mound groundwater is split into three projects. The first consists of three small schemes which are Mirrabrooke, Lexia and Muchea, the second is Pinjar stage 2 and 3 and the third is the dual system of Yeal and Barragoon projects both of which include conveyance costs. The first project in the irrigation water scheme consists of three smaller projects namely Logue Brook Dam, Sampson Dam and Waroona Dam and the second is the Stirling Dam.

The percentage of operating cost to capital cost in the conveyance cost is again assumed to be 36 %. These results will then be compared to the same cases for the 9 project problem. The results of this study are shown in Tables 7.13 to 7.15.

Table 7.13 Sequence of Projects with Conveyance Cost Included for Minimum Demand Growth

Sequencing Method	Project Sequence						PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	14	11	2	13				
	Timing	0	6	12	18		150.83	85.41	236.23
EC1	Project	14	4	7	6	2			
	Timing	0	6	9	13	16	118.04	102.84	220.87
EC2	Project	14	13	11	2				
	Timing	0	6	11	16		165.58	72.12	237.70
GA	Project	14	2	4	8	6			
	Timing	0	6	12	15	16	112.09	94.91	206.99

Table 7.14 Sequence of Projects with Conveyance Cost Included for Most Likely Demand Growth

Sequencing Method	Project Sequence							PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	14	11	2	13	4	7			
	Timing	0	4	8	12	16	18	200.03	106.49	306.52
EC1	Project	14	4	7	2	6	15			
	Timing	0	4	6	9	13	15	166.47	145.76	312.73
EC2	Project	14	11	13	2	4	7			
	Timing	0	4	8	11	16	18	206.58	100.29	306.88
GA	Project	11	14	2	4	7	6			
	Timing	0	4	8	12	15	18	172.82	110.56	283.38

Table 7.15 Sequence of Projects with Conveyance Cost Included for Maximum Demand Growth

Sequencing Method	Project Sequence										PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	14	11	2	13	4	7	15					
	Timing	0	3	6	9	11	13	15			255.40	146.60	402.00
EC1	Project	14	4	7	2	6	15	5	12				
	Timing	0	3	4	6	10	11	15	18		247.53	207.99	455.51
EC2	Project	14	11	13	2	4	7	8	1	6			
	Timing	0	3	6	8	11	13	15	16	18	268.90	134.71	403.61
GA	Project	14	11	2	7	4	15	8	6				
	Timing	0	3	6	9	11	13	17	18		224.13	163.05	387.17

Once again the GA produces the least cost solution for all the growth rates. In addition, the PVTC in this study is considerably less than the equivalent study with only 9 projects. Similar results were found in this study as for the 9 project case. The improvement in PVTC is brought about by a reduction in PVCC and in the PVOC. The reduction is greater in the PVCC than the PVOC. This would seem to indicate that the PVCC plays a more significant role than the PVOC. This is a similar conclusion to that found in the previous study. It seems more projects which are cheaper in capital cost will be expanded even if they have higher operating costs. From the GA results the most likely first projects are Waroona Dam, Sampson Brook Dam and Logue Brook Dam (14), Serpentine-Dandalup pipehead (11), Pinjar stage 2 and 3 (2), Quinns (7) and Whitfords (4). The order of these projects will vary with the demand growth. These above projects are found in projects 1, 9, 6 and 2 for the 9 project example. The savings in PVTC by using the GA method compared to the UC method range from 3.7 % for the maximum demand growth rate case to 12.4 % for the minimum demand growth rate case.

7.4.3 Effect of Planning Period

One problem which needs to be examined is that of the finite planning period. As was mentioned in the results of the previous sections, the finite period can affect the PVCC obtained by the methods which assumed all projects are needed. The effect is a higher PVTC than is possible as a larger project may be built near the end of the planning period, where a smaller, less costly project could satisfy the remaining demand. Thus a lower PVCC can be obtained resulting in a lower PVTC. The short planning period utilised previously means that this end of period effect can be significant. Thus, with a 19 year planning period the results of the GA will be better than the other methods partially due to this end of period effect as the GA is the only method which allows for the finite period. However, it must be stressed that this problem is not the sole reason for the GA producing better results and the following study which utilises an extended period is undertaken to highlight this. The planning period considered is 40 years. This will help reduce the finite period effect but will not eliminate it entirely. The only way to eliminate the finite period effect is to use a period which requires all projects to be expanded. This in fact will occur for the maximum demand growth rate for the 40 year planning period, so this result will be of great interest. It will be assumed that the demand growth is linear for the 40 year planning period and the same as the growth rate in demand for the shorter planning period. The case of both 9 and 15 available projects will be considered.

The first study to be examined uses the original 9 projects. The results of this are shown in Tables 7.16 to 7.18.

The results again show that the GA produces the lowest PVTC solution. The percentage difference between the GA and the other methods based on the figures presented decreases as the demand growth increases. The next best solution was found by the EC2 method. In fact the sequences produced by the GA and the EC2 method are very similar. For the minimum demand growth the first three projects are the same, for the most likely growth case the first six projects are the same and for the maximum growth case all projects sequenced are the same but the order is different. In the case of the maximum growth rate however, this can be said for all methods as all projects are required. However, the sequence produced by the GA and EC2 methods are similar for all demand growths with the major differences being swapping of adjacent projects in the order. The finite period problem can still be seen for the minimum demand growth as the GA sequences a lower cost alternative at the end of the period, however for the higher growth rates and the results of the GA, EC2 and UC methods this cannot be found. Thus these results illustrate that the GA method produces the lowest cost solution of all the methods examined.

Table 7.16 Sequence of Projects with Conveyance Cost Included for Minimum Demand Growth

Sequencing Method	Project Sequence								PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	6	8	9	1						
	Timing	0	5	10	25				246.87	213.02	459.89
EC1	Project	9	2	6	7						
	Timing	0	15	28	34				203.98	334.30	538.28
EC2	Project	8	6	3	5	9	4	2			
	Timing	0	4	10	11	14	29	33	261.65	184.54	446.19
GA	Project	6	8	3	9	2					
	Timing	0	5	10	11	26			235.09	206.70	441.79

Table 7.17 Sequence of Projects with Conveyance Cost Included for Most Likely Demand Growth

Sequencing Method	Project Sequence									PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	6	8	9	1	2						
	Timing	0	4	7	18	30				308.20	296.67	604.87
EC1	Project	9	2	7	6	3	1					
	Timing	0	10	20	28	32	33			272.49	441.69	714.17
EC2	Project	6	8	3	9	5	2	1				
	Timing	0	4	7	8	19	21	30		311.91	288.90	600.81
GA	Project	6	8	3	9	5	2	4	7			
	Timing	0	4	7	8	19	21	30	33	306.56	287.56	594.12

Table 7.18 Sequence of Projects with Conveyance Cost Included for Maximum Demand Growth

Sequencing Method	Project Sequence										PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	6	8	9	1	2	3	5	7	4			
	Timing	0	2	5	13	22	29	29	31	37	401.00	410.06	811.86
EC1	Project	9	2	7	6	3	1	4	5	8			
	Timing	0	7	14	20	23	24	33	35	36	356.27	555.01	911.28
EC2	Project	6	8	3	9	5	2	1	4	7			
	Timing	0	2	5	5	13	15	22	31	33	405.84	413.73	819.57
GA	Project	8	6	9	5	3	1	2	4	7			
	Timing	0	2	5	13	14	15	24	31	33	408.79	398.41	807.20

An interesting fact is found when examining the results of the GA, EC2 and UC methods. For the minimum and most likely demand growths the GA method produces a lower PVCC compared to the EC2 and UC methods. However, for the maximum growth case the GA produces a higher PVCC. At the same time as the demand grows the GA produces an increasingly lower PVOC than the EC2 and UC methods. Thus, at the maximum demand growth case the GA method produces a lower PVOC and the higher PVCC when compared to the next lowest PVTC solution (UC). However, at the minimum demand growth case the reverse is found when a comparison is made between the GA and the next lowest PVTC solution (EC2). As the GA method produces the lowest cost solution it would appear that the importance of the capital cost and operating cost changes with demand growth. So at a higher demand growth the lowering of PVTC will be more efficiently obtained by lowering the PVOC. It can be shown that with increasing demand the PVOC contributes more to the composition of PVTC in the lower cost solution. Thus it can be said that the capital cost plays a more important role than the operating cost at low demand growth rates but as demand growth increases, the importance of operating cost increases. This is similar to the conclusions of the previous section but the results here highlight this to a greater extent. In addition, these results indicate, to ignore either the operating cost or capital cost in the selection of future projects will result in high cost sequences as is illustrate by the results of method EC1.

The effect the discount rate will have on the sequence of projects was also examined for the 40 year planning period. In this case the most likely demand growth case is used for the discount rates of 3 and 9 %. The results of these cases are shown in Tables 7.19 and 7.20.

Table 7.19 Sequence of Projects with Conveyance Cost Included for Most Likely Demand Growth and a Discount Rate of 3 %

Sequencing Method	Project Sequence								PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	8	6	9	1	3	2				
	Timing	0	3	7	18	30	31		419.31	560.34	979.65
EC1	Project	9	2	7	6	1					
	Timing	0	10	20	28	32			384.23	805.00	1189.23
EC2	Project	8	6	3	9	5	1	2			
	Timing	0	3	7	8	19	21	33	438.49	545.34	983.83
GA	Project	8	6	3	9	1	2				
	Timing	0	3	7	8	19	31		419.38	552.85	972.24

Table 7.20 Sequence of Projects with Conveyance Cost Included for Most Likely Demand Growth and a Discount Rate of 9 %

Sequencing Method	Project Sequence									PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	6	9	8	2	1						
	Timing	0	4	14	18	28				224.14	195.24	419.38
EC1	Project	9	2	6	3	7	4	1				
	Timing	0	10	20	24	25	33	36		214.90	262.65	477.55
EC2	Project	6	8	3	9	5	2	4	1			
	Timing	0	4	7	8	19	31	30	33	246.53	162.34	408.87
GA	Project	6	8	3	9	5	2	4	7			
	Timing	0	4	7	8	19	31	30	33	242.33	162.45	404.78

In these case the GA again produced the lowest PVTC sequence. For the 3 % discount rate case the UC method obtains the next lowest PVTC result while for the 9 % discount rate case EC2 obtains the second lowest PVTC. It is also evident that the discount rate effects the sequence of projects. As was stated when the discount rate was examined previously, the higher discount rate will cause initial costs to be more important. Thus, the operating cost will tend to have less impact on the sequencing decision than for a lower discount rate. This is seen for the GA result where at a higher discount rate the sequence changes so that the lower capital cost project, 6 is sequenced first. However, project 6 has a higher operating cost than project 8 but because of the discounting the lower capital cost will have a larger effect on the PVTC. Also smaller projects with lower capital cost replace projects with higher capital cost for the higher discount rate case for the GA sequence.

The final study examines the expanded system where there are 15 projects and 19 a planning period of 40 years. The results of this are illustrated in Tables 7.21 to 7.23.

Table 7.21 Sequence of Projects with Conveyance Cost Included for Minimum Demand Growth

Sequencing Method	Project Sequence											PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	14	11	2	13	4	7	15	1					
	Timing	0	6	12	18	22	25	30	38			186.75	170.23	356.98
EC1	Project	14	4	7	6	2	5	15	11					
	Timing	0	6	9	13	16	22	26	34			154.94	221.54	376.48
EC2	Project	14	13	11	2	4	7	8	1	6	10			
	Timing	0	6	11	16	22	25	30	31	36	38	202.66	151.42	354.08
GA	Project	14	13	2	11	4	8	7	1	5				
	Timing	0	6	11	17	22	25	27	31	36		195.79	153.18	348.97

Table 7.22 Sequence of Projects with Conveyance Cost Included for Most Likely Demand Growth

Sequencing Method	Project Sequence														PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	14	11	2	13	4	7	15	1	8	6	10	5	3			
	Timing	0	4	8	12	16	18	21	27	31	32	33	35	38	262.05	241.65	503.70
EC1	Project	14	4	7	2	6	15	5	12	11	1						
	Timing	0	4	6	9	13	15	21	24	33	37				224.21	333.06	551.27
EC2	Project	14	11	13	2	4	7	8	1	6	15	10	5	3			
	Timing	0	4	8	11	16	18	21	22	25	27	33	35	38	270.19	232.70	502.89
GA	Project	14	2	13	11	7	4	1	15	6	3	5					
	Timing	0	4	8	12	16	19	21	25	31	33	37			255.91	236.99	492.90

Table 7.23 Sequence of Projects with Conveyance Cost Included for Maximum Demand Growth

Sequencing Method	Project Sequence																PVCC ($Million)	PVOC ($Million)	PVTC ($Million)
UC	Project	14	11	2	13	4	7	15	1	8	6	10	5	3	12	9			
	Timing	0	3	6	9	11	13	15	20	22	23	24	26	28	31	37	347.28	352.10	699.37
EC1	Project	14	4	7	2	6	15	5	12	11	1	3	8	9	10	13			
	Timing	0	3	4	6	10	11	15	18	23	26	29	32	33	35	36	321.45	458.30	779.75
EC2	Project	14	11	13	2	4	7	8	1	6	15	10	5	3	9	12			
	Timing	0	3	6	8	11	13	15	16	18	19	24	26	28	31	33	356.96	345.13	702.10
GA	Project	14	11	2	13	4	1	7	15	8	6	10	5	3	9	12			
	Timing	0	3	6	9	11	13	1	18	22	23	23	26	28	31	33	350.02	346.88	696.90

The GA again finds the lowest cost solution of the methods, with the UC and EC2 methods producing the next best solutions. For these cases the UC and EC2 method produce similar results. The results are somewhat surprising as it is expected that the EC2 method would produce lower PVTC results than the UC method. The reason this does not occur is unclear but is thought to be due to the inclusion of the operation costs in the sequencing evaluation methods.

For the GA, UC and EC2 methods the first 6 projects for the two larger demand growths are the same however the order varies with the method and demand growth. The projects to be selected first were 14, 2, 11, 13, 4 and 7. In the minimum and most likely demand cases these are the same except the GA method replaces project 7 with project 8 and project 1 for the two demand growth cases respectively. From the GA runs the first four projects selected will be 14, 11, 2 and 13. The UC and EC2 Models also select these four projects first although the sequencing of these projects is different for each method.

It should also be noted that using models which incorporate the finite period within the selection decision can also cause problems. This is because with a different planning period there is more than likely to be a different project sequence. The sequence produced will be the minimum for that method for that particular period. However, this will mean the theoretical optimum sequence for all projects sequenced will not be reached unless the planning period is set so that all projects are required to be built. In practice the finite period is acceptable and utilised for two reasons. The first is that generally the water authority will only be interested in the next project to be expanded or in the extreme case the next three or four projects. Secondly, to plan to far in advance is dangerous in practice. The reasons for this statement are that it is possible new technology may be developed which results in a new source becoming a better option than one planned to be built. Alternatively, a significant change in demand may occur, so that either some of the future resources may never be needed or the change in demand will result in a lower cost sequence of future resources than is already specified.

7.5 Conclusions

It was shown in this study that operational cost needs to be considered in the system planning decision to enable low PVTC solutions to be obtained. Where it is considered in conjunction with capital cost and operation policy, as in the GA Model, the tradeoffs between lowering PVCC and PVOC can be made so that the lowest PVTC solution can be found. The importance of conveyance costs was also illustrated and the neglecting of such costs will result in poor PVTC solutions and sequences. It appeared from the results of this study that the capital cost plays a more significant role than operational cost in lowering PVTC. The significance of capital and operational cost varied with demand growth, project yield and many other factors.

The benefits of splitting the original 9 projects into 15 smaller projects was also seen with a substantial reduction in PVTC brought about particularly by a reduction in PVCC.

As far as the Perth Water Supply System goes it was found from the expanded study, for a 19 year planning period that the irrigation water scheme involving Logue Brook, Sampson and Waroona Dams, the Serpentine-Dandalup pipehead, Pinjar groundwater and two projects in the North-West Corridor groundwater scheme namely Whitfords and Quinns groundwater schemes were the best alternatives. For the 9 project problem all of the above but the Pinjar groundwater scheme were included. In addition the rest of the North West corridor scheme and the Stirling Dam in the irrigation scheme would be utilised. Also the projects involving the raising of the Mundaring and Canning Dams and Jandakot South groundwater would also be included in the sequence of projects. The same projects are found to be the best for the 40 year planning period although the Gnangara Mound ground water scheme is included in the best sequences for the 9 project problem. The actual sequence of the schemes is dependent on the growth rate of demand.

The result of increasing the planning period was to reduce the possibility of the finite planning period playing a major role in the selection process. The increased planning period results illustrate more clearly the benefit of using the GA, as the finite planning period effect is reduced or removed and the GA produced the best results on all occasions. It should be noted however, that the results of the GA in this study cannot be guaranteed to be optimum but it is considered that the GA solution is near optimal. It may be possible to improve the GA results by using a larger population than 100, say 500, however it is unclear whether this will result in significantly better results. The possibility of improving the GA Model by using different parameter values will be examined in Chapter 8.

While the GA method produced the best sequence it requires more effort to obtain a solution for this method than the EC2 and UC methods. If a quick, approximate sequence is required then these other methods would be more appropriate than the GA method. Of these methods, the EC2 methods seems to produce lower PVTC cost solution than the UC on the majority of occasions. In the case were this observation is not true, it is considered the problem of using a finite planning period effects the EC2 sequence. It is expected that the EC2 method should produce better results than the UC method as it includes the demand growth in the project sequencing evaluation. Also, the sequences produced by the EC2 method are closer to the sequences produced by the GA method than the UC method sequences. Thus, if a water authority requires a quick approximation of the optimum sequence of projects then the EC2 method would be the better method to use.

It is considered that the results of the 15 project study are more representative because of the splitting of schemes into those projects which include conveyance cost and those which do not and those of similar operational cost. If the splitting up of the original schemes in the planning stage is feasible and possible, it is suggested that this is done as this will allow a more representative staging of projects and a lower cost development strategy for the entire system.

Chapter 8

Sensitivity Analysis of Genetic Algorithm Parameters

8.1 Introduction

In Chapter 5 the theory of genetic algorithms is presented and adapted for the water resources sequencing problem. The GA methodology is then applied to the sizing and sequencing of projects for the South-East Queensland System and the sequencing problem including operating cost for the Perth Water Supply System. A limited range of different GA models were used to solve the problems in question. For the sizing and sequencing problem in Chapter 6 a continuous coded GA was utilised, while for solving the sequencing problem in Chapter 7 an real coded GA was used. In both studies as well as in Chapter 5 the parameters used by the GA models were examined. The parameter values of interest were the population size, number of generations, probability of crossover and mutation as well as the selection method. The values utilised by the studies in Chapter 6 and 7 were a result of recommended values in the literature and from a limited sensitivity analysis in the chapters examining the GA methodology.

The purpose of this study is to perform a more detailed analysis of the GA models utilised previously and the parameter values which provide the best and most efficient GA model. The reason for this more detailed study is that values in the literature are applied to different problems than the one examined here, so it is expected that a different range of parameter values may be more applicable for the problems examined. In addition to this, only a few runs per parameter value were examined in previous chapters before a decision on the best value was made. Under a more detailed study, better parameter values may be found.

As mentioned above, the GA methodology has been applied to two different problems. For this study two variations to the sizing and sequencing problem and the sequencing problem including operating cost will be used to determine the best of three GA models overall and for the best for these specific problems. The variation to the sizing and sequencing problem is simply an examination of the no upsizing allowed and upsizing allowed questions previously considered. The models used are the Models T1, T5 and T6 detailed in Chapter 5 and which are also examined in Chapters 6 and 7. In this chapter the three models will be referred to as Models 1, 2 and 3 respectively. Each model will be applied to the three problems being examined. Then the best model based on an initial analysis will be used for the sensitivity analysis on the various GA parameters previously mentioned. The best model is defined as that model which provides the lowest average minimum PVC solution. In the case where two models produce the same PVC, the one which obtains this result in the smallest number of evaluations is considered the better model. Thus the best model and parameters will be determined and some conclusions can be made with regard to the genetic algorithm models, the parameters of importance and typical values of those parameters.

8.2 Case Studies used in the Analysis

To test the effectiveness of various GA models three problems taken from Chapters 6 and 7 were used. The first problem examined is the South-East Queensland problem when projects can not be upsized. The second problem was also described in Chapter 6 and is when projects can be upsized. In these cases a single situation was selected to be examined rather than investigating the variations in demand, discount rate and upsizing cost. For this study the situation chosen was demand forecast 3, discount rate of 6 % and when upsizing is allowed, an upsizing cost equal to 120 % of the incremental cost was used. This problem was chosen from Chapter 6 as it was considered to be the most difficult of the problems examined and the higher demand growth will mean more projects are required to be sequenced.

The final problem to be examined was investigated in Chapter 7 for the Perth Water Supply System. The particular problem chosen is when there are 15 projects, the demand growth is at a maximum and a 40 year planning period is examined. This problem will require all projects to be sequenced which is the major reason for its selection. This factor will mean that the ability of the GA to sequence projects optimally will be tested and the finite planning period problem discussed in previous chapters will not be a factor in the sequencing of projects.

8.2.1 The Genetic Algorithm Models utilised

The GA models used in this study are the Models T1, T5 and T6 discussed in Chapters 5, 6 and 7. These models will be refereed to as Models 1, 2 and 3 and a brief description of these various model is as follows:

Model 1 (T1) : Continuous Coding with bit mutation
Model 2 (T5) : Real Coding with PMX crossover and Random String mutation
Model 3 (T6) : Real Coding with PMX crossover and Adjacent String mutation

These models were chosen based on the results obtained in Chapters 5, 6 and 7. The GAs described above will be applied to the three cases mentioned in an effort to obtain the most appropriate GA operators and parameters for particular problems. The general GA process will not change between the various problems examined. However, the decoding of the strings and the string lengths will change. For the first two problems the decoding of the string will include the sizing and sequencing of projects. So in general when a project is sequenced a smaller size of that project cannot be sequenced at a later time and this is built into the decoding routine of the GA. For the no upsizing case, the decoding routine will examine the string and any projects at the same site will not be sequenced once a project has already been sequenced at that site. Any bit which represents upsizing of a project in this case will not contribute to the PVC or the fitness of the string. In the case with upsizing allowed, a larger size will be allowed to be sequenced but the cost and yield of the larger size will be adjusted accordingly. For the Perth Water Supply problem every bit represents a different project and each project will have an associated annual operating cost as well as a capital cost and yield. In this case all bits contribute to the fitness of a string.

The GA parameters which will be investigated are

1) Population size
2) Probability of mutation (p_m)
3) Probability of crossover (p_c)

The purpose of examining the population size is that it is considered that when problems are complex or large the population size should be larger. The reason is that it is expected that a larger population size is more likely to contain the necessary sequences of bits which will produce the optimal sequence of bits or optimal string. Thus the optimal string will be found through the use of crossover and mutation. Simpson and Goldberg (1994) found that for larger population sizes, higher fitness results were obtained, but the number of evaluations did increase. Thus in this study the population size will start at 100 and be increased until it is considered that there will be no further improvement in the result obtained using a higher population size.

For the examination of the probability of mutation only two values were examined. Firstly the initial value is used which is selected from the results discussed in the previous chapters and then a zero probability is applied to investigate whether mutation is a necessary operator. The effect of mutation is expected to be reduced as a larger population size is used. The reason for this conclusion is that it is more likely that the information required to obtain an optimal solution will be present with higher population sizes. However, with lower population sizes mutation may provide a piece of information not present in the population and may lead to the optimal solution being obtained.

The effect of varying the probability of crossover is examined to investigate the degree of mixing which needs to occur in order to produce better solutions. The importance of having adequate mixing was addressed by Simpson and Goldberg (1994) with the conclusion that the type of crossover is not of great importance as long as adequate mixing occurs. This implies that the selection of crossover probability is important. Thus, the crossover probability will be reduced from 90 %, which is the initial value used, to 70 % and 50 % for the cases where probability of crossover is considered important. In addition, it is considered that for low population sizes a p_c of 90 % is an appropriate value, thus various values of p_c will only be tested when larger population sizes are investigated. The reason for this is that it is thought that large values of p_c when a large population size is used may be disruptive and may cause too much mixing. This may result is poor performance of the GA. At lower population sizes, lower values of p_c will result in inadequate mixing which will also result in a poor performance of the GA.

The selection procedure was also examined. However, the selection procedure is only examined for the South-East Queensland problem with upsizing allowed and for the Perth Water Supply problem, which are considered to be the slightly more difficult problems. The selection procedures examined are tournament selection and proportionate selection. The primary purpose of this is to find the better selection procedure. In addition, the number of tournament participants will be examined. The number of participants will vary from the standard value of two used in the previous chapters, to 5 and 10 competitors per tournament.

For each GA model used there will be ten runs each with a different random seed. Ten runs are used so that if a particular solution is obtained on all ten occasions, it is more than likely that this will be the optimal solution. This conclusion can be made as the ten different seeds should provide significantly different initial populations and therefore starting points. In the case where a solution is only near optimal it is considered that the problem being examined is sufficiently difficult that not even a good parameter selection will provide the optimal solution. A reason why the GA may not provide the optimal solution is due to a phenomena called "blocking". Blocking of a solution was discussed by Goldberg (1990) when real coded GA's are used. An optimal solution may not be found if the global optimum occurs behind two local optimum peaks which the GA will search. However, to search the global optimum peak the changes required to the string are dramatic and unlikely to occur within the GA process. At this stage it is unclear how to combat this problem considering the complex solution space being examined for the sequencing problem.

A further change to the GA process from that used in Chapters 5, 6 and 7 is that with an examination of higher population sizes the Borland Turbo Pascal version used is too small to enable such an analysis. Thus the models were run on a Unix system (ie. DECstation 5000/240 computer) with a Pascal compiler. This change of system and compiler resulted in a change to the random number generator used. Previously using Borland Turbo Pascal a built in random number generator was used in the GA. This random number generator was not available using the new system so a new random number generator developed by Barnard and Skillcorn (1989) was used. This will guarantee that when using the same seed, the same random number sequences will be provided. This random number generator was used successfully by Murphy and Simpson (1992), Dandy et al. (1993) and Murphy et al. (1993) in their work with GAs. Thus it is considered that it will be appropriate for these studies. The seed required by the random number generator is selected from the range of 1 to 10,000. The same ten seeds will be used when different values of population size, probability of crossover and mutation and selection operator are examined. This will allow a comparison of the effectiveness of the various values of the GA parameters as the initial populations used by the GA will then be the same. Thus any change in the results will be due to the different parameter values used. The only case where this is not true is for change in population size. In this case what can be said is that a proportion of the initial population at higher population sizes will be the same as the initial population for lower population sizes. However, the random number sequence responsible for obtaining the results for lower population sizes will not be the same when population size is increased.

The initial case to be used is a population of 100 with p_c = 90 %. The p_m value will depend on the model used and the situation being examined. The number of generations used will depend on the difficulty of the problem being examined. As mentioned previously, the best model is identified by taking into account the average minimum PVC solution obtained and the average number of evaluations for the ten runs. The average minimum PVC is the average of the minimum PVC obtained for each of the ten runs in $ Million and the average no. evaluations is the number of evaluations taken to find the minimum PVC averaged for the ten runs. The number of evaluations required to obtain the minimum PVC solution is calculated by multiplying the population size, by the generation number when the minimum PVC first appears, by the probability of crossover. Thus for a population size of 100 and a p_c equal to 90 %, if it takes 50 generations to find the minimum PVC for the GA run, then the number of evaluations made to find the minimum is $100\times50\times0.9$ which equals 4500 evaluations. The final value given in the Tables below is the average computation time for the ten runs, which is the time taken to run the model for the total number of generations. This time is the user plus system time on a DECstation 5000/240 computer and not the elapsed time. The elapsed time is system load dependent so will vary depending on the number of users on the system whereas the time given is largely independent of the load on the system.

8.3 Results of GA Model Comparison

8.3.1 South-East Queensland Case Study with No Upsizing

The first problem to be examine is that of the South-East Queensland problem when there is no upsizing of projects allowed. The initial parameter set is as mentioned above and the number of generations is set at 500. This should enable an adequate number of evaluations to obtain an optimum solution. When the population size is increased the number of generations will change so that the total number of evaluations remains constant. The results of the three models for this case are shown in Table 8.1.

Table 8.1 Comparison of the PVC Obtained for Three Genetic Algorithm Models for the Parameter Set : Pop = 100, Gen = 500, p_c = 90 %

RUN	MODEL 1 p_m = 3 %	MODEL 2 p_m = 10 %	MODEL 3 p_m = 10 %
1	73.2517	73.2517	73.2517
2	73.2517	73.8495	73.8495
3	73.2517	73.2517	73.2517
4	73.2517	73.2517	73.2517
5	73.2517	73.2517	73.2517
6	73.2517	73.8495	73.2517
7	73.2517	73.3858	73.2517
8	73.2517	76.1482	73.2517
9	73.2517	73.2517	73.2517
10	73.2517	73.2517	73.2517
Average Minimum PVC	73.2517	73.6743	73.3115
Average No. Evaluations	2763	2664	4662
Average Run Time (Sec)	69.06	46.16	47.61

The results in Table 8.1 illustrate that Model 1 produces the best average minimum PVC of the three methods tried. The next best method based on minimum PVC is Model 3. However, Model 2 provides the solution in the smallest number of evaluations. As the results of Models 1 and 3 are more encouraging than those of Model 2, the effect of increasing the population size from 100 to 500 will not be examined for Model 2. Thus the results in Table 8.2 are for the results of using a population size of 500 for Models 1 and 3 for two different values of p_m.

In the above cases both Models 1 and 3 give the same minimum PVC for all ten runs. This indicates two factors. Firstly the mutation probability has no effect on the ability of the GA to solve the problem under examination. However, it is expected that if the value of p_m was higher than those used the result may be different. The reason for this is that at high p_m values mutation can be disruptive. In fact in this case it would appear that using mutation disrupts the GA process as the GA without mutation produces the same result in fewer evaluations. The second observation is that Model 1 outperforms

Model 3 in regard to the average number of evaluations to obtain the minimum PVC solution. However, Model 1 does take just over twice as long to run. The reason for this is that using real number requires more computer memory and a longer computation time than when integers are utilised.

Table 8.2 Comparison of the Genetic Algorithm Models for the Parameter Set : Pop = 500, Gen = 100, p_c = 90 %

RUN	MODEL 1		MODEL 3	
	p_m = 3 %	p_m = 0 %	p_m = 10 %	p_m = 0 %
1	73.2517	73.2517	73.2517	73.2517
2	73.2517	73.2517	73.2517	73.2517
3	73.2517	73.2517	73.2517	73.2517
4	73.2517	73.2517	73.2517	73.2517
5	73.2517	73.2517	73.2517	73.2517
6	73.2517	73.2517	73.2517	73.2517
7	73.2517	73.2517	73.2517	73.2517
8	73.2517	73.2517	73.2517	73.2517
9	73.2517	73.2517	73.2517	73.2517
10	73.2517	73.2517	73.2517	73.2517
Average Minimum PVC	73.2517	73.2517	73.2517	73.2517
Average No. Evaluations	8055	7245	10890	9945
Average Run Time (Sec)	53.89	47.17	25.96	23.86

In regard to a comparison between Tables 8.1 and 8.2 there is no change in the result of Model 1. However, it does take approximately three times as many evaluations to obtain the same result. One benefit of using Model 3 is that it finds the lowest PVC solution in considerably less time. However, the run time shown is that for all generations being evaluated rather than for the time taken until the lowest PVC solution is obtained. Also, in later analysis the number of generations used will vary, with more generations producing the longer evaluation times. However, in these cases the number of evaluations required to obtain the minimum PVC solution should be similar. These are the reason the number of evaluations are used to evaluate which is the better model. Thus for this problem it would appear better to use the population size of 100 for Model

1 as it achieves the minimum PVC in the least number of evaluations. As far as Model 3 goes, the increase in population size results in a better solution although it takes just over twice as many evaluations to achieve that solution. As the first priority is to obtain the minimum PVC solution then the higher population size should be used for Model 3. Overall, however it appears that Model 1 performs the best in regard to solution obtained and number of evaluations taken to obtained that solution.

The next step is to examine the case of allowing upsizing to occur to projects and to investigate which GA model performs the best for this problem.

8.3.2 South-East Queensland Case Study with Upsizing

In this study the South-East Queensland case with upsizing is considered. The upsizing cost is assumed to be 120 % of the incremental cost. This is thought to be representative on the likely cost of upsizing projects. For this case a larger number of evaluations are required as the problem is more difficult than that with no upsizing allowed. With a population size of 100, the number of generations is set equal to 1000. In addition, when larger population sizes are examined the number of generations should also change so that the number of evaluations is the same. Thus for population sizes of 100, 500 and 1000 the respective number of generations will be 1000, 200 and 100. The results of using the initial values of population and number of generation, for the three models are shown in Table 8.3.

It is quite clear from these results that Model 1 is the far superior model. Although it takes more evaluations to obtain the minimum cost solution, the solution is considerably better. The other models give poor results and when the average fitness of the population is examined it is clear that no further improvement of the results is likely to occur with more generations. It is quite possible however, that a larger population may produce a better solution but it is unlikely that Models 2 and 3 would perform as well as Model 1. Thus it was decided that only Model 1 will be used for the examination of variation in population size, p_c , p_m and selection procedure.

The next section examines what effect the population size has on the result of the continuous coded GA. As mentioned previously the corresponding number of generations are 1000, 200, 100 for the population sizes of 100, 500 and 1000 respectively. These results are given in Table 8.4.

Table 8.3 Comparison of the PVC Obtained for Three Genetic Algorithm Models for the Parameter Set : Pop = 100, Gen = 1000, p_c = 90 %

RUN	MODEL 1 $p_m = 3$ %	MODEL 2 $p_m = 10$ %	MODEL 3 $p_m = 10$ %
1	71.4870	73.1976	72.9410
2	71.4870	73.0263	72.8463
3	71.4870	75.1480	71.8746
4	71.4870	72.8463	72.9410
5	71.4870	73.1976	72.7972
6	71.4870	72.8463	73.1029
7	71.5039	71.7145	71.6180
8	71.4870	73.1029	72.9410
9	71.4870	71.6345	72.7972
10	71.4870	71.8746	72.3969
Average Minimum PVC	71.4887	72.8589	72.6256
Average No. Evaluations	28278	5463	21789
Average Run Time (Sec)	150.48	102.85	98.4

The results in Table 8.4 are somewhat confusing on first inspection. In this case there is an improvement in the minimum PVC obtained when the population size is increased from 100 to 500. However, on further increasing the population size to 1000 the minimum PVC result obtained is the highest found of the population sizes evaluated. This result would seem to contradict the results found by Simpson and Goldberg (1994) with regard to increasing population size resulting in a better solution. However, on closer inspection of the results where the lowest PVC solution is not found, the GA process is still converging for the higher population size. Thus for a population size of 1000, 200 generations were examined. For this case the value of 71.4870 was obtained on all ten occasions which is the same as when the population size of 500 was used. The average number of evaluations to obtain this solution was 99270 and the average run time was 210.29 seconds. This would indicate that the number of generations will also play an important role in obtaining a solution for this particular problem. Thus for this problem it is considered that a higher population size will provide better solutions but only if a considerable number of evaluations are made. Therefore, good results will be found when both the population size and number of generations are increased. However, it must be said that there is likely to be a limit to the increase in those parameters which will result in improvement in the results obtained. For instance there is likely to be a limit to the benefit obtained when using a larger population size. If a population size of 50,000 obtains the same result as a population size of 5,000 but takes 10 times as long to obtain that solution, then the best population size to use would be that of 5,000. So to state that improvement in a solution will be obtained with higher population size will only be true if a more optimum solution exist. Therefore, there exists a population size which can be considered optimal in regard to the solution obtained and the time and number of evaluations required to find that solution.

Table 8.4 Comparison of the Population Size for Model 1 : $p_m = 3\%$, $p_c = 90\ \%$

RUN	Population Size		
	100	500	1000
1	71.4870	71.4870	71.5161
2	71.4870	71.4870	71.4870
3	71.4870	71.4870	71.4870
4	71.4870	71.4870	71.4870
5	71.4870	71.4870	71.5039
6	71.4870	71.4870	71.5039
7	71.5039	71.4870	71.5039
8	71.4870	71.4870	71.5161
9	71.4870	71.4870	71.5161
10	71.4870	71.4870	71.5161
Average Minimum PVC	71.4887	71.4870	71.5037
Average No. Evaluations	28278	50670	78030
Average Run Time (Sec)	150.48	113.45	103.94

Another factor to come from the results in Table 8.4 is that the mutation operator is likely to be an important operator in this case. It was seen in the previous study that mutation resulted in more evaluations being needed to obtain the same solution. However, the results obtained when 200 generation are examined for the 1000 population size case indicate that mutation will play a role in providing a better solution.

The reason for this statement is that as the number of generations and thus the number of evaluations increases the mutation operator is most likely to provide improved results. The crossover operator will be the major influence in the initial generations which will lead to similar strings in later generations. Thus when crossover occurs between similar strings there is little improvement in the PVC obtained. If significant improvement is found in the GA procedure in the later generations it is more likely to as a result of mutation. Thus, the next examination for this case will be the mutation rate. The effects of using mutation are shown in Table 8.5.

Table 8.5 The Effect of Mutation Using Model 1 for the Parameter Set : Pop = 2000, Gen = 200, p_c = 90 %

RUN	p_m = 3 %	p_m = 0 %
1	71.4870	71.5808
2	71.4736	71.5161
3	71.4870	71.5362
4	71.4870	71.5161
5	71.4870	71.5329
6	71.4870	71.5161
7	71.4870	71.5161
8	71.4780	71.5688
9	71.4870	71.5161
10	71.4870	71.5161
Average Minimum PVC	71.4848	71.5315
Average No. Evaluations	203400	76680
Average Run Time (Sec)	428.21	425.62

Before a discussion is made on the results of using mutation it must be stated that the results in Table 8.5 cannot be directly compared to those results in previous Tables. The reason is that a higher population size has been used as it is expected that the effect of mutation is likely to decrease as population size increases. Therefore for the results in Table 8.5 more evaluations were made than in the previous cases examined. For this problem, a population size of 2000 with 200 generations were used to investigate the effect of mutation. It is quite clear from the results of Table 8.5 that the mutation operator is required in the GA process so that good solutions can be obtained. Although the number evaluations required to obtain the better solution is larger, this illustrates the effect of mutation in the later generations. This point was discussed in relation to the results of Table 8.4. Thus without mutation the GA process finds an inferior solution earlier and the crossover operator alone cannot improve on that solution.

A somewhat surprising result in Table 8.5 is the improvement of the previous minimum PVC value of 71.4870. The result is surprising as the previous lowest PVC was obtained on such a consistent basis that it was considered to be the optimum. In fact, a number of lower PVC values where found. The lowest value obtained by the GA was 71.4736 in run 2. However, in run 8 a value of 71.4780 was found and also in run 2 a value of 71.4770 was also obtained. Prior to these results it had been considered that the value of 71.4870 was the optimum value. This conclusion was reached as in a number of cases this was the best solution obtained on a regular basis and in two cases this was the best solution obtained with all ten runs (ie. populations of 500 and 1000 using 200 generations, Table 8.4). However, on inspection of the sequences obtained with the various values specified there is quite a difference between the optimum found here and the sequence which has a PVC of 71.4870. The difference is such that if a solution settles on the optimum path to the 71.4870 solution then it is very unlikely that the 71.4736 sequence will be found. The reason is that there needs to be a number of changes to bits within the string to get to the optimal path. This will either occur through a number of mutations or an advantageous crossover or both.

A successful crossover is considered advantageous as the real numbers within the two strings need to be in the correct magnitudes with respect to each other, to produce the desired result. Mutation is unlikely to achieve the better solution as the correct mutations required will need to occur over a number of generations and the first mutations are likely to produce a result which is inferior to other strings in the population, thus the mutated string will have less chance of being selected as a parent in the next generation. However, on inspection of the results it appears that mutation has produced the string with the PVC of 71.4736. In this case a string with a PVC of 72.3710 was mutated to produce the lowest PVC solution.

Although the general sequences of the four solutions mentioned are similar, differences occur later in the string. To illustrate this the sequences for the PVC values of 71.4736 and 71.4870 are shown below in Table 8.6.

Table 8.6 Comparison of Two of the Better Sequences Obtained by the GA

Project Sequence																	PVC
8/1	8/2	1/1	1/2	7/1	7/2	9/1	9/2	9/3	5/2	5/3	8/3	7/3	10/1	10/2	10/3	1/3	71.4736
8/1	8/2	1/1	1/2	7/1	7/2	9/1	9/2	9/3	5/2	5/3	13/1	10/1	10/2	10/3			71.4870

As can be seen, the difference is the use of projects 8/3, 7/3 and 1/3 rather than using project 13/1. The sequences which result in the values of 71.4770 and 71.4780 are similar to the 71.4736 sequence in that they also utilise projects 8/3, 7/3 and 1/3 but in a different order. Otherwise the four sequences are very similar.

It may be asked why the GA does not converge to the better sequence. The answer appears to be that although the paths to achieving either of the solutions above are similar the path to achieving the 71.4870 solution contains fitter strings than the paths to the other solutions. That is the fitness values of strings which will produce the PVC of 71.4870 are higher than those which will result in the 71.4736 string. For instance the string that is mutated to produce the 71.4736 solution has a PVC of 72.3710 whereas there are numerous strings with PVC lower than 71.5329 that produce the 71.4870 result when mutated. The sequence of projects which produces the PVC of 71.4736 utilises smaller projects and therefore is affected by the planning period used. So if just one of the smaller, less costly projects is not used in the sequence, a larger more expensive project will replace it, leading to a significantly higher PVC. On the other hand for the other sequence in question (where larger projects are used), when one of these is not used or an extra small project appears in the sequence, then the PVC is not substantially affected. For instance, when a PVC of 72.3710 is produced, project 8/3 is missing from the sequence which results in the next project to be sequence being included in the fitness evaluation. It just happens the next project is 4/3 which increases the PVC substantially. Even if the lowest cost project of the remaining projects (ie. 4/1 or 13/1) was sequenced, the PVC would be considerably higher than the optimum PVC. Thus the path to producing the PVC of 71.4736 is less stable and has lower fitness than the path to produce the PVC of 71.4870. So even, if the path to the lower PVC exists, at some stage it is more than likely that these strings will be lost from the population due to their lower fitness. It just so happens that this was not the case for run 2 in Table 8.5 and one of the lower fitness strings still existed in the population. The above conclusion about the stability of the lower PVC solution is illustrated in this result as once the 71.4736 string was produced, it disappeared in the next generation as a result of crossover and mutation. The best string in the next generation had a PVC of 71.4770. This was subsequently lost in the following generation where the lowest PVC solution was 71.4870. This string was then obtained for the remaining generations. The situation which appears in this problem would appear to be an example of blocking of a solution (Goldberg, 1990). In this case the solution 71.4870 will block the GA from obtaining the sequences which lead to the solution of 71.4736. Due to the complexity of this problem it is unclear whether a measure can be devised in general which will overcome the blocking problem. It may be possible in a particular case to overcome the blocking problem by using various trials of the GA but this may not result in a general solution.

The next parameter to be examined is the probability of crossover. In this case the probabilities of crossover examined are 50 %, 70 % and 90 %. The number of generations used for the various values of p_c will be varied so the same number of evaluations are performed for each different value of p_c. The number of generations examined are 360, 260 and 200 for the values of p_c of 50 %, 70 % and 90 % respectively. The results are shown in Table 8.7. These results cannot be compared to those in other Tables as a different population size is used and thus the number of evaluations to obtain a solution is different.

Table 8.7 The Effect of Crossover Using Model 1 for the Parameter Set : Pop = 2000, p_m = 3 %

RUN	Probability of Crossover		
	90 %	70 %	50 %
1	71.4870	71.4870	71.4870
2	71.4736	71.4870	71.4870
3	71.4870	71.4870	71.4780
4	71.4870	71.4870	71.4870
5	71.4870	71.4780	71.4376
6	71.4870	71.4870	71.4770
7	71.4870	71.4870	71.4376
8	71.4780	71.4870	71.4870
9	71.4870	71.4868	71.4870
10	71.4870	71.4376	71.4870
Average Minimum PVC	71.4848	71.4811	71.4752
Average No. Evaluations	203400	184800	173100
Average Run Time (Sec)	428.21	533.15	710.28

From these results it can be seen that the lower value of p_c will provide better solutions. For most of the runs shown in Table 8.7 the PVC solution of 71.4870 was obtained and the difference in the average minimum PVC was because lower values of PVC were obtained for the lower values of p_c. At the lower p_c values less evaluations where required to obtain the better solution, although it took more time to run the model.

In addition, the probability of crossover was examined when 5 member tournament selection is used. In this case, probabilities of 90 % and 70 % were examined with the better average solutions being obtained with a higher probability of crossover. For the 70 % case, 260 generations were examined while 200 generations were examined for the 90 % case. These solutions are shown in Table 8.8. The 90 % case is also shown in Table 8.9.

Table 8.8 The Effect of Crossover Using Model 1 for the Parameter Set : Pop = 1000, p_m = 3 %, 5 Tournament Members

RUN	Probability of Crossover	
	90 %	70 %
1	71.4870	71.4870
2	71.4870	71.4870
3	71.4870	71.4870
4	71.4870	71.4870
5	71.5263	71.4870
6	71.4870	71.4870
7	71.4870	71.4870
8	71.4870	71.4870
9	71.4870	71.4870
10	71.4870	71.5263
Average Minimum PVC	71.4909	71.4909
Average No. Evaluations	33120	39060
Average Run Time (Sec)	222.24	284.60

For the cases shown in Table 8.8, although using both crossover values obtains the same PVC, the value of 90 % achieves this solution in fewer evaluations and less computer time. Thus when using tournament selection with 5 members, a higher probability of crossover provides slightly better results. Thus, the results in Tables 8.7 and 8.8 indicate that as the number of members in the tournament selection procedure increases, the probability of crossover should also increase to produce better results. A possible reason for this is that with a larger numbers of members in the tournament selection procedure, the diversity going from one generation to another will be less. So the probability of crossover should be set higher to allow greater mixing to occur, which will increase the diversity within a generation.

The final study to undertake for the problem with upsizing allowed is the evaluation of various selection operators. The selection criteria investigated are proportionate, 2, 5 and 10 member tournament selection. The purpose of this study is to find the best selection operator. Before the results are presented however a brief clarification needs to be made about the proportionate selection routine. When using proportionate selection fitness scaling was used in order to improve on its performance. The term fitness scaling was discussed in Chapter 5. Fitness scaling increases the difference between the fitnesses of various strings so that in later generations when the strings become similar slightly higher fitness strings will have a better chance of being selected as parents for the next generation. In addition, the fitness scaling used will not be constant but will vary as the number of generations increase. The variation in fitness scaling will be an increasing fitness scaling which is calculated as follows :

1) generation<20% of maximum generations : fitness = $1/(PVC)^2$
2) 20% of maximum generations<generation<50% of maximum generations : fitness = $1/(PVC)^3$
3) 50% of maximum generations<generation<70% of maximum generations : fitness = $1/(PVC)^4$
4) 70% of maximum generations<generation : fitness = $1/(PVC)^5$

The results of comparing the various selection criteria are shown in Table 8.9.

The best selection procedure is tournament selection as it obtains superior results in fewer evaluations than the proportionate selection. The best number of members to use in the tournament appears to be 10 as it obtains the best result in the smallest number of evaluations. The surprising aspect of these results is the 5 member tournament as it produces one result which is inferior to that of the 2 member tournament. The reason for this result is unknown. Examining the particular run in question, it appears that the better solution path is missed, due to the variation in the use of the same random number sequence as used with the other cases. The difference between the two sequences is that rather than project 10 being upsized, project 4 replaces it. Thus this could be a case of blocking where as a result of the values used in the GA model the sequence with project 4 in it is the first found and the path to obtaining the best PVC using that project is searched. Thus the sequence with project 10 will not be examined. This phenomena becomes more baffling when it is considered that at the lower p_c of 70 % the run in question obtains the 71.4870 solution. Thus what may be said is the GA is prone to some inconsistent results depending on the values of parameters used and the possibility of blocking of the solution. However, if a number of seeds or different parameter values are used to test the GA it will provide a good solution. Proportionate selection produces the poorest result as there is no guarantee that the best string will be represented as a parent for the next generation. Thus the GA will not continually produce the best offspring if the best parents are not used.

Table 8.9 The Effect of Selection Procedure for the Parameter Set : Pop = 1000, Gen = 200, p_m = 3 %, p_c = 90 %

RUN	Selection Procedure			
	Proportionate	Tournament-2	Tournament-5	Tournament-10
1	71.7434	71.4870	71.4870	71.4870
2	71.6468	71.4870	71.4870	71.4870
3	71.7415	71.4870	71.4870	71.4870
4	71.6888	71.4870	71.4870	71.4870
5	71.7189	71.4870	71.5263	71.4870
6	71.7027	71.4870	71.4870	71.4870
7	71.7434	71.4870	71.4870	71.4870
8	71.6180	71.4870	71.4870	71.4870
9	71.7170	71.4870	71.4870	71.4736
10	71.7137	71.4870	71.4870	71.4870
Average Minimum PVC	71.7034	71.4870	71.4909	71.4857
Average No. Evaluations	128250	99270	33120	31860
Average Run Time (Sec)	342.98	210.29	222.24	222.91

As a result of the solutions in Tables 8.7 and 8.9 a small test was performed using 5 and 10 member tournament selection, with a population size of 2000 and p_m and p_c as they appear in these Tables. The reason for doing this is to try and obtain the string with a corresponding PVC of 71.4736 on more occasions. The reason for increasing the population size and number of participants in tournament selection is that in Tables 8.7 and 8.9 these increases have resulted in better solutions. For both the 5 and 10 member tournaments the minimum PVC obtained for all runs was 71.4870. This is a somewhat disappointing result as it was considered that the 71.4736 value would be obtained at some stage. However, this just confirms the above conclusion regarding the occurrence of blocking and the reliance of the GA method on the random number sequences produced and the various parameters utilised.

For the problem examined it was found that population size, probability of crossover and mutation and the selection criteria all affect the result of the GA. The best results (ie. lowest PVC) were found when a population size of 2000 was used, with probability of crossover and mutation of 50 % and 3 % respectively, a 2 member tournament selection and 200 generations. This was the best set of results however, the best individual result of any particular run was 71.4736. This was found using the above parameters and also when a p_c value of 70 % and 90 % was used. In addition this result was obtained when, a 10 member tournament selection, a population size of 1000 and the p_c and p_m values of 90 % and 3 % respectively, were used.

In general it is considered that good results will be obtained by the continuous coding GA when a large population size is used (>500), there are a large number of members in the tournament selection procedure and a reasonably higher probability of crossover (50 % < p_c < 90 %) is used. In addition, the use of mutation will enable the GA to obtain a better solution as will a significant number of evaluations. The number of generations which should be used however will vary depending on population size and tournament selection. The reason for this conclusion is that larger populations may require more evaluations so that adequate mixing of all strings through crossover occurs. The number of generations will be reduced somewhat if the number of members in the tournament selection is increased as generations with similar strings will occur earlier in the GA procedure. Thus the success of crossover will be limited once this situation is reached. However, on the other hand, due to the type of coding used, the mutation operator can be successful in improving the GA results in later generations.

The final case to investigate is that of using the GA models for the Perth Water Supply System.

8.3.3 Western Australian Water Authority Case Study

The Perth Water Supply System problem differs from the previous cases as it is more a straight forward sequencing problem. In the previous studies due to the definition of the problem a number of bits within a string may not effect the fitness of the string. The result is the effectiveness of mutation and crossover are reduced. In the case examined here however, all bits will contribute to the string's fitness. This is a good opportunity to evaluate the various GA models and their associated parameter values to obtain the best overall GA model for a sequencing problem. The initial case examined used a population size of 100, 500 generations and a p_c value of 90 %. The p_m value will vary for the different GA models and will be specified where necessary. The results of the three GA models for the initial case are shown in Table 8.10.

Table 8.10 Comparison of the Three Genetic Algorithm Models for the Parameter Set : Pop = 100, Gen = 500, p_c = 90 %

RUN	MODEL 1 p_m = 3 %	MODEL 2 p_m = 5 %	MODEL 3 p_m = 5 %
1	696.8981	696.8981	696.8981
2	696.8981	697.5916	696.8981
3	696.8981	697.8887	696.8981
4	696.8981	698.1766	696.8981
5	696.8981	697.5916	697.7012
6	696.8981	696.8981	696.8981
7	696.9018	697.6219	696.8981
8	696.8981	697.5916	696.8981
9	697.6651	696.8981	696.8981
10	696.8981	697.5916	697.5916
Average Minimum PVC	696.9752	697.4748	697.0478
Average No. Evaluations	7677	2727	3384
Average Run Time (Sec)	54.70	61.23	58.38

The best model again is Model 1 as it produces the lowest PVC results. However, it does take considerably more evaluations than the other models. In addition, Model 3 produces the lowest PVC results for 8 out of the 10 runs. This is the same as Model 1 however, Model 1 produces lower PVC estimates than Model 3 on the other occasions. The second model produces the worst results and only produces the lowest PVC solution for 3 out of the 10 runs examined. For this reason it will not be used for the remainder of this study. Models 1 and 3 however will be further examined with regard to population size. For this case the population size will be increased from 100 to 500 and both models will be utilised. The results of this are given in Table 8.11.

Table 8.11 Comparison of the Genetic Algorithm Models for the Parameter Set : Pop = 500, Gen = 100, p_c = 90 %

RUN	MODEL 1 p_m = 3 %	MODEL 3 p_m = 5 %
1	696.8981	696.8981
2	696.8981	696.8981
3	696.8981	696.8981
4	696.8981	696.8981
5	696.8981	696.8981
6	696.8981	696.8981
7	696.8981	696.8981
8	696.8981	696.8981
9	696.8981	696.8981
10	696.8981	696.8981
Average Minimum PVC	696.8981	696.8981
Average No. Evaluations	18720	12285
Average Run Time (Sec)	42.20	35.11

The best model from the results of Table 8.11 appears to be Model 3. Both models produce the lowest PVC solution on all ten occasions but Model 3 takes fewer evaluations. In addition, it is considered that Model 3 will be more appropriate for this problem as the real coding, PMX crossover and mutation will provide a more efficient method than the continuous coding model. This conclusion is based on the fact that mutation of a continuous coded bit may not affect the sequence of projects but mutation of the real coded string will affect the sequence. Thus, the search for an optimal solution should be achieved more quickly with Model 3 and more of the search space will be examined for a similar number of evaluations. In addition, Model 1 has been examined in detail in the previous studies and it has been shown in Table 8.11 that it achieves the lowest PVC solution thus it is decided that for this problem Model 3 will be examined further.

The next step is to examine the result of using different population sizes for Model 3. These results are illustrated in Table 8.10 and 8.11 but for comparison purposes they appear together in Table 8.12.

Table 8.12 Comparison of the Population Size for Model 3

RUN	Population Size		
	100	500	1000
1	696.8981	696.8981	696.8981
2	696.8981	696.8981	696.8981
3	696.8981	696.8981	696.8981
4	696.8981	696.8981	696.8981
5	697.7012	696.8981	696.8981
6	696.8981	696.8981	696.8981
7	696.8981	696.8981	696.8981
8	696.8981	696.8981	696.8981
9	696.8981	696.8981	696.8981
10	697.5916	696.8981	696.8981
Average Minimum PVC	697.0478	696.8981	696.8981
Average No. Evaluations	3384	12285	24210
Average Run Time (Sec)	58.38	35.11	30.79

It can be seen that the larger population sizes result in the better solution with regard to minimum PVC produced, although they take considerably more evaluations to achieve that solution. However, it does take less computation time for the total run. This computer time is for all generations examined and does not reflect the time taken to obtain the best solution. The actual time taken to obtain the best solution is directly related to the number of evaluations made. Thus, if time taken to obtain the best solution is of interest, then the number of evaluations should be examined. Thus, the population size of 500 is considered to be better as it obtains the best result in fewer evaluations.

The reason for the better solutions for the larger population sizes, is that a greater number of different project sequences are present within the initial population. Thus the likelihood of a better solution being obtained is increased. Although the number of evaluations is significantly greater, the larger population size case takes fewer generations to converge to the minimum PVC solution. In this case for a population size of 100 the solution is found in the 38th generation, for a population size of 500, the minimum is found within 28 generations and for the population size of 1000, the solution is obtained in the 27th generation.

The next step is to examine the effect of mutation on Model 3 for this problem. These results are shown in Table 8.13.

Table 8.13 The Effect of Mutation Using Model 3 for the Parameter Set : Pop = 500, Gen = 100, p_c = 90 %

RUN	p_m= 5 %	p_m= 0 %
1	696.8981	696.8981
2	696.8981	696.8981
3	696.8981	696.8981
4	696.8981	696.8981
5	696.8981	696.8981
6	696.8981	696.8981
7	696.8981	696.8981
8	696.8981	696.8981
9	696.8981	696.8981
10	696.8981	696.8981
Average Minimum PVC	696.8981	696.8981
Average No. Evaluations	12285	10440
Average Run Time (Sec)	35.11	35.02

The effect of mutation in this case is to hinder the GA process. This is concluded as Model 3 takes more evaluations on average to obtain the same result when a probability of mutation is used. It is expected in this case that the PMX crossover operator should be effective in solving this problem. It is only when more complex problems like those previously examined are investigated that mutation is likely to be a necessary operator to obtain good solutions. Otherwise, for straight forward sequencing problem such as this one, mutation will tend to disrupt the PMX crossover process and delay the obtaining of the minimum PVC solution.

The next parameter of interest is that of the crossover probability. This will be examined in both Tables 8.14 and 8.15. The first table will include mutation in Model 3 whereas Table 8.15 results will assume a probability of mutation of 0 %.

Table 8.14 The Effect of Crossover Using Model 3 for the Parameter Set : Pop = 500, Gen = 100, p_m = 5 %

RUN	Probability of Crossover		
	90 %	70 %	50 %
1	696.8981	696.8981	696.8981
2	696.8981	696.8981	696.8981
3	696.8981	696.8981	696.8981
4	696.8981	696.8981	696.8981
5	696.8981	696.8981	696.8981
6	696.8981	696.8981	696.8981
7	696.8981	696.8981	696.8981
8	696.8981	696.8981	696.8981
9	696.8981	696.8981	697.5916
10	696.8981	696.8981	696.8981
Average Minimum PVC	696.8981	696.8981	696.9675
Average No. Evaluations	12285	10045	8025
Average Run Time (Sec)	35.11	42.77	57.79

For the various cases examined in the above table the number of generations are varied so the same number of evaluations are examined. For the 50 % , 70 % and 90 % cases the number of generations examined are 180, 130 and 100 respectively. The best value of p_c for this case appears to be the 70 % probability. This provides the same result as the 90 % value but in fewer evaluations. When p_c is reduced to the 50 % level, it would appear not enough mixing occurs for this population size and a higher PVC is obtained. However, this only applies for one particular run for this value of p_c and in general the minimum PVC solution is found in fewer evaluations with a lower value of p_c. A factor which can be seen from these results is the rate of convergence of the GA to a solution based on generation and not evaluations, as p_c changes. For the higher p_c case mixing in a generation is higher and the number of generations taken until the minimum is found is less. For the above values of p_c of 90 %, 70 % and 50 % the generation in which the minimum is first obtained are 28, 29 and 33 respectively. When obtaining a solution, if the number of generations was considered to be more important than the number of evaluations, then the p_c value of 90 % would be the best value to use.

Table 8.15 also examines the effect of different levels of probability of crossover. However, in this case it will be examined when there is no mutation.

Table 8.15 The Effect of Crossover Using Model 3 for the Parameter Set : Pop = 500, Gen = 100, p_m = 0 %

RUN	Probability of Crossover		
	90 %	70 %	50 %
1	696.8981	696.8981	696.9018
2	696.8981	696.8981	696.8981
3	696.8981	696.8981	696.8981
4	696.8981	696.8981	697.3883
5	696.8981	696.8981	696.8981
6	696.8981	696.8981	697.3883
7	696.8981	696.8981	697.3883
8	696.8981	697.6703	697.3883
9	696.8981	696.8981	696.8981
10	696.8981	696.8981	696.8981
Average Minimum PVC	696.8981	696.9753	697.0946
Average No. Evaluations	10440	9870	7525
Average Run Time (Sec)	35.02	42.89	58.53

The same number of generations as used in Table 8.14 are used for the results in Table 8.15 for the various values of p_c. In Table 8.15 the best value of p_c is 90 % as it provides the lowest average minimum PVC solution. In addition, the number of evaluations taken to find a solution is not considerably greater than the smaller values utilised for p_c. The reason for the higher PVC results for the other values of p_c is thought to be from inadequate mixing in the GA process. However, in the case of the 70 % p_c value the minimum PVC solution is not obtained in only one out of the ten runs. Again as was the case in Table 8.14 the number of generations required to find the minimum cost PVC solution is less when the value of p_c is high. In this case for the values of p_c of 90 %, 70 % and 50 %, the number of generations examined before the minimum PVC solution is obtained, are 24, 29 and 31.

When a comparison is made of the results of Tables 8.14 and 8.15 it is seen that mutation does have an effect on the solutions obtained. When mutation is not included the number of evaluations taken to find the minimum PVC solution is reduced. However, for the p_c values of 70 % and 50 % the minimum values of PVC obtained are higher. For the highest probability of crossover the result does not change and is found in fewer evaluations when there is no mutation. Thus it can be said that if the probability of crossover is low then mutation may be important. This result indicates the importance of having adequate mixing due to the type of mutation operator used. In this case a swap mutation operator is used which effectively enhances the mixing of strings by swapping bit values within a string. Thus when p_c is low the use of mutation allows adequate mixing still to occur thus the result found using a p_c of 70 % in Table 8.14. However, when mutation is removed from the GA the value of p_c must be increased so that adequate mixing still occurs. In regard to the number of generations taken to find the minimum PVC solution without mutation, for a p_c of 90 % the number of generations is substantially reduced from 28 to 24. However, for the other cases the number of generations remain relatively constant with a slight decrease when there is no mutation. Thus the most effective parameter values to use for the GA from these results are either with p_c equal to 90 % and no mutation or p_c equal to 70 % with mutation. In both cases the solution obtained is the same and the number of evaluations are approximately the same. The case of p_c equals 70 % with mutation takes slightly fewer evaluations (ie. approximately 4 % less). However, the GA model with a p_c of 90 % and no mutation will take fewer generations (ie. 24 compared to 28) to obtain the minimum PVC solution.

In addition, the probability of crossover was examined for a 5 member tournament selection. In this case probabilities of 90 % and 70 % were examined and these results are given in Table 8.16. The 90 % case is also given in Table 8.17.

Table 8.16 The Effect of Crossover Using Model 3 for the Parameter Set : Pop = 500, p_m = 5 %, 5 Tournament Members

RUN	Probability of Crossover	
	90 %	70 %
1	696.8981	696.8981
2	696.8981	696.8981
3	696.8981	696.8981
4	696.8981	697.5916
5	696.8981	696.8981
6	696.8981	696.8981
7	696.8981	696.8981
8	696.8981	696.8981
9	696.8981	696.8981
10	696.8981	696.8981
Average Minimum PVC	696.8981	696.9675
Average No. Evaluations	7290	5565
Average Run Time (Sec)	37.53	44.09

It can be seen in the above Table that the higher probability of crossover provides the best result. In addition, as was the case with the previous problem, the number of members used in tournament selection will affect the value of the probability of crossover. When a larger number of members are used in tournament selection, the value of pc should also be increased to ensure adequate mixing occurs.

The initial analysis to be examined is that of various selection procedures used for the GA. The same selection criteria as used in the South-East Queensland Case with upsizing allowed are investigated here. They are proportionate, 2, 5 and 10 member tournament selection procedures For the proportionate selection procedure three levels of fitness scaling will be initially examined to determine the best one to use in the comparison with the tournament selection procedures. The three levels of fitness scaling are 1/PVC, $1/(PVC)^3$ and the increasing fitness scaling used for the previous problem in section 8.3.2 (Table 8.9). Each different fitness scaling was used for 5 different run with a different seed per run. For the no scaling case the average minimum PVC obtained was 709.4482, for the cubic scaling the average minimum PVC was 703.9929 and for the increasing scale case the average minimum PVC was 703.0093. Although the last two methods provide similar results it was decided to use the better of the two. Thus, based on these results the increasing scaling of fitness was utilised for the comparison of the various selection criteria under examination.

Table 8.17 The Effect of Selection Procedure for the Parameter Set : Pop = 500, Gen = 100, p_m = 5 %, p_c = 90 %

RUN	Selection Procedure			
	Proportionate	Tournament-2	Tournament-5	Tournament-10
1	705.8562	696.8981	696.8981	696.8981
2	705.5262	696.8981	696.8981	696.8981
3	701.5891	696.8981	696.8981	696.8981
4	700.9249	696.8981	696.8981	696.8981
5	705.4030	696.8981	696.8981	696.8981
6	701.2121	696.8981	696.8981	696.8981
7	705.2534	696.8981	696.8981	696.8981
8	701.6753	696.8981	696.8981	696.8981
9	704.7140	696.8981	696.8981	696.8981
10	701.9505	696.8981	696.8981	696.8981
Average Minimum PVC	703.4105	696.8981	696.8981	696.8981
Average No. Evaluations	34965	12285	7290	5715
Average Run Time (Sec)	48.01	35.11	37.53	42.81

The obvious result from the above Table 8.17 is that proportionate selection even with fitness scaling is an inferior selection criteria to tournament selection. For all the tournament selection runs the same lowest PVC results were obtained. However, the greater the number of strings tested for selection as a parent string the less evaluations that are required to obtain a solution. In this case the number evaluations is halved from the 2 member to the 10 member tournament selection case. The success of the 10 member tournament selection case is due to a greater number of higher fitness strings being used as parent strings for the next generation and also a greater reduction in the number of inferior strings which are selected as parent strings. For instance when using a 10 member tournament selection criteria the best string will be used 10 times as a parent for the next generation and other high fitness strings will be used multiple times. On the other hand, the 9 lowest fitness strings will not be selected for use as parent strings. The same applies for the 2 member tournament selection only the numbers are reduced. In this case the best string will have two copies used as parents and the worst string will not be used. Thus for a lower member tournament it is more likely that lower fitness strings will be utilised as parents for the next generation.

The 10 member tournament selection result illustrated above produces the best results of all the models tested on this problem. It produces the same solution as other methods, however it obtains the solution in approximately half the number of evaluations of the next best model. As far as the parameters which should be used in conjunction with this tournament selection procedure, a low probability of crossover could be tried however, it was found with tournament selection with 5 members that a p_c of 70 % produces a higher average PVC for ten runs than a p_c of 90 %. Thus the only other change would be to the p_m value and population size. However, for the population size, the effect of using such a large number of members in the tournament selection may result inferior results when smaller population sizes are examined. The reason for this conclusion is that the solution will be produced faster but less mixing of strings will occur. Thus the appropriate mixing needed to obtain the lowest PVC solution may not occur. The use of no mutation on the other hand may result in the production of a more efficient GA model. However, it comes down to the problem of adequate mixing of the population and as was seen in the results of Tables 8.14 and 8.15 neglecting mutation can change the value of p_c that yields the best solution. With no mutation, higher values of p_c are likely to be needed to produce good results. Thus it was decided to examine the 10 member tournament selection case with a p_c of 90 % with no mutation. In 5 runs of this model the lowest PVC solution of 696.8981 was not obtained and the average minimum PVC found was 698.1345 in 4140 evaluations which is a considerably worse result than that shown above. In addition to this the 5 member tournament selection model was examined with no mutation. The result of which for 5 runs was an average solution of 697.1356 in 5580 evaluations. This is an inferior result to that shown in Table 8.17 when mutation is included in the model. Thus it is concluded that the values of parameters used in Table 8.17 for the 10 member tournament selection case are the best examined in this study and will be close to the optimum parameter values for this case.

8.4 Conclusions

This study has evaluated three different GA models and the parameter values which are used in the models. These models have been used to solve three different problems taken from Chapters 6 and 7. The first two cases were taken from Chapter 6 and examined the sizing and sequencing of projects for the no upsizing and upsizing allowed cases for the South-East Queensland System. The third problem was previously in Chapter 7 and investigated the sequencing of projects for the Perth Water Supply System based on both operational and capital cost.

It was found that Model 1 which uses continuous coding and standard mutation and crossover was the most successfully model for the South-East Queensland problems examined. In both the no upsizing and upsizing allowed cases, Model 1 produced the lowest average minimum PVC although it generally required more evaluations to obtain the minimum solution for a single run. It must be also said that Models 2 and 3 also produced the lowest average minimum PVC for the no upsizing case but the parameters needed to obtain this solution resulted in these model taking more evaluations to obtain the solution.

Model 1 also produced the lowest average minimum PVC for the Perth problem examined, although in this case Model 3 produced the same result but in fewer evaluations. Thus for the third problem examined Model 3 was considered to be the best and most appropriate model. However, from these results the overall best model would seem to be Model 1 as it is considered the best model for two out of the three situations examined and also provides the lowest average minimum PVC on the third occasion.

The GA parameters examined in this study were, population size, probability of crossover and mutation and selection procedure. The value of population size was varied and increasing values of population size resulted in better solutions for the various problems being examined. This conclusion was also reliant on the model used. For instance in the case for no upsizing of projects for the South-East Queensland problem Model 1 produced the best solution with a population size of 100 however Models 2 and 3 need a population size of 500 to obtain the best result. For the third problem examined both Models 1 and 3 improved their results when a population size of 500 was used. In addition the success of a particular population size for problem 2 was dependent on the number of generations examined. For instance going from population size 100 to 500 resulted in an improved solution. However, going from a population size of 500 to 1000 resulted in a worse solution. In this case the number of generations examined were 200 and 100 respectively. But when 200 generations were used for the 1000 population size the solution obtained was the same as found when using a population size of 500. The reason the number of generations is important for this case is that it is a more difficult problem and convergence seems to be slower. When a population size of 2000 was used for 200 generations, given the same p_c and p_m the solution was an improvement over that of using a population size of 1000. Although considerably more generations were utilised for the larger population size. However, in this case to use more generations for the lower population sizes is not expected to improve on the result. The reason is that improvement in the result will most likely occur using mutation, however mutation in the case in question is not enough to obtain the change in sequence necessary to improve the results. This is particularly so when using tournament selection, as a number of mutation are required to go from the solution obtained to a better solution. However, as a result of mutation the initial string fitness may be lower than that previously obtained so that it may not be selected to be represented in the next generation. Thus, the sequence path required to obtain the better solution may not be maintained, due to its initial fitness value and that a better solution may not be found.

In regard to the probability of mutation it was found that mutation was both effective and ineffective for the cases examined. In addition it is considered from the results that the effect of mutation is dependent of the population size as well as probability of crossover. When the population size is larger the effectiveness of mutation is decreased. This is seen in the extreme for problems 1 and 3 where using mutation results in more evaluations being required to obtain the best solution than if mutation is not used. However in problem 2 using mutation resulted in a better solution being obtained but in a larger number of evaluations. The reason for this is that mutation will improve on the solution found as the number of evaluations increases so that a better solution may be found as a result of mutation after considerably more evaluations. This may seem to contradict the statement above about the number of generations used, but it must be realised this is for a specific problem and the solutions obtained for that problem. For instance in the case discussed above the solution obtained was 71.4870. To improve on this solution a major sequence change needs to occur which is not likely to occur as a result of mutation. However for the situation just mentioned the best solutions with no mutation were in the region of 71.5161. An improvement on this result can be obtained by mutation as the difference between this sequence and sequence which produces the 71.4870 value is just the upsizing of project 8 to size 2 by sequencing project 8/1 first rather than sequencing of project 8/2 as the initial project. Thus a simple mutation of the bit corresponding to project 8/1 will give the better value of PVC. The effect of mutation will also vary depending on the probability of crossover. It was found for problem 3 that when mutation is used the corresponding probability of crossover to achieve the best results is lower. In this case though the solution achieved was the same but the number of evaluations it was achieved in was lower for the lower value of p_c. However, when there is no mutation a higher value of p_c produced the best solution but in more evaluations than when lower values of p_c are used. The reason for these results is considered to a result of the mixing of string within the GA process. So that for the population size used adequate mixing will occur when mutation is used at lower values of p_c. But if mutation is not used, to ensure adequate mixing occurs the value of p_c should be high.

The probability of crossover has been briefly discussed with regard to probability of mutation. If the cases where p_c is examined are investigated so that the probability of mutation is the same for those cases, conflicting results occur. For problem 3, when mutation is used, p_c values of 70 % and 90 % provide better solutions than when a p_c value of 50 % was used. When p_m is set to 0 % then a p_c value of 90 % gives a better result than the 70 % value. However, for problem 2 the p_c value of 50 % gave a better result than the 70 % value which in turn was better than the 90 % value. While the solutions obtained for both problems do not conclude whether the value of pc should be high or low, the selection of p_c needs to ensure adequate mixing occurs between the population of strings. However, the question of adequate mixing is not only dependent on the value of p_c used, but is also dependent on the population size, tournament selection size and as previously seen the value of p_m. So the selection of an appropriate p_c value is dependent on the other parameters used and should ensure adequate mixing occurs. This is the reason for the solutions obtained. For problem 3, the higher values of p_c were found to provide better solutions, as a low population size was used. In addition when p_m was equal to zero, the best results were found with a larger value of p_c, so that more mixing occurred between strings. On the other hand, in problem 2 a large population size was used, so for adequate mixing to occur the p_c value could be reduced. The reason for this is that the greater the population size the more likely the greater number of similar string sequences and also different string sequence. Thus an appropriate level of mixing should occur at lower values of p_c. The result of which may be a better solution. The p_c value was not examined for problem 1 as the best result was already considered to be found although, a lower value of p_c may have reduced the number of evaluations required to find that solution.

The final parameter examined is that of the selection scheme used in the GA models. In Chapter 5 it was shown that tournament selection performed better than proportionate selection. This was again shown to be true for problems 2 and 3 examined in this chapter. It was found that the larger the number of members within a tournament the better the solutions obtain. This was seen for both problems. However, it must be realised that in general, there is a limit to the number of members that can be successfully used in the tournament selection procedure. For example, if the number of members was chosen as the population size, any improvement would be a result of mutation, as crossover would occur between identical strings. Although this is an extreme case, poor results could be expected if a limit is not placed on the number of members in a tournament. From the results in this chapter, such a limit can not be specified. A limit on the number of members in a tournament should be specified with regard to the percentage of the population size (ie. less than 5 %), as the success of a particular number of members will be reliant on the population size.

In the case of problem 3 where the same results for 2, 5 and 10 member tournament were obtained the larger tournament size produced the result in fewer evaluations. This was also the case for problem 2 although the solutions also varied. In fact for problem 2 going from a 2 to a 5 member tournament resulted in a worse average minimum PVC. This was a result of one run for the 5 member tournament selection routine obtaining a higher PVC. This result is unusual but does highlight that the success of the GA method is reliant on the generated sequence of random numbers. There is no other explanation for this result other than the generated sequence of numbers was such that the lower PVC (71.4870) previously found was not obtained. Also, this highlights that the problem examined is very complex and difficult to solve optimally. This can be supported by the result of the 2 and 10 member tournaments, where using the same seed and therefore the same generated sequence of numbers the value of 71.4870 was obtained. For problem 2 it was found that the use of large member tournament will not guarantee a better PVC solution when a population size of 2000 is used. The reason for this result would seem to be due to the GA's reliance on the generated sequence of numbers and the difficulty of this problem.

For all problems the best GA model produced a result within a small fraction of the total solution space. An example of this is the best GA used to solve problem 3. In this case the number of evaluations required to produce the best solution was 3175 however the total solution space is 1307×10^{12} possible combinations of projects. Thus the GA has effectively searched 0.000000243 % of the search space to obtain the best solution. On the other hand for the more difficult problem (ie. problem 2) although it is expected the solution 71.4736 will be optimal or near optimal and therefore 71.4870 is near optimal, the GA can provide a near optimal solution by examining only a small number of evaluations compared to the total search space. For problem 2 the total number of possible combinations is approximately 3.84×10^{17}. In the best case only 31860 evaluations were made to obtain the best solution, this corresponds to only 8.28×10^{-15} % of the total possible evaluations. Even for problem 1 the solution space is approximately 1.94×10^{8} combinations and the number evaluations taken is 2763 for the best GA model which is approximately 0.0014 % of the possible solutions. Even if the most efficient GA models are not chosen the relative search space examined is still very small. The best overall model appears to be Model 1 although it is outperformed by Model 3 for problem 3. However, it is expected that Model 1 provides the optimum or near optimum solution for all the problems examined in this chapter.

A final comparison to be made is between the results obtained in this chapter and those obtained in Chapters 6 and 7. For problems 1 and 3 the same minimum PVC result was obtained. However, for problem 2 the same model produced better solutions in this study than previously found in Chapter 6 even though the same parameter values were used. The only difference between the two situations is that here 1000 generations were examined and only 200 generations were used previously and a different random number generator was used. The variation in number of generations may account for the difference as in only four out of the ten runs in this chapter was the solution found within 200 generations. However, the random number generator may also contribute to the improvement. The reason for this is that the new random number generator produces the same number sequence given the same seed however, on checking of the random number generator used previously this did not turn out to be the case. The use of different generators may not be the reason for the difference in the solutions. However, as the consistency of the random number sequence seems to be important to the GA process, the generator developed by Barnard and Skillcorn (1989) and used in this chapter, is regarded as the better method of generating random numbers.

In conclusion as is shown in this study the GA is useful in obtaining a good or optimal solution for a large number of the various parameter values. This study has shown the effectiveness of solving relatively hard water resources problems in a relatively small number of evaluations, while obtaining an optimum solution. In addition, for very difficult problems the GA performs extremely well in providing either an optimum or near optimum solution.

Chapter 9

Conclusions and Recommendations

9.1 Introduction

This thesis has examined the following capacity expansion problems:

1) the scheduling and sequencing problem ;
2) the scheduling, sequencing and sizing problem ;
3) the pricing, scheduling and sequencing problem ; and
4) the pricing, scheduling, sequencing and sizing problem

With the variation in capacity expansion problems and the inclusion of price a number of different objectives and parameters were studied.

An extensive review has been undertaken of previous methods and the various problems studied. A number of these techniques have been used to solve the capacity expansion problems investigated. These include heuristic and mathematical programming methods. The techniques used in this study to sequence projects are the equivalent cost per period method (Erlenkotter, 1973a), the unit cost method and an integer/linear programming method. In addition, a new method called genetic algorithms was adapted and applied to the capacity expansion problem.

This chapter summarises the conclusions made in this thesis. These conclusions relate to the success of the various models used as well as the parameters which are likely to affect the capacity expansion decision. In addition, the success of yield estimation techniques used will be discussed.

Finally, a number of recommendations are made regarding the capacity expansion problem and possible extensions to the work presented.

9.2 Contributions of the Research

This thesis has made the following contributions :

1) A methodology proposed for optimal expansion of water supply systems. This involved an interactive approach where the yield of potential projects is evaluated and the projects are sequenced using the equivalent cost and unit cost sequencing methods. The purpose was to obtain a sequence of projects such that the present value of capital cost was minimised. This methodology was applied to the Canberra Water Supply System.

2) A number of techniques for sequencing and sizing have been compared for a variety of problems. The unit cost, equivalent cost, genetic algorithm (GA) and integer/linear programming procedures were used for the sizing and sequencing of projects for the South-East Queensland System. Two situations were examined with regard to the sizing of projects. These were that projects were and were not allowed to be increased in size once they are built.

3) The GA technique has been introduced and successfully applied to the sequencing problem. Previously the GA had not been applied to the water resources sequencing problem. The successful application of the GA to this problem has involved using different coding schemes, crossover operators, mutation operators and selection procedures. The GA was successfully applied to the various capacity expansion problems examined in this thesis.

4) A technique for optimal pricing and capacity expansion has been developed and demonstrated. Two techniques were produced. The first involves an iterative technique where the price is set and the optimum sequence of projects is evaluated at that price. The net present value of consumer benefits (NPV) is evaluated for that price and project

sequence and the price is then increased and the process repeated. The optimum price corresponds to the largest value of NPV. This method was used for the Canberra Water Supply System and the equivalent cost method was used to sequence the projects. The second technique involves using the GA method. In this case the optimum water price, size and sequence of projects is evaluated and the NPV is calculated. This technique was used for the South-East Queensland case study.

5) The GA parameter values have been examined in an effort to provide the best GA model for the sequencing problem. The GA parameter values of population size, the probabilities of crossover and mutation and the selection procedure were varied to determine the effect of these parameters on the performance of the GA. Thus the best GA model for various problems was determined.

6) Finally, the effect of various parameters on the pricing and capacity expansion decision were investigated. The parameters of interest for the capacity expansion problem were the project yield and cost, demand growth rate, discount rate and planning period. When the optimum price was included, the effect of the price elasticity of demand on the optimum price and sequence was examined. The effect of including operating cost on the sequencing of projects was evaluated in the Perth case study. In addition, when sizing of projects is examined, the effect of the upsizing cost on the optimal sequence of projects was investigated.

9.3 Yield Estimation Models

As part of the sequencing problem addressed for the Canberra Water Supply System, it was necessary to estimate the existing system yield and the yield of the future reservoir projects. For the existing system yield estimates, four models were utilised. These were two optimisation methods (the yield model and the optimisation model), a combined simulation and optimisation package (WATHNET) and a simulation method developed for the Canberra System, ACTEW. All of the models except the simulation model were used for the estimation of the future reservoirs' yields. Due to the interdependencies of the existing system and the future reservoirs, the yields of the future reservoirs were estimated by adding each one to the model of the existing system and reestimating the total system yield. The following methodology was proposed in Chapter 4 to obtain the optimal sequence of reservoirs.

(1) The yield of the existing system is evaluated;

(2) The yield of the expanded system is determined with each proposed project added individually. Hence the incremental yield of each project is determined;
(3) A sequencing method is used to select the best alternative ;
(4) The incremental yields of the remaining projects are evaluated as the next expansion to the system; and
(5) the sequencing method is used again to select the next expansion.

This procedure continues until either all projects are expanded or enough projects are expanded so that demand is satisfied for the entire planning period.

As can be expected in the estimation of the existing system yield, the simulation model developed by ACTEW obtained the lowest estimate of yield. The reason is due to the use of the existing operating rules and the fact that it is a simulation model. The WATHNET model, on the other hand, uses improved operating conditions, which helps it obtain a higher estimate of yield. Other than this difference, WATHNET is basically a simulation model from period to period. It is only within a period that optimisation is used to decide on releases and transfers within the system. In the case when operating cost is included in the model, the WATHNET yield estimate was reduced, but was still higher than that produced by the simulation model. The two optimisation methods obtained the highest estimates of yield. This is because both assume perfect knowledge of future inflows so that more water can be either supplied or stored in a particular period depending on the future inflows. In addition, these models use perfect operating rules of the system which are more efficient than the operating conditions used in the other models. In this case the yield model produces a higher estimate of the yield than the optimisation model. This clearly is not possible due to the fact the optimisation model will produce the highest yield estimate possible. This highlights a problem with the yield model in that the performance of the model is dependent on the selection of the critical year, which depending on the system, may cause an inaccurate result. This problem was examined further and it was found that with different critical years the estimates varied significantly. Overall, it was considered that the selection of critical year used should be the driest year on the record. This should produce a yield estimate close to that of the optimisation model, with differences being due to how well the flows in the critical year represented the months flows used in the optimisation model.

For the estimate of future reservoir yield all the models used produced similar results. The yield model result produced a good approximation of the optimisation model estimates for all projects. Even the WATHNET estimates were in the same range as the yield and optimisation model. In fact the final estimates of system yield only differ due to the initial difference in yield estimates of the existing system. Actually, some of the estimates of yield by WATHNET were greater than the other models. On first glance this is unusual, but on further examination the explanation is clear. It would appear in these situations the operating objectives in WATHNET utilise more interaction between the new project and the existing system and the extra yield is due to a lower estimate for the previous project sequenced.

The WATHNET results are expected to be more realistic than the yield model or the optimisation model results, as the simulation examines the system on a month to month basis in a similar way to the traditional operation of a reservoir system. However, whether the estimate of yield is realistic will also be dependent on whether the operating objectives in WATHNET approximate the true operation of the system. The use of WATHNET could be expanded to evaluate restriction rules for the system.

These results indicate the benefits of using a model such as the yield model. In this case good approximations of the yield were produced with far less computational effort than the optimisation model. In addition, a longer annual data set was used for the yield model, which should improve the estimate of yield. This is one problem with the optimisation model. Due to the use of monthly data, the length of data which can be used without the process becoming burdensome, is only very short. However, because of the approximations made in the yield model a longer data set can be used.

The estimate of yield produced by these models is based on finding the maximum safe yield. No preference is placed on the use of any particular supply source as may be the case in the real world situations. In addition, no examination is undertaken on lowering operating cost while determining the system yield. This case was briefly examined in Chapter 4 for the existing system yield by placing operating cost in the WATHNET model. The result was a reduction in the yield obtained. The same result would be expected if costs were included in the optimisation and yield models. However, in this study the aim is to supply the maximum yield regardless of the operating cost.

9.4 The Capacity Expansion Problem

In the various studies undertaken there were two different capacity expansion problems investigated. These were the sequencing and scheduling of projects examined in Chapters 3, 4 and 7 and the sizing, scheduling and sequencing of projects in Chapter 6. In addition, the determination of the optimum water price for these problems was also examined in Chapters 4 and 6. The conclusions for the various capacity expansion problems will be discussed in relation to particular case studies. This will include, conclusions regarding the success of the models used in the study as well as an evaluation of the parameters which affect the capacity expansion decision.

9.4.1 Sequencing Water Resources Projects

The sequencing of water resource projects was examined in Chapter 3 where a simple example was used to compare the equivalent cost and unit cost methods. The results of this comparison showed that the equivalent cost method provided the better sequence of projects in terms of minimising the present value of project costs. The equivalent cost method involves the use of the demand growth rate and the discount rate whereas the unit cost method does not. It was concluded that both of these parameters affect the optimal sequencing of projects. This conclusion contradicts the results of Morin (1973) which indicated that the optimum sequence of projects is reliant on the demand growth rate but is not affected by the discount rate. However, the conclusion of Morin (1973) that both discount rate and the demand growth rate had an effect on the discounted cost was found to be true. No strict relationship can be found to relate the discount rate or demand growth rate to which projects are likely to be favoured in the sequencing decision. For this study, a larger project was favoured when demand growth was high and discount rate was low, with the sequencing of the smaller projects first providing the better PVC for the other combinations of demand growth rate and discount rate.

However, such a generalisation cannot be made from the results of sequencing of projects for the Canberra Water Supply System in Chapter 4. In this case the effect of the discount rate and demand growth rate was not as pronounced. It is considéred that the projects' yield and cost will be a major factor in the sequencing decision. Thus, not only is the sequencing decision sensitive to the demand growth rate and the discount rate but also the relative magnitudes of the projects' costs and yields. Thus, the conclusion of Morin (1973) may be correct in some cases but not generally. Alternatively, in another study the discount rate and demand growth rate may not effect the optimum sequence of projects and a conclusion to that effect may be reached. However, in reality it should be said that the effect of the discount rate and demand growth rate is reliant on the relative magnitude of the projects' costs and yields and that all four parameters should be included in any sequencing method to ensure that the best solution is obtained.

The difference in sequence between the equivalent cost method and unit cost method obtained in Chapter 4 was only minor and the PVC obtained for the two sequencing methods were very similar. The results of Chapter 4 however, still show that the equivalent cost method is the better sequencing method. The success of the equivalent cost method in Chapter 4 is reduced as the situation examined includes a non-linear demand growth. It has been discussed previously that the equivalent cost method will provide an optimum sequence when demand growth is linear but can only guarantee a good solution when demand is non-linear. However, it was found in Chapter 4 that unless the equivalent costs of projects were similar then the sequence provided will be optimal. In the cases where the equivalent costs of a few projects are similar, the PVC for several sequences should be calculated to determine the best sequence. While in difficult situations and for large problems this may not guarantee an optimal solution, in the case study in Chapter 4 it has provided the optimal solution. Thus, based on the results of Chapters 3 and 4, the equivalent cost sequencing method is considered to be a better method than the unit cost method. In the case of linear growth in demand it will achieve the optimal solution. For non-linear growth in demand, the equivalent cost method will obtain a good, if not optimal solution. Checks may need to be made on the sequence, in the cases where the equivalent cost of several projects are similar.

The conclusions of Chapters 3 and 4 do not hold for the sequencing of projects for the Perth case study in Chapter 7. In this case both methods have their relative success in obtaining a better sequence than the other. The difference in sequencing in this case, is that the objective also includes the annual operating cost of projects. With this inclusion, the unit cost and equivalent cost methods as used in Chapters 3 and 4, are adjusted to include the operating cost of a project. The changes are detailed in Chapter 3 and the objective becomes the minimisation of the present value of capital and operational cost (PVTC). In addition, to using the adapted methods, the equivalent cost method as used in Chapters 3 and 4, was also utilised. Apart from these methods, a new method called genetic algorithms was examined.

As far as the equivalent cost is concerned, when the operating cost was included in the sequencing method, a lower PVTC was obtained. This in itself, indicates that the operating cost needs to be included in the sequencing decision to provide a lower PVTC sequence. In regard to which of the equivalent cost and unit cost methods produce the better solution, no general conclusion can be made. Both produce better solutions than the other on occasions without any consistency being indicated. The results are somewhat disappointing, as it was expected that the equivalent cost method, with operating cost included, would provide the optimum solution, assuming linear growth in demand. On a theoretical basis the equivalent cost method is considered better and is likely to be better for a infinite planning period.

However, this was not the case, as the genetic algorithm outperforms all methods in this case. The genetic algorithm in all cases produced the lowest PVTC solution and it is reasonable to believe that the solutions obtained are optimal or close to optimal. Only on one occasion did the adapted equivalent cost method produce the same result as the genetic algorithm.

The success of the GA was very encouraging and the results of this method highlighted some pronounced problems in the other methods. One of these was to do with using a finite planning period and a sequencing method which requires all projects to be sequenced to obtain its best performance. Both the equivalent cost and unit cost methods sequence projects based on the assumption that all projects will be built eventually. The problem here is that the best sequence for a shorter planning period may not be found, as larger projects may be sequenced towards the end of the planning period when a smaller, less costly project would be sufficient. This is one reason for the inconsistency of the equivalent cost method and unit cost methods performance. However, in the case where this was not a factor, the GA still outperformed those methods.

The GA seems to include operating cost better than the other methods. The result of the GA model indicated the relative importance of the various costs changed as the demand growth rate changed. As the demand growth increased the importance of the operating cost also increased. However, at no stage did the sequence change so that the value of PVOC was lowered at the expense of increasing the value of PVC. It appears that the best solution occurs when a trade-off is made between lowering PVC and PVOC. This is concluded as the other methods obtain either lower values of PVC or PVOC but not a lower value of PVTC.

The final discussion for this problem is the effect on the sequence when projects can be subdivided. The benefits of subdivision were seen in Chapter 7, where lower PVTC sequences were found. This is achieved by delaying part of a project and therefore discounting the costs to a greater extent. The sub division of projects in the planning stage is important when there are projects which consist of smaller sub projects with different capital and operating costs. In this case, subdivision will enable the poorer options to be scheduled later which will result in a better (ie. lower PVTC) project schedule and sequence.

9.4.2 Optimum Pricing and Sequencing of Water Resources Projects

The optimum pricing and sequencing of projects was examined in Chapter 4 as part of the study on the Canberra water supply system. With the inclusion of price, it is expected that the future demand should change and therefore the scheduling and sequencing of projects will also vary. The degree to which demand varies with a price change is governed by the price elasticity of demand. In this study, it was found that the sequencing decision was not greatly affected by changes in the various parameters.

The conclusions from this study are mainly to do with the effect of price on the sequence and timing of projects and the subsequent effect of various parameters on the optimum price. It was also found that in the majority of circumstances, the optimum price changed when there was a change in the discount rate, the population growth rate, the price elasticity or the planning period. The amount the optimum price changed, for a change in any of the above variables, seems to be dependent on the values of the other variables. For the discount rate, it is found that if the same conditions apply, (ie. the same projects expanded) then as the discount rate increases, the difference between the optimum price and the initial price will remain the same or decrease. This is also the conclusion for changes in the price elasticity of demand. As for the amount the optimum price varies with changes in the various parameters, this was dependent on the value of the other variables. For the price elasticity in demand, the closer the optimum price was to the initial price, the more likely the change in the optimum price was either small or non existent. In addition, when the discount rate is high, a drop in the optimum price will generally be a result of another project being sequenced within the planning period. Also, in the case of discount rate and demand growth rate, if a project is no longer required within the planning period, the optimum price will increase. As far as the demand growth rate is concerned, apart from more projects being required when the demand growth rate is higher, the optimum price tends to be higher.

The effect of planning period was also investigated. It was concluded that this factor can play a very important role in the sequencing of projects and value of optimum price obtained. Thus careful consideration must be given to the planning period used especially where price is included in the study.

Another factor examined in this study was the effect of demand management on the decisions of optimum price and sequence of projects. As the level of demand management increases, the price will tend to decrease, unless a project is no longer required in the sequence. In this case, the optimum price will be higher. The actual effect on the price is not entirely dependent on the level of demand management but also on the various other factors mentioned. What can be concluded from this study, is that with the economic criteria utilised, the optimum price will be obtained when there is full utilisation of the system's water supply over the specified planning period. For instance in the case of increasing demand management with the same projects expanded, the optimum price falls, so that the same level of demand is maintained. In the case where a project is not required, the price will rise to decrease demand to the desired level. Thus if a project is not dropped from the sequence then the effect of demand management is negated by price. This will make the use of demand management ineffective, as the purpose of demand management is to reduce consumption. However, there are a number of case where the price will fall to keep demand at pre-demand management levels. This is due to the economic criteria used where full utilisation of the system is required.

9.4.3 Sizing and Sequencing of Water Resources Projects

The sizing and sequencing of projects for the South-East Queensland system was examined in Chapter 6. This included an investigation into the possibility of allowing projects to be upsized. For this study the unit cost and equivalent cost methods were utilised as was the genetic algorithm. In addition, a integer/linear programming model was used.

The most successful model for this case was the genetic algorithm. It produced the solution with the lowest PVC on every occasion for both the no upsizing and upsizing cases. For the no upsizing case, the equivalent cost method obtained the same result as the GA in some cases. The problem with using the equivalent cost method for this study, was that non-linear growth in demand was assumed and thus, it was unlikely that the optimum sizing and sequencing of projects would be found. In all cases the unit cost method produced the highest PVC result of the three methods. This illustrates the inability of the method to consider variations in discount rate and demand growth rate and the importance of these parameters in the size and sequencing decision. The integer/linear programming method produced the same sequence as the GA for the majority of occasions. However, in the cases where the sequences varied, it was due to the use of 5 year discrete time periods in the integer/linear programming model. Thus the size and sequencing of projects was dependent on the time step used. It is considered that a continuous time scale needs to be examined and therefore the GA model was considered the better technique. In addition, the computation time required for the integer/linear programming model is restrictively large, even when simplifying assumptions are utilised. This is not a problem with the GA model.

As far as the parameters investigated are concerned, it was found that discount rate, demand growth rate and planning period, all affected the sequence produced. As the discount rate was increased it was apparent that the sequencing of smaller projects resulted in a lower PVC solution. This was not always the case, with no change in the size or sequence of projects for one of the demand forecasts investigated. Thus, the ultimate effect of discount rate will depend on the demand forecast, project cost and yield and planning period. No relationship between demand growth rate increases and project size and sequence could be established. The effect of demand growth rate on the project size and sequence was dependent on the other factors indicated previously.

It was mentioned in the previous section that planning period is an important factor in obtaining a good sequence of projects. This was also found in this study and is one of the reasons the equivalent cost and unit cost methods perform poorly. These methods do not consider the planning period but rather, sequence under the assumption all projects will be sequenced. However, there may be less costly options which may be sufficient to meet demand during the finite planning period. The length of the planning period is considered by the GA and the integer/linear programming model, and is a distinct advantage of these methods.

For the upsizing case, the GA again performed better than the other models. The difference between the equivalent and unit cost results and the GA are more pronounced for this case. The reason is that the other methods do not consider the use of upsizing of projects to their full potential and the finite planning period has a more distinct effect for this problem. On the other hand, the GA utilises upsizing of projects more, which results in lower PVC sequences. The integer/linear programming model also considers upsizing and the finite planning period and thus gives better sequences than the equivalent cost and unit cost methods. However, the problems mentioned in the previous section with computation time and discrete timing are a major disadvantage with the integer/linear programming method. The point must be made, however, that the GA does not achieve the optimal size and sequence of projects on all occasions. This is especially true for the case of upsizing cost equal to incremental cost. However, the result obtained is still the best sequence found by any of the methods and it was the GA process itself which highlighted the sub-optimality of the result. The identification of sub optimal results was achieved by examining other good solutions produced by the GA method. In some cases these solutions identified better sequences of projects. This result is one of the reasons a further study of the GA and its parameters was performed in Chapter 8, in an effort to improve the GA performance.

The level of upsizing of projects which occurred tended to be dependent on the upsizing cost, discount rate and demand growth rate. For the lowest upsizing cost case the degree of upsizing was at a maximum in order to produce the lowest PVC sequence. As the upsizing cost increased, the level of project upsizing reduced. This factor was also dependent on the discount rate and demand growth rate. For higher values of discount rate more upsizing occurred as the costs were discounted to a greater extent. In addition, the upsizing of projects tended to be later in the sequence when upsizing cost increased. However, this effect was marginally offset by a larger discount rate. An increase in upsizing cost also altered the sequence of projects. In one extreme, the first projects were continually swapped as the upsizing cost increased. Thus no trend can be established by behaviour of this sort, other than to say the effect on the sequence of projects of upsizing cost was dependent on the values of other variables. The benefits of upsizing projects was shown to be significant. This is achieved through the delaying of the higher cost alternatives which results in a lower PVC.

The discount rate will effect the level of upsizing that occurs, however it will also have an effect on the sequence of projects. The larger the discount rate, the more likely smaller projects will occur within the sequence of projects. As for the demand growth rate, there is no general conclusion that can be made other than to say that it affects the sequence of projects.

A conclusion regarding the use of demand management can be made for this study as it is included within the demand forecasts. In this case, demand management reduces the amount and the sizes of the projects required, which substantially reduces the PVC.

9.4.4 Optimum Pricing, Sizing and Sequencing of Water Resources Projects

The optimum pricing, sizing and sequencing problem was an extension to the problem just discussed. Thus the factors of upsizing cost, demand growth rate and planning period were considered. For this problem the integer/linear programming model is not utilised due to the complexity of the problem and the difficulty in using this method to model the problem successfully. The other methods were utilised with the GA model producing the best results, although in the no upsizing case, the equivalent cost method produced similar results. The major variation between the results was due to the finite planning period problem, mentioned previously for the equivalent cost method. For the upsizing case, the GA again gave the best results. As was the case previously, the GA uses more upsizing than the unit cost and equivalent cost methods.

When the upsizing cost increases, it was found that the number of projects upsized, decreases and the sequence of projects varies. In addition, the optimum price will also change with increased upsizing cost. The price change however, only occurs for the largest upsizing cost case and the change in price is dependent on the demand forecast under examination. Whether the price will rise or fall will depend on the final project sequenced, however, for the higher demand growths, the price increased.

The only other observation to make is the effect of demand management on price and sequence. In this case the use of demand management is to lower the optimum price obtained. This is the same result as found in Chapter 4. In addition, the use of demand management in this case results in less projects being required and a variation in the upsizing and sequence of projects.

Again the planning period was shown to be of great importance when the determination of optimum price is included in the capacity expansion problem.

9.5 Success of Models Used for Pricing and Capacity Expansion Problems

The success of the various models has been discussed with relevance to the problems examined. Of all the methods used in this work the most encouraging is the genetic algorithm. This discussion will focus on the success of the GA, the various GA's examined and a conclusion of the parameters of importance and the most successful GA models. The various advantages over the other methods has been discussed. The advantages of the GA which lead to its use for the capacity expansion of water resources are as follows:

1) Its successful application to other large combinatorial problems and
2) The ability of the GA to produce not just one good solution, but many near-optimal solutions;

The basic alterations to the traditional GA to produce suitable methods to solve the sequencing problem were:

1) Use of both continuous and real coding instead of binary coding;
2) The changes to the crossover and mutation operators particularly for real coding and
3) The use of tournament selection rather than proportionate selection.

A brief and limited sensitivity analysis was performed in Chapter 5 in which three of the most encouraging models were selected for further use. In addition, from this analysis and criteria outlined in the literature, values of population size, number of generations, probability of crossover and mutation were selected. The models selected to be used for the case studies examined were

1) T1 - continuous coding, one-point crossover, bit mutation and tournament selection ;
2) T5 - real coding, PMX crossover, adjacent swap mutation and tournament selection and
3) T6 - real coding, PMX crossover, random swap mutation and tournament selection.

The first problem the GA was used for was the sizing and sequencing of projects in Chapter 6. Model T1 was used to solve the no upsizing and upsizing cases, with price included and not included. In all cases this model was very successful in providing a near-optimal solution. A near optimal solution is only specified as there is some improvement that can be made to the solution for the upsizing case. The improvement was realised through the examination of the numerous near-optimal solutions obtained in the runs of the GA. It was considered that such improvement could be made if the GA model was to undergo further sensitivity analysis especially for its parameters. This was carried out in Chapter 8. The problem of upsizing is very complex and is difficult for any of the other methods to solve. The actual results obtained by the GA for this case are very good.

The GA method was also applied to the Perth case study in Chapter 7. Again the model outperformed the other methods substantially. The Perth problem was not as difficult as the South-East Queensland problem examined in Chapter 6 and the GA was expected to provide the optimal solutions. However, it cannot be determined whether this was actually the case. The problem examined was a straight forward sequencing problem with operating cost included in the analysis. For this study the GA Model, T6, was utilised.

As a result of performance of the different GA models in Chapter 6 and 7, a more detailed analysis was performed using the three models specified and three problems examined in Chapters 6 and 7. For each problem a number of the GA parameters were investigated. The results of this study were that the model using continuous coding (T1) was the best overall model for the problems examined. In two out of the three problems it was clearly the best. These problems were the no upsizing and upsizing cases for the South-East Queensland system. For the upsizing case the best parameter values obtained were :

Population size = 100, number of generations = 500, probability of crossover (p_c) of 90 % and probability of mutation (p_m) of 3 % and tournament selection with two members.

The population size was the only case examined for this problem and for the larger size, the same result was obtained, but in more evaluations. The value of p_m was also set to 0.0 for the larger population size. For this case, mutation was found to hinder the GA process, as more evaluations were need to obtain the same solution when mutation is used. However, it was considered that mutation would be required for the lower population size.

For the upsizing case, a more extensive analysis of the various parameters was performed. A number of different population sizes were examined and a number of values of p_c and p_m were investigated, for the larger population sizes. In addition, a number of selection criteria were analysed, once an appropriate population size was obtained. The selection criteria examined were, proportionate selection with fitness scaling and tournament selection with three different tournament sizes of 2, 5 and 10. The best parameter values were concluded to be:

Population size = 2000, number of generations = 200, probability of crossover (p_c) of 50 % and probability of mutation (p_m) of 3 % and tournament selection with two members.

The above parameters produced the best average minimum PVC result, although the best individual run was obtained using the above parameters as well as when the values of p_c of 70 % and 90 % were used. In addition, the best individual solution was also obtained when a population size of 1000, p_c and p_m of 90 % and 3 % respectively and 200 generations were used.

For this problem, it was found that even when a large population size was used, mutation was an important parameter. In addition, as population size increases, the chance of producing a better solution also increases. The best solutions were also found when a high value of p_c was used. It was concluded that the problem was very difficult to solve and even with larger population sizes or the best parameter values, there is no guarantee of an improvement in the results. But the GA did provide a very good, if not an optimal result for the problem examined.

The final problem was taken from the Perth Water Supply System problem in Chapter 7. This was the only case where Model T1 was not the best model. However, Model T1 did provide the lowest PVTC solution, but took more evaluations than Model T6. Thus, Model T6 was used for this problem. As was the case with the upsizing problem, a number of different parameter values and tournament selection criteria were tested. In this case, a number of different combinations of parameter values produced the lowest PVTC results. However, the parameter values which produced the best result in the least number of evaluations were:

Population size = 500, number of generations = 100, probability of crossover (p_c) of 90 % and probability of mutation (p_m) of 5 % and tournament selection with ten members.

As far as the importance of the various parameters is concerned, a number of conclusions can be made for this problem and model. The success experienced with the various parameter values, was dependent on the other parameter values used. It was found that, when mutation was utilised, the best solution was obtained in more evaluations, than if mutation was not used. This was true when a high p_c value was used (ie 90 %), the tournament selection uses only two members and the population size was large. When the value of p_c was reduced, or if a 5 or 10 member tournament selection was used, or if the population size was reduced, then mutation was important. For instance, a p_c value of 70 % was better when two member tournament selection was used, provided mutation was also used. If mutation was not used, the best value of p_c was 90 %. The reason there is such variability in the solution, when there are changes in some of the parameters values, is due to the mixing present in the GA process. For a GA to be successful, there must be adequate mixing of the population of strings. This is achieved through using carefully selected values of p_c and p_m , for a particular population size and selection criteria.

For this problem it was also seen that increased population size resulted in an improved solution. However, the best population size was considered to be 500 and any further increase in population would not have improved the solution, even if different parameter values were used. If a larger population size was used it is expected that the solution will be the same but will be obtained in more evaluations.

The ability of the GA to produce good solutions, given only average parameter values, was shown in Chapters 6 and 7. The further analysis of Chapter 8 has provided the improvement which can be achieved in the GA when better parameter values are used. However, it was also shown that the GA will perform to the same standard given a number of different parameter sets. The solutions obtained in Chapter 8 are the same as for Chapters 6 and 7 for the no upsizing case and the Perth Water Supply case. However, improvement was made in the solution for the upsizing case. The study of the GA in Chapter 8 has indicated the need to provide adequate mixing within the GA process through the correct selection of various parameters. Although the parameter values vary for the different problems, in general, larger population sizes, higher values of p_c and low values of p_m and the use of tournament selection will provide adequate mixing and good results for the GA. As an indication of the performance of the GA, the percentage of the solution space searched for the various problems was calculated. The percentages ranged from 0.0014 % for the no upsizing problem to 8.28×10^{-15} % for the upsizing problem. This is exceptional performance considering that the solutions obtained will be either optimal or near-optimal. These percentages highlight the true benefits of the GA method. In addition, when it is considered that the GA will provide a number of good to near-optimal solutions and the GA uses a fitness function which could be coded to include other factors, then the benefits of the GA are considerable.

The performance of the GA also seems to improve as the problems get larger and more difficult. This is highlighted by the result of the upsizing case. This is also an important factor, as there are no other realistic methods of providing even a good solution to such problems. At best, current techniques could be applied to large problems by separating the problem into smaller sets, however this will not guarantee an optimal or near-optimal solution. For difficult problems such as the upsizing case, the method of separation would not provide a good solution, due to the dependencies within a water supply system, particularly when reservoirs are present. However, a solution may be obtained using an heuristic approach (ie. equivalent cost method) with some iterative technique to search more of the solution space. Such a technique may not achieve a better solution than the GA method.

The GA method does have its limitations although these are not particular important. Firstly, there are other methods which are better for smaller problems. Such a technique is the equivalent cost method of sequencing projects. This method will provide an optimum solution, in a small number of hand calculations, for the simple sequencing problem provided the growth in demand is linear. Also, linear and dynamic programming are useful when only a small number of projects are involved. The GA will provide a near-optimal solution for this case, but will take considerably more time to achieve a solution. It was found that the results of the GA are not particularly sensitive to the chosen parameters. Further improvement of the model can be obtained through further analysis of parameter values.

Finally, some conclusion should be made on the other models used for sequencing in this study. Of these the equivalent cost method is considered to be better than the unit cost method. The inclusion of discount rate and demand growth rate in the equivalent cost method improves the solutions obtained. It has been mentioned that this will provide an optimal solution when demand is linear for the sequencing problem. When demand is non-linear the solution produced may be optimal but this cannot be guaranteed. The benefit of this method is the solutions obtained are found from only one calculation for each project. However, with the more difficult problems of sizing and inclusion of operating cost, the performance of this method was not as good. Thus, for the less difficult problem, the equivalent cost method would be the preferred method of the other methods examined. However, when a sequencing of projects is required for a finite planning period the equivalent cost method should be used carefully. The reason for this has been outlined previously. If this is the situation then a closer examination of the final project implemented at the end of the planning period should be undertaken.

The results obtained when applying the integer/linear programming method to the upsizing case were good. However, a number of simplifying assumptions were made to achieve this solution. These included using discrete time periods and fewer projects, in order to reduce computation time and difficulty. Even so the computation times achieved were excessive. If the integer/linear programming method could be used without these simplifications and if it could be solved more efficiently then the technique would be useful.

9.6 Parameters Effecting the Capacity Expansion Decision

The parameters which effect the various problems examined have been discussed previously. However, this section is included to give an overview of the most important parameters for the capacity expansion decision.

All of the parameters used in this thesis have some degree of uncertainty associated with them. For example, a project's yield have some degree of error involved in its estimation. The yield utilised will generally have some failure criteria associated with it. Thus, depending on the value of failure criteria utilised the yield estimate may vary considerably. Also, future demand forecasts are based on present consumption trends and expected population estimates. Both of these parameters can be affected by unexpected future factors which will change the actual demand. In addition, the discount rate is a parameter whose value is dependent on the person or authority making the decision. The effect of the uncertainty in these parameters can be assessed by performing a sensitivity analysis. This was carried out for some of the parameters in this thesis, but not for all the problems examined.

The most important variables to include in the capacity expansion problem in order to obtain good solutions are the projects costs and yields, the demand growth rate and the discount rate. The projects yields and the demand growth rate will affect the timing and scheduling of projects while the projects costs and discount rate will affect the present value of costs obtained. To ignore any of these parameters in the sequencing procedure will result in poor solutions when the objective is the minimisation of PVC. The inaccuracy of the solution will depend on the relative magnitudes of all these variables and in some cases the same solution may be obtained regardless of whether the discount rate or demand growth rate are included in the decision process. A further project cost, which was found to be an important factor in obtaining the lowest PVTC, was operating cost. The inclusion of operating cost resulted in a variation in the sequence obtained compared to when only capital cost is considered. However, estimates of operating costs for future projects are not always available which is why operating costs are usually excluded from the analysis. Such an exclusion can result in a sequence of projects which increases the total system cost considerably. Thus, if estimates of project operating costs are available in the planning stage, they should be included so that the project sequence, which provides the lowest PVTC, can be obtained.

Another parameter which was seen to affect the sequence produced was the planning period. This is particularly so if the combined yield of the available projects greatly exceeds the maximum demand during the planning period and the aim is to find the best solution for that planning period. The reason is that the sequence may change for different planning periods. Thus, the expenditure for a water authority will depend on the selection of planning period. It is suggested that the selection of the planning period should be such that the projects sequenced for that period are part of the optimal sequence of projects for the infinite period. This may not always be possible and then the problem that can be experienced with the sequence with a particular planning period should be acknowledged. The selection of planning period is a difficult problem. If too short a planning period is chosen this may affect the initial project sequence. Too long a planning period may produce a sequence which is not flexible enough to change with changes in demand and technology. In addition, most water authorities are only interested in the next project, or in the extreme, the next couple of projects to build. Thus, a small planning period is favoured. However, what must be considered is that these first projects still need to be the best projects for a long planning period. Thus the planning period should be chosen to accomplish this objective, but the decision should not be cast in concrete and a constant review of technology, demand and therefore sequence should be carried out at regular intervals (ie. 5 to 10 years).

Another consideration is the choice of time step. This was addressed when the integer/linear programming method was used in Chapter 6. The sequences produced using discrete 5 year time intervals was different than when a continuous time period was used. Thus, at all possible times, all attempts should be made to sequence projects and also size projects, based on a continuous time scale. If this cannot be achieved, the problems involved with using the discrete time scale should be addressed.

When pricing is included in the problem, it is evident that this effects the sequencing of projects. In addition, the above parameters will affect the optimum price obtained and thus they should be included in the analysis. With price included, this will affect the demand through the price elasticity of demand.

The study also demonstrated the effects of demand management on the optimum price and sequence of projects. However, the effect was not as expected. The reason for this conclusion is that demand management is expected to reduce demand but not affect price. However, the price tended to drop to offset the demand reduction so that the system was fully utilised. It is only in the case where the demand reduction is considerable that the price rises and a project is no longer required within the planning period. This is the ideal response to demand management but was not always found with the economic criteria used.

Another factor which was found to be important in the sizing of projects was the upsizing of projects and the associated cost. The study found that when upsizing cost is low, significant benefits can be obtained by using upsizing of projects. It is only when the upsizing cost of projects is prohibitive that upsizing is not beneficial. On the subject of sizing of projects, it was found that the maximum size was not always the best option. In fact, depending on the value of the other parameters, the relative size of a particular project varied from the smallest size to the largest size.

Finally, depending on the specifics of the problem, the various parameters mentioned here should all be included in the analysis in some way. Those methods and studies which fail to do this, will provide solutions which are at best, near optimal and, at worst, will waste millions of dollars of taxpayers' money.

9.7 Recommendations For Further Work

From the various studies involved in this thesis, a number of different models and various parameters have been used to examine the capacity expansion problem. Of the models used, the GA model has given the best and most encouraging results. It is unclear whether further improvement of the GA models developed can be obtained but this is certainly one area which should be examined. In particular, the use of other coding schemes and parameter values could be investigated. Also, more recently, the theory of messy GAs has been introduced and this could be examined to see whether it can be applied to the water resources capacity expansion problem. A technique which was also tried in this study but not reported on, is the seeding of the initial population with superior strings. In this study the equivalent cost and unit cost methods were used to generate a small percentage of the initial population. While in some cases this resulted in the GA finding a solution faster, there was also a problem when the sequence produced by these strings was significantly different from the optimum sequence. In this case, the optimum was not found. So a more detailed study of such a technique could be examined to improve the performance of the GA.

In addition, the use of the GA to solve the capacity expansion problem using multiple objectives is considered possible. Such objectives which come to mind are economic, environmental and social/political. With the GA utilising a fitness function all these objectives can be included in the decoding of a GA string. One problem is assigning various weighting between the objectives. For instance it must be decided whether the environmental or economic objective is more important and how to include this information within the fitness function. This is not an easy task and is situation dependent and has been a reason why the objectives of environmental quality and economics are seldom considered together. Another problem is finding a suitable quantitative measures for the environmental and social objectives.

Further work could also be undertaken on the capacity expansion problem. This could involve the inclusion of operating policies applying to future projects in order to reduce total system cost. In addition, a more adaptive pricing policy could be examined to see if it increases the NPV. The use of demand management in a more interactive manner could then be examined. Some problems which were evident when examining the optimum price were the use of a constant price elasticity and the economic evaluation criteria. On the first point, it has been mentioned in the discussion how the price elasticity could vary when price rises and falls. Thus, a more extensive analysis is desirable to identify the behaviour of the price elasticity, which could then be used to obtain the optimum price and capacity expansion of a system. The problem with a more extensive analysis is that actual data is required to analyse the effect of price on demand and thus various levels of price and corresponding demand would need to be recorded. Therefore, in the absence of this data, various price and demand relationships could be examined.

The uncertainty of the various parameters examined could also be included in the analysis. In this thesis this was achieved to some degree by performing a sensitivity analysis with a number of different values of the parameter. This is acceptable when there are only a few parameters, however as the number of parameters increases such a method can be restrictive and time consuming. A way of including uncertainty in parameters is by a probabilistic analysis. This is where probabilities are assigned to certain values of a parameter and the analysis is carried out. Thus, the sequence produced would be given a certain probability which relates to the parameter values utilised. The problem then is how to assign probability values to certain values of a particular parameter. Thus it may be more appropriate to use a sensitivity analysis approach and only examine the more important parameters.

In regard to the economic evaluation criteria used, it is considered that it does not reflect the true desire of the community. This is concluded because when demand management was examined the optimum price fell which offset the effect of demand management. However, the true desire of using demand management is to reduce demand and therefore delay expansion. In addition, it was evident that the model using purely economic criteria strived for full utilisation of a water supply system. However, it is more likely that a water authority will strive to produce a more efficient system and a system where there is sufficient supply available at all times.

This may be because the economic model used in this thesis was based on a partial equilibrium analysis. A general equilibrium model may be a more appropriate way to handle demand management and water pricing. This could be explored in further work.

Further to the problem of economic criteria used, it was seen in this study that if a curve of NPV versus price is examined that it is a very flat curve. Thus, any price within reason could be selected without the loss of major benefits. This may even be significantly higher than the optimum price. A similar result was obtained by Kuczera and Ng (1994) in a study which used a similar economic criteria. Also, the chosen economic criteria is not favoured by water authorities. The reason is that it gives consideration to consumer surplus which is considered theoretical and of no real concern to the water authorities. The consumer surplus is included to indicate the value of supplying water to the consumer. However, while the water authority wants to keep the consumers happy and the consumer surplus may be an indicator of this, the use of consumer surplus may exaggerate the benefits obtained by the community and certainly the water authority. If the consumer surplus is taken out of the calculation, the objective becomes the maximisation of profits and this will occur at a considerably higher price than would otherwise be charged. This would make the water authority happy but may be politically, socially and economically unacceptable. Unfortunately, there is no criteria which finds middle ground between the two objectives and will also reflect the nature of using demand management.

Finally, a method which combines the work of Kuczera and Ng (1994) on augmentation timing and the work here on optimal sequencing of projects, would produce a complete model for the timing and sequencing of projects. In addition, if the optimum price could also be involved in such a study this would produce a rather complete model for the optimum pricing, sequencing and scheduling of water resource projects.

Appendix A

WATHNET Model Identification

The WATHNET model consists of four different programs, EDNET, WATSTRM, SIMNET and WATOUT. The relationship between these four programs is illustrated by the flow chart in Figure A.1. A brief description of each of these programs is as follows :

(a) EDNET : The program sets up the system to be modelled. There are seven node types and a choice of two arc types to model the system. EDNET can be used to create a new system or to edit an old system. It enables capacities and costs to be assigned to pipelines (ie. pumping and treatment cost for water supplied) as well as the possibility of commission and decommission years. Riparian releases for streams can be set to ensure streams are always flowing at greater than the minimum allowed.

(b) WATSTRM : Takes the systems historical streamflow, demand, rainfall and evaporation data and reformats this data to a manner in which WATHNET can utilise it. There are seven possible options available in WATSTRM, however in this study, only option U is utilised as this performs the reformating of data to WATHNET readable data. WATSTRM also gives the option of generating new data. An example of a formatted datafile which WATHNET converts to a file which it can read is given in Figure A.2 of Appendix A.

(c) SIMNET : This program identifies the run model (ie. S, O, F) and then proceeds through various steps to set up the simulation. These steps are displayed as individual windows (and label as pages. ie. page 1, 2, 3, etc.) when working through SIMNET and are shown in a flow chart in Figure A.3 of Appendix A. At the end of setting up the model it is executed and the output is sent to a file. A summary of execution time is then print on the screen.

(d) WATOUT : Displays the system performance by graphical representation. There are three graphical alternatives to view to evaluate systems performance, a plot of total systems storage versus time with an indication of shortfalls over the same period, a system schematic in which individual reservoirs and pipe performance can be evaluated over the period and step by step operation of the system which shows the system operation from one period to another.

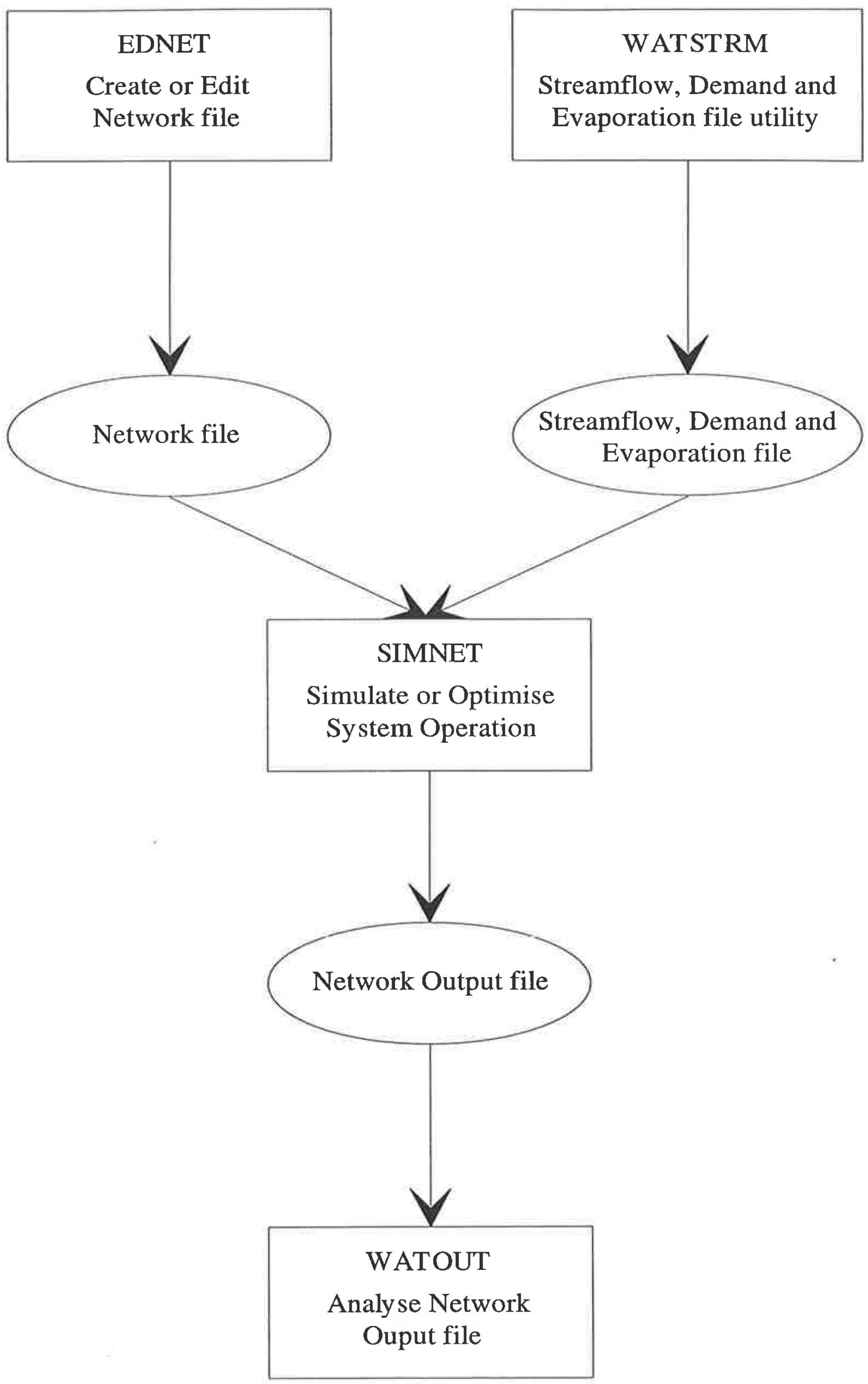

Figure A.1 Flow Chart of WATHNET Procedures

STREAMFLOW DATA FILE

13 1 720 1 1924 12 1983

2i5, 13(i8)

CORIN FLOW

CORIN EVAP

CORIN RAIN

BENDORA FLOW

BENDORA EVAP

BENDORA RAIN

COTTER FLOW

COTTER EVAP

COTTER RAIN

GOOGONG FLOW

GOOGONG EVAP

GOOGONG RAIN

CANBERRA DEMAND

1	1924	1541	135	74	1090	135	73	1128	159	52	720	205	41	12352
2	1924	4715	105	216	3334	105	231	3450	124	200	3420	166	83	1554
3	1924	1270	116	28	898	116	22	930	141	5	410	188	0	9455
4	1924	1066	63	70	753	63	68	780	75	48	680	113	59	6802
5	1924	934	51	45	661	51	40	684	61	22	500	95	17	5366
6	1924	1508	24	55	1067	24	52	1104	30	33	580	47	15	4702
7	1924	1225	27	55	867	27	52	897	33	33	550	44	27	4580
8	1924	6994	32	122	4947	32	126	5118	38	102	1040	46	58	4690
9	1924	9257	47	58	6548	47	55	6774	56	36	580	71	48	5280
10	1924	6465	77	64	4573	77	62	4731	92	42	720	110	43	6679
11	1924	14452	86	210	10222	86	224	10575	103	194	5640	138	129	8791
12	1924	4108	72	91	2905	72	92	3006	87	70	2720	118	32	11935
1	1925	5785	99	112	4091	99	115	4233	117	92	3520	158	79	12352
2	1925	2033	107	68	1438	107	66	1488	126	46	3380	169	26	11554

Figure A.2 Sample Formatted Streamflow and Demand Data File for WATSTRM

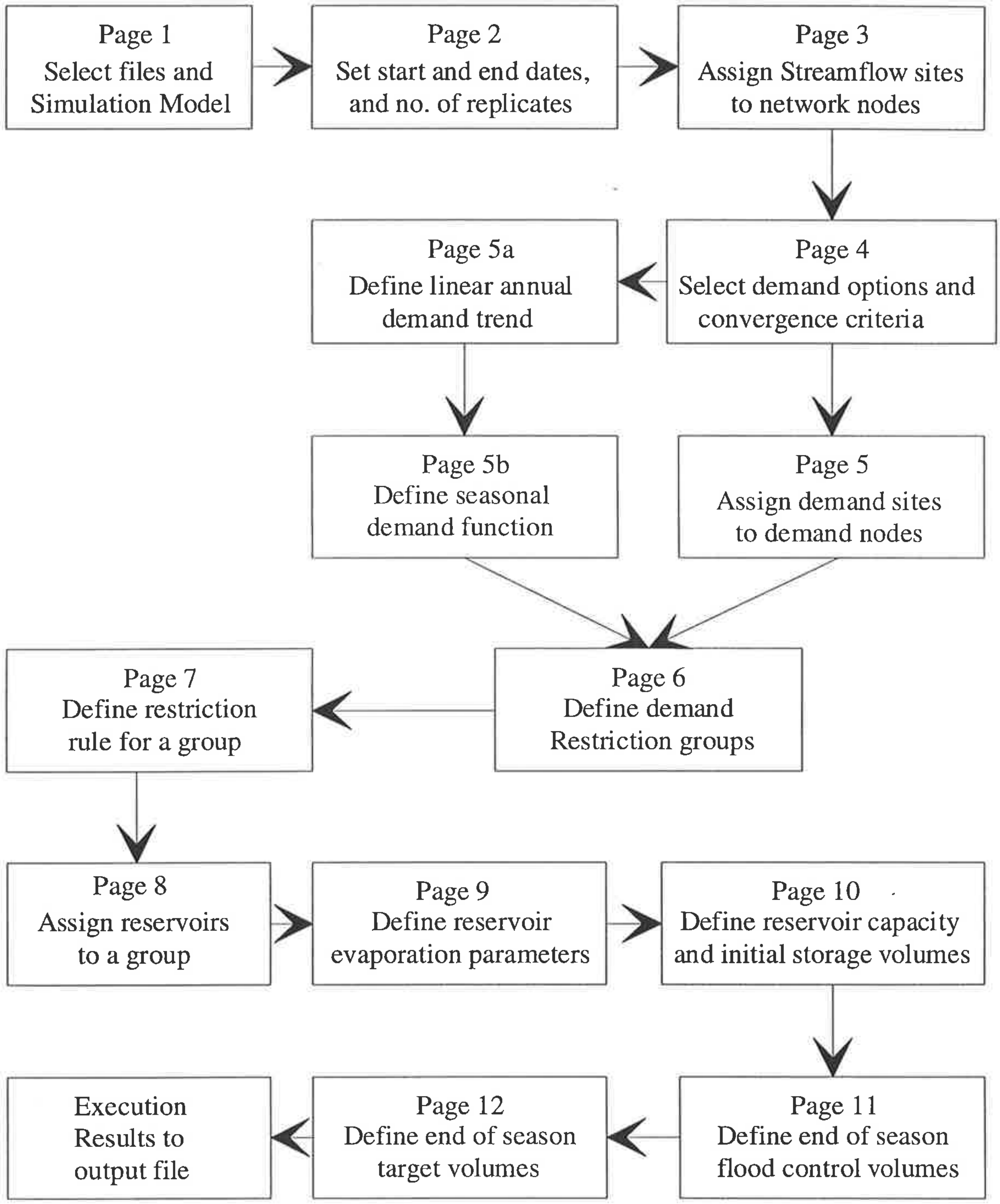

Figure A.3 Flow Chart Identifying SIMNET Formulation Procedure

Appendix B

WATHNET Formulation for the Existing Canberra Water Supply System

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The first procedure in the formulation was to convert the available data into a format which could be manipulated by WATSTRM to a formatted data readable by the other WATHNET programs. After completing this and running WATSTRM the next step was to create a network for the Canberra system using the EDNET program. The schematic created is shown in Figure C.1 in Appendix C. SIMNET was then executed and the formulation was set up. In this the period to be considered was defined. The version of WATHNET used has a limit of 360 on the number of time periods, thus the simulation was run in monthly time steps from 1924 to 1953 (ie 30 years, 12 months per year) and then re-run for the period 1954 to 1983. This should give a reasonable length of record to ensure an adequate result is obtained.

All reservoirs were included in the system and Canberra was the only demand node. At Page 5a of the SIMNET set up (see Kuczera, 1990 or Figure A.3 of this report), an annual demand was specified and monthly demand allocations were specified as a percentage of the annual demand on Page 5b. These demand percentages are the same values as the ALPHA parameter in the yield model and are found in Appendix E of this report.

There was no demand restriction placed on the system and therefore no values are entered on Page 7. The values of A and B in the yield model, relating surface area to storage volume to find evaporation are entered in Page 9. The first problem arises at this stage due to WATHNET using only integer values. Therefore all figures input into WATHNET are multiplied by 1000 to remove any chance of possible round off occurring. Thus the storage dependent value for the evaporation calculation (ie. A in the yield model) needs to be divided by 1000 to ensure the surface area remains in the correct proportion. The surface area value will then be correct for the storage volume and can be then multiplied by the open water evaporation (already multiplied by 1000) to get the correct loss due to evaporation.

The capacities of the four reservoirs is entered on Page 10. At the same time the initial volume of the reservoirs is assigned and for this study it is assumed that the initial volume of all reservoirs are less than or equal to the final storage volumes of the reservoirs. The filling priority is set equal for all reservoirs, but could be changed if system operations were of interest. The percentage capacity reserved for flood control is 0 % and the end of season target volume is 99 %. These are shown in Pages 11 and 12 respectively.

The SIMNET program is then run to see if any shortfall occurs for the annual demand value input in Page 5a. As the restriction on supply has been removed, shortfall may occur when supply is exhausted. If shortfalls occur for the annual demand value selected, then SIMNET is run again with a reduced demand value. This iteration procedure is continued until a maximum value for annual demand is found which produces no shortfalls. Once this is obtained for the first period 1924-1953 and the results have been analysed, the procedure is repeated for the period 1954-1983. However to make the time periods continuous the boundary condition at the end of 1953 must be the same as the initial boundary condition in 1954. For the Canberra analysis, the only values which need to be changed between the runs, are the initial volumes of the reservoirs in 1954, as at the end of 1953 the reservoirs are not full.

Appendix C

Schematic of the Canberra Water Supply System from EDNET

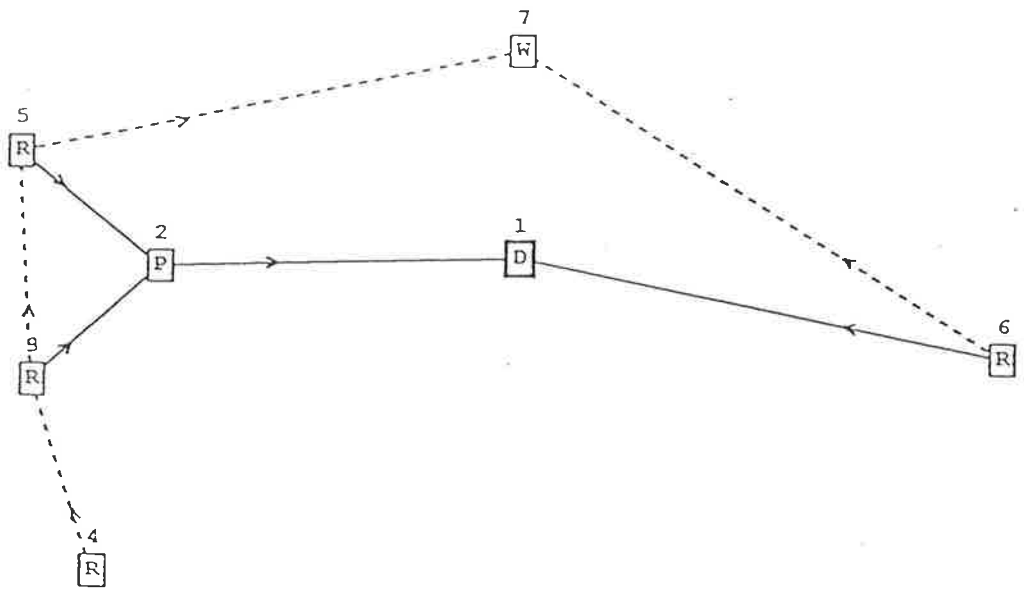

Figure C.1 EDNET Schematic Identifying the Existing System Layout

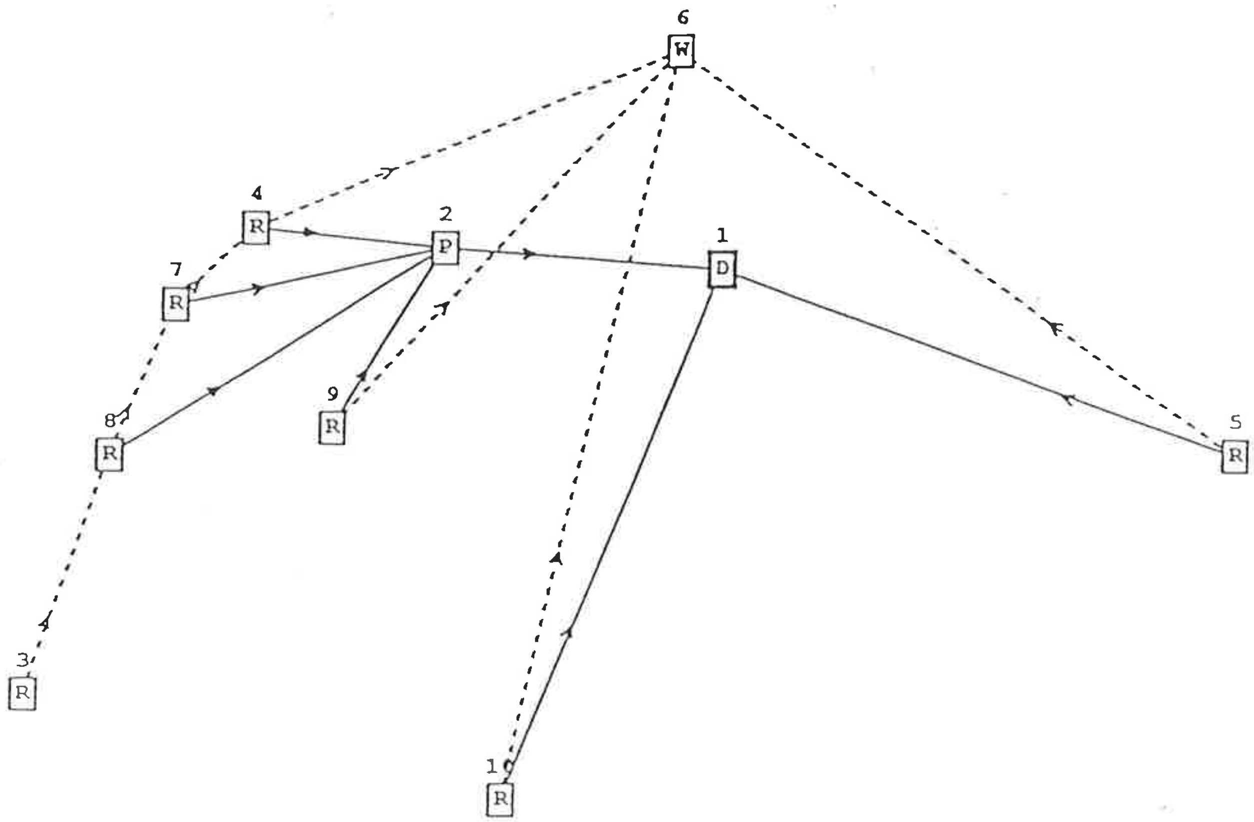

Figure C.2 EDNET Schematic Identifying the New Reservoirs

Appendix D

Yield Model Formulation for the Existing Canberra Water Supply System

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The first section of the formulation defines the parameters in the model and the number of values assigned to a particular parameter (ie. Q1 has 72 values). The numbers accompanying the parameters are defined as follows :

1 - Corin Reservoir (Q1 - flow to Corin)
2 - Bendora Reservoir (R2 - Release from Bendora)
3 - Cotter Reservoir (S3 - Storage of Cotter)
4 - Googong Reservoir (E4 - Evaporation from Googong)

The parameters DBEN, DCOT and DGOO are the yields of Bendora, Cotter and Googong respectively.

The next section identifies the objective and the constraints of the model. The objective is simply the maximisation of the yield and appears as line 8. Following this are the evaporation constants A and B (Ψ and α respectively in Chapter 3) which relate storage volume to surface area so a good estimation of evaporation can be found. These values of A and B, for the four reservoirs, are obtained from Figures H.1 to H.4 in Appendix H. The equations which appear from lines 22 to 95 are the over year and within year storage constraints for the four reservoirs. The parameters in these equation are defined as follows:

(i) S - Over year storage;
(ii) Q - Yearly inflow;
(iii) R - Yearly release;
(iv) E - Yearly evaporation;
(v) P - Yearly precipitation;
(vi) SW - Monthly storage;
(vii) EW - Monthly evaporation;
(viii) PW - Monthly precipitation;
(ix) INF - Monthly inflows; and
(x) ALPHA - proportion of yearly flow in a particular month.

The final section of the constraints are the reservoir capacities (both within and over-year) and supply capacities. There is also a maximum release constraint from Corin Reservoir and a riparian release from Googong Reservoir for the Queanbeyan River. The riparian release for the Queanbeyan River is 0.5 for the months November to March and 0.05 for the remaining months of the year. The final equation in the formulation ensures the total volume supplied equals the demand

The final section of the formulation is the assigning of the necessary data to the parameters from specific data files. These data files are found in Appendix E.

```
MODEL:
SETS:
 TIME/ 1..72/ :Q1,E1,P1,Q2,E2,P2,Q3,E3,P3,Q4,E4,P4,R1p;
 PERI/ 1..12/ :ALPHA,INF2,INF3,INF4,SW1,SW2,SW3,SW4,EW2,EW3
              ,EW4,PW2,PW3,PW4,EW1,PW1,INF1;
 LINKS(TIME):DBEN,DCOT,DGOO,S1,S2,S3,S4,R1,R2,R3,R4;
ENDSETS
    MAX=YEI;
    ! Reservoir Water Balance equations;
  [A1]    A1=0.0358 ;
  [B1]    B1=0.5    ;
  [A2]    A2=0.0514 ;
  [B2]    B2=0.2    ;
  [A3]    A3=0.104  ;
  [B3]    B3=0.05   ;
  [A4]    A4=0.0523 ;
  [B4]    B4=0.8    ;
@FOR(TIME(I)|I#LE#71:[CORIN]
 S1(I+1)*(1+A1*(E1(I)-P1(I))/2000.0)-S1(I)*(1-A1*(E1(I)-P1(I))/2000.0)
           -Q1(I)+R1(I)+R1p(I)+(E1(I)-P1(I))*B1/1000.0=0);
@FOR(TIME(J)|J#GT#71:
 S1(1)*(1+A1*(E1(J)-P1(J))/2000.0)-S1(J)*(1-A1*(E1(J)-P1(J))/2000.0)
           -Q1(J)+R1(J)+R1p(J)+(E1(J)-P1(J))*B1/1000.0=0);
@FOR(PERI(I)|I#LE#11:[CORIN]
            SW1(I)+INF1(I)/Q1(71)*((R1(71)+R1p(71))+((B1+
           A1*(S1(71)+S1(72))/2)*(E1(71)-P1(71))/1000.0))
           -(R1(71)+R1p(71))*ALPHA(I)-((B1+A1*(SW1(I)+SW1(I+1))/2)
           *(EW1(I)-PW1(I))/1000.0)=SW1(I+1));
@FOR(PERI(I)|I#GT#11:[CORIN]
            SW1(I)+INF1(I)/Q1(71)*((R1(71)+R1p(71))+((B1+
           A1*(S1(71)+S1(72))/2)*(E1(71)-P1(71))/1000.0))
           -(R1(71)+R1p(71))*ALPHA(I)-((B1+A1*(SW1(I)+SW1(1))/2)
```

```
            *(EW1(I)-PW1(I))/1000.0)=SW1(1));
@FOR(TIME(I)|I#LE#71:[BENDORA]
 S2(I+1)*(1+A2*(E2(I)-P2(I))/2000.0)-S2(I)*(1-A2*(E2(I)-P2(I))/2000.0)
      -Q2(I)-R1(I)-R1p(I)+R2(I)+DBEN(I)+(E2(I)-P2(I))*B2/1000.0=0);
@FOR(TIME(J)|J#GT#71:
 S2(1)*(1+A2*(E2(J)-P2(J))/2000.0)-S2(J)*(1-A2*(E2(J)-P2(J))/2000.0)
      -Q2(J)-R1(J)-R1p(J)+R2(J)+DBEN(J)+(E2(J)-P2(J))*B2/1000.0=0);
@FOR(PERI(I)|I#LE#11:[BENDORA]
             SW2(I)+INF2(I)/Q2(71)*(DBEN(71)+((B2+
            A2*(S2(71)+S2(72))/2)*(E2(71)-P2(71))/1000.0))
            -DBEN(71)*ALPHA(I)-((B2+A2*(SW2(I)+SW2(I+1))/2)
            *(EW2(I)-PW2(I))/1000.0)=SW2(I+1));
@FOR(PERI(I)|I#GT#11:[BENDORA]
             SW2(I)+INF2(I)/Q2(71)*(DBEN(71)+((B2+
            A2*(S2(71)+S2(72))/2)*(E2(71)-P2(71))/1000.0))
            -DBEN(71)*ALPHA(I)-((B2+A2*(SW2(I)+SW2(1))/2)
            *(EW2(I)-PW2(I))/1000.0)=SW2(1));
@FOR(TIME(I)|I#LE#71: [COTTER]
 S3(I+1)*(1+A3*(E3(I)-P3(I))/2000.0)-S3(I)*(1-A3*(E3(I)-P3(I))/2000.0)
           -Q3(I)-R2(I)+R3(I)+DCOT(I)+(E3(I)-P3(I))*B3/1000.0=0);
@FOR(TIME(J)|J#GT#71:
 S3(1)*(1+A3*(E3(J)-P3(J))/2000.0)-S3(J)*(1-A3*(E3(J)-P3(J))/2000.0)
           -Q3(J)-R2(J)+R3(J)+DCOT(J)+(E3(J)-P3(J))*B3/1000.0=0);
@FOR(PERI(I)|I#LE#11:[COTTER]
             SW3(I)+INF3(I)/Q3(71)*(DCOT(71)+((B3+
            A3*(S3(71)+S3(72))/2)*(E3(71)-P3(71))/1000.0))
            -DCOT(71)*ALPHA(I)-((B3+A3*(SW3(I)+SW3(I+1))/2)
            *(EW3(I)-PW3(I))/1000.0)=SW3(I+1));
@FOR(PERI(I)|I#GT#11:[COTTER]
             SW3(I)+INF3(I)/Q3(71)*(DCOT(71)+((B3+
            A3*(S3(71)+S3(72))/2)*(E3(71)-P3(71))/1000.0))
            -DCOT(71)*ALPHA(I)-((B3+A3*(SW3(I)+SW3(1))/2)
```

```
          *(EW3(I)-PW3(I))/1000.0)=SW3(1));

@FOR(TIME(I)|I#LE#71:[GOOGONG]
 S4(I+1)*(1+A4*(E4(I)-P4(I))/2000.0)-S4(I)*(1-A4*(E4(I)-P4(I))/2000.0)
          -Q4(I)+R4(I)+DGOO(I)+(E4(I)-P4(I))*B4/1000.0=0);
@FOR(TIME(J)|J#GT#71:
 S4(1)*(1+A4*(E4(J)-P4(J))/2000.0)-S4(J)*(1-A4*(E4(J)-P4(J))/2000.0)
          -Q4(J)+R4(J)+DGOO(J)+(E4(J)-P4(J))*B4/1000.0=0);

@FOR(PERI(I)|I#LE#11:[GOOGONG]
           SW4(I)+INF4(I)/Q4(71)*(DGOO(71)+((B4+
          A4*(S4(71)+S4(72))/2)*(E4(71)-P4(71))/1000.0))
          -DGOO(71)*ALPHA(I)-((B4+A4*(SW4(I)+SW4(I+1))/2)
          *(EW4(I)-PW4(I))/1000.0)=SW4(I+1));
@FOR(PERI(I)|I#GT#11:[GOOGONG]
           SW4(I)+INF4(I)/Q4(71)*(DGOO(71)+((B4+
          A4*(S4(71)+S4(72))/2)*(E4(71)-P4(71))/1000.0))
          -DGOO(71)*ALPHA(I)-((B4+A4*(SW4(I)+SW4(1))/2)
          *(EW4(I)-PW4(I))/1000.0)=SW4(1));


    ! Capacity constraints on the reservoirs, capacities of reservoirs
  are corin=75.5, bendora=10.7, cotter=4.70, googong=124.5;

@FOR(TIME(K): [CORINST]
        S1(K)<KAP1);
@FOR(TIME(I): [BENDST]
        S2(I)<KAP2);
@FOR(TIME(I): [COTST]
        S3(I)<KAP3);
@FOR(TIME(I): [GOOST]
        S4(I)<KAP4);

    ! Dead storage levels;

@FOR(TIME(K): [CORINST]
        S1(K)>0.18);
```

```
@FOR(TIME(I): [BENDST]
        S2(I)>0.18);
@FOR(TIME(I): [COTST]
        S3(I)>0.02);
@FOR(TIME(I): [GOOST]
        S4(I)>1.62);

    !within year storage constraints;

@FOR(PERI(K): [GOOST]
        SW4(K)+KAP4<124.5);
@FOR(PERI(K): [COTST]
        SW3(K)+KAP3<4.7);
@FOR(PERI(K): [BENDST]
        SW2(K)+KAP2<10.7);
@FOR(PERI(I): [CORINST]
        SW1(I)+KAP1<75.5);

    ! Riparian releases GOOGONG reservoir;

@FOR(TIME(I): [RIGOO]
        R4(I)>3.12);

    ! Maximum release from corin to bendora(162.0);

@FOR(TIME(I): [MAXRCOR]
        R1(I)<162.0);

    ! pipe capacity restriction on water supplied from a
  particular reservoir;

@FOR(TIME(I): [BENPCAP]
        DBEN(I)<115.2);

@FOR(TIME(I): [COTPCAP]
        DCOT(I)<14.4);

    ! Water treatment plant capacity restrictions;
```

```
@FOR(TIME(I): [WTPS]
        DCOT(I)+DBEN(I)<144.0);
@FOR(TIME(I): [WTPG]
        DGOO(I)<68.4);
@FOR(TIME(I):[AYIEL]
        DBEN(I)+DGOO(I)+DCOT(I)=YEI);
DATA:
  Q1= @FILE(YCORD.LDT) ;
  INF1= @FILE(YCORD.LDT);
  E1= @FILE(YCORD.LDT) ;
  EW1= @FILE(YCORD.LDT) ;
  P1= @FILE(YCORD.LDT) ;
  PW1= @FILE(YCORD.LDT) ;
  Q2= @FILE(YBEND.LDT) ;
  INF2= @FILE(YBEND.LDT);
  E2= @FILE(YBEND.LDT) ;
  EW2= @FILE(YBEND.LDT) ;
  P2= @FILE(YBEND.LDT) ;
  PW2= @FILE(YBEND.LDT) ;
  Q3= @FILE(YCOTD.LDT) ;
  INF3= @FILE(YCOTD.LDT);
  E3= @FILE(YCOTD.LDT) ;
  EW3= @FILE(YCOTD.LDT) ;
  P3= @FILE(YCOTD.LDT) ;
  PW3= @FILE(YCOTD.LDT) ;
  Q4= @FILE(YGOOD.LDT) ;
  INF4= @FILE(YGOOD.LDT);
  E4= @FILE(YGOOD.LDT) ;
  EW4= @FILE(YGOOD.LDT) ;
  P4= @FILE(YGOOD.LDT) ;
  PW4= @FILE(YGOOD.LDT) ;
  ALPHA= @FILE(DCANBY.LDT) ;
ENDDATA
END
```

Appendix E

Data Files for the Yield Model Formulation

The data required for the yield Model formulation includes the monthly demand allocation percentages of the annual demand (ALPHA) and the annual and critical year streamflow, evaporation and precipitation. This data is shown below :

! Information on Canberra's demand etc. (ALPHA);
0.130, 0.110, 0.100, 0.070, 0.060, 0.050,
0.050, 0.060, 0.060, 0.080, 0.100, 0.130~

! data for corin reservoir;
! streamflow data;
62.73, 25.72, 11.31, 83.94, 130.33, 212.61,
74.15, 14.75, 58.38, 95.14, 63.42, 73.38,
53.54, 115.98, 90.39, 37.36, 34.77, 38.22,
25.67, 83.06, 39.54, 47.89, 141.20, 51.86,
48.10, 36.42, 22.15, 97.10, 19.15, 29.37,
50.55, 45.72, 9.91, 22.02, 44.28, 50.15,
67.31, 64.60, 127.88, 60.09, 139.33, 46.43,
23.94, 71.21, 237.50, 16.85, 63.25, 56.09,
83.16, 85.75, 59.41, 51.82, 111.25, 23.07,

57.82, 15.24, 40.99, 69.17, 70.47, 56.92,
32.37, 62.14, 150.20, 88.94, 44.03, 41.35,
97.36, 20.14, 19.47, 65.98, 6.41, 95.84~
! critical year flow data;
0.66, 0.36, 0.85, 0.58, 0.41, 0.56,
0.40, 0.58, 0.98, 0.72, 0.21, 0.10~
! evaporation data;
1006.90, 965.50, 986.10, 974.15, 804.95, 758.40,
811.00, 1057.55, 910.40, 869.50, 987.00, 988.05,
838.80, 834.75, 899.00, 845.55, 877.10, 972.80,
801.00, 906.90, 872.55, 861.30, 744.50, 778.10,
825.60, 877.40, 950.95, 877.75, 1022.75, 901.55,
995.70, 886.20, 1108.50, 988.10, 1021.95, 929.15,
817.95, 812.80, 730.05, 871.75, 866.05, 872.35,
829.70, 699.90, 725.15, 983.70, 838.80, 765.20,
828.05, 803.85, 781.70, 761.35, 938.25, 919.10,
792.90, 937.55, 1043.80, 788.70, 869.95, 849.50,
871.25, 890.60, 825.60, 815.65, 724.05, 864.50,
768.05, 860.95, 953.95, 876.30, 1002.75, 857.50~
! critical year evaporation data;
154.70, 141.10, 81.90, 52.00, 46.20, 22.10,
23.00, 45.05, 60.00, 93.00, 160.50, 123.20~
! precipitation data;
815.00, 773.00, 898.00, 939.00, 1262.00, 1171.00,
876.00, 787.00, 1013.00, 1311.00, 925.00, 1047.00,
1088.00, 1202.00, 897.00, 1083.00, 816.00, 903.00,
763.00, 1017.00, 809.00, 900.00, 1361.00, 904.00,
1101.00, 900.00, 829.00, 1129.00, 730.00, 843.00,
987.00, 952.00, 553.00, 833.00, 982.00, 1074.00,
1087.00, 1092.00, 1483.00, 965.00, 1568.00, 824.00,
886.00, 1128.00, 1501.00, 684.00, 1114.00, 1161.00,
1081.00, 1371.00, 1069.00, 1005.00, 1203.00, 772.00,
1183.00, 573.00, 997.00, 1198.00, 1303.00, 1025.00,
713.00, 1217.00, 1444.00, 1308.00, 902.00, 840.00,
1483.00, 786.00, 1135.00, 1333.00, 505.00, 1496.00~
! critical year precipitation data;
41.00, 34.00, 94.00, 31.00, 20.00, 33.00,
10.00, 23.00, 143.00, 24.00, 7.00, 45.00~

! data for bendora reservoir;
! streamflow data;
44.37, 18.19, 8.00, 59.37, 92.19, 150.39,
52.45, 10.43, 41.30, 67.29, 44.86, 51.90,
37.87, 82.04, 63.94, 26.42, 24.59, 27.04,
18.15, 58.75, 27.96, 33.87, 99.87, 36.68,
34.02, 25.76, 15.67, 68.68, 13.55, 20.77,
35.76, 32.34, 7.01, 15.57, 31.32, 35.47,
47.61, 45.69, 90.45, 42.51, 98.55, 32.84,
16.94, 50.37, 167.99, 11.92, 44.74, 39.67,
58.82, 60.65, 42.02, 36.66, 78.69, 16.32,
40.90, 10.78, 28.99, 48.92, 49.85, 40.26,
22.90, 43.95, 106.24, 62.91, 31.15, 29.25,
68.86, 14.24, 13.77, 46.67, 4.54, 67.79~
! critical year flow data;
0.47, 0.25, 0.60, 0.41, 0.29, 0.40,
0.28, 0.41, 0.69, 0.51, 0.15, 0.07~
! evaporation data;
1006.90, 965.50, 986.10, 974.15, 804.95, 758.40,
811.00, 1057.55, 910.40, 869.50, 987.00, 988.05,
838.80, 834.75, 899.00, 845.55, 877.10, 972.80,
801.00, 906.90, 872.55, 861.30, 744.50, 778.10,
825.60, 877.40, 950.95, 877.75, 1022.75, 901.55,
995.70, 886.20, 1108.50, 988.10, 1021.95, 929.15,
817.95, 812.80, 730.05, 871.75, 866.05, 872.35,
829.70, 699.90, 725.15, 983.70, 838.80, 765.20,
828.05, 803.85, 781.70, 761.35, 938.25, 919.10,
792.90, 937.55, 1043.80, 788.70, 869.95, 849.50,
871.25, 890.60, 825.60, 815.65, 724.05, 864.50,
768.05, 860.95, 953.95, 876.30, 1002.75, 857.50~
! critical year evaporation data;
154.70, 141.10, 81.90, 52.00, 46.20, 22.10,
23.00, 45.05, 60.00, 93.00, 160.50, 123.20~
! precipitation data;
793.00, 748.00, 885.00, 935.00, 1297.00, 1193.00,
864.00, 764.00, 1019.00, 1347.00, 915.00, 1053.00,
1097.00, 1225.00, 882.00, 1093.00, 797.00, 893.00,

737.00, 1020.00, 790.00, 889.00, 1403.00, 894.00,
1114.00, 890.00, 811.00, 1144.00, 700.00, 825.00,
985.00, 949.00, 502.00, 816.00, 983.00, 1083.00,
1098.00, 1106.00, 1538.00, 961.00, 1635.00, 804.00,
877.00, 1142.00, 1560.00, 682.00, 1171.00, 944.00,
1402.00, 1412.00, 1108.00, 1135.00, 1487.00, 755.00,
1250.00, 547.00, 1053.00, 1232.00, 1105.00, 925.00,
734.00, 1166.00, 1695.00, 1221.00, 896.00, 918.00,
1323.00, 723.00, 912.00, 1426.00, 507.00, 1527.00~
! critical year precipitation data;
43.00, 17.00, 121.00, 27.00, 12.00, 69.00,
8.00, 24.00, 120.00, 28.00, 5.00, 33.00~

! data for cotter reservoir;
! streamflow data;
45.90, 18.82, 8.27, 61.42, 95.37, 155.57,
54.26, 10.79, 42.72, 69.62, 46.40, 53.69,
39.18, 84.87, 66.14, 27.33, 25.44, 27.97,
18.78, 60.78, 28.93, 35.04, 103.31, 37.94,
35.19, 26.65, 16.21, 71.05, 14.01, 21.49,
36.99, 33.46, 7.25, 16.11, 32.40, 36.69,
49.25, 47.27, 93.57, 43.97, 101.95, 33.97,
17.52, 52.11, 173.78, 12.33, 46.28, 41.04,
60.85, 62.75, 43.47, 37.92, 81.40, 16.88,
42.31, 11.15, 29.99, 50.61, 51.57, 41.65,
23.69, 45.47, 109.90, 65.08, 32.22, 30.26,
71.24, 14.73, 14.25, 48.28, 4.69, 70.13~
! critical year flow data;
0.49, 0.26, 0.62, 0.43, 0.30, 0.41,
0.29, 0.42, 0.71, 0.53, 0.15, 0.08~
! evaporation data;
1204.95, 1155.35, 1179.80, 1165.75, 961.75, 908.20,
971.60, 1265.75, 1091.35, 1040.95, 1181.75, 1181.65,
1004.05, 1000.70, 1075.10, 1012.50, 1050.60, 1164.55,
959.25, 1084.70, 1043.25, 1029.95, 891.95, 932.40,
988.10, 1050.40, 1140.05, 1049.45, 1223.75, 1081.15,
1192.05, 1060.95, 1327.40, 1183.75, 1223.90, 1112.50,
980.65, 972.60, 873.55, 1044.75, 1036.90, 1045.40,

994.60, 837.35, 868.05, 1178.15, 1004.20, 915.75,
990.65, 961.85, 936.85, 912.10, 1123.20, 1100.90,
949.00, 1123.60, 1248.50, 944.10, 1042.50, 1016.05,
1045.20, 1066.30, 989.20, 976.10, 868.15, 1034.70,
919.75, 1030.25, 1142.45, 1050.80, 1199.10, 1025.50~
! critical year evaporation data;
182.00, 166.00, 100.10, 62.40, 54.60, 27.20,
28.00, 53.00, 72.00, 111.60, 192.60, 149.60~
! precipitation data;
552.00, 509.00, 639.00, 682.00, 1022.00, 925.00,
617.00, 524.00, 762.00, 1070.00, 667.00, 795.00,
837.00, 957.00, 639.00, 833.00, 553.00, 646.00,
499.00, 764.00, 548.00, 642.00, 1122.00, 647.00,
851.00, 643.00, 568.00, 880.00, 466.00, 582.00,
732.00, 697.00, 280.00, 571.00, 729.00, 823.00,
837.00, 844.00, 1248.00, 709.00, 1338.00, 563.00,
629.00, 878.00, 1268.00, 416.00, 865.00, 914.00,
829.00, 1131.00, 819.00, 750.00, 956.00, 490.00,
852.00, 408.00, 716.00, 1016.00, 1020.00, 918.00,
624.00, 1158.00, 1394.00, 962.00, 780.00, 657.00,
901.00, 497.00, 423.00, 818.00, 277.00, 786.00~
! critical year precipitation data;
14.00, 16.00, 133.00, 0.00, 0.00, 14.00,
0.00, 6.00, 77.00, 12.00, 0.00, 5.00~

! data for googong reservoir;
! streamflow data;
37.00, 105.38, 52.41, 82.10, 152.06, 90.28,
59.68, 20.17, 125.39, 118.41, 173.62, 55.24,
17.56, 291.79, 14.55, 16.84, 32.47, 83.65,
10.81, 55.95, 28.86, 20.82, 394.69, 95.43,
88.05, 37.93, 39.39, 47.61, 15.53, 65.71,
40.61, 77.59, 25.88, 89.24, 31.90, 79.64,
175.56, 144.10, 533.75, 219.03, 326.94, 128.43,
43.49, 65.52, 611.97, 32.27, 50.65, 276.51,
150.85, 290.52, 119.80, 147.15, 136.86, 25.45,
133.92, 53.84, 22.45, 78.47, 73.94, 86.20,
34.63, 44.54, 370.39, 299.47, 140.23, 55.44,

262.42, 45.30, 12.63, 54.43, 11.60, 82.78~
! critical year flow data;
2.13, 0.72, 1.94, 0.88, 0.83, 0.76,
0.67, 0.89, 0.74, 0.77, 0.72, 0.55~
! evaporation data;
1605.94, 1539.66, 1579.23, 1559.23, 1304.15, 1231.48,
1315.30, 1673.63, 1466.51, 1397.32, 1575.67, 1578.44,
1346.79, 1348.52, 1446.51, 1364.51, 1404.35, 1561.23,
1295.00, 1453.26, 1398.43, 1393.24, 1220.85, 1266.14,
1333.66, 1420.40, 1527.55, 1411.09, 1627.03, 1446.25,
1586.43, 1429.92, 1749.67, 1566.97, 1614.49, 1483.26,
1326.08, 1318.34, 1195.51, 1404.27, 1394.77, 1407.11,
1344.33, 1152.05, 1188.35, 1574.44, 1355.60, 1247.10,
1341.06, 1300.91, 1268.32, 1239.06, 1446.40, 1479.90,
1248.73, 1541.60, 1628.90, 1335.94, 1306.80, 1325.79,
1451.71, 1358.19, 1250.17, 1417.10, 1388.30, 1624.00,
1353.17, 1706.65, 1708.38, 1591.40, 1776.71, 1569.49~
! critical year evaporation data;
256.70, 237.15, 153.45, 113.42, 107.38, 61.88,
52.64, 73.83, 98.49, 144.05, 266.76, 210.96~
! precipitation data;
454.00, 428.00, 508.00, 540.00, 769.00, 734.00,
412.00, 447.00, 826.00, 734.00, 559.00, 568.00,
552.00, 848.00, 455.00, 437.00, 410.00, 540.00,
380.00, 601.00, 513.00, 439.00, 880.00, 634.00,
633.00, 484.00, 403.00, 593.00, 412.00, 534.00,
543.00, 553.00, 261.00, 498.00, 534.00, 650.00,
742.00, 647.00, 1053.00, 592.00, 929.00, 525.00,
531.00, 751.00, 970.00, 376.00, 687.00, 842.00,
799.00, 832.00, 593.00, 574.00, 665.00, 352.00,
748.00, 357.00, 607.00, 714.00, 770.00, 566.00,
457.00, 827.00, 922.00, 727.00, 517.00, 511.00,
719.00, 405.00, 426.00, 593.00, 244.00, 721.00~
! critical year precipitation data;
17.00, 18.00, 96.00, 7.00, 2.00, 17.00,
4.00, 11.00, 44.00, 8.00, 2.00, 18.00~

Appendix F

Yield Model Formulation for the New System

```
MODEL:
SETS:
  TIME/ 1..18/ :Q1,E1,P1,Q2,E2,P2,Q3,E3,P3,Q4,E4,P4,R1;
  PERI/ 1..12/ :ALPHA,INF2,INF3,INF4,SW1,SW2,SW3,SW4,EW2,EW3
           ,EW4,EW5,SW5,EW1,INF1,PW1,PW2,PW3,PW4,PW5,PW6
           ,INF5,INF7,SW7,EW7,PW7,SW6,EW6,INF6,EWT1,EWT2
               ,EWT3,EWT4,EWT5,EWT6,EWT7,PWT1,PWT2,PWT3,PWT4
               ,PWT5,PWT6,PWT7;
  LINKS(TIME):DBEN,DCOT,DGOO,S1,S2,S3,S4,S5,R2,R3,R4,R5
           ,E5,Q5,P5,DCOR,DRIV,Q7,R7,P7,ET1,ET2,ET3,ET4,ET5
           ,ET6,ET7,PT1,PT2,PT3,PT4,PT5,PT6,PT7
               ,S7,E7,DTEN,Q6,E6,S6,R6,P6;
ENDSETS

   [YIELD] MAX=YEI;

    ! Reservoir Water Balance equations;
```

```
[A1]    A1=0.0358  ;
[B1]    B1=0.5;
[A2]    A2=0.0812  ;
[B2]    B2=0.0;
[A3]    A3=0.0264   ;
[B3]    B3=0.55 ;
[A3]    A3=0.104   ;
[B3]    B3=0.05 ;
[A4]    A4=0.0523  ;
[B4]    B4=0.8;
[A5]    A5=0.038  ;
[B5]    B5=0.43  ;
[A6]    A6=0.068  ;
[B6]    B6=1.1  ;
[A7]    A7=0.06  ;
[B7]    B7=.55  ;

SUM2-@SUM(PERI(I):INF2(I)/Q2(17))=0;
SUM3-@SUM(PERI(I):INF3(I)/Q3(17))=0;
SUM4-@SUM(PERI(I):INF4(I)/Q4(17))=0;
SUM5-@SUM(PERI(I):INF5(I)/Q5(17))=0;
SUM6-@SUM(PERI(I):INF6(I)/Q6(17))=0;
SUM7-@SUM(PERI(I):INF7(I)/Q7(17))=0;

@FOR(TIME(I)|I#LE#17:[CORIN]
 S1(I+1)-S1(I)-Q1(I)+R1(I)+ET1(I)-PT1(I)=0);
@FOR(TIME(J)|J#GT#17:
 S1(1)-S1(J)-Q1(J)+R1(J)+ET1(J)-PT1(J)=0);

@FOR(TIME(I)|I#LE#17:[CORIN]
ET1(I)=B1*E1(I)/1000.0+((S1(I)+S1(I+1))/2)*A1*E1(I)/1000.0);
@FOR(TIME(I)|I#GT#17:[CORIN]
ET1(I)=B1*E1(I)/1000.0+((S1(I)+S1(1))/2)*A1*E1(I)/1000.0);
@FOR(TIME(I)|I#LE#17:[CORIN]
PT1(I)=B1*P1(I)/1000.0+((S1(I)+S1(I+1))/2)*A1*P1(I)/1000.0);
@FOR(TIME(I)|I#GT#17:[CORIN]
PT1(I)=B1*P1(I)/1000.0+((S1(I)+S1(1))/2)*A1*P1(I)/1000.0);
```

```

@FOR(TIME(I)|I#LE#17:[BENDORA]
 S2(I+1)-S2(I)
      -Q2(I)-R1(I)+R2(I)+DBEN(I)+ET2(I)-PT2(I)=0);
@FOR(TIME(J)|J#GT#17:
 S2(1)-S2(J)
      -Q2(J)-R1(J)+R2(J)+DBEN(J)+ET2(J)-PT2(J)=0);

@FOR(TIME(I):[BENDORA]
ET2(I)=B2*E2(I)/1000.0+(S2(I)+SWET2)*A2*E2(I)/1000.0);
@FOR(TIME(I):[BENDORA]
PT2(I)=B2*P2(I)/1000.0+(S2(I)+SWPT2)*A2*P2(I)/1000.0);

SWET2=@SUM(PERI(I)|I#LE#11:
      (EW2(I)/E2(17))*((SW2(I)+SW2(I+1))/2))+
      (EW2(12)/E2(17))*((SW2(12)+SW2(1))/2);
SWPT2=@SUM(PERI(I)|I#LE#11:
      (PW2(I)/P2(17))*((SW2(I)+SW2(I+1))/2))+
      (PW2(12)/P2(17))*((SW2(12)+SW2(1))/2);

@FOR(PERI(I)|I#LE#11:
   EWT2(I)=B2*EW2(I)/1000.0
          +(S2(17)+(SW2(I)+SW2(I+1))/2)*EW2(I)*A2/1000.0);
@FOR(PERI(I)|I#GT#11:
   EWT2(I)=B2*EW2(I)/1000.0
          +(S2(17)+(SW2(I)+SW2(1))/2)*EW2(I)*A2/1000.0);

@FOR(PERI(I)|I#LE#11:
   PWT2(I)=B2*PW2(I)/1000.0
          +(S2(17)+(SW2(I)+SW2(I+1))/2)*PW2(I)*A2/1000.0);
@FOR(PERI(I)|I#GT#11:
   PWT2(I)=B2*PW2(I)/1000.0
          +(S2(17)+(SW2(I)+SW2(1))/2)*PW2(I)*A2/1000.0);
    EWTS2=@SUM(PERI(I):EWT2(I));
    PWTS2=@SUM(PERI(I):PWT2(I));
@FOR(PERI(I)|I#LE#11:[BENDORA]
 SW2(I)+INF2(I)/Q2(17)*(DBEN(17)+EWTS2-PWTS2)
 -(DBEN(17))*ALPHA(I)-EWT2(I)+PWT2(I)=SW2(I+1));
```

```
@FOR(PERI(I)|I#GT#11:
 SW2(I)+INF2(I)/Q2(17)*(DBEN(17)+EWTS2-PWTS2)
 -(DBEN(17))*ALPHA(I)-EWT2(I)+PWT2(I)=SW2(1));



@FOR(TIME(I)|I#LE#17:[COREE]
 S5(I+1)-S5(I)
            +R5(I)-Q5(I)-R2(I)+DCOR(I)+ET5(I)-PT5(I)=0);
@FOR(TIME(J)|J#GT#17:
 S5(1)-S5(J)
            +R5(J)-Q5(J)-R2(J)+DCOR(J)+ET5(J)-PT5(J)=0);

@FOR(TIME(I):[COREE]
ET5(I)=B5*E5(I)/1000.0+(S5(I)+SWET5)*A5*E5(I)/1000.0);
@FOR(TIME(I):[COREE]
PT5(I)=B5*P5(I)/1000.0+(S5(I)+SWPT5)*A5*P5(I)/1000.0);

SWET5=@SUM(PERI(I)|I#LE#11:
        (EW5(I)/E5(17))*((SW5(I)+SW5(I+1))/2))+
        (EW5(12)/E5(17))*((SW5(12)+SW5(1))/2);
SWPT5=@SUM(PERI(I)|I#LE#11:
        (PW5(I)/P5(17))*((SW5(I)+SW5(I+1))/2))+
        (PW5(12)/P5(17))*((SW5(12)+SW5(1))/2);

@FOR(PERI(I)|I#LE#11:
   EWT5(I)=B5*EW5(I)/1000.0
            +(S5(17)+(SW5(I)+SW5(I+1))/2)*EW5(I)*A5/1000.0);
@FOR(PERI(I)|I#GT#11:
   EWT5(I)=B5*EW5(I)/1000.0
            +(S5(17)+(SW5(I)+SW5(1))/2)*EW5(I)*A5/1000.0);
@FOR(PERI(I)|I#LE#11:
   PWT5(I)=B5*PW5(I)/1000.0
            +(S5(17)+(SW5(I)+SW5(I+1))/2)*PW5(I)*A5/1000.0);
@FOR(PERI(I)|I#GT#11:
   PWT5(I)=B5*PW5(I)/1000.0
            +(S5(17)+(SW5(I)+SW5(1))/2)*PW5(I)*A5/1000.0);
```

```

     EWTS5=@SUM(PERI(I):EWT5(I));
     PWTS5=@SUM(PERI(I):PWT5(I));

@FOR(PERI(I)|I#LE#11:[COREE]
 SW5(I)+INF5(I)/Q5(17)*(DCOR(17)+EWTS5-PWTS5)
 -(DCOR(17))*ALPHA(I)-EWT5(I)+PWT5(I)=SW5(I+1));

@FOR(PERI(I)|I#GT#11:
 SW5(I)+INF5(I)/Q5(17)*(DCOR(17)+EWTS5-PWTS5)
 -(DCOR(17))*ALPHA(I)-EWT5(I)+PWT5(I)=SW5(1));




@FOR(TIME(I)|I#LE#17: [COTTER]
 S3(I+1)-S3(I)
            -Q3(I)-Q5(I)-R2(I)+R3(I)+DCOT(I)+ET3(I)-PT3(I)=0);
@FOR(TIME(J)|J#GT#17:
 S3(1)-S3(J)
            -Q3(J)-Q5(J)-R2(J)+R3(J)+DCOT(J)+ET3(J)-PT3(J)=0);
! @FOR(TIME(I)|I#LE#17: [COTTER]
 S3(I+1)-S3(I)
            -Q3(I)-R5(I)+R3(I)+DCOT(I)+ET3(I)-PT3(I)=0);
! @FOR(TIME(J)|J#GT#17:
 S3(1)-S3(J)
            -Q3(J)-R5(J)+R3(J)+DCOT(J)+ET3(J)-PT3(J)=0);

@FOR(TIME(I):[COTTER]
ET3(I)=B3*E3(I)/1000.0+(S3(I)+SWET3)*A3*E3(I)/1000.0);
@FOR(TIME(I):[COTTER]
PT3(I)=B3*P3(I)/1000.0+(S3(I)+SWPT3)*A3*P3(I)/1000.0);

SWET3=@SUM(PERI(I)|I#LE#11:
        (EW3(I)/E3(17))*((SW3(I)+SW3(I+1))/2))+
        (EW3(12)/E3(17))*((SW3(12)+SW3(1))/2);
SWPT3=@SUM(PERI(I)|I#LE#11:
        (PW3(I)/P3(17))*((SW3(I)+SW3(I+1))/2))+
```

```
        (PW3(12)/P3(17))*((SW3(12)+SW3(1))/2);

@FOR(PERI(I)|I#LE#11:
   EWT3(I)=B3*EW3(I)/1000.0
          +(S3(17)+(SW3(I)+SW3(I+1))/2)*EW3(I)*A3/1000.0);
@FOR(PERI(I)|I#GT#11:
   EWT3(I)=B3*EW3(I)/1000.0
          +(S3(17)+(SW3(I)+SW3(1))/2)*EW3(I)*A3/1000.0);
@FOR(PERI(I)|I#LE#11:
   PWT3(I)=B3*PW3(I)/1000.0
          +(S3(17)+(SW3(I)+SW3(I+1))/2)*PW3(I)*A3/1000.0);
@FOR(PERI(I)|I#GT#11:
   PWT3(I)=B3*PW3(I)/1000.0
          +(S3(17)+(SW3(I)+SW3(1))/2)*PW3(I)*A3/1000.0);
    EWTS3=@SUM(PERI(I):EWT3(I));
    PWTS3=@SUM(PERI(I):PWT3(I));

! @FOR(PERI(I)|I#LE#11:[COTTER]
 SW3(I)+INF3(I)/Q3(17)*(DCOT(17)+EWTS3-PWTS3)
 -(DCOT(17))*ALPHA(I)-EWT3(I)+PWT3(I)=SW3(I+1));

! @FOR(PERI(I)|I#GT#11:
 SW3(I)+INF3(I)/Q3(17)*(DCOT(17)+EWTS3-PWTS3)
 -(DCOT(17))*ALPHA(I)-EWT3(I)+PWT3(I)=SW3(1));

@FOR(PERI(I)|I#LE#11:[COTTER]
 SW3(I)+((INF3(I)+INF5(I))/(Q3(17)+Q5(17)))*(DCOT(17)+EWTS3-PWTS3)
 -(DCOT(17))*ALPHA(I)-EWT3(I)+PWT3(I)=SW3(I+1));

@FOR(PERI(I)|I#GT#11:
 SW3(I)+((INF3(I)+INF5(I))/(Q3(17)+Q5(17)))*(DCOT(17)+EWTS3-PWTS3)
 -(DCOT(17))*ALPHA(I)-EWT3(I)+PWT3(I)=SW3(1));





@FOR(TIME(I)|I#LE#17:[GOOGONG]
```

```
 S4(I+1)-S4(I)
            -Q4(I)+R4(I)+DGOO(I)+ET4(I)-PT4(I)=0);
@FOR(TIME(J)|J#GT#17:
 S4(1)-S4(J)
            -Q4(J)+R4(J)+DGOO(J)+ET4(J)-PT4(J)=0);

@FOR(TIME(I):[GOOGONG]
ET4(I)=B4*E4(I)/1000.0+(S4(I)+SWET4)*A4*E4(I)/1000.0);
@FOR(TIME(I):[GOOGONG]
PT4(I)=B4*P4(I)/1000.0+(S4(I)+SWPT4)*A4*P4(I)/1000.0);

SWET4=@SUM(PERI(I)|I#LE#11:
        (EW4(I)/E4(17))*((SW4(I)+SW4(I+1))/2))+
        (EW4(12)/E4(17))*((SW4(12)+SW4(1))/2);
SWPT4=@SUM(PERI(I)|I#LE#11:
        (PW4(I)/P4(17))*((SW4(I)+SW4(I+1))/2))+
        (PW4(12)/P4(17))*((SW4(12)+SW4(1))/2);

@FOR(PERI(I)|I#LE#11:
    EWT4(I)=B4*EW4(I)/1000.0
            +(S4(17)+(SW4(I)+SW4(I+1))/2)*EW4(I)*A4/1000.0);
@FOR(PERI(I)|I#GT#11:
    EWT4(I)=B4*EW4(I)/1000.0
            +(S4(17)+(SW4(I)+SW4(1))/2)*EW4(I)*A4/1000.0);
@FOR(PERI(I)|I#LE#11:
    PWT4(I)=B4*PW4(I)/1000.0
            +(S4(17)+(SW4(I)+SW4(I+1))/2)*PW4(I)*A4/1000.0);
@FOR(PERI(I)|I#GT#11:
    PWT4(I)=B4*PW4(I)/1000.0
            +(S4(17)+(SW4(I)+SW4(1))/2)*PW4(I)*A4/1000.0);
    EWTS4=@SUM(PERI(I):EWT4(I));
    PWTS4=@SUM(PERI(I):PWT4(I));

@FOR(PERI(I)|I#LE#11:[GOOGONG]
 SW4(I)+INF4(I)/Q4(17)*(DGOO(17)+EWTS4-PWTS4)
 -(DGOO(17))*ALPHA(I)-EWT4(I)+PWT4(I)=SW4(I+1));

@FOR(PERI(I)|I#GT#11:
```

```
 SW4(I)+INF4(I)/Q4(17)*(DGOO(17)+EWTS4-PWTS4)
 -(DGOO(17))*ALPHA(I)-EWT4(I)+PWT4(I)=SW4(1));




@FOR(TIME(I)|I#LE#17:[TENNENT]
 S6(I+1)-S6(I)
            -Q6(I)+R6(I)+DTEN(I)+ET6(I)-PT6(I)=0);
@FOR(TIME(J)|J#GT#17:
 S6(1)-S6(J)
            -Q6(J)+R6(J)+DTEN(J)+ET6(J)-PT6(J)=0);

@FOR(TIME(I):[TENNENT]
ET6(I)=B6*E6(I)/1000.0+(S6(I)+SWET6)*A6*E6(I)/1000.0);
@FOR(TIME(I):[TENNENT]
PT6(I)=B6*P6(I)/1000.0+(S6(I)+SWPT6)*A6*P6(I)/1000.0);

SWET6=@SUM(PERI(I)|I#LE#11:
        (EW6(I)/E6(17))*((SW6(I)+SW6(I+1))/2))+
        (EW6(12)/E6(17))*((SW6(12)+SW6(1))/2);
SWPT6=@SUM(PERI(I)|I#LE#11:
        (PW6(I)/P6(17))*((SW6(I)+SW6(I+1))/2))+
        (PW6(12)/P6(17))*((SW6(12)+SW6(1))/2);

@FOR(PERI(I)|I#LE#11:
    EWT6(I)=B6*EW6(I)/1000.0
              +(S6(17)+(SW6(I)+SW6(I+1))/2)*EW6(I)*A6/1000.0);
@FOR(PERI(I)|I#GT#11:
    EWT6(I)=B6*EW6(I)/1000.0
              +(S6(17)+(SW6(I)+SW6(1))/2)*EW6(I)*A6/1000.0);
@FOR(PERI(I)|I#LE#11:
    PWT6(I)=B6*PW6(I)/1000.0
              +(S6(17)+(SW6(I)+SW6(I+1))/2)*PW6(I)*A6/1000.0);
@FOR(PERI(I)|I#GT#11:
    PWT6(I)=B6*PW6(I)/1000.0
              +(S6(17)+(SW6(I)+SW6(1))/2)*PW6(I)*A6/1000.0);
     EWTS6=@SUM(PERI(I):EWT6(I));
```

```
    PWTS6=@SUM(PERI(I):PWT6(I));
@FOR(PERI(I)|I#LE#11:[TENNENT]
 SW6(I)+INF6(I)/Q6(17)*(DTEN(17)+EWTS6-PWTS6)
 -(DTEN(17))*ALPHA(I)-EWT6(I)+PWT6(I)=SW6(I+1));
@FOR(PERI(I)|I#GT#11:
 SW6(I)+INF6(I)/Q6(17)*(DTEN(17)+EWTS6-PWTS6)
 -(DTEN(17))*ALPHA(I)-EWT6(I)+PWT6(I)=SW6(1));
@FOR(TIME(I)|I#LE#17:[riverlea]
 S7(I+1)-S7(I)
            -Q7(I)+R7(I)+DRIV(I)+ET7(I)-PT7(I)=0);
@FOR(TIME(J)|J#GT#17:
 S7(1)-S7(J)
            -Q7(J)+R7(J)+DRIV(J)+ET7(J)-PT7(J)=0);
@FOR(TIME(I):[RIVER]
ET7(I)=B7*E7(I)/1000.0+(S7(I)+SWET7)*A7*E7(I)/1000.0);
@FOR(TIME(I):[RIVER]
PT7(I)=B7*P7(I)/1000.0+(S7(I)+SWPT7)*A7*P7(I)/1000.0);
SWET7=@SUM(PERI(I)|I#LE#11:
        (EW7(I)/E7(17))*((SW7(I)+SW7(I+1))/2))+
        (EW7(12)/E7(17))*((SW7(12)+SW7(1))/2);
SWPT7=@SUM(PERI(I)|I#LE#11:
        (PW7(I)/P7(17))*((SW7(I)+SW7(I+1))/2))+
        (PW7(12)/P7(17))*((SW7(12)+SW7(1))/2);
@FOR(PERI(I)|I#LE#11:
    EWT7(I)=B7*EW7(I)/1000.0
              +(S7(17)+(SW7(I)+SW7(I+1))/2)*EW7(I)*A7/1000.0);
@FOR(PERI(I)|I#GT#11:
    EWT7(I)=B7*EW7(I)/1000.0
```

```
             +(S7(17)+(SW7(I)+SW7(1))/2)*EW7(I)*A7/1000.0);
@FOR(PERI(I)|I#LE#11:
   PWT7(I)=B7*PW7(I)/1000.0
             +(S7(17)+(SW7(I)+SW7(I+1))/2)*PW7(I)*A7/1000.0);
@FOR(PERI(I)|I#GT#11:
   PWT7(I)=B7*PW7(I)/1000.0
             +(S7(17)+(SW7(I)+SW7(1))/2)*PW7(I)*A7/1000.0);
    EWTS7=@SUM(PERI(I):EWT7(I));
    PWTS7=@SUM(PERI(I):PWT7(I));

@FOR(PERI(I)|I#LE#11:[RIVER]
 SW7(I)+INF7(I)/Q7(17)*(DRIV(17)+EWTS7-PWTS7)
 -(DRIV(17))*ALPHA(I)-EWT7(I)+PWT7(I)=SW7(I+1));

@FOR(PERI(I)|I#GT#11:
 SW7(I)+INF7(I)/Q7(17)*(DRIV(17)+EWTS7-PWTS7)
 -(DRIV(17))*ALPHA(I)-EWT7(I)+PWT7(I)=SW7(1));



    ! Capacity constraints on the reservoirs, capacities of reservoirs
   are corin=75.5, bendora=10.7, cotter=4.70, googong=124.5, coree=86.0
   , tennent=151.0 , riverlea=83.0;


@FOR(TIME(K): [CORINST]
         S1(K)<KAP1);
@FOR(TIME(I): [BENDST]
         S2(I)<KAP2);
@FOR(TIME(I): [COTST]
         S3(I)<KAP3);
@FOR(TIME(I): [GOOST]
         S4(I)<KAP4);
@FOR(TIME(I): [COREEST]
         S5(I)<KAP5);
@FOR(TIME(I): [TENNENT]
         S6(I)<KAP6);
@FOR(TIME(I): [RIVERLEA]
```

```
        S7(I)<KAP7);

    ! Dead storage levels;

@FOR(TIME(K): [CORINST]
        S1(K)>0.18);
@FOR(TIME(I): [BENDST]
        S2(I)>0.18);
@FOR(TIME(I): [COTST]
        S3(I)>0.02);
@FOR(TIME(I): [GOOST]
        S4(I)>1.62);
@FOR(TIME(I): [COREEST]
        S5(I)>0.00);
@FOR(TIME(I): [TENNST]
        S6(I)>0.00);
@FOR(TIME(I): [RIVERST]
        S7(I)>0.00);

    !within year storage constraints;

@FOR(PERI(K): [GOOST]
        SW4(K)+KAP4<124.5);
@FOR(PERI(K): [COTST]
        SW3(K)+KAP3<76.0);
@FOR(PERI(K): [BENDST]
        SW2(K)+KAP2<10.7);
@FOR(PERI(K): [CORIST]
        SW1(K)+KAP1<75.5);
@FOR(PERI(K): [CORST]
        SW5(K)+KAP5<86.0);
@FOR(PERI(K): [TENST]
        SW6(K)+KAP6<151.0);
@FOR(PERI(K): [RIVERST]
        SW7(K)+KAP7<83.0);

    ! Riparian releases GOOGONG reservoir;

```

```
@FOR(TIME(I): [RIGOO]
        R4(I)>7.45);

    ! Maximum release from corin to bendora(164.25);

@FOR(TIME(I): [MAXRCOR]
        R1(I)<164.25);

    ! pipe capacity restriction on water supplied from a
    particular reservoir;

@FOR(TIME(I): [BENPCAP]
         DBEN(I)<116.8);
@FOR(TIME(I): [COTPCAP]
         DCOT(I)<27.375);
@FOR(TIME(I): [COTPCAP]
         DCOT(I)<64.0);
@FOR(TIME(I): [RIVCAP]
         DRIV(I)<100.0);

    ! Water treatment plant capacity restrictions;

@FOR(TIME(I): [WTPS]
         DCOT(I)+DBEN(I)+DCOR(I)<300.0);
@FOR(TIME(I): [WTPG]
         DGOO(I)<69.35);
@FOR(TIME(I): [WTPT]
         DTEN(I)<195.0);
@FOR(TIME(I):[AYIEL]
   DCOR(I)+DRIV(I)+DBEN(I)+DGOO(I)+DCOT(I)+DTEN(I)=YEI);

DATA:
  Q1= @FILE(YCORF.LDT)  ;
  INF1= @FILE(YCORF.LDT);
  E1= @FILE(YCORF.LDT)  ;
  EW1= @FILE(YCORF.LDT) ;
  P1= @FILE(YCORF.LDT)  ;
  PW1= @FILE(YCORF.LDT) ;
```

```
Q2= @FILE(YBENF.LDT) ;
INF2= @FILE(YBENF.LDT);
E2= @FILE(YBENF.LDT) ;
EW2= @FILE(YBENF.LDT) ;
P2= @FILE(YBENF.LDT) ;
PW2= @FILE(YBENF.LDT) ;
Q3= @FILE(YCOTF.LDT) ;
INF3= @FILE(YCOTF.LDT);
E3= @FILE(YCOTF.LDT) ;
EW3= @FILE(YCOTF.LDT) ;
P3= @FILE(YCOTF.LDT) ;
PW3= @FILE(YCOTF.LDT) ;
Q4= @FILE(YGOOF.LDT) ;
INF4= @FILE(YGOOF.LDT);
E4= @FILE(YGOOF.LDT) ;
EW4= @FILE(YGOOF.LDT) ;
P4= @FILE(YGOOF.LDT) ;
PW4= @FILE(YGOOF.LDT) ;
Q5= @FILE(YCREF.LDT) ;
INF5= @FILE(YCREF.LDT);
E5= @FILE(YCREF.LDT) ;
EW5= @FILE(YCREF.LDT) ;
P5= @FILE(YCREF.LDT) ;
PW5= @FILE(YCREF.LDT) ;
Q6= @FILE(YTENF.LDT) ;
INF6= @FILE(YTENF.LDT);
E6= @FILE(YTENF.LDT) ;
EW6= @FILE(YTENF.LDT) ;
P6= @FILE(YTENF.LDT) ;
PW6= @FILE(YTENF.LDT) ;
Q7= @FILE(YRIVF.LDT) ;
INF7= @FILE(YRIVF.LDT);
E7= @FILE(YRIVF.LDT) ;
EW7= @FILE(YRIVF.LDT) ;
P7= @FILE(YRIVF.LDT) ;
PW7= @FILE(YRIVF.LDT) ;
ALPHA= @FILE(DCANBY.LDT) ;
ENDDATA
END
```

Appendix G

Data Files for the New Yield Model Formulation

The data required for the yield Model formulation includes the monthly demand allocation percentages of the annual demand (ALPHA) and the annual and critical year streamflow, evaporation and precipitation. The monthly demand allocation percentages of the annual demand are shown in Appendix E and the remaining required data is shown below :

! data for corin reservoir;
! streamflow data;
57.82, 15.24, 40.99, 69.17, 70.47, 56.92,
32.37, 62.14, 150.20, 88.94, 44.03, 41.35,
97.36, 20.14, 19.47, 65.98, 6.41, 95.84~
! critical year flow data;
0.66, 0.36, 0.85, 0.58, 0.41, 0.56,
0.40, 0.58, 0.98, 0.72, 0.21, 0.10~
! evaporation data;
792.90, 937.55, 1043.80, 788.70, 869.95, 849.50,
871.25, 890.60, 825.60, 815.65, 724.05, 864.50,
768.05, 860.95, 953.95, 876.30, 1002.75, 857.50~
! critical year evaporation data;

154.70, 141.10, 81.90, 52.00, 46.20, 22.10,
23.00, 45.05, 60.00, 93.00, 160.50, 123.20~
! precipitation data;
1183.00, 573.00, 997.00, 1198.00, 1303.00, 1025.00,
713.00, 1217.00, 1444.00, 1308.00, 902.00, 840.00,
1483.00, 786.00, 1135.00, 1333.00, 505.00, 1496.00~
! critical year precipitation data;
41.00, 34.00, 94.00, 31.00, 20.00, 33.00,
10.00, 23.00, 143.00, 24.00, 7.00, 45.00~

! data for bendora reservoir;
! streamflow data;
40.90, 10.78, 28.99, 48.92, 49.85, 40.26,
22.90, 43.95, 106.24, 62.91, 31.15, 29.25,
68.86, 14.24, 13.77, 46.67, 4.54, 67.79~
! critical year flow data;
0.47, 0.25, 0.60, 0.41, 0.29, 0.40,
0.28, 0.41, 0.69, 0.51, 0.15, 0.07~
! evaporation data;
792.90, 937.55, 1043.80, 788.70, 869.95, 849.50,
871.25, 890.60, 825.60, 815.65, 724.05, 864.50,
768.05, 860.95, 953.95, 876.30, 1002.75, 857.50~
! critical year evaporation data;
154.70, 141.10, 81.90, 52.00, 46.20, 22.10,
23.00, 45.05, 60.00, 93.00, 160.50, 123.20~
! precipitation data;
1250.00, 547.00, 1053.00, 1232.00, 1105.00, 925.00,
734.00, 1166.00, 1695.00, 1221.00, 896.00, 918.00,
1323.00, 723.00, 912.00, 1426.00, 507.00, 1527.00~
! critical year precipitation data;
43.00, 17.00, 121.00, 27.00, 12.00, 69.00,
8.00, 24.00, 120.00, 28.00, 5.00, 33.00~

! data for coree reservoir;
! streamflow data;
40.19, 10.59, 28.49, 48.08, 48.99, 39.56,
22.50, 43.19, 104.41, 61.83, 30.61, 28.74,
67.68, 14.00, 13.53, 45.86, 4.46, 66.62~

! critical year flow data;
0.46, 0.25, 0.59, 0.40, 0.28, 0.39,
0.28, 0.40, 0.68, 0.50, 0.15, 0.07~
! evaporation data;
949.00, 1123.60, 1248.50, 944.10, 1042.50, 1016.05,
1045.20, 1066.30, 989.20, 976.10, 868.15, 1034.70,
919.75, 1030.25, 1142.45, 1050.80, 1199.10, 1025.50~
! critical year evaporation data;
182.00, 166.00, 100.10, 62.40, 54.60, 27.20,
28.00, 53.00, 72.00, 111.60, 192.60, 149.60~
! precipitation data;
852.00, 408.00, 716.00, 1016.00, 1020.00, 918.00,
624.00, 1158.00, 1394.00, 962.00, 780.00, 657.00,
901.00, 497.00, 423.00, 818.00, 277.00, 786.00~
! critical year precipitation data;
41.00, 34.00, 94.00, 31.00, 20.00, 33.00,
10.00, 23.00, 143.00, 24.00, 7.00, 45.00~

! data for cotter reservoir;
! streamflow data;
2.12, 0.56, 1.50, 2.53, 2.58, 2.08,
1.18, 2.27, 5.50, 3.25, 1.61, 1.51,
3.56, 0.74, 0.71, 2.41, 0.23, 3.51~
! critical year flow data;
0.02, 0.01, 0.03, 0.02, 0.02, 0.02,
0.01, 0.02, 0.04, 0.03, 0.01, 0.00~
! evaporation data;
949.00, 1123.60, 1248.50, 944.10, 1042.50, 1016.05,
1045.20, 1066.30, 989.20, 976.10, 868.15, 1034.70,
919.75, 1030.25, 1142.45, 1050.80, 1199.10, 1025.50~
! critical year evaporation data;
182.00, 166.00, 100.10, 62.40, 54.60, 27.20,
28.00, 53.00, 72.00, 111.60, 192.60, 149.60~
! precipitation data;
852.00, 408.00, 716.00, 1016.00, 1020.00, 918.00,
624.00, 1158.00, 1394.00, 962.00, 780.00, 657.00,
901.00, 497.00, 423.00, 818.00, 277.00, 786.00~
! critical year precipitation data;

14.00, 16.00, 133.00, 0.00, 0.00, 14.00,
0.00, 6.00, 77.00, 12.00, 0.00, 5.00~

! data for googong reservoir;
! streamflow data;
133.92, 53.84, 22.45, 78.47, 73.94, 86.20,
34.63, 44.54, 370.39, 299.47, 140.23, 55.44,
262.42, 45.30, 12.63, 54.43, 11.60, 82.78~
! critical year flow data;
2.13, 0.72, 1.94, 0.88, 0.83, 0.76,
0.67, 0.89, 0.74, 0.77, 0.72, 0.55~
! evaporation data;
1248.73, 1541.60, 1628.90, 1335.94, 1306.80, 1325.79,
1451.71, 1358.19, 1250.17, 1417.10, 1388.30, 1624.00,
1353.17, 1706.65, 1708.38, 1591.40, 1776.71, 1569.49~
! critical year evaporation data;
256.70, 237.15, 153.45, 113.42, 107.38, 61.88,
52.64, 73.83, 98.49, 144.05, 266.76, 210.96~
! precipitation data;
748.00, 357.00, 607.00, 714.00, 770.00, 566.00,
457.00, 827.00, 922.00, 727.00, 517.00, 511.00,
719.00, 405.00, 426.00, 593.00, 244.00, 721.00~
! critical year precipitation data;
17.00, 18.00, 96.00, 7.00, 2.00, 17.00,
4.00, 11.00, 44.00, 8.00, 2.00, 18.00~

! data for tennent reservoir;
! streamflow data;
79.39, 24.34, 21.97, 62.24, 54.51, 79.40,
45.55, 47.77, 216.38, 148.12, 90.48, 57.71,
181.08, 33.17, 14.78, 37.69, 6.69, 99.78~
! critical year flow data;
0.47, 0.18, 0.82, 0.53, 0.53, 0.82,
0.69, 0.75, 1.25, 0.55, 0.09, 0.00~
! evaporation data;
792.90, 937.55, 1043.80, 788.70, 869.95, 849.50,
871.25, 890.60, 825.60, 815.65, 724.05, 864.50,
768.05, 860.95, 953.95, 876.30, 1002.75, 857.50~

! critical year evaporation data;
154.70, 141.10, 81.90, 52.00, 46.20, 22.10,
23.00, 45.05, 60.00, 93.00, 160.50, 123.20~
! precipitation data;
1183.00, 573.00, 997.00, 1198.00, 1303.00, 1025.00,
713.00, 1217.00, 1444.00, 1308.00, 902.00, 840.00,
1483.00, 786.00, 1135.00, 1333.00, 505.00, 1496.00~
! critical year precipitation data;
41.00, 34.00, 94.00, 31.00, 20.00, 33.00,
10.00, 23.00, 143.00, 24.00, 7.00, 45.00~

! data for riverlea reservoir;
! streamflow data;
30.57, 8.97, 17.47, 49.18, 38.18, 56.94,
22.23, 37.69, 114.80, 59.95, 32.51, 31.66,
59.85, 11.43, 6.81, 34.32, 3.21, 64.55~
! critical year flow data;
0.32, 0.13, 0.53, 0.33, 0.28, 0.34,
0.31, 0.24, 0.43, 0.26, 0.03, 0.00~
! evaporation data;
949.00, 1123.60, 1248.50, 944.10, 1042.50, 1016.05,
1045.20, 1066.30, 989.20, 976.10, 868.15, 1034.70,
919.75, 1030.25, 1142.45, 1050.80, 1199.10, 1025.50~
! critical year evaporation data;
182.00, 166.00, 100.10, 62.40, 54.60, 27.20,
28.00, 53.00, 72.00, 111.60, 192.60, 149.60~
! precipitation data;
852.00, 408.00, 716.00, 1016.00, 1020.00, 918.00,
624.00, 1158.00, 1394.00, 962.00, 780.00, 657.00,
901.00, 497.00, 423.00, 818.00, 277.00, 786.00~
! critical year precipitation data;
14.00, 16.00, 133.00, 0.00, 0.00, 14.00,
0.00, 6.00, 77.00, 12.00, 0.00, 5.00~

Appendix H

Surface Area Versus Storage Volume Curves for the Existing and Future Reservoirs

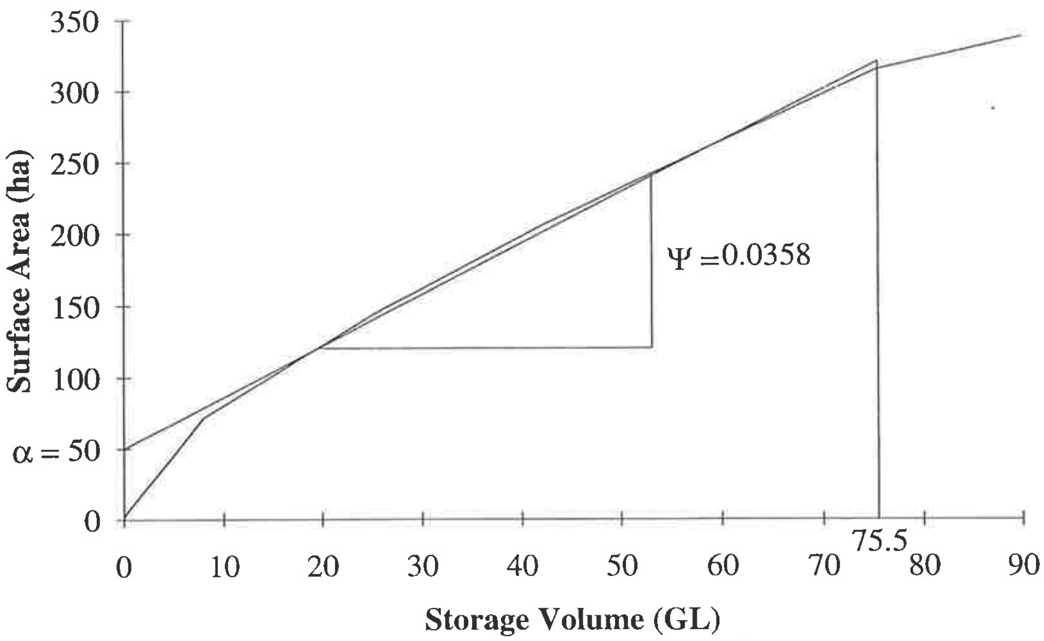

Figure H.1 Surface Area versus Storage Volume For Corin Reservoir

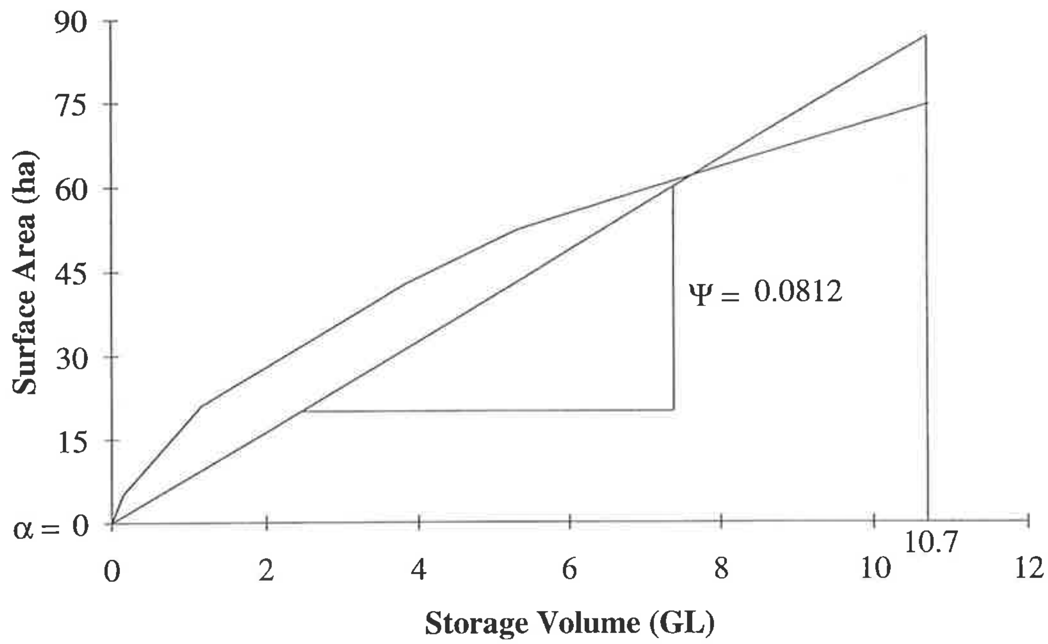

Figure H.2 Surface Area versus Storage Volume For Bendora Reservoir

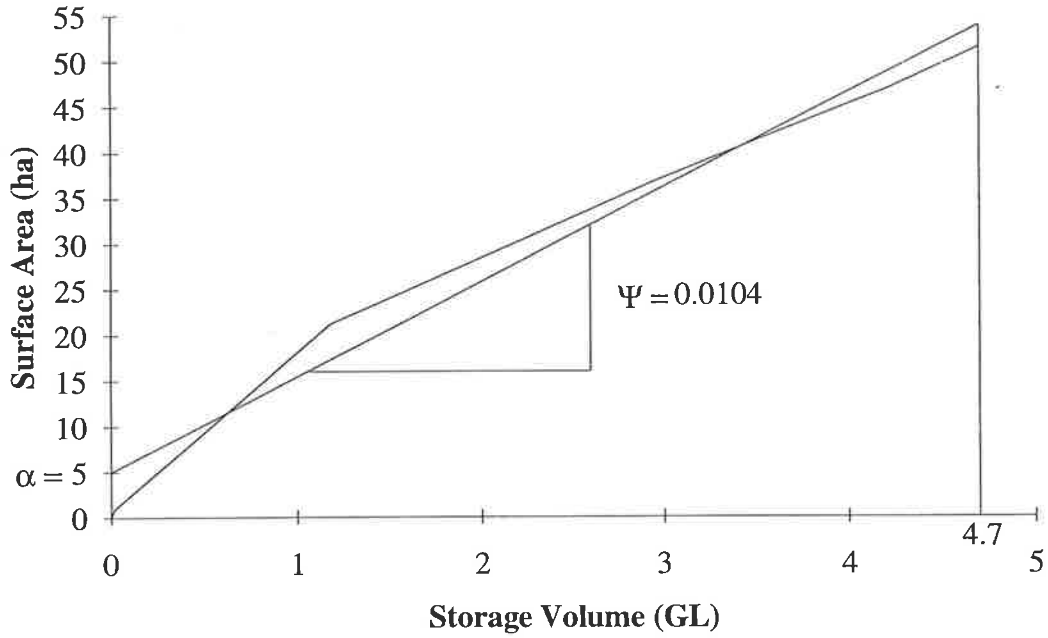

Figure H.3 Surface Area versus Storage Volume For Cotter Reservoir

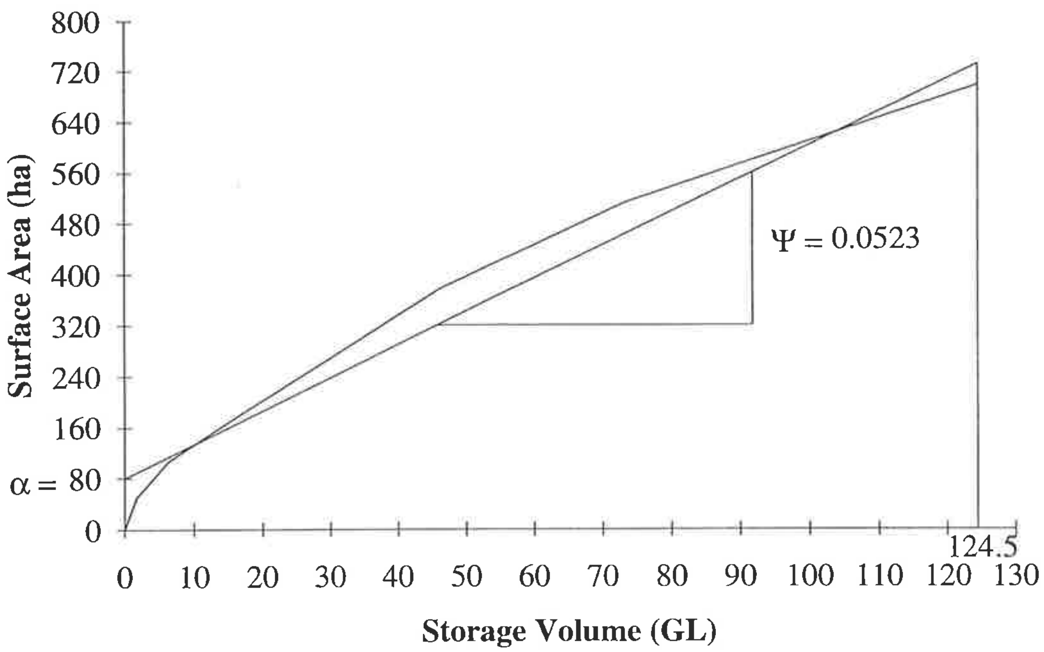

Figure H.4 Surface Area versus Storage Volume For Googong Reservoir

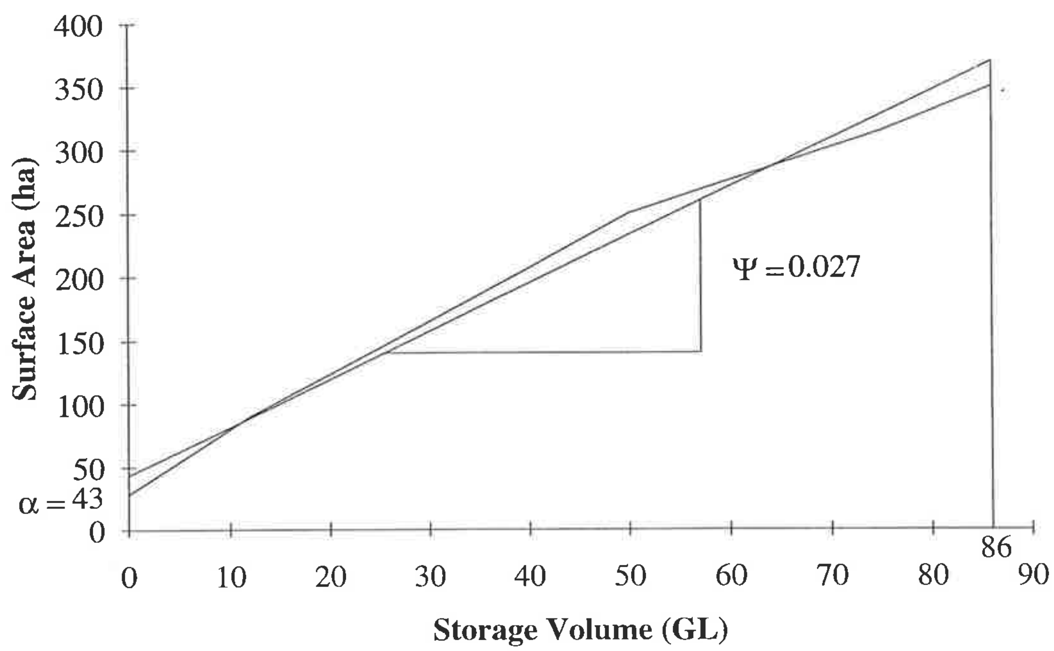

Figure H.5 Surface Area versus Storage Volume For Coree Reservoir

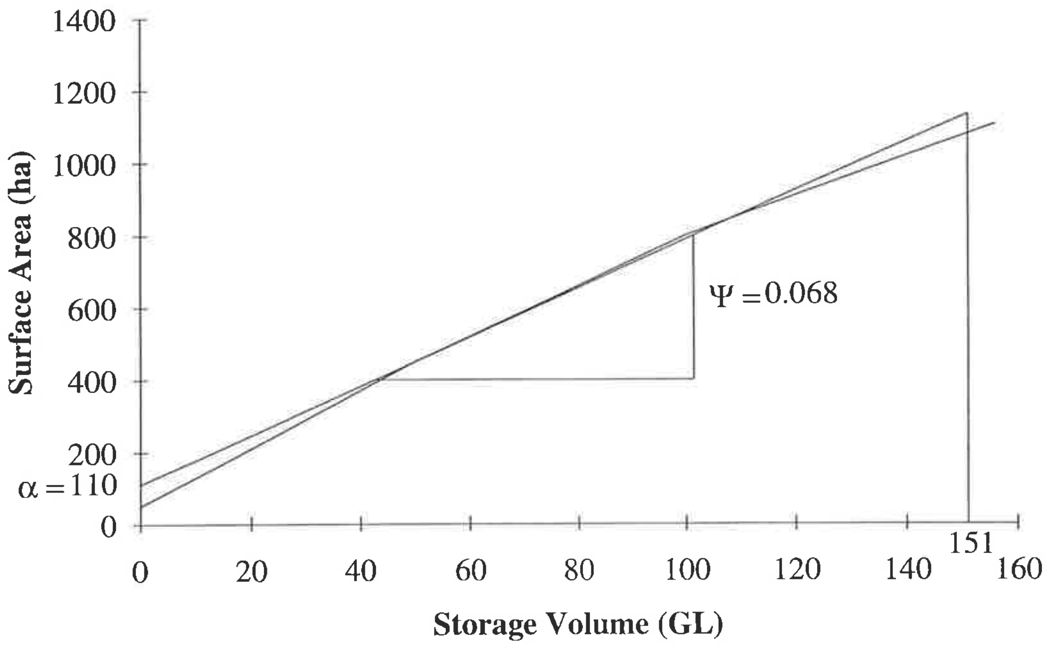

Figure H.6 Surface Area versus Storage Volume For Tennent Reservoir

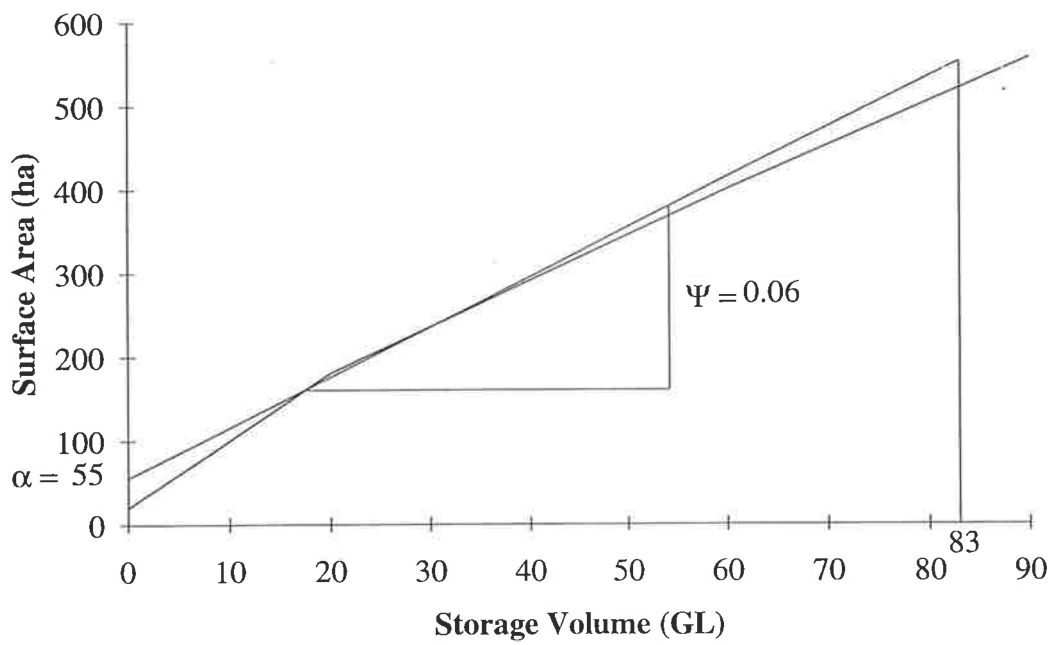

Figure H.7 Surface Area versus Storage Volume For Riverlea Reservoir

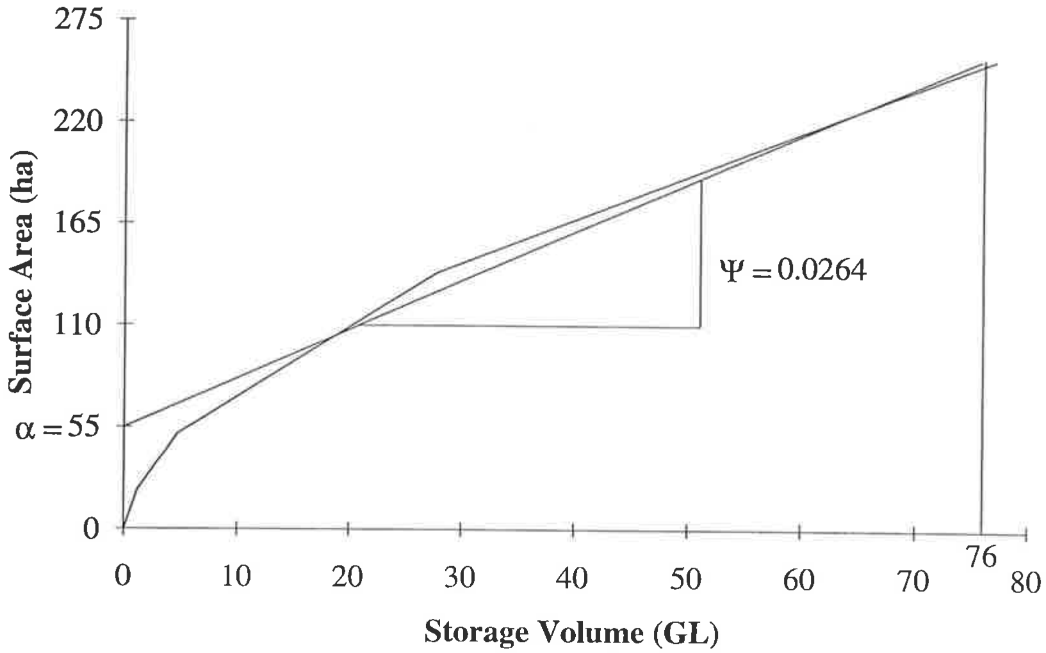

Figure H.8 Surface Area versus Storage Volume For Cotter Reservoir

Appendix I

Future Water Demand Projections for Canberra

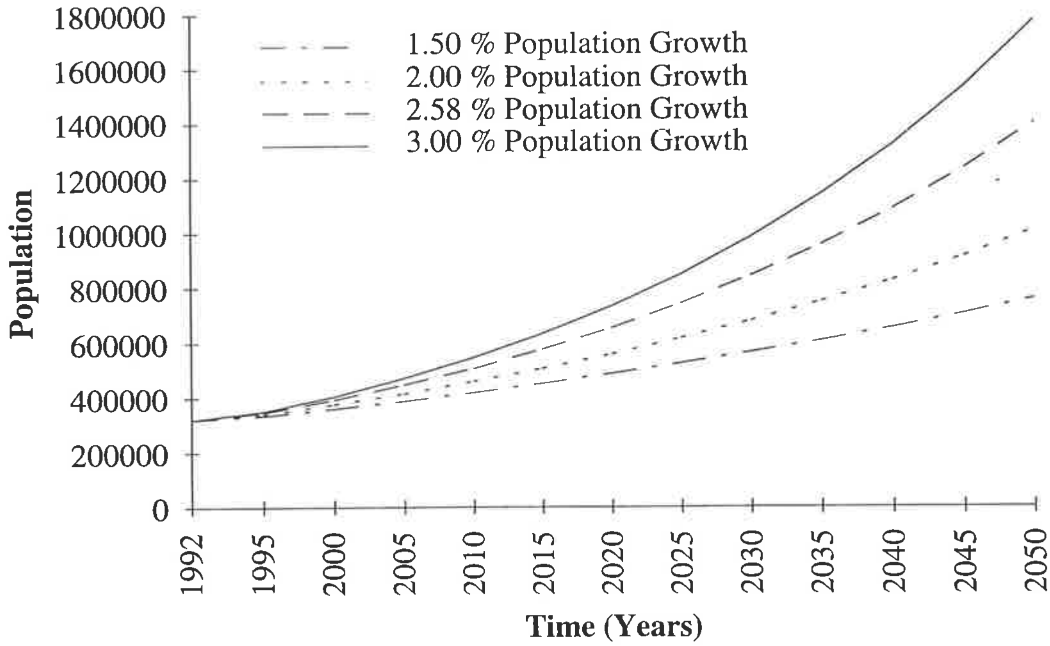

Figure I.1 Future Water Demand Projections for Canberra

Appendix J

GA Model Evaluation for the South-East Queensland System

As mentioned a sensitivity of the GA Models T1, T5 and T6 is performed to find the best model and the parameter values to use in that model. The parameter of interest is the mutation rate and also for Models T5 and T6 the type of mutation. Two types of mutation have been described in Chapter 5. They are bit mutation and string mutation. Therefore, in total three mutation rates will be examined per model, per mutation operator.

The models will be tested using various cases from the South-East Queensland problem to be examined. The cases examined are:

Case 1 : Demand forecast 2, Discount rate = 5.0 %
Case 2 : Demand forecast 2, Discount rate = 2.5 %
Case 3 : Demand forecast 3, Discount rate = 10.0 %

These cases were examined for the no upsizing and upsizing cases. When upsizing is allowed the upsizing cost is assumed to be 120 % of the incremental cost. In addition, only cases 2 and 3 are examined for the upsizing case. The reason for choosing these cases is that they are expected to be the more difficult cases. In regard to the other parameters which are used, the population size is set at 100, probability of crossover equals 90 % and the number of generations examined is 200. The selection of these parameter values was performed and discussed in Chapter 5. The string length is 25 bits which represents 8 projects with three sizes and one project with only one size (eg. project 13). Each case was tested on each model with three runs performed with each model. The random seed was varied for each run so that the initial starting solution will be significantly different to avoid bias occurring. The probabilities of mutation examined are, for the bit mutation p_m = 1 %, 3 %, 5 % and 10 % and for the string mutation 5 %, 20 % and 30 %. The results for the no upsizing cases for Models T1, T5 and T6 for the various mutation rates and operators are shown in Tables J.1 to J.3

Table J.1 Sensitivity Analysis of Model T1 for the No Upsizing Problem

Case	PVC for various probabilities of mutation (bit mutation)			
	1 %	3 %	5 %	10 %
1	116.2305	116.2305	116.2305	116.3378
2	246.9520	245.9375	245.9375	245.9673
3	15.8131	15.8131	15.8131	15.8231

The results shown in Table J.1 are the averaged minimum PVC results from three different runs. For the 3 % and 5 % mutation rates the result shown is obtained by all the runs. For the 1 % p_m value, the PVC shown is obtained for cases 1 and 3 for the three runs examined. However for case 2 only on two occasions did the GA obtained the lowest PVC of 245.9375. For the 10 % mutation rate the minimum PVC, as found when using the 3 and 5 % mutation rates, was obtained on one occasion for cases 1 and 2 but not on any occasion for case 3. From these results it would appear that either a mutation rate of 3 % or 5 % would be suitable to use.

Table J.2 Sensitivity Analysis of Model T5 for the No Upsizing Problem

Case	PVC for various probabilities of mutation (bit mutation)				PVC for various probabilities of mutation (string mutation)		
	1 %	3 %	5 %	10 %	5 %	20 %	30 %
1	116.2305	117.4351	116.4600	116.8522	116.9623	116.7429	116.2305
2	247.7990	245.9375	246.4307	247.3576	247.5462	247.8503	247.4641
3	15.8131	15.8241	15.8249	15.8351	15.8351	15.8241	15.8351

In all cases in Table J.2, although the average of the three runs is not the minimum PVC, on at least one occasion for the various cases and mutation rates considered, the lowest cost solution shown in Table J.1 (for a p_m of 3%) was obtained. As can be seen, Model T5 does not perform as well as Model T1, regardless of the mutation operator used or the value of the mutation rate . In regard to the best mutation operator to use for Model T5 it appears bit mutation is better. The best results for cases 1 and 3 were found using bit mutation with a p_m value of 1 %. For case two the higher mutation rate of 3 % produced the best result. For string mutation, the 30 % p_m value produced the best results. The best averaged minimum PVC from the three runs for case 1 was found using both the string and bit mutation, for cases 2 and 3 the bit mutation produced the same averaged minimum PVC for the three runs.

Table J.3 Sensitivity Analysis of Model T6 for the No Upsizing Problem

Case	PVC for various probabilities of mutation (bit mutation)				PVC for various probabilities of mutation (string mutation)		
	1 %	3 %	5 %	10 %	5 %	20 %	30 %
1	116.2305	116.2305	116.4641	118.0613	116.3403	116.2305	116.2305
2	246.4304	246.4453	247.0589	250.3768	245.9524	247.8503	247.3574
3	15.8131	15.8151	15.8461	15.8884	15.8131	15.8131	15.8131

In all cases in Table J.3 when string mutation is used, the lowest PVC solution shown in Table J.1 (ie. 116.2305, 245.9375 and 15.8131 respectively for the various cases) was obtained at least once in the three runs performed for each mutation rate. For the results in Table J.3 when bit mutation was used, the lowest PVC solution was not obtained for the mutation rate of 10 % for any of the three cases and is not obtained for cases 2 and 3 for a mutation rate of 5 %. For the mutation rate of 1 %, the lowest PVC solution was obtained at least once in the three runs performed for the various cases. This was also the case with the 3 % mutation rate for bit mutation, except for case 3 where the minimum PVC is not obtained. For Model T6, the best results were obtained for bit and string mutation when the p_m values of 1 % and 30 % respectively, were used.

The p_m` seemed to be more important to Model T6 as at high mutation rates there seemed to be more disruption to the string, which hindered the PMX crossover operation achieving a good solution. However, in general, if the mutation is too low (ie <1%) there is a loss of diversity in the population which may lead to poor results. The reason for such sensitivity to the mutation rate when using the random swap mutation is thought to be due to the large disruption to the string when bits at various positions of the string are swapped. This may result in a larger variation in PVC when a swap occurs than would have been obtained without the swap. For example, when the swapping of bits results in a larger, more costly project being sequenced much earlier, the PVC will increase dramatically. However, with the swapping of bits in closer proximity to each other, the change in PVC will not be as dramatic. The change in PVC will be the lowest when the adjacent bits are swapped. This may be why the adjacent mutation operator appears to be less sensitive to variation in the mutation rate.

In addition, in all cases using Models T5 and T6 the average fitness of the population were close to the maximum fitness obtained, particularly when the string mutation operator is used. This suggests the loss of diversity within the population (ie. the strings are nearly all the same). This can lead to problems associated with sub-optimum results and which occurs in some of the above solutions. This loss of diversity was thought to be a result of a low mutation rate. This is the reason various mutation rate for both bit by bit mutation and string mutation were examined. However, this was not the case, although the solutions did improve with slightly higher mutation rates, but when mutation rate is too high the mutation tends to disrupt the solution process.

It is quite clear that Model T1 consistently produces the lowest PVC results. Therefore it will be used for the remainder of the study especially for the no upsizing case. Another comparison to make is between Models T5 and T6. Although it is hard to compare Models T5 and T6 due to the variation in solutions produced, it would appear that Model T6 produces the slightly better results with string mutation being the best mutation operator. It appears that good results are obtained with all mutation rates, for the GA model just mentioned. It is unclear which is the best, however the 5 % mutation rate obtains slightly better results over the three cases examined. Therefore if Model T6 was used, it appears a string mutation with 5 % mutation probability would produce the best results.

The performance of the three models and the various mutation operators can be seen by examining Figures K.1 to K.4 for the no upsizing, for case 2. The curves are plots of the minimum and average fitness of a typical run of the models utilised. For the various mutation operators, the curves represent a bit mutation rate of 3 % and a string mutation rate of 20 %. The Models T5b and T6b represent the used of bit mutation while Models T5s and T6s indicate the use of string mutation. These curves illustrate the conclusions made above regarding the effect of mutation operator and rate on the various models. It is evident when using bit mutation that Model T6 is affected more, as the run illustrated has a much higher average PVC than the other models. This represents a greater diversity in the population and may result in slow convergence to a solution. For Model T6, when string mutation is used the diversity in the population is reduced and the solution converges faster to a solution. The average PVC seems to be very similar regardless of the mutation operator for Model T5, although a faster convergence is obtained when string mutation is used. However, the convergence is to a higher PVC than has been found with Model T1. This is a problem when the diversity in the population is low and the average and minimum PVC is similar.

The next step is to examine the models in regard to their performance in solving the upsizing case. Only cases 2 and 3 will be examined and the results for the upsizing cases for Models T1, T5 and T6 for the various mutation rates and operators are shown in Tables J.4 to J.6

Table J.4 Sensitivity Analysis of Model T1 for the Upsizing Problem

Case	PVC for various probabilities of mutation (bit mutation)			
	1 %	3 %	5 %	10 %
2	242.9823	241.9271	242.2677	243.4874
3	15.0100	15.0800	15.0863	15.2009

The results obtained in Table J.4 illustrate that the lowest PVC solution is obtained for case 2 using the 3 % mutation rate and for case 3 using a mutation rate of 1 %. At these rates the lowest PVC is obtained for the runs for the particular cases considered. Whether, the 1 % or 3 % mutation rate is better is uncertain. However, using a low mutation rate may cause diversity in the population to be lost. So the 3 % mutation rate may be the better rate to use, for this reason.

Table J.5 Sensitivity Analysis of Model T5 for the Upsizing Problem

Case	PVC for various probabilities of mutation (bit mutation)				PVC for various probabilities of mutation (string mutation)		
	1 %	3 %	5 %	10 %	5 %	20 %	30 %
2	245.0495	243.4793	243.3746	243.4229	245.2533	244.132	246.1130
3	15.3264	15.1441	15.1304	15.1102	15.1450	15.1916	15.2988

In this case Model T5 with bit mutation appears the slightly better model. However, the decision of the best mutation rate is difficult as for the two cases examined the averaged lowest PVC is obtained by different mutation rates. It is interesting to note that the best single result out of the three runs per mutation rate for case 2, was when a mutation rate of 5 % was used with bit mutation and for case 3 the best result from the three runs performed per mutation rate, occurs for bit mutation and a mutation rate of 1 %. However, for these mutation rates, for the remaining runs the values obtained were considerably higher, thus a higher average PVC is obtained.

Table J.6 Sensitivity Analysis of Model T6 for the Upsizing Problem

Case	PVC for various probabilities of mutation (bit mutation)				PVC for various probabilities of mutation (string mutation)		
	1 %	3 %	5 %	10 %	5 %	20 %	30 %
2	243.5106	243.4805	245.0249	247.6146	243.0533	243.1491	242.7014
3	15.2135	15.1789	15.2161	15.3796	15.4100	15.1564	15.2135

The best model in Table J.6 appears to be that using string mutation. The best single result found for the three runs per mutation rate, for case 2 and 3, was when a mutation rate equal to 20 % was used with string mutation. However, the best mutation rates, based on the best average PVC obtained from the three runs performed was 30 % for case 2 and 20 % for case 3.

In regard to the overall best model for the upsizing case it appears Model T1 is the best. It gives the best results for both cases. In addition, it appears that a mutation rate of 3 % will give the best results, although a mutation rate of 1 % has also produced good results. It appears from the results of the upsizing case that Models T5 and T6 experience some problems in obtaining reliable solutions consistently. This is thought to be due to the mutation operators used and the path to optimality. It is possible that a number of mutations of a string would be required using theses mutation operators, before an improvement is made to the fitness of the string. This is particularly true as the fitness of the strings approaches the optimum. However, this will not occur with the GA operators being utilised. No conclusion can be made on which of Models T5 or T6 is the better, as they both perform on a similar level. The performance of the models for the upsizing case is shown in Figure K.5 to K.8. In these cases the bit mutation rate was 3 % and the string mutation rate was 20 %. From the runs illustrated it is quite clear that

Model T1 provides the lowest PVC. In addition, the average population fitness for the Model T1 seems to be neither not too diverse or too similar which may be a problem with the other models illustrated. If a population becomes too similar, the problem that arises is the effect of crossover becomes minimal, as effectively, crossover occurs between similar strings resulting in similar strings being produced. The likelihood of obtaining an improved result through crossover is small and therefore the GA is more reliant on mutation to provide better results. This will result in a relatively inefficient process. This phenomena seems to occur with the Model T5, which explains the performance of this model. The Model T6 on the other hand, illustrates the production of both a very similar population and a diverse population depending on the mutation operator. Of these the string mutation operator appears to be better as it provides a lower PVC, a definite convergence to a solution and the average population is similar to that of Model T1.

As is illustrated and mentioned above, it was found that the probability of mutation had a definite effect on the result obtained. Apart from the results discussed above, it was found that at high probability of mutations (p_m>0.15) for bit mutation, a string could be mutated more than once and possible the best solution could be missed. Thus, generally the result was a higher PVC and what appeared to be more of a random search (ie. a change in the maximum fitness in every generation however the change varied from a reduction to an addition with rarely the same result reappearing in the solution space). In addition the process will become more of a random process rather than the successful structured optimisation process it is meant to be if high mutation rates are used. Conversely, at low mutation rates for both mutation operators (ie p_m<0.02), the solution was slow to converge to a particular solution and if it did the solution was far from optimum. The conclusion in regard to what may occur with high or low mutation rates is the justification for examining the two different mutation methods of string mutation and bit by bit mutation. The benefit of a sting mutation operator is that even if mutation rate is high only one mutation or swap in this case will occur and the chance of multiple mutations occurring in the one string is eliminated. As mentioned multiple mutation of a string may cause the optimal result or a higher fitness result to be lost. It could be argued that this is unlikely to occur as the probability of mutation is low. However, when generating random numbers the probability of producing a number of low values is the same as producing high values and therefore there is a chance it may occur. In addition, the sting mutation operator can be made to perform like the bit by bit mutation operator if an appropriate mutation rate is used, without the chance of multiple mutation occurring within a string.

Appendix K

GA Model Performance for the South-East Queensland Problem

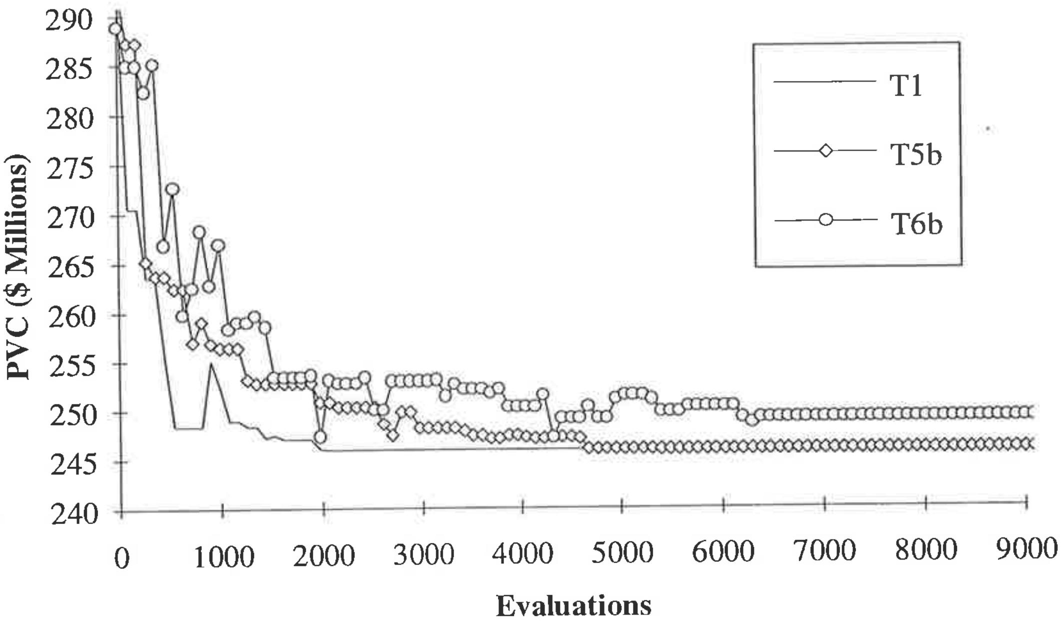

Figure K.1 The Minimum PVC Solution versus Number of Evaluations for Various GA Models for the No Upsizing Case

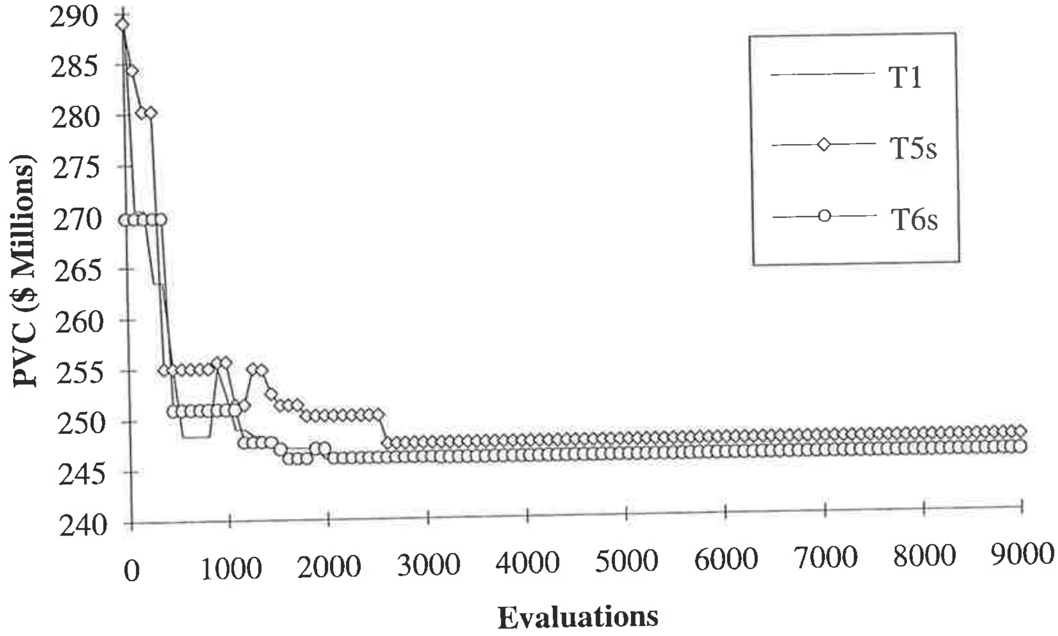

Figure K.2 The Minimum PVC Solution versus Number of Evaluations for Various GA Models for the No Upsizing Case

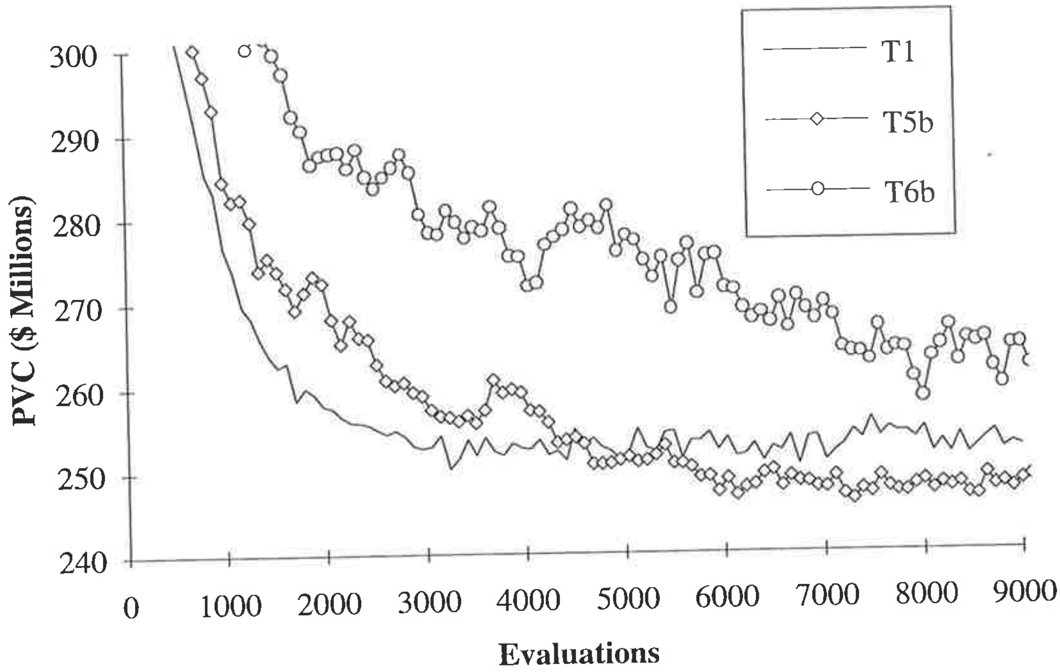

Figure K.3 The Average PVC Solution versus Number of Evaluations for Various GA Models for the No Upsizing Case

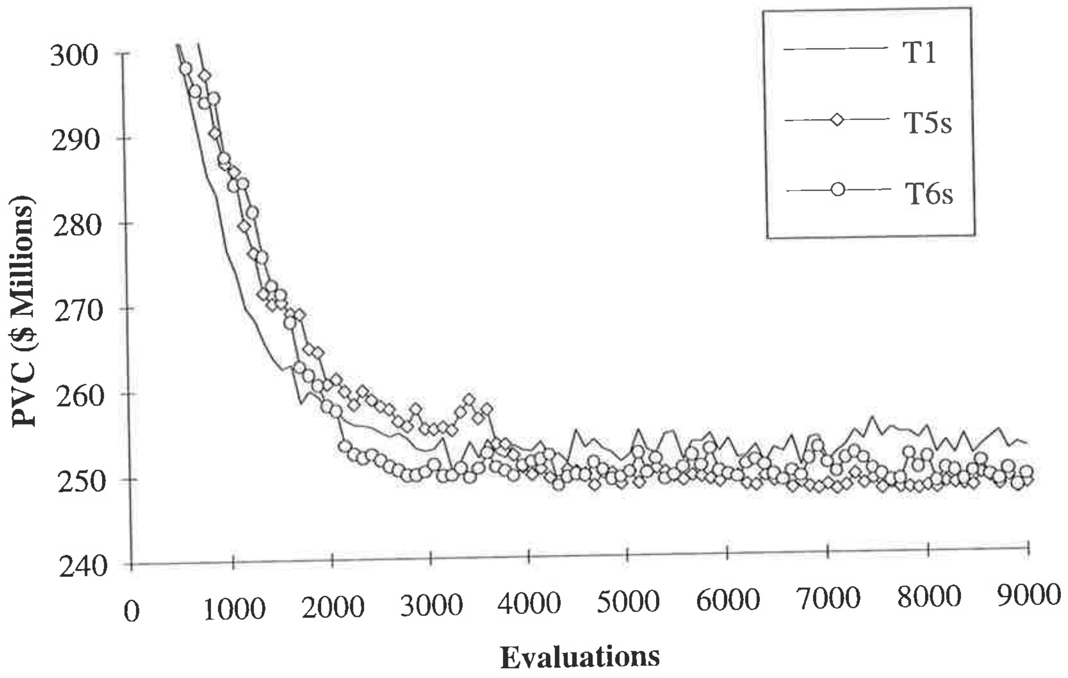

Figure K.4 The Average PVC Solution versus Number of Evaluations for Various GA Models for the No Upsizing Case

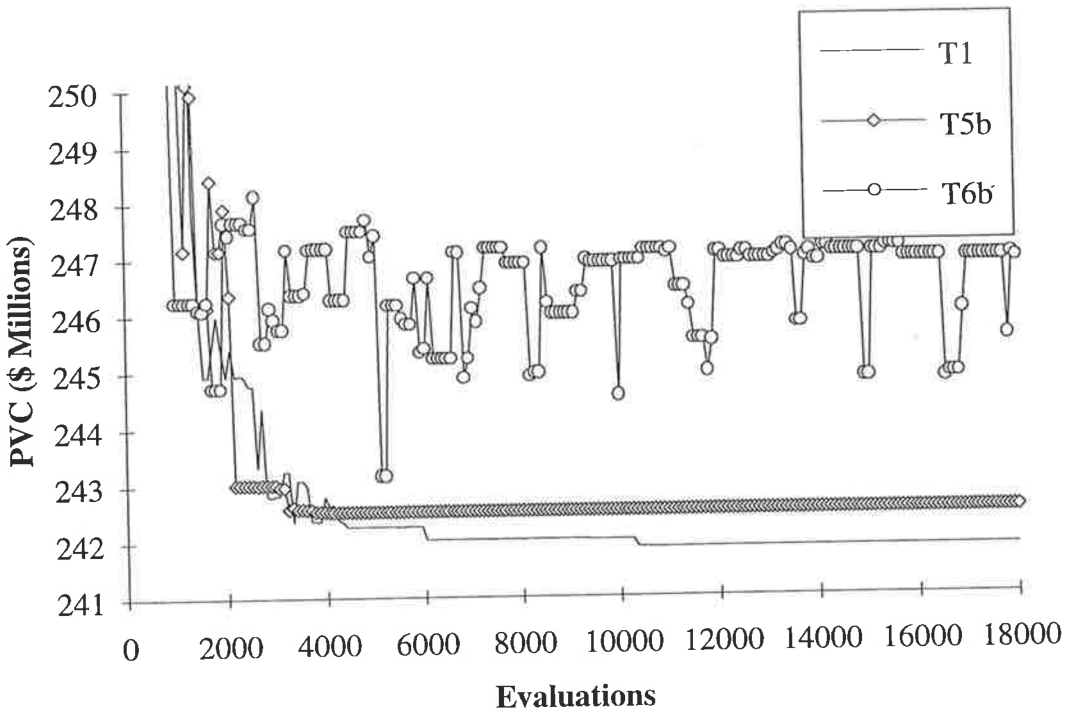

Figure K.5 The Minimum PVC Solution versus Number of Evaluations for Various GA Models for the Upsizing Case

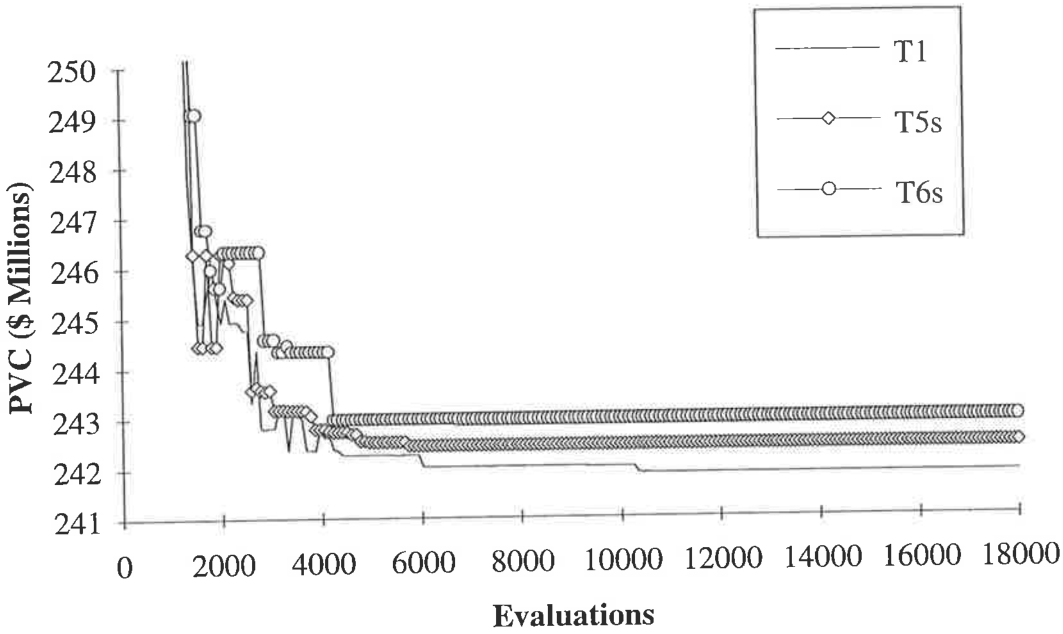

Figure K.6 The Minimum PVC Solution versus Number of Evaluations for Various GA Models for the Upsizing Case

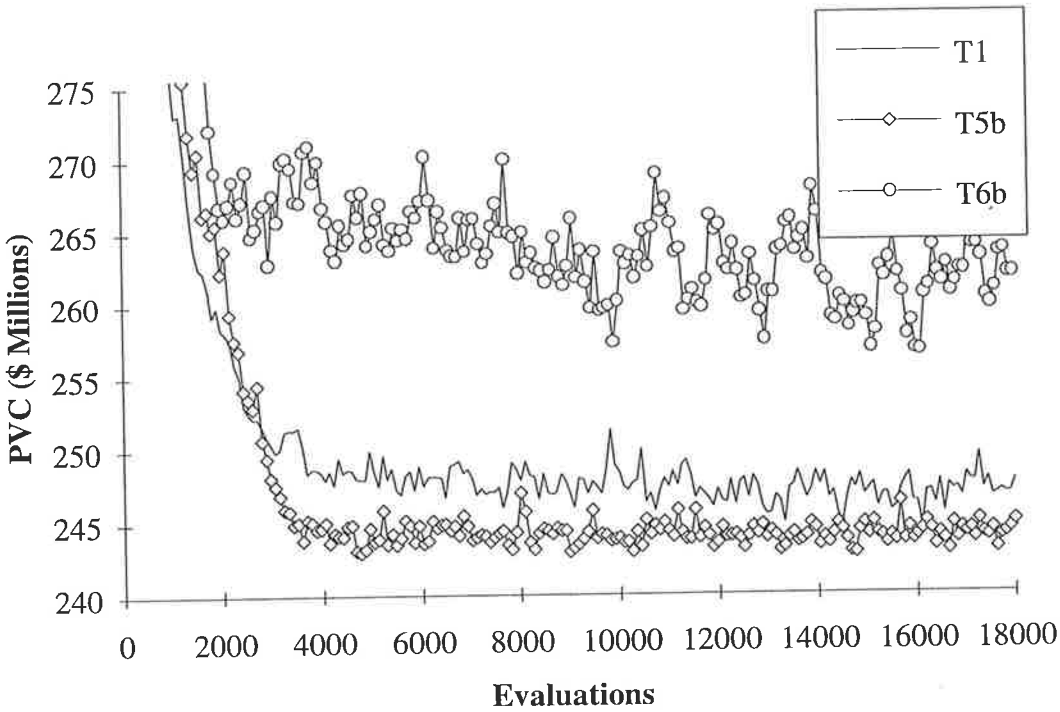

Figure K.7 The Average PVC Solution versus Number of Evaluations for Various GA Models for the Upsizing Case

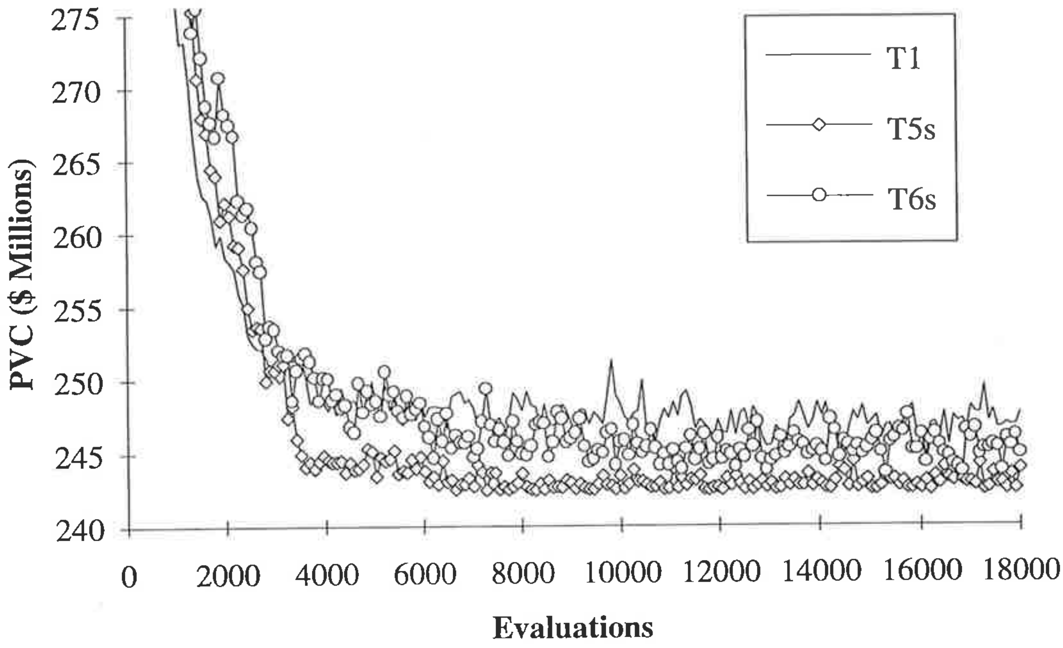

Figure K.8 The Average PVC Solution versus Number of Evaluations for Various GA Models for the Upsizing Case

Appendix L

Results for the Upsizing Case for the South-East Queensland Case Study

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The following results are for the South-East Queensland Case Study in Chapter 6. The results shown in this Appendix are for the cases of demand forecast 2 and 3, the discount rates of 2.5 % and 10 % and for the three levels of upsizing cost. These results are referred to in Chapter 6, section 6.4.2.

Table L.1 Project Sequence for Demand Forecast 2, Discount rate of 2.5 % and Upsizing Cost Equal to the Incremental Cost

Method	Project Sequencing and Timing																PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	8/3	1/3	7/3	13/1								
	Timing	15	27	34	45	58	79	84	86	89							241.47	193.24
Equivalent Cost	Project	1/2	8/2	7/2	8/3	9/3	1/3	7/3	5/3	13/1								
	Timing	15	27	34	45	48	62	64	67	89							240.88	193.24
GA (100 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2	9/1	9/3	8/3	7/3	5/1	5/2	5/3	1/3	13/1		
	Timing	15	24	27	30	34	37	45	54	58	62	65	67	74	87	89	234.50	188.20
ILP (55 years)	Project	1/1	1/2	7/1	7/2	8/2	9/1	9/2										
	Timing	15	20	25	30	35	45	50									-	190.68
GA (55 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2	9/1	9/2									
	Timing	15	24	27	30	34	37	45	54								-	185.56

Table L.2 Project Sequence for Demand Forecast 2, Discount rate of 2.5 % and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing														PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	8/3	1/3	7/3						
	Timing	15	27	34	45	58	79	90	95	97					243.00	193.24
Equivalent Cost	Project	1/2	8/2	7/2	9/3	5/3	8/3	13/1	1/3	7/3						
	Timing	15	27	34	45	58	79	84	94	97					242.96	193.24
GA (100 years)	Project	1/1	1/2	8/2	7/2	9/1	9/2	9/3	5/2	5/3	8/3	13/1	7/3	1/3		
	Timing	15	24	27	34	45	54	56	58	67	79	84	94	98	241.86	189.37
ILP (55 years)	Project	1/2	7/2	8/2	9/2											
	Timing	15	25	35	45										-	194.97
GA (55 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2	9/1	9/2							
	Timing	15	24	27	30	34	37	45	54						-	189.37

Table L.3 Project Sequence for Demand Forecast 2, Discount rate of 2.5 % and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing										PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1				
	Timing	15	27	34	45	58	79	90			268.95	193.24
Equivalent Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	8/3	10/3			
	Timing	15	27	34	45	58	79	90	94		252.23	193.24
GA (100 years)	Project	1/2	8/2	7/2	9/3	13/1	5/3	7/3	8/3	1/3		
	Timing	15	27	34	45	58	68	90	93	98	244.89	193.24
ILP (55 years)	Project	1/2	7/2	8/2	9/2							
	Timing	15	25	35	45						-	194.97
GA (55 years)	Project	1/2	8/2	7/2	9/2							
	Timing	15	27	34	45						-	189.95

Table L.4 Project Sequence for Demand Forecast 2, Discount rate of 10 % and Upsizing Cost Equal to the Incremental Cost

Method		Project Sequencing and Timing																PVC (100 years)	PVC (55 years)
Unit	Project	1/2	8/2	7/2	9/3	5/3	8/3	1/3	7/3	13/1									
Cost	Timing	15	27	34	45	58	79	84	86	89								39.97	39.40
Equivalent	Project	8/2	1/1	1/2	7/2	8/3	1/3	7/3	9/2	9/3	13/1	5/3							
Cost	Timing	15	19	31	34	45	48	50	52	64	67	77						38.41	38.17
GA	Project	1/1	1/2	8/1	8/2	7/1	7/2	1/3	8/3	7/3	9/1	9/2	9/3	13/1	5/1	5/2	5/3		
(100 years)	Timing	15	24	27	30	34	37	45	47	50	52	62	64	67	77	79	86	36.79	36.54
ILP	Project	1/1	1/2	8/1	8/2	1/3	9/1	9/3	7/1	7/2									
(55 years)	Timing	15	20	25	30	30	35	40	45	50								-	38.87
GA	Project	1/1	1/2	8/1	8/2	7/1	7/2	8/3	13/1										
(55 years)	Timing	15	24	27	30	34	37	45	48									-	36.38

Table L.5 Project Sequence for Demand Forecast 2, Discount rate of 10 % and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing																	PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	8/3	1/3	7/3									
	Timing	15	27	34	45	58	79	90	95	97								39.98	39.40
Equivalent Cost	Project	8/2	1/1	1/2	7/2	8/3	1/3	7/3	9/2	9/3	13/1	5/3							
	Timing	15	19	31	34	45	48	50	52	64	67	77						38.72	38.48
GA (100 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2	1/3	9/1	9/2	9/3	7/3	8/3	13/1	5/1	5/2	5/3		
	Timing	15	24	27	30	34	37	45	47	56	58	60	63	67	77	79	86	37.56	37.09
ILP (55 years)	Project	1/1	1/2	8/1	8/2	1/3	7/2	9/1											
	Timing	15	20	25	30	30	35	45										-	39.70
GA (55 years)	Project	1/1	1/2	8/1	8/2	7/1	7/2	8/3	13/1										
	Timing	15	24	27	30	34	37	45	48									-	37.06

Table L.6 Project Sequence for Demand Forecast 2, Discount rate of 10 % and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing														PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1								
	Timing	15	27	34	45	58	79	90							40.03	39.40
Equivalent Cost	Project	8/2	1/1	1/2	7/2	9/1	9/2	9/3	13/1	1/3	8/3	7/3	5/3			
	Timing	15	19	31	34	45	54	56	58	68	70	74	77		39.02	38.46
GA (100 years)	Project	1/1	1/2	8/2	7/2	9/1	9/2	9/3	13/1	8/3	7/3	1/3	5/2	5/3		
	Timing	15	24	27	34	45	54	56	58	68	72	75	77	86	38.37	37.81
ILP (55 years)	Project	1/1	1/2	8/1	8/2	1/3	7/2	9/1								
	Timing	15	20	25	30	30	35	45							-	40.81
GA (55 years)	Project	1/1	1/2	8/2	7/2	9/1	9/2									
	Timing	15	24	27	34	45	54								-	37.81

Table L.7 Project Sequence for Demand Forecast 3, Discount rate of 2.5 % and Upsizing Cost Equal to the Incremental Cost

Method	Project Sequencing and Timing																PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	8/3	1/3	7/3	13/1	6/1							
	Timing	23	38	46	56	68	83	86	87	89	96						221.04	125.37
Equivalent Cost	Project	8/2	1/2	7/2	9/3	8/3	1/3	7/3	5/3	13/1	10/3							
	Timing	23	30	46	56	68	71	72	74	89	96						203.61	125.37
GA (100 years)	Project	8/2	1/1	1/2	7/1	7/2	9/1	9/3	7/3	5/2	5/3	8/3	1/3	10/1	10/2	10/3		
	Timing	23	30	42	46	50	56	64	68	70	76	85	88	89	96	98	192.47	121.87
ILP (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2											
	Timing	20	25	30	40	45	50										-	124.80
GA (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2											
	Timing	23	27	30	42	46	50										-	121.49

Table L.8 Project Sequence for Demand Forecast 3, Discount rate of 2.5 % and Upsizing Cost Equal to 120 % of the Incremental Cost

Method	Project Sequencing and Timing												PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	8/3	1/3	7/3	6/1			
	Timing	23	38	46	56	68	83	90	93	94	96		222.39	125.37
Equivalent Cost	Project	8/2	1/2	7/2	9/3	5/3	8/3	13/1	1/3	7/3	10/3			
	Timing	23	30	46	56	68	83	86	93	94	96		204.93	125.00
GA (100 years)	Project	8/2	1/1	1/2	7/2	9/1	9/2	9/3	5/3	13/1	10/2	10/3		
	Timing	23	30	42	46	56	64	66	68	83	90	98	197.97	124.18
ILP (55 years)	Project	8/2	1/1	1/2	7/2									
	Timing	20	30	40	45								-	127.98
GA (55 years)	Project	8/2	1/1	1/2	7/2									
	Timing	23	30	42	46								-	124.18

Table L.9 Project Sequence for Demand Forecast 3, Discount rate of 2.5 % and Upsizing Cost Equal to 150 % of the Incremental Cost

Method	Project Sequencing and Timing								PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1		
	Timing	23	38	46	56	68	83	90	219.21	125.37
Equivalent Cost	Project	8/2	1/2	7/2	9/3	5/3	13/1	10/3		
	Timing	23	30	46	56	68	83	90	199.02	125.00
GA (100 years)	Project	8/2	1/2	7/2	9/3	5/3	13/1	10/3		
	Timing	23	30	46	56	68	83	90	199.02	125.00
ILP (55 years)	Project	8/2	1/2	7/2						
	Timing	20	30	45						128.45
GA (55 years)	Project	8/2	1/2	7/2						
	Timing	23	30	46					-	125.00

Table L.10 Project Sequence for Demand Forecast 3, Discount rate of 10 % and Upsizing Cost Equal to the Incremental Cost

Method		Project Sequencing and Timing																PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	8/3	1/3	7/3	13/1	6/1								
	Timing	23	38	46	56	68	83	86	87	89	96							17.38	16.60
Equivalent Cost	Project	8/2	1/1	1/2	8/3	1/3	7/2	7/3	9/1	9/2	9/3	13/1	5/3	10/2					
	Timing	23	30	42	46	48	49	60	61	70	72	74	81	96				15.14	14.67
GA (100 years)	Project	8/1	8/2	1/1	1/2	1/3	7/1	7/2	7/3	9/1	9/3	8/3	13/1	5/1	5/2	5/3	10/1		
	Timing	23	27	30	42	46	47	51	57	59	67	71	74	81	83	89	98	14.77	14.17
ILP (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2												
	Timing	20	25	30	40	45	50												16.31
GA (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2												
	Timing	23	27	30	42	46	50											-	14.07

Table L.11 Project Sequence for Demand Forecast 3, Discount rate of 10 % and Upsizing Cost Equal to 120 % of the Incremental Cost

Method		Project Sequencing and Timing																PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	8/3	1/3	7/3	6/1								
	Timing	23	38	46	56	68	83	90	93	94	96							17.38	16.60
Equivalent Cost	Project	8/2	1/1	1/2	7/2	9/3	8/3	1/3	7/3	13/1	5/3	10/2							
	Timing	23	30	42	46	56	68	71	72	74	81	96						15.26	14.53
GA (100 years)	Project	8/1	8/2	1/1	1/2	1/3	7/1	7/2	9/1	9/2	9/3	8/3	7/3	13/1	5/2	5/3	10/2		
	Timing	23	27	30	42	46	47	51	57	65	67	69	72	74	81	87	96	15.07	14.44
ILP (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2												
	Timing	20	25	30	40	45	50											-	16.58
GA (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2												
	Timing	23	27	30	42	46	50											-	14.42

Table L.12 **Project Sequence for Demand Forecast 3, Discount rate of 10 % and Upsizing Cost Equal to 150 % of the Incremental Cost**

Method	Project Sequencing and Timing														PVC (100 years)	PVC (55 years)
Unit Cost	Project	1/2	8/2	7/2	9/3	5/3	13/1	6/1								
	Timing	23	38	46	56	68	83	90							17.39	16.60
Equivalent Cost	Project	8/2	1/1	1/2	7/2	9/3	13/1	8/3	1/3	7/3	5/3	10/2				
	Timing	23	30	42	46	56	68	74	77	79	81	96			15.37	14.62
GA (100 years)	Project	8/2	1/1	1/2	7/2	9/1	9/2	9/3	13/1	1/3	5/2	5/3	10/1	10/2		
	Timing	23	30	42	46	56	64	66	68	74	76	82	91	98	15.32	14.62
ILP (55 years)	Project	8/1	8/2	1/1	1/2	7/1	7/2									
	Timing	20	25	30	40	45	50								-	16.98
GA (55 years)	Project	8/2	1/1	1/2	7/2											
	Timing	23	30	42	46										-	14.62

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