MONITORING THE NUTRIENT INFLOWS AND OUTFLOWS OF A CONSTRUCTED URBAN WETLAND

SIMON GAMBLE

(B.E.(Hons), GradIEAust (PEng))

THESIS SUBMITTED FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

in

The University of Adelaide
(Faculty of Engineering)

August 1997

Abstract

The design, construction and installation of a field monitoring network was carried out at a small artificial wetland in Happy Valley, South Australia. The aim of this research was to study the transient nature of wetland stormwater effluent during events, and also to determine the overall improvement in stormwater quality achieved.

Prior to field application, a general overview of the nutrient and sediment cycle in wetlands was undertaken. This dealt with the processes at work in the distribution of nutrients in wetlands at a simplified chemical and biological level. A review of the uptake or removal of nutrients through macrophyte and micro-organism action is presented. Nitrate and phosphate were identified as the most important sources of nutrient to the wetland system, and were the nutrient constituents targeted in the study. A review of other monitored wetlands in South Australia and Australia was carried out prior to initial field trials to gain an understanding of the standard and extent of other current field installations.

In order to calculate hydraulic factors, such as basin flow and volume, a stadia survey and associated numerical basin analysis was performed. Relationships relating flow, volume and surface area to wetland water levels were derived. A reverse routing procedure was used to obtain upstream hydrographs at the wetland inlet where no other flow information was available.

The development and improvement of the monitoring system is dealt with in detail. Discussion focuses on the decisions made at each phase and the innovative solutions to the problems that arose during the entire process. The final monitoring system was composed two automatic samplers, one at each end of the wetland, governed by a microprocessor controller. Field sensors were also installed at the inlet and outlet of the wetland, and logged at regular intervals. The capability existed for these field sensors to control the initiation and sampling frequency of the samplers, although this was not achieved in this study. The specialised equipment, such as data loggers and the automatic sampler control device were designed and constructed for this research work.

Analysis was carried out on 7 events monitored with the sampling network. Event loads, event mean concentrations, quiescent and dynamic decay rates were calculated using a combination of event and daily grab sampled data. The aim of determining the water quality improvement due to wetland influence on an individual event basis was not achieved. It proved too difficult to account for and isolate individual event flows. The wetland was found to be lowering total suspended solids and nitrate in effluent by 61% and 24% respectively, on an average load basis. Total dissolved solids was found to be increased in the outflow during events by 170%, however, deposition of dissolved solids was occurring during base flows. The average reduction in phosphate observed was 24%. Phosphate load at the outlet was quite varied, some events reported additions in the effluent. This was attributed to *in-situ* wetland action.

As a means of observing the relationships between water quality variables, a number of correlations were carried out between individual constituents and assorted flow variables. Phosphate was found to be linearly related to total suspended solids load, supporting similar findings in stormwater studies elsewhere.

On comparison with other wetland systems, Minkara Wetland was found to perform favourably in respect to suspended solids and nutrient removal. Total dissolved solids removal was below that of other wetlands reported in the literature.

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 this copy of my thesis, when deposited in the University Library, being available for loan or photocopy.

SIGNED : .. .. DATE : 27/08/97...

Acknowledgments

Firstly the author would like to thank his supervisor, David Walker, for his consistent and open help and advice. David's style of supervision allowed me the freedom to progress at my own pace, and to direct my work, whilst keeping a watchful eye over the entire project.

Thanks must also go to the many support staff at The University of Adelaide, who assisted in all phases of the research. In instrumentation, Stan Woithe and Bruce Lucas for their expert help, and patience, when circuits refused to function due to the authors proficiency, or lack there of, in electronics. In the laboratory and workshop many thanks to Robert Kelman, Greg Atkins, David Hale and Werner Eidam. None were ever too busy to lend a hand, in the field or in the laboratory, rain, hail or shine. Thanks also to the computer officers Stephen Carr and Byron Reisson. Mention must also be made of the secretarial staff for their aid in the necessary office duties that go hand in hand with field research. Thanks to Diane, Anne, Tina and Bernie.

Acknowledgment must also go to Trevor Daniell for his assistance on all hydrologic matters, and the sharing of his knowledge on the Minkara Wetland project from inception.

In the time spent as a post-graduate student at the university, there has been one ever unfailing source of assistance, fellow students. Thanks to all those in the annexe. If there is anything worth doing on a PC they are sure to have done it at some stage. Thanks in particular to Bryan for his long distance help, without his assistance in the last months of writing, my completion would not have been possible. Thanks also to Jo for her ground support in Adelaide.

Many thanks also to Ben Raymond for his thorough proof reading, one not frightened by the use of a red pen.

Finally I would like to thank my family, my parents and my sister for their support during my candidature. Their continual inquiry as to the date of my submission was a driving force behind my eventual success.

Table of Contents

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Evaluation of the Data Set 98

Chapter 6

List of Figures

Chapter 2 : Nutrients in Wetlands - An Overview

Chapter 3 : The Minkara Wetland and Catchment

Chapter 4 : Monitoring the Minkara Wetland

Chapter 5 : Evaluation of the Data Set

Appendix A Stadia Surveying

Appendix B Example of Reverse Routing Procedure

Appendix D A Logic Method for Automatic Sampler Control

Appendix G Plots of Sampling Times for All Monitored Events

Appendix I Example of Event Water Quality Constituent Plots (Event 5 : 23/09/95)

Appendix M Plots of Peak Water Quality Constituent Occurrence

List of Tables

Chapter 2 : Nutrients in Wetlands - An Overview

Chapter 3 : The Minkara Wetland and Catchment

Chapter 4 : Monitoring the Minkara Wetland

Chapter 5 : Evaluation of the Data Set

Chapter 6 : Conclusions and Recommendations

Appendix B Example of Reverse Routing Procedure

Appendix E Results of Parameter Analysis of Event Record for Minkara Wetland

Appendix J Example of the Calculation of Effluent Detention Time

Appendix K Monitored Event Water Quality Data

Appendix L Results of Event Water Quality Data Analysis

Appendix N Daily Sampling Data for Quiescent Decay Rate

Glossary

BOD	Biochemical oxygen demand
C	Carbon
CUMECS	Flow in cubic metres per second
DCEEL	Department of Civil and Environmental Engineering Logger
DO	Dissolved oxygen
MFP	Multi Function Polis
N	Nitrogen
P	Phosphorus
SAR	Surface Area Ratio. The ratio of the area of the detention basin to the area of the serving catchment
TDS	Total dissolved solids
TKN	Total Kjeldahl nitrogen
TN	Total Nitrogen
TON	Total organic nitrogen
TP	Total phosphorus
TSS	Total suspended solids

Chapter One

Introduction

1.1 Introduction

Increased urbanisation of municipal catchments has been identified as a key factor in the alteration of the standard of stormwater quality. Changes in peak stormwater flow and the total volume of runoff and pollutant load, have been attributed to urbanisation (Daniell, 1996; Livingston, 1989). Mean annual flooding has been observed to increase by a factor of three as a result of catchment urbanisation (Leopold, 1968; referenced by Allison *et al.*, 1994). The result is an urgent need for better management of urban catchments. The use of wetlands is rapidly becoming an integral part of this plan, faster in many ways than the advancing field of knowledge on their ability to improve stormwater quality.

The use of wetlands in other applications, such as in the treatment of wastewater, is not as new, and evidence has shown wetlands can provide adequate effluent treatment. Kadlec and Knight (1996) highlight that natural wetlands have been used for this purpose for over 100 years, although no monitoring of the emergent water quality was carried out until quite recently. Modern studies have shown remarkable improvements in wastewater effluent water quality (Jelliffe, 1995; Sakedevan *et al., 1995*; Willunga, 1996). The wider use of wetlands in this capacity can be attributed to fact that the design and operation of a wetland for wastewater treatment is inherently simpler than the artificial urban stormwater system. Municipal wastewater tends to have consistent and more predictable flow patterns, making the optimisation of the performance of the wetland simpler (Silverman, 1989). Stormwater inflows, however, are more directly related to rainfall events and changing catchment conditions, both in season and spatial landuse. This results in water quality conditions that are not necessarily dependent on flow (Silverman, 1989). The result is a complex natural system, with extremely variable inputs, leading to a lack of understanding, and hence, control. This lack of knowledge of stormwater wetland behaviour is a barrier to the efficient and widespread use of wetlands in urban catchments.

Broadly stated, a simplistic definition of a wetland (Howard-Williams, 1985; Cowardin *et al.*, 1979) is “an area where the water table is at or above the land surface for long enough each year to promote the formation of hydric soil and to support the growth of aquatic vegetation, much of which is emergent (photosynthetic organs above the water surface)”. Here the term hydric means “saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions that favour the growth and regeneration of hydrophytic vegetation” (U.S. Soil Conservation Services, 1991). With this partly aquatic, partly terrestrial quality, wetlands can be viewed as forming an intermediate zone, both in terms of location and the amount of stored water, between terrestrial and open water ecosystems (Mitsch and Gosselink, 1991).

With such a broad definition it follows that there are an enormous variety of wetlands. A classification system has been developed in order to categorise the various forms. A typical approach is that used by Cowardin *et al.* (1979) and Howard-Williams (1985), to categorise a wetland by means of functionality. They use the following categories to describe the variety of wetland types:

a) Freshwater versus Saline;
b) Permanently flooded versus periodically flooded;
c) Periodically frozen or snow covered versus permanently non-frozen; and
d) Rooted versus floating vegetation.

Each of these categories contains further subcategories, that better define and classify the various types of wetland. These include information about the species of vegetation, for example *Typha* or *Phragmites* rooted wetlands, the age or nutrient level, and physical characteristics. It is apparent from this list that any one wetland may belong to more than one of these categories. The category of the wetland under investigation in this study is a rooted freshwater, permanently non frozen wetland.

Artificial wetlands, when well designed, act to improve stormwater quality through both physical hydraulic response, and biological and chemical action. Hydraulically, as storages or detention basins, they attenuate floods, slow flows and increase residence time, reducing the load carrying ability of the runoff through sedimentation, adsorption and filtration (Livingston, 1989; Silverman, 1989). As will be shown, this physical load reduction is strongly associated with a reduction in many nutrient and chemical pollutants. Biochemically, healthy wetlands rely on an abundance of aquatic plants and micro-organisms to carry out the full cycle of growth and decay, the recycling of organic matter. As stated by Dowling and Stephens (1996), aquatic plant life in wetlands act to aid the water cleansing process by:

- the direct uptake of nutrients from the open water and sediments;
- impeding and reducing water velocities, acting as filters and aiding sedimentation;
- providing an increased growing area for micro-organisms, increasing bio-activity;
- aerating the open water through photosynthesis, allowing for greater bio-activity;
- providing aerobic micro-environments in anaerobic soils, reducing nitrogen through increased nitrification; and
- providing shade, helping to prevent the explosion of algal blooms.

Wetland plant density is a key factor in cleansing performance, as it is this that alters water flow paths and causes significant reductions in suspended solid matter (Faulkner and Richardson, 1989).

Reduction of many of the common urban non-point source pollutants found in urban stormwater is possible using artificial wetlands. Daniell and McCarty (1996) highlight a number of these pollutants and the processes responsible for their reduction:

- Sediment: Reduced by settling of heavier material and through flocculation of finer particles, vegetative filtration;
- Nutrients: Generally reduced by extended residence times, although the effectiveness is affected seasonally;
- Oil: Usually in low enough concentration in urban areas to allow for evaporative degradation through exposure to sunlight; and
- Heavy Metals: Captured in particulate and adsorbed form through sedimentation, held in stable anaerobic conditions in the sediment.

The use of wetlands for stormwater quality improvement still involves a great deal of uncertainty, both in design and performance. Designs have suffered due to the lack of knowledge on the behaviour of artificial urban wetlands. Wetlands should not be viewed as the wonder cure for treating urban runoff (Livingston, 1989). The discussion as to the successful application of wetlands in the urban environment continues. The question as to whether urban stormwater wetlands act as nutrient sources or sinks remains largely unanswered. This can be attributed to the ambiguous use of the terms source and sink, and also to the lack of appropriate measuring techniques (Mitsch and Gosselink, 1991). Answers to this question are made no easier by the variety of urban catchments, the resulting variability in stormwater and wetland design. Although wetlands have been shown to be nutrient sinks in some studies, there is a growing view that not all systems act as such, and that this behaviour changes seasonally and with ageing (Mitsch and Gosselink, 1991). Questions as to the performance and optimisation of wetlands can only be answered by weight of operational data collected through research (Kadlec and Knight, 1996).

At present the design of wetlands is, to a large extent, based on experience and a number of simple design parameters, such as the ratio of pond area to catchment area, the ratio of pond volume to catchment area, or average detention time. Efforts to give a more detailed design procedure based on the processes at work have not proved successful. There is still wide variation in performance reported in the literature. If the stormwater processed by wetlands is to be used for aquifer recharge, irrigation or injection into reservoirs then there must be greater confidence in the efficiency and design of the wetland. This can only be brought about by a greater understanding of the internal mechanisms.

Presently design procedures, such as the Australian Water and Wastewater Association Design Guidelines for Water Pollution Control Ponds (Phillips, 1990), use detention time as the basis for wetland design. No allowance is made for the effect of the complexity of flow patterns, mixing, or interaction with aquatic wetland macrophytes, due to a lack of detailed wetland studies, and the limited success of wetland models. There are already computer packages available that numerical model wetland basins. XP-SWMM (WP Software, 1993) includes a module that allows detention basins to be modelled if the reaction rates can be specified and if the type of flow regime, plug flow or completely mixed is given. It has been suggested by a number of researchers, for example Kadlec *et al.* (1993), that a number of stormwater pollutants should be able to be modelled as a first order chemical reaction. Nitrogen and BOD are two such quantities. If this were the case it should be possible to model the wetland as a chemical reaction tank, by determining the reaction, or decay rate, from monitoring the inflows and outflows during specific events and in periods of base flow. This would have the advantage that it would allow a more detailed design procedure to be undertaken.

Although there are numerous constructed wetlands where water quality data have been collected few have involved data sets that would allow reaction rates to be determined.

1.2 Aims and Scope of Study

The aim of this study was to determine the ability of a constructed urban wetland to improve stormwater quality, and to calculate reaction or decay rates for pollutants during dynamic and quiescent periods. Further was the aim to compare the observed performance with other wetlands and accepted water quality guidelines, and to identify features common to similar performing systems. Additional aims were to investigate any specific relationships observed between water quality parameters, and compare to those reported in the literature.

In order to determine the performance of the wetland system, to calculate the constituent loads, decay rates and event mean concentration values, a comprehensive and objective-specific data set, needed to be collected. This involved designing and constructing a field monitoring network, primarily to study the dynamic nature of event water quality, and operating this field network, collecting and collating high quality data.

1.3 Layout of the Thesis

An outline of the relevance of nutrients to healthy aquatic ecosystems has been presented in Chapter 2. Through a review of literature published on lake and wetland systems, as well as general environmental texts, the importance of the elements nitrogen and phosphorus is detailed. The cycles of each of these nutrients, and the various forms of each element is presented, to highlight the nutrient forms most readily available for use for plant nutrition. The problem arising from excessive nutrient supply, eutrophication, again particularly with reference to nitrogen and phosphorus is discussed. This gives the reader a knowledge of the many sources and forms of nutrient supply to aquatic systems. Chapter 2 also details the water quality variables of significance to this study, and why they were desirable in a study of this nature.

A description of the Minkara Wetland and catchment is presented in Chapter 3. Detail is given of the formation of the wetland by adding a weir structure to the wing walls of an existing culvert, allowing permanent ponding. The result of retro-fitting this wetland to an existing natural stream bed, the flooding of several large Redgums, and the effects this had on the study, is also discussed. Presented also in Chapter 3 are the relationships derived from a stadia survey of the basin, carried out during an annual draw down of the water level of the wetland. These included volume, surface-area, and flow relationships. Also detailed is a procedure for the calculation of flow at the inlet of the wetland by using calibrated weir outflow. This was achieved using a reverse routing procedure, a two point approximation of the continuity equation.

A review of other monitoring studies on constructed stormwater wetlands is given in Chapter 4. Particular focus is placed on wetlands in South Australia, however, wetlands interstate and overseas are reviewed. This review shows the standard of wetland performance monitoring elsewhere, and the techniques and sampling strategies used. This has been included to allow the reader to gauge the relative ingenuity and complexity, inherent in the Minkara Wetland monitoring system. The development of an extensive network of automatic samplers, field sensors, loggers, and a sampler controller, is detailed in Chapter 4. Included in this discussion is a thorough description of the conception, design, and installation of this monitoring system. Information about problems encountered, including unfortunate delays and breakdowns of the system, due to equipment failure, incorrect operation, and limited budget and personnel, have also been included. This is to show in full, the learning process that carried out during the 18 month study period.

The results of the monitoring program, which ran intermittently for 15 months, are presented in Chapter 5. The total data set achieved during this period, the number of events sampled, and the type and quality of this data is detailed. Presented here also is a description of the calculations of the selected event water quality parameters, which included event peak concentrations, event load reductions, and event mean concentrations. Key results of this analysis are described in graphical form, and explanations given as to the observed behaviour.

Comparison of the water quality leaving the Minkara Wetland and the recommended water quality for natural waterways by ANZECC (1992) guidelines is given. In addition to the event water quality analysis, the results of a decay rate analysis are presented, obtained using a combination of daily sampled and event water quality results. This clearly indicates the effect a vegetated channel upstream of the wetland had on improving stormwater quality.

The final chapter, Chapter 6, summarises the findings of the study, in particular the results of the data analysis, detailed in Chapter 5. Here a comparison of the overall observed performance of the Minkara Wetland and other interstate and international constructed urban wetlands is presented. The outcomes of the study are reviewed, and the success of the research evaluated.

Chapter Two

Nutrients in Wetlands - An Overview

2.1 Introduction

Chapter 2 presents a review of the common nutrients found in wetlands and water bodies. Focus is placed on the two nutrients most associated with biomass production in these systems, namely nitrogen and phosphorus. To allow an understanding of the interaction of these nutrients in this environment, a review of the cycling of these elements is given. Further to this, the species of nitrogen and phosphorus considered to be of greatest nutritional value are identified, in order to select the most suitable nutrient species to target in this study.

2.2 Nutrients Required by Wetlands

Nutrients are simply the elements essential for all life. The supply of these nutrients from external sources influences the productivity of a wetland, or the organic matter produced with time (Miller and Armstrong, 1982). Of the several dozen known nutrients, only 6 make up 95% of the mass of all living organisms, and these are known as the macro nutrients. These are carbon, oxygen, hydrogen, phosphorus, nitrogen, and sulphur (Miller and Armstrong, 1982).

Nitrogen and phosphorus levels are often the lowest of the 6 macro nutrients required by the biota (living matter). It is common for nitrogen or phosphorus concentrations to limit the growth of the primary food chain element, algae, which in turn effects the abundance of all life on higher trophic levels. The reason nitrogen and phosphorus are such key nutrients when considering the health and productivity of a freshwater system stems from the elemental make up of plant tissue of the species common to freshwater lakes and wetlands. Macrophytes and algae contain the elements phosphorus, nitrogen and carbon in the following ratios (Wetzel, 1983):

1P : 7N : 40C

In a system where all the micronutrients are abundant (those required in trace amounts), and one of these three elements is limiting growth, per 500gm of algae, phosphorus can produce 500 times its weight in plant tissue, nitrogen 71 times (500/7), and carbon 12 times (500/40). Phosphorus and nitrogen concentrations in influent, when looked at in this purely proportional view take, on a much greater significance. The production capability of waters containing nitrogen and phosphorus in levels exceeding requirement is particularly evident. Table 2-I outlines the ratio of macro nutrient plant tissue requirements to the available supply in Mean World River Water. From Table 2-I it is clear that nitrogen and phosphorus, especially phosphorus, are likely to be the limiting nutrients, quickly affecting productivity when increased.

Table 2-I : Proportions of macro nutrients required by living plant tissue and available in Mean River Water, and the approximate ratio of required to available[1]

Element	Average Plant Requirements (%)	Average Supply in Water (%)	Ratio of Plant Requirements to Supply Available
Oxygen	80.5	89	1
Hydrogen	9.7	11	1
Sulfur	0.06	0.0004	<1000
Carbon	6.5	0.0012	5000
Nitrogen	0.7	0.000023	30,000
Phosphorus	0.08	0.000001	80,000

Notes on Table 2-I:

[1] Adapted from Wetzel (1983).

Increased loading of phosphorus, and to a lesser extent nitrogen, to a wetland system such that nutrient supply outweighs demand, results in increased productivity. This increased productivity is termed eutrophy, whereby the wetland becomes more enriched with time. This can occur for many natural reasons but in urban areas such as the study area in Happy Valley it is primarily due to human intervention. As will be seen, both nutrients are used in common urban activities.

For these reasons the study of nutrient loads to freshwater systems focuses primarily on the macro nutrients nitrogen and phosphorus.

It is necessary to look at the nitrogen and phosphorus cycles to understand the distribution and use of these vital nutrients in the wetland ecosystem. This information enables a clearer understanding as to how the wetland is using the supplied nutrients, preventing a build up of nutrients in waters downstream. This also helps to identify those species of phosphorus and nitrogen that would yield the greatest information on the available nutrient supply.

2.3 The Nitrogen Cycle

The nitrogen cycle is the biochemical transformation of gaseous dinitrogen N_2 by fixation and assimilation into proteins, and the breakdown of these proteins to reform dinitrogen (O'Neill, 1985). It is the process that provides organisms with essential nucleic acids, enzymes and hormones for life and is largely a microbial assisted process. In the first half of the cycle energy is released in the fixation and assimilation phases and this is used by the micro-organisms. For the completion of the closed nitrogen cycle, proteins are broken down to replace the dinitrogen originally used. This part of the cycle requires energy input, equivalent to that released in the other half, which is provided by micro-organisms. Figure 2-1 shows a simplified version of the nitrogen cycle, indicating the processes at work in each transformation.

Nitrogen in the gaseous state is not able to be used by most organisms as a nutrient source (Miller and Armstrong, 1982). Only a small number of bacteria and blue-green algae are able to use atmospheric nitrogen by fixing or converting it to the more useful ammonia, generally present as NH_4^+. This process is called nitrogen fixation and is the first step in the cycle. The bacteria responsible for this process are known as legumes.

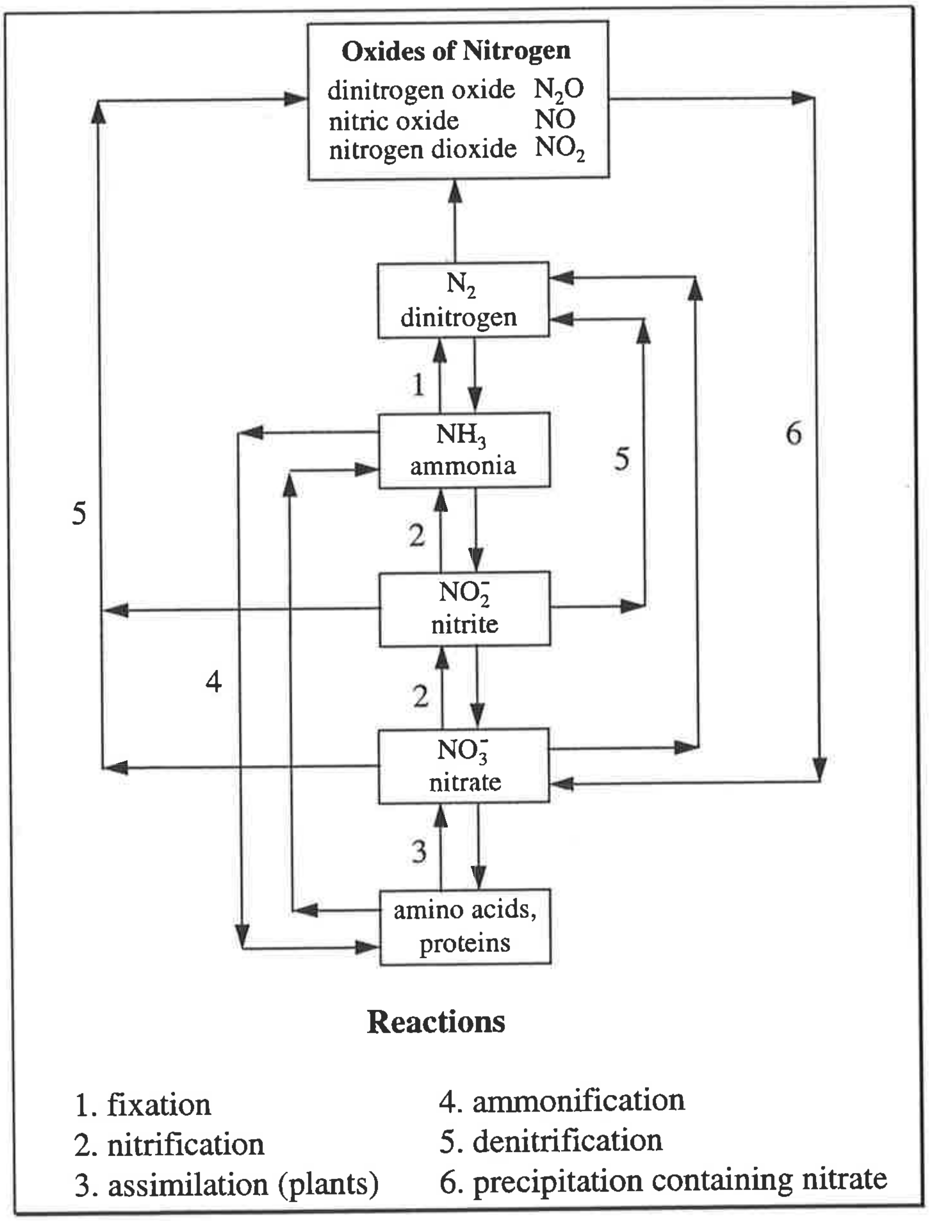


Figure 2-1 : Simplified nitrogen cycle, adapted from O'Neill (1985).

2.3.1 Nitrogen Fixation

Nitrogen fixation is the reduction of dinitrogen with an oxidation state of 0, to ammonium ions with an oxidation state of minus 3, and can be described by Equation 2.1. (O'Neill, 1985).

$$3CH_2O + 3H_2O + 2N_2 + 4H^+ \rightarrow 3CO_2 + 4NH_4^+ \qquad (2.1)$$

Although a good nitrogen source for plants, ammonia is only used for such in alkaline conditions. Most algae and macrophytes grow better with nitrate as their nitrogen source, even though this has to be reduced to ammonia by the plant (Wetzel, 1983).

For the nitrogen fixation process to be carried out in nature requires micro-organisms which contain the enzyme nitrogenase. Species capable of nitrogen fixation *in-situ* include varieties of algae, bacteria and plankton. This can be the major source of significant nitrogen for wetlands.

The majority of nitrogen fixing carried out by algae is by the blue-green algae, in particular the variety that produce aerobic heterocysts, a specialised cell that acts as the sole site for nitrogen fixation (Wetzel, 1983). However, species of non-heterocyst producing blue-green algae, such as the Anabaena, do contribute to the *in-situ* nitrogen fixation process. The rate of nitrogen fixation of the blue-green algae, is reduced in conditions where sources of combined nitrogen, such as nitrate or ammonia, are present. There is therefore an inverse relationship between the rate of nitrogen fixation by blue-green algae and the concentration of inorganic nitrogen in the water. In comparison there is a direct correlation between the presence of dissolved organic nitrogen and the rate of nitrogen fixation.

Seasonally *in-situ* nitrogen fixation varies in accordance with the blue-green algae population. In winter, as the blue-green algae population drastically reduces, so does the rate of nitrogen fixation.

Plankton are also able to fix nitrogen in the open water, however, this process relies on the availability of light and ATP (adenosine triphosphate) which is generated in photosynthesis.

The abundance of ATP in turn relies on sufficient concentrations of total phosphorus being present (Wetzel, 1983).

Photosynthetic and heterotrophic bacteria are involved in the *in-situ* nitrogen fixation process, but in a more limited fashion than the algae. Large numbers of nitrogen fixing heterotrophic bacteria exist in the sediments of lakes and wetlands, most highly concentrated in the upper 20 millimetres. The most common variety of heterotrophic bacteria capable of nitrogen fixing are the Azotobacter and the Clostridium pasteurianum, found in submerged aquatic plants and in the sediments (Brezonik, 1976). In general the rate of nitrogen fixation by Azotobacter is several orders of magnitude lower than blue-green algae. Unlike the heterotrophic bacteria, almost all photosynthetic bacteria are capable of nitrogen fixing, under both anaerobic and aerobic conditions, the anaerobic species yielding the higher rate of fixing.

The process of nitrogen fixation is still not completely understood. Present knowledge on the subject is largely qualitative. The nitrogen cycle continues to nitrification.

2.3.2 Nitrification

Nitrification is the conversion of the nitrogen compound ammonia, produced during nitrogen fixation, to a more oxidised state, primarily nitrite and nitrate as the end products of the process. Nitrate is essential to the majority of plants for growth, as this is the only source of nitrogen they can absorb, ammonia and ammonium are not suitable (O'Neill, 1985). In algae, although nitrate absorption is independent of phosphate concentrations, optimal growth is achieved with a high phosphate concentration and nitrate, as opposed to ammonia, as the nitrogen source.

The importance of the nutrient species nitrate and phosphate as critical growth controlling nutrient forms, is highlighted here for the first time. Nitrate, although not the only nitrogen nutrient source, is the most common and easily absorbed. Nitrate, therefore, represents a reliable indicator of the readily available supply of nitrogen for plant nutrition.

The first product in the nitrification sequence is nitrite, as seen in Equation 2.2.

$$4NH_4^+ + 6O_2 \rightarrow 4NO_2^- + 8H^+ + 4H_20 \tag{2.2}$$

The bacteria responsible for oxidising the ammonia to nitrite are the nitrosomonas, although others are capable but not as prevalent (Golterman, 1975). The reaction continues to produce nitrate, as in Equation 2.3.

$$4NO_2^- + 2O_2 \rightarrow 4NO_3^- \tag{2.3}$$

The oxidation of nitrite to nitrate is carried out primarily by the nitrobacter genus of bacteria (Golterman, 1975). The overall nitrification reaction requires 2 moles of oxygen to each NH_4^+ oxidised, and so aerobic conditions are needed for nitrification. The bacteria responsible for this conversion inhabit the sediments. Rates of nitrification in quiescent sediments are greatly reduced due to the limited supply of oxygen, and hence they do not supply much nitrate to the water, except in the surface layer and during turbulence.

Another factor controlling nitrification is the acidity of the water body. In waters of pH of 5 or less there is little, if any, detectable nitrate as it is being used as quickly as it is being produced.

Nitrate is very soluble and easily leached from soils, making the build up of a reserve difficult (O'Neill, 1985).

2.3.3 Formation of Proteins and Amino Acids

The formation of proteins and amino acids in the nitrogen cycle is carried out by assimilation by plants. Plants take up the nitrogen in a limited number of forms, nitrate and to a lesser extent ammonia and nitrite, then produce proteins and amino acids, organic forms of nitrogen. Animals do not have this ability to produce proteins from simple nutrient intake and so rely on digesting other plants and or animals for their basic protein needs. These proteins are used as a source of amino acids to synthesise other required proteins.

2.3.4 Ammonification or Nitrate Reduction

Ammonia is produced in three ways. Firstly, by heterotrophic bacteria as the end product of the decomposition of plant and animal matter, through the reduction of nitrate during assimilation by algae and other green plants, and as an excretion product of aquatic organisms (Wetzel, 1983). The production of ammonia by excretion is minor compared to the amount produced by decomposition and reduction. Ammonia is then either re-assimilated in plants, or recycled to nitrite and nitrate through nitrification.

Ammonia is present primarily as NH_4^+ and NH_4OH, although at neutral pH levels NH_4^+ is far more common. An example of ammonification can be seen in Equation 2.4.

$$(NH_2)_2CO_{(urea)} + H_2O \rightarrow 2NH_3 + CO_2 \tag{2.4}$$

2.3.5 Denitrification

Denitrification involves the reduction of nitrate and nitrite to gaseous nitrogen. It is carried out by bacteria during the oxidation of organic matter, and under increased rates in anaerobic conditions (Wetzel, 1983). For this reason denitrification occurs in greater amounts in the sediments of basins than in the water column. The reaction is usually carried out in the order shown in Equation 2.5.

$$NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2 \tag{2.5}$$

The reduction of nitrate does not always go to completion, forming dinitrogen. Dinitrogen oxide N_2O is produced in significant amounts. The total amount of combined nitrogen is reduced during denitrification, and this can be lost from the system if this is not refixed.

Nitrification and denitrification can occur simultaneously.

2.3.6 Sources and Losses of Nitrogen

Nitrogen comes from various sources such as rainfall, groundwater and stormwater runoff, directly by fixation of nitrogen from the atmosphere, and from dry particle fallout.

Losses of nitrogen from the wetland include:

- outflow of effluent containing inorganic and organic compounds;
- denitrification by bacteria converting nitrate (NO_3^-) to atmospheric molecular nitrogen N_2;
- diffusion of volatile compounds such as ammonia from the surface, more so at higher pH values; and

- entrapment of nitrogen compounds in the sediments by the adsorption of these to inorganic particulate matter.

2.3.7 Nitrate, Identified as a Significant Source of Nitrogen

On review of the nitrogen cycle, nitrate was identified as the form of nitrogen that would yield the largest amount of information on the readily available supply of the nutrient. Nitrate is the nitrogen species most easily absorbed by algae and macrophytes, both vital wetland plant life.

2.4 The Phosphorus Cycle

Phosphorus is essential for all living organisms, as phosphorus compounds are vitally important to almost all metabolic reactions. They are crucial to energy transfer, where phosphorus is necessary for the formation of nucleotides and phosphatides, two of the intermediate compounds in the photosynthesis process. Phosphorus is also present in enzymes and vitamins needed for metabolic reactions by algae, and also in the genetic molecules DNA and RNA. Phosphorus is the least abundant of the macro nutrients and thus is commonly the limiting factor to growth (O'Neill, 1985).

Naturally occurring phosphorus compounds have very low solubility. This limits the movement of phosphorus in the environment to suspended solid transfers, either in water, as with lakes rivers and streams, or air, as with the atmosphere (O'Neill, 1985). Because of this lack of availability it is often the limiting nutrient in soil and aquatic ecosystems. Concentrations of phosphorus in the aquatic environment are very low, of the order of 60 parts per billion.

Phosphorus is rapidly cycled, mostly in the particulate phase of the biota, by the algae. Some of the colloidal fraction is lost by hydrolyzation to soluble orthophosphate which is assimilated by the biota, and some is deposited in the sediments. Soluble phosphorus is replaced during the decomposition process, by release from sediments, and from inflow (Wetzel, 1983). This cycling process can be seen in Figure 2-2. In the open water, the percentages of each form of phosphorus are shown. Note that the vast majority of the phosphorus available in the open water is contained in the particulate phase.

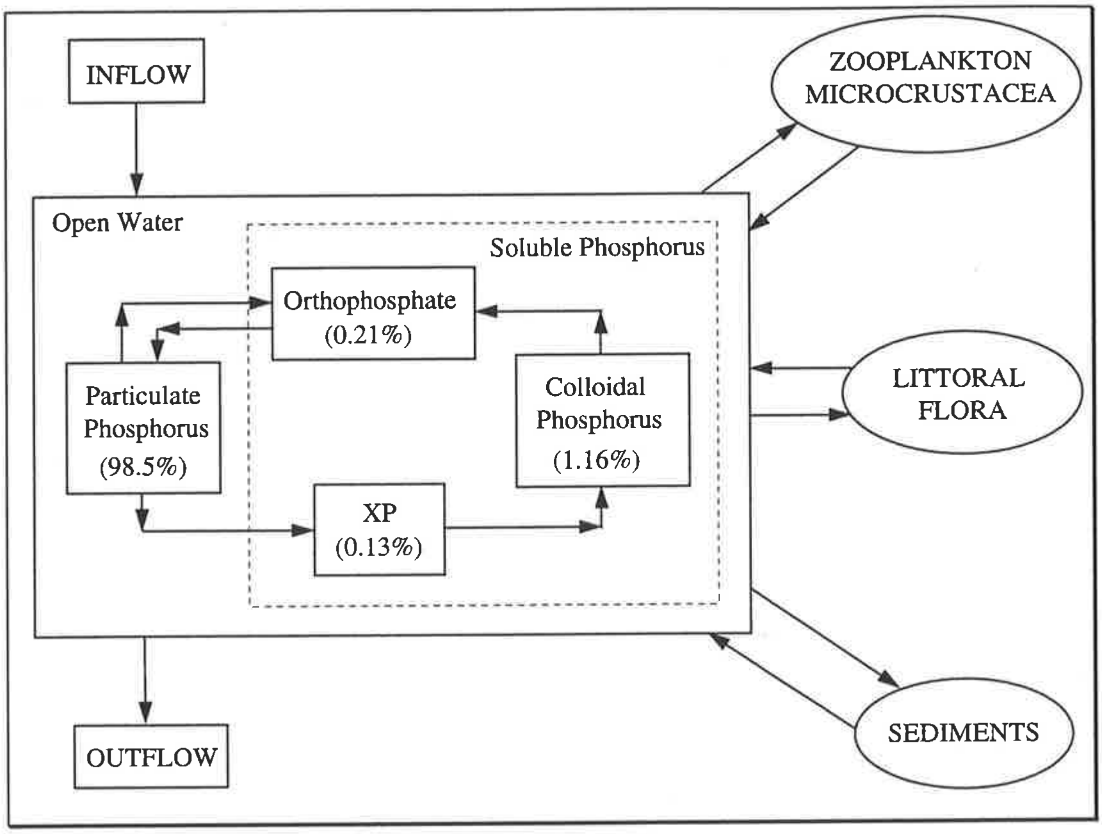


Figure 2-2 : Phosphorus cycle for fresh water bodies, modified from Wetzel (1983)

2.4.1 Forms of Phosphorus

Of the total phosphorus, the majority (>90%) exists as organic phosphorus, and of this generally greater than 70% is particulate organic material, the rest being dissolved or colloidal (Wetzel, 1983). The organic fraction is bound in phosphates or living cellular particulate matter, or is adsorbed to inorganic and dead particulate organic materials.

The open water contains the most important phosphorus source regarding growth of freshwater biota, the unfiltered inflow. The unfiltered flow consists of particulate and dissolved phosphorus in the following forms:

Particulate phosphorus (contains >95% of phosphorus):

- phosphorus in organisms (nucleic acids DNA, RNA);
- phosphorus adsorbed onto inorganic complexes such as clays, carbonates; and
- phosphorus adsorbed onto dead particulate organic matter.

Dissolved inorganic phosphates:

- orthophosphates (soluble reactive phosphate);
- polyphosphates (detergents); and
- organic colloids.

The most important form of phosphorus for plant nutrition is ionised inorganic orthophosphate PO_4, which accounts for only 5% of the total phosphorus in most natural waters. The orthophosphate group is either bound to a cation in an insoluble inorganic compound like iron phosphate ($FePO_4$) or aluminium phosphate ($AlPO_4$), or as a component of an organic molecule (Wetzel, 1983). It is the inorganic phosphate that is used by the algae, which are very efficient in removing it from solution (Golterman, 1975). There is a high turnover rate in orthophosphate in water bodies, algae have been found to release up to 50% of the particulate phosphorus contained in their structure as phosphate just prior to death, in a process called autolysis. This increases to 80% after a few days (Golterman, 1975).

2.4.2 Sources and Losses of Phosphorus

The main natural source of phosphorus is from the chemical and physical erosion of rock. A substantial natural source of phosphate is that adsorbed onto clay particles. Phosphate is released from the clay and sediment if concentrations are low in the open water, possibly as a result of the reduction in the concentration of soluble PO_4-P due to the growth of algae (Golterman, 1975). Phosphate release from the sediments also occurs under anaerobic conditions, further discussed in Section 2.4.3. Natural sources are no longer the primary provider of phosphorus to urban waterways. Total phosphorus loading in runoff entering water bodies has increased markedly recently due to increased use of phosphorus in (O'Neill, 1985):

- fertilisers (agriculture);
- industry;
- detergents; and
- domestic waste.

It is the failure to recover the phosphorus that poses the greatest problem in terms of enrichment of the receiving waters. If phosphorus levels in the inflow to a water body are reduced, the amount of phosphorus in the cycle is reduced, hence rapidly reducing the production capacity of the system.

Soluble organic phosphorus added to soils in fertiliser is rapidly immobilised by inorganic compound formation. Increases in phosphorus in water bodies is, therefore, not greatly attributable to enriched runoff from fertiliser additions (O'Neill, 1985). Sewage effluent and highly soluble polyphosphates from detergents are a major source of dissolved phosphorus.

The loss of phosphorus, or rather the transition to an unusable form for plants and animals, is due to (Mitsch and Gosselink, 1986):

- formation under aerobic conditions of insoluble phosphates with iron, calcium, and aluminium;
- absorption of phosphates onto clay particles; and
- binding into organic matter, incorporating in the living biomass.

Much of the data on freshwater systems has been recorded as total phosphorus concentration and inorganic soluble phosphorus or orthophosphate. Total phosphorus concentrations in natural waters range from 10 to 50 μg/L. The variation is brought about largely by the geology of the particular site. Waters rich in organic matter tend to have higher total phosphorus concentrations (Wetzel, 1983).

2.4.3 Phosphorus Interaction with the Sediments

Due to the highly insoluble nature of phosphorus complexes and the ease with which they become bound to particulate matter, much of the phosphorus cycle is contained within the movement of phosphorus between the sediment and the water body.

There is an apparent net movement of phosphorus into the sediment and large amounts of phosphorus are contained within the sediments (Kramer, 1972). Values can be several orders of magnitude higher than those in the water column (Wetzel, 1983). For this reason the productivity of a water body cannot be correlated with the amount of phosphorus in the underlying sediments. There are many factors involved with the sediment acting as a sink and also in the release of the phosphorus back into the water column. The biota within the sediments as well as the conditions in the water body affect the transport of phosphorus from the sediments.

The critical area for phosphorus exchange is at the sediment-water interface, which covers the first few millimetres of the defining boundary between the two media. A key factor in the exchange of phosphorus at the boundary is the oxygen content of this zone, which is influenced by the bacteria and planktonic invertebrates that live at the interface. There is a high demand of oxygen contained in the water from the sediment, due to microbial activity (respiration), chemical diffusion and inorganic complex formation. Oxygen can only penetrate a few centimetres into the sediment layer, and this is called the microzone. The state of the zone of oxidation is a key factor in determining the rate of adsorption or desorption of phosphorus from sediments to the interstitial water.

A well oxidised microzone is a very effective barrier against the release of phosphorus into the water body. This is because it traps iron and manganese, which form ferric oxide and hydroxide complexes with phosphorus to greatly reduce its transport. This zone also acts to remove phosphorus from the water body for the same purpose, as concentrations of phosphorus are lower than the metal ions.

Beneath the microzone the retention of phosphorus is aided by the fact that much of it has been decomposed. It is inorganic and adsorbed onto clay particles as well as having been precipitated with iron, manganese and carbonates.

Under aerobic conditions the direction of phosphorus movement is almost entirely toward the sediments. As the oxygen of the microzone and the overlying water is reduced, so is the barrier to phosphorus release to the water. Under anaerobic conditions, there is a migration of phosphorus from the sediment, from a depth of up to 10 centimetres, into the water. This is a result of redox conditions being present.

The migration process is aided by the anaerobic phosphorus mobilising bacteria such as the pseudomonas, which are abundant in sediments composed of silts with a high organic matter content (Wetzel, 1983). However, the importance of these bacteria in the expedition of phosphorus from the sediments is not very significant compared to their role in phosphorus cycling in the water column.

Under turbulent conditions the rate of export from the sediment increases markedly (Kramer, 1972). Phosphorus sources from sediments disturbed by turbulence, even particulate inorganic compounds of low solubility, provide sufficient phosphorus for active algal growth. Without the expedition of phosphorus due to the agitation of the sediments the phosphorus content of most natural water bodies would be growth limiting (Wetzel, 1983).

2.4.4 Open Water Interactions

Open water interactions involve phosphorus in particulate suspension and dissolved forms.

Soluble phosphorus encourages the growth of photosynthetic algae in the upper levels of the water body (Golterman, 1975). As the phosphorus is assimilated or bioaccumulated the residual concentration of the dissolved phosphorus in the open water decreases. Upon death the biota are deposited on the bed. The phosphorus may be remobilised during the decay of the biota into organic compounds, or may be immobilised by formation of inorganic phosphates like aluminium phosphate.

Phosphate anions, most commonly orthophosphate, form insoluble salts with a number of metal ions in natural waters. The extent to which this occurs depends on the relative concentration of phosphate anions to metal ions and the pH. As the concentrations of the phosphate anions are low this complex formation can have a marked effect, removing a great percentage of phosphate. Further phosphate removal is carried out at pH levels between 5 and 6, when they become adsorbed to clay particles. The phosphate anions chemically bond to the positively charged edges of the clay particles.

2.4.5 Littoral Flora Interaction

On addition to an aquatic ecosystem there is a rapid uptake of phosphorus by the root systems of the littoral vegetation, macrophytes, and by the phytoplankton. Phosphorus is slowly released from the plant during its lifetime, and from the resident epiphytic algae. Release is far more rapid on death of the macrophytes when it is leached from the leaves and root systems during decay. Up to 50% of the total phosphorus contained in the plant may be leached to the water in a matter of hours (Wetzel, 1983).

2.4.6 Uptake and Release of Phosphorus

Much of the information regarding the rates and directions of phosphorus movement in aquatic systems, including Sections 2.4.2-2.4.5, has been collected using tracer experiments. These have shown that turnover of phosphorus in the surface layer and littoral plant zone is approximately 10 times faster than that occurring in the sediments. This is not as prevalent in wetland systems where light penetrates to almost full depth, but it demonstrates the effectiveness of the littoral flora and plankton to take up phosphorus.

The rate of uptake in the surface waters varies according to the inflow of phosphorus from the catchment. There are also marked seasonal effects. Changes from uptake to release of phosphorus occur as the annual plants of the littoral zone decay.

In the open water, crustaceans and rotifers consume particulate phosphorus at high rates. The release or excretion is dependent on body weight and metabolism; the lower the body weight the higher the excretion per unit weight.

2.4.7 Phosphate, Identified as a Significant Source of Phosphorus

It has been shown that the most important nutritional species of phosphorus is inorganic phosphate. Although this is not the most abundant species in natural aquatic systems it represents a substantial nutrient supply to the primary produces, and is thus critical to biomass production. As seen in Section 2.3.1 on nitrogen fixation, total phosphorus and, therefore, phosphate is also important in the assimilation of nitrate, already identified as the most important nitrogen nutrient source.

2.5 Eutrophication

A eutrophic water body has an excess supply of nutrients. That is, the amount of nutrients entering the body are more than adequate to allow for natural growth of the biota. This results in a decrease in the diversity of the community (Hutchinson, 1970) and explosive plant growth, especially in species such as green and blue-green algae (Wetzel, 1983). Blue-green algae, or cyanobacteria, are a particular problem as they (Maier and Dandy, 1994):

- give the water an undesirable taste;
- give the water an undesirable odour;
- discolour the water; and

- release toxic chemicals.

There are other indirect ecological effects of the bloom, to species not immediately competing for resources with the algae (Harper, 1992). The rapid increase in the volume of algae chokes the water-way and crowds all the other aquatic vegetation. The blue-green algae possess gas vacuoles in their cells which provide buoyancy, keeping them high in the water column (Wood, 1972). This prevents light penetration below the water surface and hence disrupts the energy and food cycles of the subsurface biota (Miller and Armstrong, 1982). Blue-green algae is very persistent once established because of its efficient use of solar radiation. The species of blue-green algae most frequently occurring in Australia are *Anabaena, Cylindrospermopsis, Microcystis, Nodularia* and *Oscillatoria* (Maier and Dandy, 1994).

In bloom conditions blue-green algae absorb the incoming radiation and warm the surface waters, providing optimum growth conditions (Mason, 1991). While they grow, they contribute oxygen to the water through photosynthesis (Miller and Armstrong, 1982). However, the reduction of heat penetrating beneath the surface reduces turbulence, and the non-buoyant species of algae sink and die. In addition to this the thermal trap reduces the upward movement of ammonia, limiting nitrogen, which in turn greatly favours those species able to fix nitrogen, such as the cyanobacteria (Mason, 1991). Blue-green algae also have the ability to the alter organically bound phosphorus into a useable inorganic form (Wood, 1975). This, and the fact that the number of blue-green algae are not affected greatly by herbivores, as their size is too large to accommodate most filter feeders, enables the blue-green algae to multiply quickly and persist. It follows that conditions most suitable for cyanobacteria blooms are, therefore, warm dry weather, high concentrations of dissolved inorganic phosphorus (orthophosphate), and low concentrations of dissolved inorganic nitrogen (Mason, 1991).

The process of eutrophication continues as oxygen consuming bacteria devour the organic remains of the non-buoyant algal species that have settled out, depleting the oxygen supply of the hypolimnion. With shallow water bodies, such as wetlands, the oxygen depletion spreads throughout the water column and without oxygen the only life in the water becomes the anaerobic bacteria. These produce foul smelling hydrogen sulphide and other toxins (Miller and Armstrong, 1982). The toxins associated with blooms of cyanobacterial plankton are not always present, occurring at any time during the bloom and at varying concentrations, which makes prediction difficult (Mason, 1991).

These changes effect humans as (Wood, 1975):

- water for potable use may have an undesirable taste or odour;
- filtration becomes difficult, involves increased cleaning, is slower and more expensive;
- water becomes unhealthy, poisonous (carcinogenic nitrosamines, methaemoglobinaemia (high nitrate levels in the stomach));
- increased vegetation impedes flow and navigation; and
- the water has an increased corrosion potential.

As stated in Section 2.2, due to the limited availability of the nutrients nitrogen and phosphorus, generally an excess of these, in particular phosphorus, causes rapid algal growth. When loading of phosphorus occurs, such that the carbon nitrogen phosphorus ratio (see page 9) shifts to 6C:4N:1P, phosphorus is no longer limiting growth. Productivity can then increase until limited by the next least abundant nutrient, nitrogen (Wetzel, 1983). It is then that algae capable of fixing nitrogen from the atmosphere, such as some blue-green algae, out-compete and exclude other algal species. The addition of nitrate and phosphate to a number of European Lakes, has shown that these two species alone are capable of markedly increasing production (Thomas, 1970). This emphasises the importance of these two species in productivity, and the process of eutrophication.

Eutrophication can be brought about by natural causes, or by intervention by humans, when it is known as artificial or cultural eutrophication (Mason, 1991). The time scales for natural eutrophication generally far exceed those induced by human intervention, as a result of the slow process of natural nutrient accumulation. The three main cultural nutrient sources are agriculture, industry and urbanisation (Wood, 1975).

As the focus of this study is an artificial urban wetland and stormwater system, discussion will only be given of cultural nutrient sources of urban stormwater origin. Duncan (1995) carried out a thorough review of urban stormwater quality processes and concluded, in part, that the process is extremely complex and is largely influenced by spatial and temporal factors. Given that there is variation in the relative sources within individual catchments, it is certain that this variation extends across the whole gamut of urban catchments. This must be understood when presented with a generalised description of common urban sources of nutrients. The given ranges of the relative and quantified contributions reflect this variability. Generally speaking, for urban catchments the most important nutrient sources are (Rosich and Cullen, 1982):

- atmospheric fallout (rainfall and dry particle);
- garden fertiliser;
- animal waste;
- soil erosion; and
- vegetation (cuttings, leaves, lawn clippings).

Atmospheric fallout is a major contributor of nutrients to the urban catchment, with as much nitrogen supplied through this process as from urban runoff. Phosphorus is supplied in smaller proportions (Duncan, 1995). Nitrogen deposition in rainfall is generally an order of magnitude higher. This can be attributed to the fact that atmospheric nitrogen has been greatly affected by human intervention, through the decomposition of human and animal wastes, producing gaseous ammonia, and from burning fossil fuels (Harper, 1995). Fertiliser additions supply nutrients to stormwater in two forms. Firstly, as nitrates, mostly as soluble compounds and generally in solution in soil moisture, which are easily leached from the soil (Harper, 1995). Secondly, as phosphorus which is quickly immobilised through complex formation with iron and aluminium or through strong association with clay particles, and becomes available through soil erosion. Vegetation and other natural debris are a significant contributor of nitrogen, and can be the major source of phosphorus in runoff (Duncan, 1995). Animal waste is another highly nutrient enriched source available through transport to the stormwater system. The soil itself is a natural source of phosphorus, as it is composed of weathered rock. Apatite, found in igneous rocks, is formed of complexes of phosphate and calcium. Through weathering the phosphate is released and becomes tightly bound to clay particles (Harper, 1992). Nitrogen is present in the soil from this process, however, in far smaller quantities.

Industrial waste and domestic sewage sources do not appear in this list, and although a factor in many urban environments, these are not present in the catchment under consideration.

The pollution of stormwater is a result of the contamination of rainfall through contact, from the time of atmospheric formation to final discharge into the waterbody (Andoh, 1994). The following processes are involved in the nutrient and pollutant loading of urban stormwater runoff (Duncan, 1995):

- interception;
- buildup;
- washoff; and
- transport.

The extent to which each of these acts in a catchment determines to a large extent the quality of the stormwater.

Interception is simply the action of vegetation, and artificial surfaces such as housing, in initially preventing rainfall from falling directly on the ground. The extent to which this interaction with impervious surfaces relates to the increased nutrient loading of runoff is closely linked with the process of buildup. Buildup is the accumulation of atmospheric fallout, or dry particle deposition, on the interception surfaces. This buildup is removed by washoff, as a result of rainfall, and mixed with the resultant runoff. Material contained within the flow, specifically the suspended matter such as sediment and debris, is moved through the process of transport. The extent to which this is successful is a function of the flow, and therefore rainfall, as turbulence is heavily involved. Increasing runoff inflows into stormwater drains results in greater turbulence causing the re-entrainment of accumulated sediments and the wash-out of partly degraded organic products (Andoh, 1994).

From this brief description of the processes involved in stormwater loading, the complexity and number of influencing factors is apparent. Factors such as the duration and intensity of rainfall, land use (residential, garden/vegetated reserve), wind, street cleaning and antecedent conditions, such as the duration between rainfall events, all impact on the quality of stormwater (Wood, 1975).

A summary of the expected range concentrations of nutrient species found in urban stormwater can be viewed in Table 2-II. Rainfall concentrations have also been included as these have been found to be a major source of nitrogen in urban runoff (Duncan, 1995). A great deal has been reported in the literature on the annual exportation of nutrients from urban catchments (Wetzel, 1983; Harper, 1992; Rosich and Cullen, 1982; Mason, 1991; Wood, 1975). As no annual load studies were involved in this research these values were excluded.

Table 2-II : Urban sources of nitrogen and phosphorus, various sources

Author	Parameter	Rainfall (mg/L)	Stormwater Runoff (mg/L)
[1]Andoh (1994)	nitrate	0.05 - 1.0	0.48 - 0.91
	phosphorus (total as P)	0.02 - 0.15	0.67 - 1.66
[2]Weibel (1970)	inorganic nitrogen	0.69	1.0
	total phosphate	0.08	0.36
[3]Duncan (1995)	total nitrogen	1.0 - 2.0	NA
	total phosphorus	0.01 - 0.1	NA
[4]Wood (1975)	total nitrogen	NA	0 - 12.0
	phosphate	NA	0 - 1.5

Notes on Table 2-II:

[1] Compiled from literature survey.

[2] Average results from a 16 month study in Cincinati, Ohio. 27 acre urban catchment.

[3] Compiled from literature survey.

[4] Compiled from literature survey.

Of note in Table 2-II is the large range of nutrient concentrations, reported in both rainfall and stormwater runoff. The variation in the species reported does not allow for direct comparisons across all studies. It is apparent, however, that there is an order of magnitude difference between the highest concentrations of nitrogen and phosphorus species cited within both rainfall and runoff groups. There is also a general trend for nutrient stormwater runoff concentrations to be significantly higher than rainfall concentrations, for both nitrogen and phosphorus species. This is not uniform across all studies with Andoh (1994) reporting lower concentrations of nitrate in runoff than in rainfall. This is not discussed in the published work, and could be the result of the reviewing process. If the stormwater values quoted do not relate directly to the rainfall for the catchment, then spatiality and catchment use may be the reason for the peculiarity. The alternative scenario, the reduction of nitrate through absorption, or other uptake mechanism during washoff and transportation, is less likely, due to the predominate nature of reports to the contrary.

Duncan (1995) mentions threshold values quoted by Weibel *et al.* (1966) of the concentrations of inorganic nitrogen and phosphate that lead to algal blooms in water bodies, of 0.3 mg/L of inorganic nitrogen, and 0.03 mg/L of phosphate. In viewing Table 2-II, it is clear that certain studies have shown nutrient concentrations in urban catchments exceed these guidelines. Andoh (1994) and Weibel (1970) report higher than recommended levels of inorganic nitrogen in rainfall alone. Rainfall, therefore, cannot be ignored as a nutrient source in the eutrophication of urban waterways.

From this discussion it is clear that an increase in nitrogen and/or phosphorus levels, to an extent where neither are limiting growth, can cause eutrophication or an increased productivity of the water system. This has the potential to produce algal blooms under the correct conditions of flow, temperature and light. The consequences of this sequence of events, already discussed, results in the degradation of the natural ecosystem and a reduction of the value of the waterway as a resource for the community at large.

It is widely accepted that the most effective ecological method of eutrophication control is by the prevention of nutrient addition to waterbodies (Hutchinson, 1970). Other methods such as specific species removal lead to further problems, as introduced species can cause further damage to the ecosystem.

It follows, therefore, that systems such as wetlands, capable of reducing nutrient additions to waterways downstream of urban catchments, are vital contributors to the control of cultural eutrophication.

2.6 Selection of the Water Quality Constituents for this Study

Nitrogen as nitrate, and phosphorus as orthophosphate have been selected as the most suitable nutrient constituents. Both are considered to be the primary plant and algal growth nutrient form of these two essential elements, as discussed above. Knowledge of these would provide information on the freely available nutrient supply to the wetland ecosystem. However, these two nutrients are not the sole source of nitrogen and phosphorus nutrition. As detailed in the discussion above, there are number of processes continually at work to transform the chemical and physical composition of nitrogen and phosphorus forms in the water body. To gain a fuller understanding of the potential for the reduction or production of a particular nutrient in a wetland system it would be necessary to monitor several of the known species. For nitrogen as an example, measurement of nitrate, ammonia, nitrite, organic nitrogen, and total nitrogen would be required. The situation is similar for phosphorus. Monitoring all these water quality variables was not feasible in a study of this size. As a compromise only those limiting nutrients most directly attributed to readily available plant nutrition were selected.

An integral part of this study was monitoring the general improvement in stormwater quality due to the wetlands' filtration action. This dictates the study of sediment removal, both suspended and dissolved, and the lowering of turbidity. In addition to the nutrient study this would give information on the relationship between the ability to remove suspended solids, and remove nutrients from stormwater.

Constituents of further possible interest, and easily attainable with continuous field monitoring, were dissolved oxygen and water temperature. Both have been shown to affect the nutrient cycling process, and the eutrophication potential in a water body.

This results in the following water quality constituent list of interest for this study:

- nitrogen as nitrate;
- phosphorus as phosphate;
- total suspended solids (TSS);
- turbidity;
- total dissolved solids (TDS);
- water temperature; and
- dissolved oxygen (DO).

Chapter Three

The Minkara Wetland and Catchment

3.1 Introduction

Chapter three focuses on the formation of the Minkara Wetland, the location, and the upstream catchment area. Also presented is the history of the wetland from conception, including the flooding and water balance history, and the growth and decline of the vegetation. Results of a survey on the wetland basin are given. These include the physical properties of the Minkara Wetland, flow, volume, and surface area relationships, used in later analysis.

3.2 Location

The Minkara Wetland is situated in the Happy Valley District Council of Adelaide, South Australia. As can be seen from Figure 3-1 this area is approximately 20 kilometres south of the Adelaide CBD, in the foothills of the Mount Lofty Ranges. The wetland is positioned 400 metres east of the Happy Valley Reservoir, between Manning Road and Happy Valley Drive, which can be seen in Figure 3-2. Outflow from the wetland, as with all other stormwater runoff in the region, is diverted around the reservoir by a cutoff drain. Runoff then continues down the Field River before flowing out to sea.

3.3 Formation of the Minkara Wetland

As part of a research project carried out by the Department of Civil and Environmental Engineering into the effects of urbanisation on stormwater quality, two artificial urban wetlands were constructed in the rapidly developing Happy Valley District Council. As discussed in Daniell and McCarty (1994), the Minkara Wetland was formed in November 1992 by damming a natural stream, named the Minkara Creek.. This creek collects stormwater from road and land runoff from the catchment indicated in Figure 3-2. The creek is lined with a number of large River Redgums and blackberry bushes. The blackberry bushes in the lower reaches of the creek have died as a result of the flooding. The stream passes under Happy Valley Drive, a main arterial urban roadway, in a culvert, comprised of two 1.5 metre diameter concrete pipes. Daniell and McCarty (1994) used the artificial embankment of Happy Valley Drive and the natural slope of the stream banks in their design, to form a wide shallow basin suitable for wetland macrophytes. This basin shape can be seen in Figure 3-3, prior to the filling of the wetland. The vegetation prior to inundation can also be seen in this figure, as can the stream bed. A Faiyum weir and dam wall structure was constructed at the inlet of the culvert, incorporating the existing culvert wing walls. The headwall was positioned approximately 3 culvert pipe diameters upstream, to allow for flow transition from weir overflow to culvert entrance. The stream bed prior to flooding can been seen in Figure 3-4, lined with River Redgums, reeds and blackberry bushes. A small gate valve and a galvanised steel drainage plate were included at the base of the weir wall, to allow for future drainage of the wetland. A pressure sensor and logger was installed at the weir in November 1992, to provide 'continuous' stage height information.

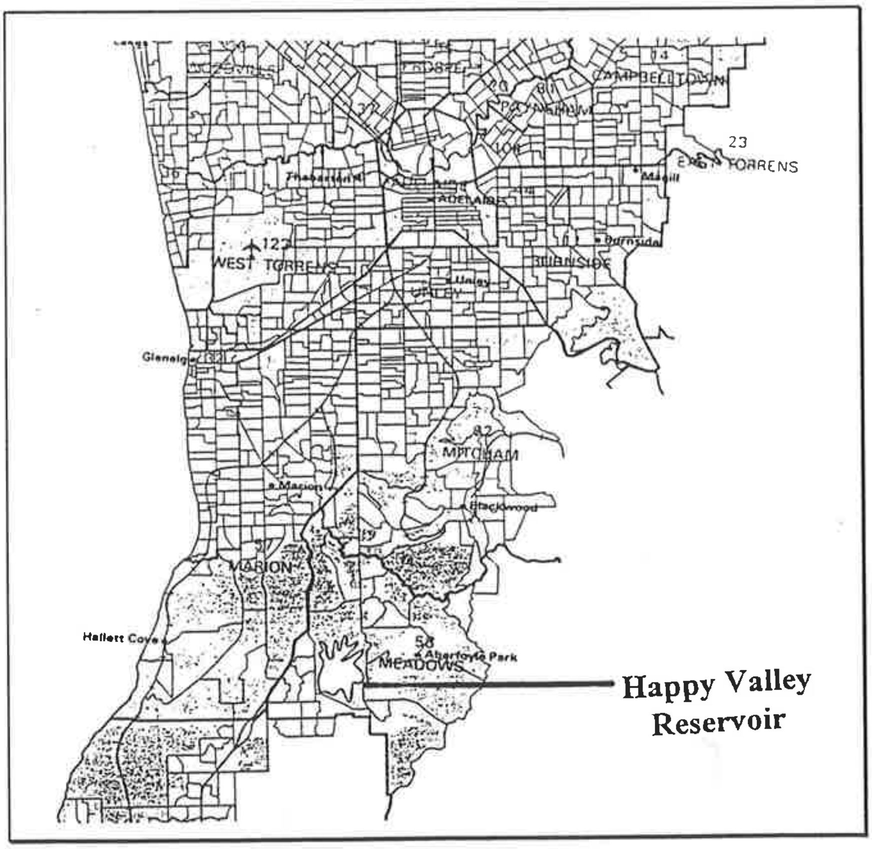


Figure 3-1 : Location of Minkara Wetland relative to Adelaide CBD

Upstream of the wetland, where the underground stormwater network ends, a rip-rap lined natural channel of 200 metres leads into the Minkara Creek. This lined channel can be seen in Figure 3-5. After passing through a culvert and under a road the channel becomes heavily vegetated. Runoff reaches the wetland along this 400 metre long channel basically via overland flow, as can be seen in Figure 3-5, taken during a small event. As the channel nears the wetland inlet, the vegetation becomes more reeded, and of higher density.

Figure 3-7 shows the density of the reeds looking upstream from the inlet of the wetland.

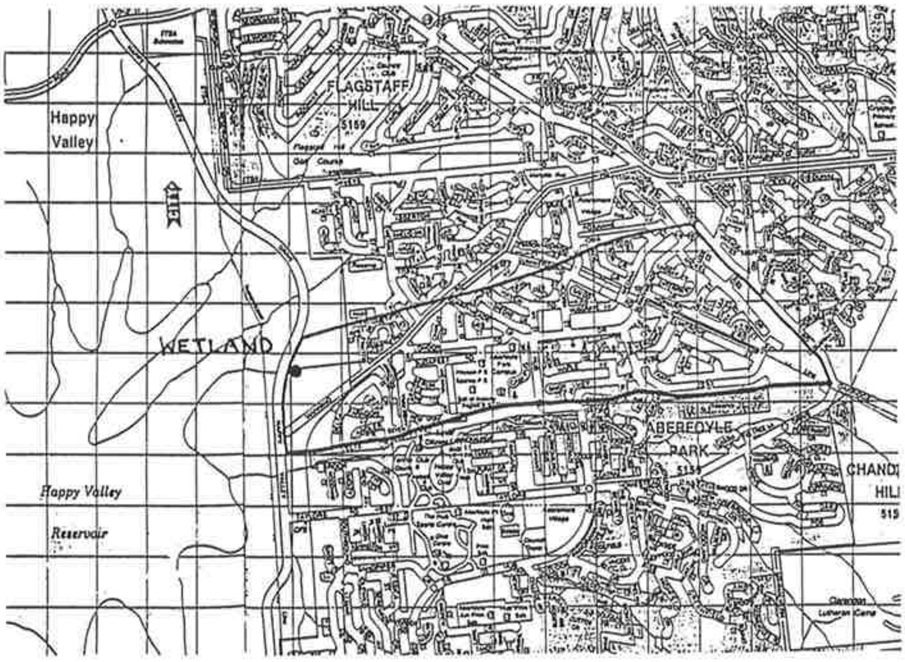


Figure 3-2 : Minkara Wetland and catchment. Detailed view of urbanisation

3.4 The Minkara Creek Catchment

The Minkara Creek catchment is highly urbanised, of the order of 90 percent. This entails a large area of housing and access roads with the associated guttering and stormwater drains. In the lower reaches of the catchment there is an area of park and reserve which includes the wetland. The catchment was studied in a fourth year research project in the Department of

Civil and Environmental Engineering by Williams and Smythe (1994). This study was focused on determining and calibrating the parameters for the flow modelling program XP-RAFTS (WP Software, 1992). A number of catchment properties useful to this work were determined during this study and these are shown in Table 3-I.

Table 3-I : Minkara catchment properties, from Williams and Smythe (1994)

Total Catchment Area	127 hectares
Impervious Area	25.5 hectares (20 percent)
Pervious Area	101.5 hectares
Initial Loss (Impervious Area)	1.2 mm
Initial Loss (Pervious Area)	5.5 mm
Continuing Loss (Pervious Area, Proportional loss)	93 percent
Time Lag (Rainfall to Flow)	23 minutes
Rainfall Volume to Runoff Volume	29 percent

3.5 Behaviour of the Minkara Wetland 1992-1996

When the inlet valve was closed in October 1992 filling of the wetland took approximately 2 weeks to complete. The existing grasses and bushes, that closely lined the creekbed, died out soon after, due to the prolonged inundation. No planting of aquatic vegetation was necessary, existing macrophytes were left to populate the newly formed basin.

The wetland remained full from October 1992 to January 1995, a period of 26 months. During this time there was large growth of the macrophytes on the shore line, which migrated into the shallow side regions of the wetland, and advanced towards the deeper regions of the wetland. A group of native ducks moved in not long after the filling completed, and they proceeded to nest in the reed bed island, found approximately 5 metres from the weir.

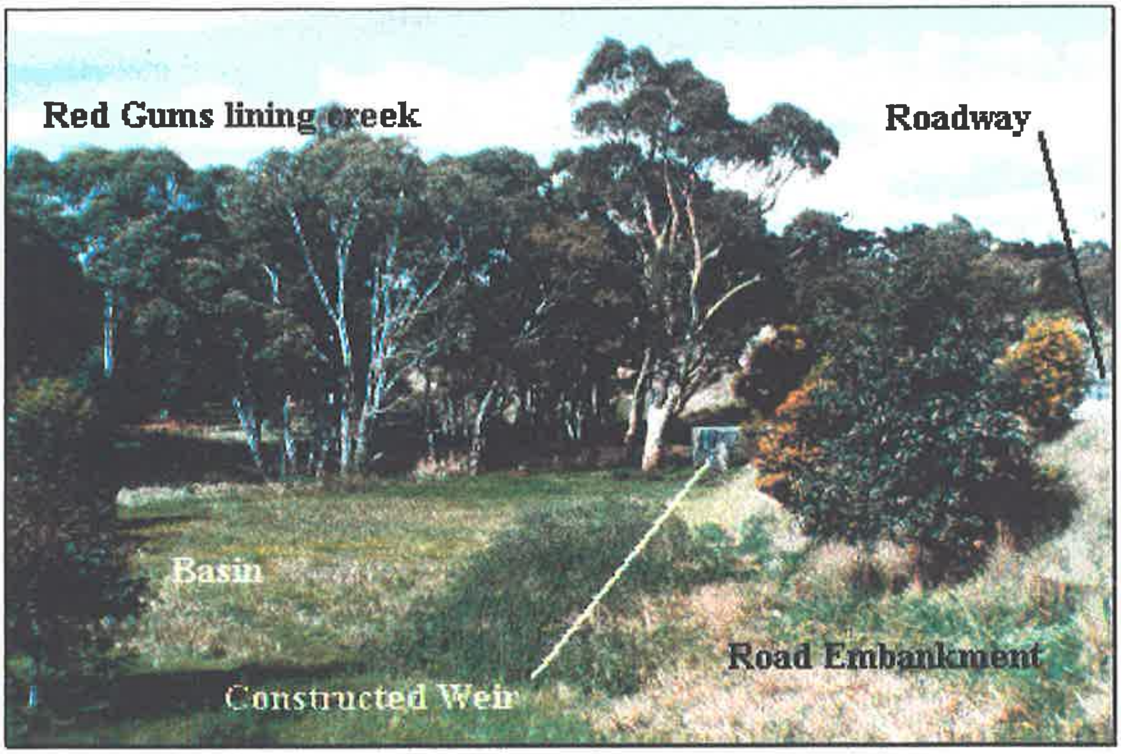


Figure 3-3 : Minkara Wetland basin, prior to filling, Spring 1992

Figure 3-4 : Minkara Wetland prior to filling, view along old creek bed, Spring 1992

Figure 3-5 : Rip-rap lined channel at stormwater outlet, 400m upstream from wetland

Figure 3-6 : Vegetated channel, 200 m upstream from wetland, showing overland flow

Figure 3-7 : View looking upstream from inlet, showing heavily reeded channel

3.6 Drainage History of the Minkara Wetland

The River Redgums (*Eucalyptus camaldulensis*) lining the Minkara Creek were inundated with water by up to 1.5 metres at their trunks. This was not viewed as being a health risk to the trees at the time. Yearly drawdowns were expected to occur over the summer months, with the increased evaporation and little to no inflow. However, the level of the weir controlling outflow was too high and the rate of drainage of the basin too low to allow complete drying out of the basin to January 1995. Appreciable evaporation loss did take place in the summer months, however, this was insufficient to lower the basin storage to normal Minkara Creek baseflow level. A lowering of the water column, exposing and aerating the soil, would happen periodically in natural systems. Species of tree common to wetlands throughout Australia and to the Minkara Wetland, such as the River Redgum, require regular flooding to promote their health (O'Malley and Sheldon, 1990).

It was decided in early 1995, that a period of draw down was the safest way of ensuring the health of all the species of gum at the site. Unfortunately, in the first summer period since flooding, the above mentioned ducks were still with their chicks, and it was thought that draining the wetland would give land predators access to the young. The draining was therefore delayed for one summer. In January 1995 the draining of the wetland was carried out by opening the outlet valve such that complete draining occurred in approximately 7 days. This valve remained open for a period of 3 months, during which time the wetland filled and dried out a number of times due to summer storms. A number of equipment installations that required the wetland to be empty were carried out during this period, including a stadia survey of the basin.

The wetland remained full for the remainder of 1995. An article titled "Trial wetlands polluted and killing Trees: councillor", was published in the 9th of August 1995 edition of the Hills and Valley Messenger. This sparked an investigation into the health of the trees at the wetland and a tree adviser from the Botanic Gardens, Tony Whitehill, inspected the site. At that time, in August 1995, the plan was to drain the wetland in the summer months, as had occurred in the summer of 1994/1995. This would leave a period of inundation of 9 months. This was explained to Tony Whitehill. In his report, Whitehill (1995) comments on the suitability of flooding the root systems of the River Redgums when he states "these are known to tolerate seasonal flooding". The period of flooding, 9 months, was considered too long for continued health of the Redgums, and it was thought 3 to 6 months would be the maximum tolerable for any long period of time. On advice a longer period of summer draining was carried out from November 1995. The wetland remained drained until April 1996, giving a period of 6 months continually drained. The side drainage plate was removed during this period. This ensured that any runoff from summer rainfall passed through the wetland without back flooding. Following the inspection by Tony Whitehill, the future drainage pattern for the wetland will be as advised, to ensure the long term health of the Redgums. This means 6 months of draining during the drier months of the year, early spring to late autumn, and 6 months as a flooded detention basin.

3.7 Results of a Wetland Survey

A survey of the wetland site was carried out, prior to the construction of the weir structure, in 1992. This was carried out using a 10 metre grid technique and was for the specific purpose of determining the extent of the future wetland. The amount of detail in this survey was insufficient to gain accurate information as to the surface area of the basin or the storage volume. Another more accurate stadia survey was carried out in January 1995, during the first

3 month drainage period. The techniques used for this stadia surveying method can be viewed in Appendix A.

The horizontal location of each point was achieved by reducing each to a relative x and y distance from the respective theodolite station, using the horizontal angle and stadia distance. These local x-y coordinates were then transformed to global coordinates.

Using the stadia survey technique, 171 points defining the contours of the basin cross section were picked up and reduced to x-y-z coordinates relative to the weir.

3.7.1 Determination of Basin Properties

Using the raw x-y-z coordinates a contour map of the basin was produced using the package SURFER (Golden Software Inc, 1990). Figure 3-8 shows a contour plot produced by SURFER. This was treated with cubic spline smoothing, with x and y expansion factors of 4. Figure 3-9 shows the same contour plot, only with all contours above weir level removed. This gives a clear picture of the extent of the water surface at static water levels. The position of the weir, the outlet station, and inlet station can also be seen in this figure. Dimensions show the width and length of the basin, and also the separation of the two stations. From this figure, it can be seen that the deepest section of the wetland basin is along the old stream bed running East-West, and directly in front of the outflow weir. A higher section of land forms a reed "island" approximately 5 metres South of the weir.

3.7.2 Volume and Surface Area Relationships

By using the volume functions available in SURFER, the basin volume at a number of elevations was obtained. These were fed into XLMath (Roy Kari, 1992) as a simple two dimensional relationship, and a polynomial was calculated to best fit the data set. The original volume relationship was derived using a planimeter, and averaging volumes over two nearest contours. The volume relationships for both old and new surveys can be seen in Figure 3-10. Plotted in this figure is the relationship derived from the first grid survey carried out prior to weir construction. Note that no information is available for basin volume below weir height. Apart from the poor accuracy of the first survey, this lack of information was a deciding factor in carrying out another basin survey. The two surveys agreed very well on basin volume for water levels only slightly exceeding static weir water level. There is, however, a divergence once levels more than 0.5 metres above weir level are reached.

The same procedure was carried out to determine the basin surface area. SURFER was used to output the surface area for various levels, and then XLMath was used to derive the polynomial relationship. The derived relationship is shown in Figure 3-11.

Table 3-II gives the volume and surface area for the Minkara Wetland Basin at weir level, or static water level.

Table 3-II : Minkara Wetland volume and surface area at weir level

Volume	2700 m^3
Surface Area	3500 m^2

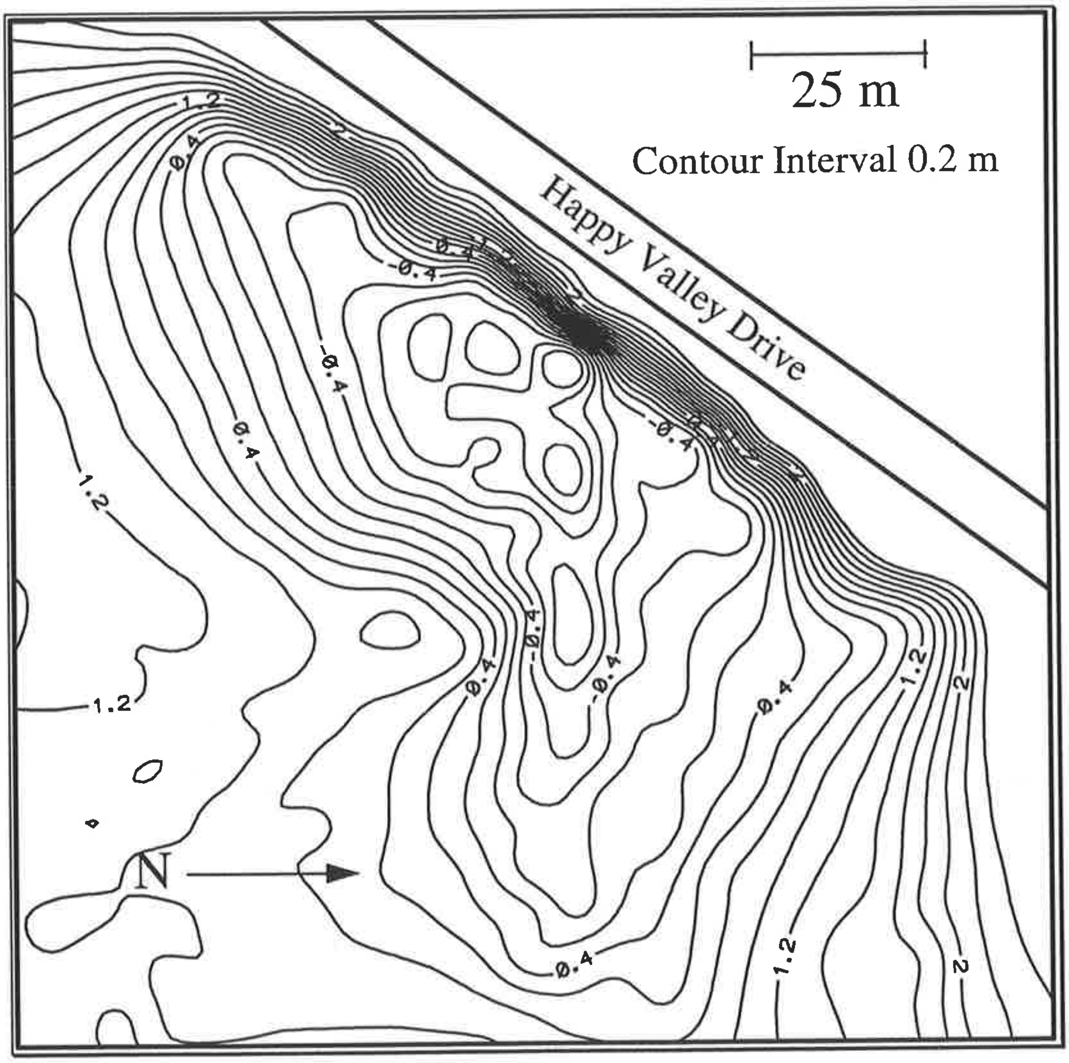


Figure 3-8 : Full contour plot of Minkara Wetland basin

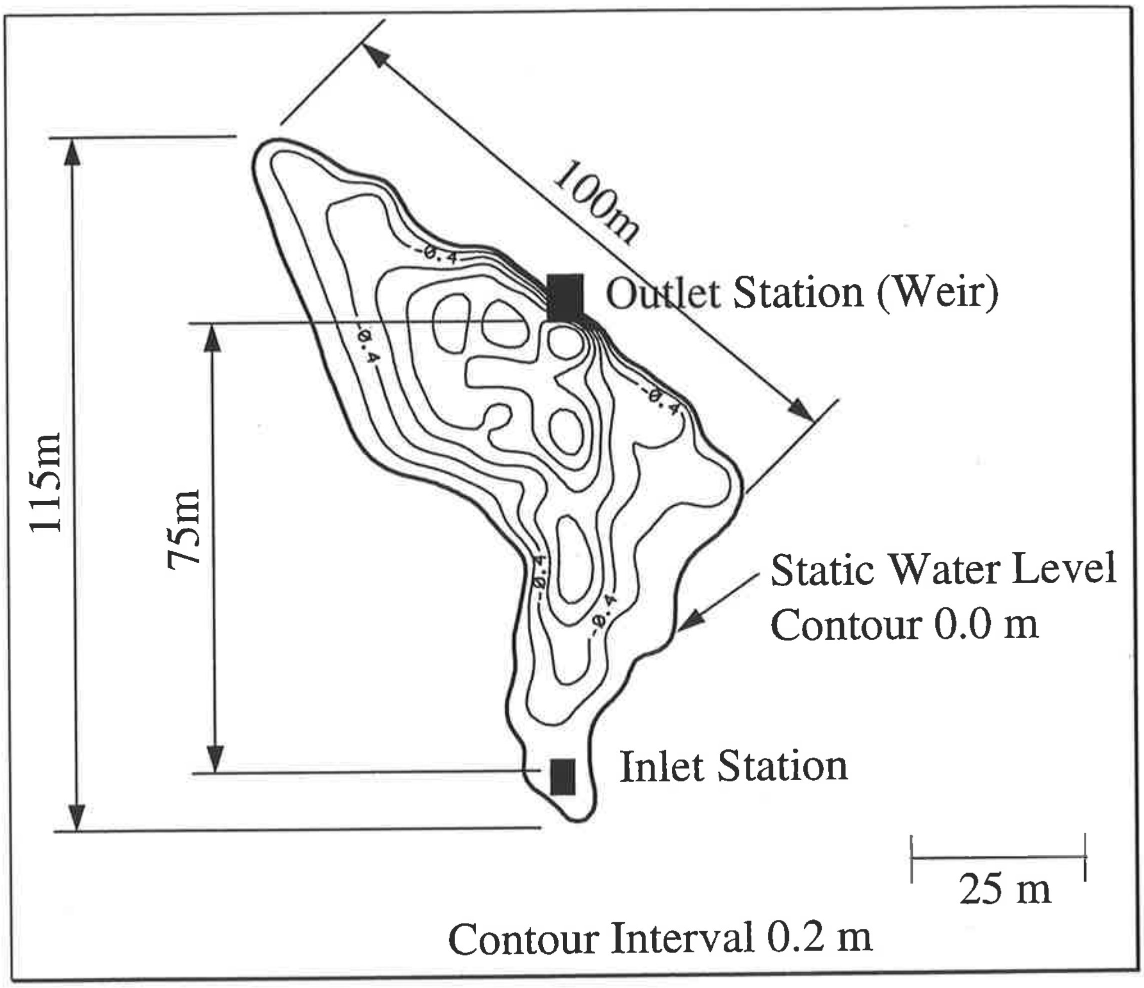


Figure 3-9 : Contour plot of Minkara Wetland basin, static water level and below

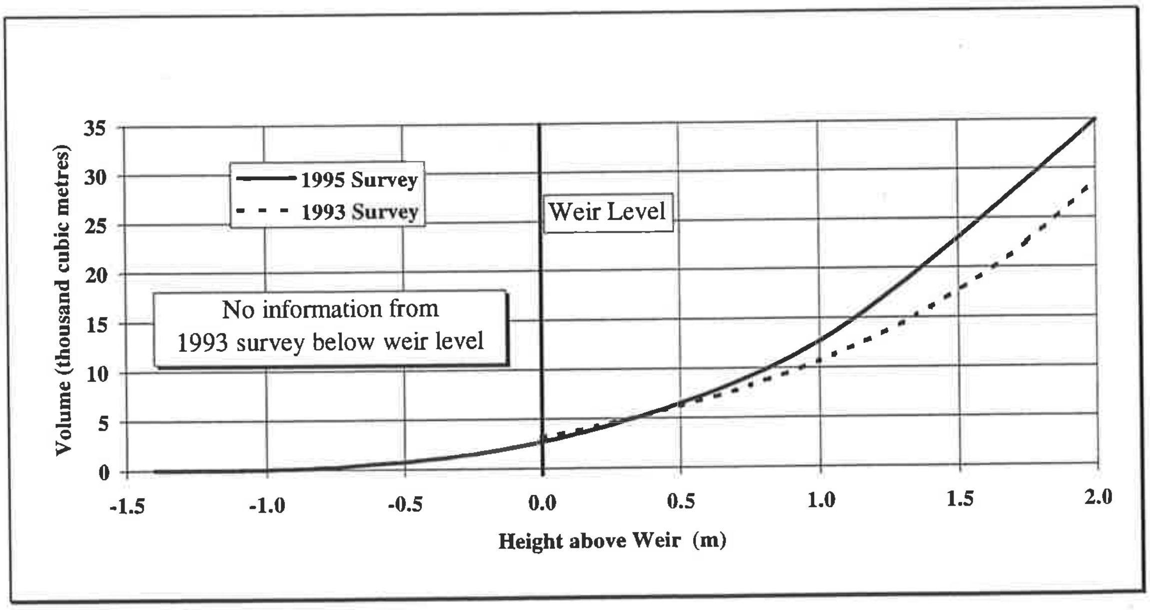


Figure 3-10 : Volume relationship for Minkara Wetland

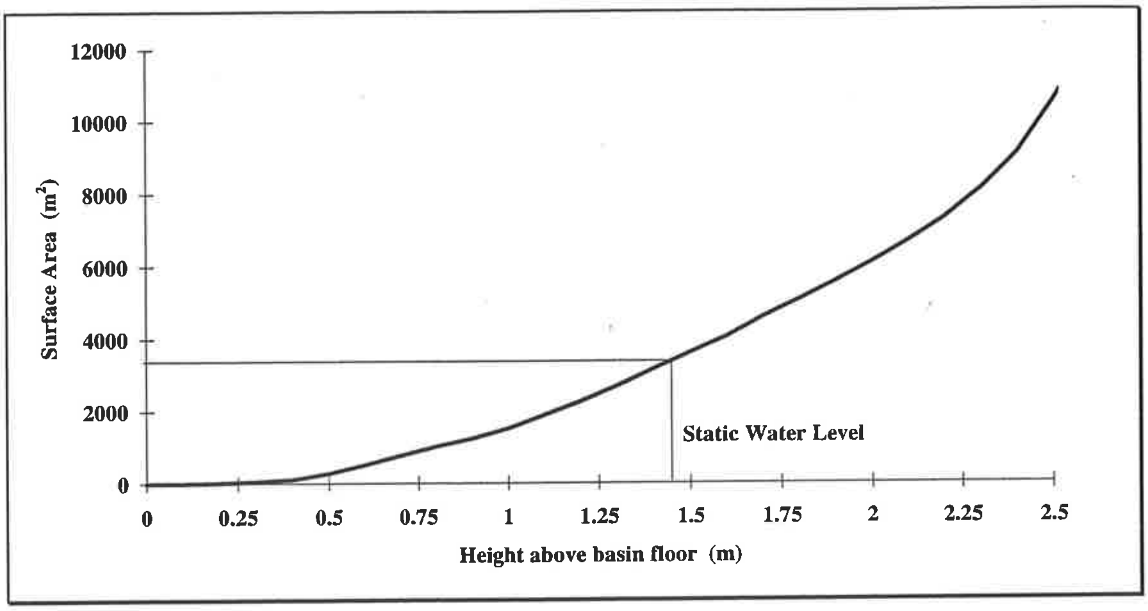


Figure 3-11 : Surface area relationship for Minkara Wetland

3.8 Flow Calculation Procedure

In order to plot water quality information of any importance it was necessary to know the flow at the given location at any given time. At the outlet this was simply achieved by converting the known stage height to a flow using the weir calibration. In the case of the Minkara wetland the weir *in-situ* is a Faiyum weir. These weirs originated in Egypt many thousands of years ago, as irrigation channel controls. Bos (1989) gives a thorough flow calculation technique for the Faiyum weir. Flow for this weir can be described by Equation 3.1.

$$Q=C_d C_v \frac{2}{3}\sqrt{\frac{2}{3}g}\, b_c h_1^{1.5} \qquad (3.1)$$

where: Q is flow (cumecs);

C_d is coefficient of drag;

C_v is coefficient of velocity;

b_c is weir crest width (m);

and h_l is height above weir crest (m).

In Equation (3.1) C_v and C_d vary with stage height, and therefore require evaluation with every computation of flow. The relationships for C_v and C_d have been graphically described by Bos

(1989) and can be seen in Figure 3-12 and Figure 3-13 respectively. The relationship of C_v and stage height was modelled using a polynomial curve fitting technique, to enable the computer calculation of C_v at arbitrary stage heights. A similar technique was used for C_d. The tenth order polynomial approximations for C_v and C_d can be seen in Figure 3-12 and Figure 3-13 respectively.

For accurate flow determination using Equation (3.1), Bos (1989) identifies a number of weir conditions that should be satisfied:

> Firstly, $b_c.h_l/A_l \leq 0.35$ for all $h_l.A_l$, to prevent contraction at the upstream edge. Here A_l is the cross-sectional area of the upstream channel. A_l changes with stage height and is required in the evaluation of C_v in Figure 3-12. Using the stadia survey data, the cross-section at the weir was plotted. This was extrapolated directly off the contour map of the basin, as shown in Figure 3-8. The cross-sectional area was evaluated graphically at a number of stage heights, producing area as a function of stage height. A tenth order polynomial was fitted to the resulting relationship, and this can be seen in Figure 3-14. Having A_l as a function of stage height meant that it was simple to evaluate in a spreadsheet situation.

In the flow calculation example in Appendix B, it is evident that the maximum value of $b_c.h_l/A_l$, using the geometry of the upstream channel, or basin in this instance, and the weir, is 0.01, well below the recommended maximum value.

> Secondly, head measurement upstream by a distance of 2-3 times $h_l$max. This was not possible at the Minkara Wetland for this study as prior to this research the weir stage height recorder was positioned on the side wall of the weir in a stilling well. The requirement of stage height to be measured upstream assumes that there would be significant head change at the weir due to placement in a narrow irrigation channel. As there was no channel in this instance, and the head measurement was carried out in a location not greatly influenced by the head contraction, the failure to meet this criterion was not a concern.

> The last condition specified by Bos is $0.08 \leq h_l/L \leq 1.6$. Here L is the length of the weir crest. As can be seen in the reverse routing example in Appendix B, this condition was

satisfied. For zero head this value will be zero, indicating that the flow equation holds only for an intermediate range of flow. For the Faiyum weir geometry at the Minkara Wetland $h_l/L=0.08$ implies a head of 0.05 metres, a head of 1.0 metres (almost overtopping the weir) yielding an h_l/L value of 1.5. Hence the weir has been designed to operate over the full extent of its calibration range.

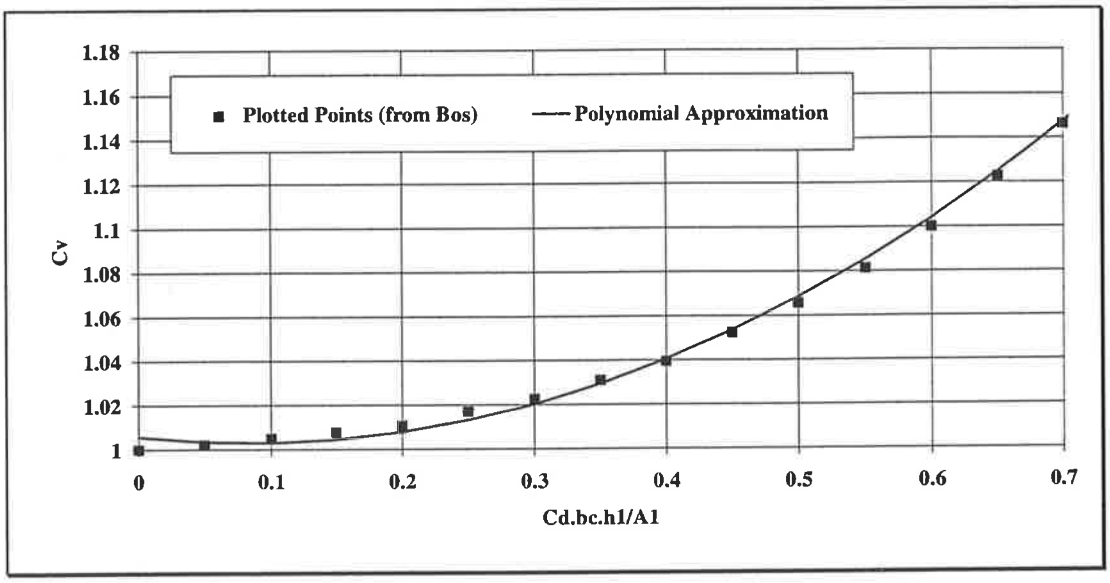


Figure 3-12 : Plot of coefficient of velocity correction for weir flow calibration, adapted from Bos (1989)

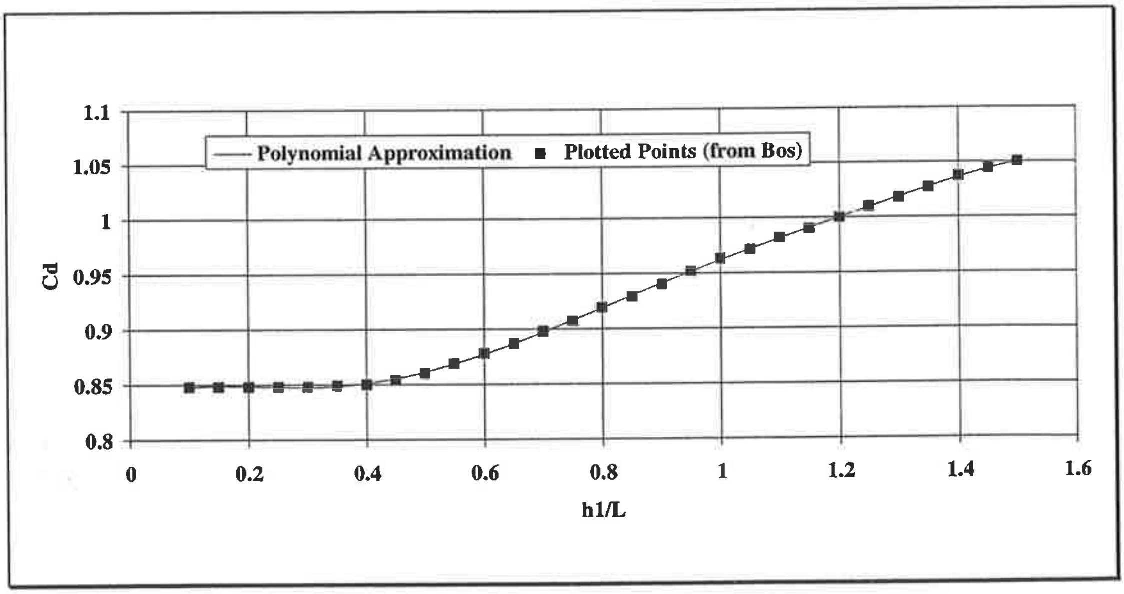


Figure 3-13 : Plot of drag coefficient for weir flow calibration, adapted from Bos (1989)

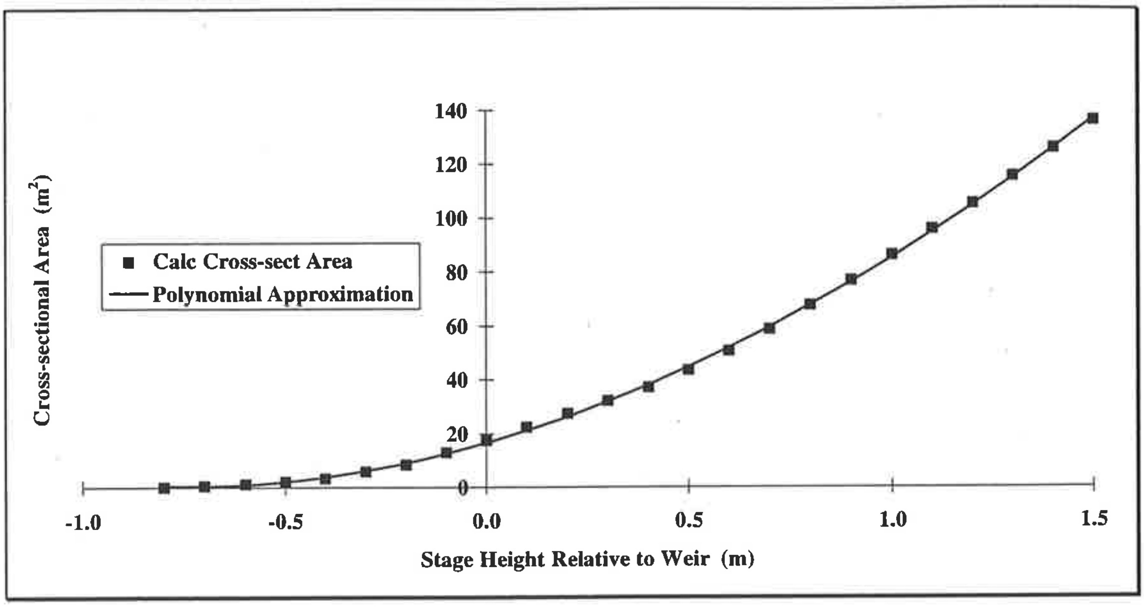


Figure 3-14 : Cross-sectional area relationship at Minkara Wetland weir

Having been able to describe all the necessary associated variables in Equation 3.1 with polynomials, the flow at varying stage heights for the Faiyum weir was easily computed. An example of this process is contained within the reverse routing example in Appendix B.

3.8.1 Reverse Routing

Unlike the outlet weir of the wetland, no flow measuring device was positioned at the inlet. With the planned inlet sampling station providing water quality data, the flow at this upstream location would need to be determined if load and peak concentration information was required. Without installing further flow measuring equipment the only way to determine flows at this inlet point was to back calculate them, using flow information at the weir. This process is known as reverse routing. The simplest method of reverse routing, successfully used by Hill *et al.* (1993) and Gamble and Pannell (1993), is the two point approximation of the continuity equation. For continuity the inflow must be equal to the outflow plus the change in storage. This is represented in Equation (3.2):

$$I_i = Q_i + \left.\frac{dS}{dt}\right|_i \tag{3.2}$$

where:

$$\left.\frac{dS}{dt}\right|_{i}=\frac{(S_{i+1}-S_{i-1})}{2.\Delta t} \tag{3.3}$$

where: I_i is Inflow at i'th time;

S_i is Storage at i'th time;

Q_i is Outflow at i'th time;

and Δt is Time interval chosen.

Equation (3.3) is the two point finite difference approximation of the change in storage volume over the time interval. Equation (3.4) shows the four point finite difference derivative, higher in order than the two point and requiring additional storage information.

$$\left.\frac{dS}{dt}\right|_{i}=\frac{(8S_{i+1}-8S_{i-1}-S_{i+2}+S_{i-2})}{12\Delta t} \tag{3.4}$$

Both the two and four point finite difference derivatives were used by Boyd *et al.* (1989) and found to produce similar results. For simplicity the two point derivative was used in this study.

A difficulty in using the finite difference derivatives described in Equations (3.3) and (3.4) is that at the beginning and end of the routing period they are not defined. Boyd *et al.* (1989) described the forward and backward derivatives that must be used at the beginning and end of the routing period respectively, as in Equation (3.5). Shown in Equation (3.5) is the derivative for use at time t=0. The signs are reversed for the final derivative of the routing procedure.

$$\left.\frac{dS}{dt}\right|_{0}=\frac{(-3S_0+4S_1-S_2)}{2\Delta t} \tag{3.5}$$

Another problem using the finite difference reverse routing technique is choosing an appropriate time step, Δt. Boyd *et al.* (1989) found that this was critical to the resulting inflow hydrograph. They found that if Δt was too small oscillations occurred, and that if Δt was too large the peak may be missed, as not all points on the hydrograph were considered. They went on to suggest that a smoothing algorithm described in Equation (3.6) should be used if oscillations did occur.

$$I_i = \frac{I_{i-1}+2I_i+I_{i+1}}{4} \tag{3.6}$$

where: I_i is upstream flow at time I.

This technique of smoothing was used, although not to reduce observed oscillations. Smoothing was used in order to reduce the spiking that occurred due to the short time interval between stage height data. These small intervals were a result of the high frequency data recording during the most dynamic times of the hydrograph.

Boyd *et al.* (1989) conclude their work by stating, "If the Muskingum equation is re-arranged to solve for I_i given I_{i+1} (i.e. moving backward in time), the solution converges and very accurate estimates of the upstream hydrograph are obtained." Given that oscillations did not occur during analysis and stable results were obtained, the upstream hydrographs produced in this study are considered to be appropriately accurate. An example of flow calculation for the Faiyum weir and the reverse routing procedure used to calculate inlet flows can be found in Appendix B.

Chapter Four

Monitoring the Minkara Wetland

4.1 Introduction

This chapter examines the aims of the monitoring program, and identifies alternative methods available to satisfy these requirements. A review of the literature on current techniques used in wetland and stormwater quality studies is given. This is to demonstrate the existing standard of monitoring, and to allow an understanding of the reasoning behind many of the decisions involved in the design and implementation of the monitoring network. A detailed description of the chronological development of the monitoring system at the Minkara Wetland is presented, to demonstrate the application of knowledge gained from the literature in this field, to this study.

4.2 Aims of the Monitoring Program

As detailed in chapter 1, the aim of the monitoring program was to collect water quality data on an event by event basis, with the intention of investigating the processes at work as well as the overall average performance. Knowledge of the performance of the wetland for different sized events at various times of the year would then allow long-term performance predictions.

4.2.1 Water Quality Parameters of Interest

This study primarily focused on determining the performance of the wetland as a sink for nutrients in stormwater runoff. Coupled with this was the performance efficiency of the wetland basin to allow the settlement of sediment and the reduction of turbidity in the outflow. As discussed in Section 2.6 the constituents identified as being most useful to this end were:

- nitrogen (nitrate);
- phosphorus (phosphate);

- total dissolved solids; and
- total suspended solids.

Other water quality constituents desired but not critical to fulfil the aims of this study were:

- turbidity;
- dissolved oxygen; and
- water temperature.

The latter water quality constituents were all available as automatically logged field sensors. This enabled the collection of a large continuous stream of water quality information that would complement the water sampling event data. Data of this nature would be available to fill in any gaps in the event data, and supplement the total information gained without substantial field effort.

4.3 Wetland and Stormwater Monitoring Systems

4.3.1 Constructed Wetlands, Selected Case Studies

Much of the data collection reported in the literature has been undertaken on wetlands in which there was essentially a constant rate of inflow. This is especially true for wetlands in the United States (U.S.), where the most common situation for wetlands appears to be as a method of treating wastewater effluent.

For a constant rate of inflow, simple time monitoring of input and output is possible and the water quality improvement can be obtained by analysis of those signals. In the case of stormwater, where the flows are intermittent, the data collection is not as straightforward. A constant high frequency sampling strategy will ensure that no events are missed, at the expense of an unnecessarily large data set. Alternatively the system can be designed such that sampling is carried out only during events, at a frequency proportional to the flow rate.

There are, and have been, a number of trial wetlands in South Australia where systematic data collection has been undertaken in an effort to gain a better understanding of the behaviour of wetlands in improving stormwater quality.

The Paddocks is a constructed wetland in the northern suburbs of Adelaide. The wetland covers 0.8 hectares and has a fully urbanised catchment of 60 hectares. Upstream from the wetland is a 400 metre long landscaped channel which leads into a wide grassed swale. The Paddocks site was studied in 1990-92 by the South Australian Engineering and Water Supply Department. The aim of the study was to quantify the improvement in water quality that came with residence time in the wetland. Details of the findings are given in a report by Tomlinson *et al.* (1993).

Based on the data retrieved, a number of relationships were developed for the removal of suspended sediment, lead, zinc, phosphorous, nitrates, nitrites, total nitrogen, TKN, and iron. In each case the relationship was based on residence time which was estimated assuming plug flow through the wetland.

Results from The Paddocks wetland system have shown substantial improvements to both sediment and nutrient constituents. Physical processes such as sedimentation and flow reduction were identified as the principle mechanisms for water quality improvement, with the grassed swale the most effective component of the system. The highest concentrations of nutrients were found to be deposited in the swale. A summary of The Paddocks, catchment and water quality results can be seen in Table 4-I. Reductions observed in total phosphorus and total nitrogen were 73% and 64% respectively.

The Greenfields wetland is another constructed wetland in the northern suburbs of Adelaide. The data collection has included time interval grab sampling during flow events and up to 6 days after. More recently, the wetland has been extended with the addition of a second stage and the setting up of an extended data collection program. This included continuously monitored turbidity meters and the aim of collecting and analysing suspended solids, nutrients, heavy metals and bacteria. It is believed that the shape of the wetland should lead to plug flow and that the water quality improvement will be related to residence time.

The Barker Inlet Wetland in Wingfield South Australia is a stormwater treatment wetland of large proportions, giving an average winter detention time of 10 days. The 172ha wetland receives runoff from a 4,475ha mixed industrial and urban catchment via 4 main stormwater drains (Williams and Daniell, 1996). Designed and built as part of the Multi-Function Polis (MFP) Australia development, the aim of the wetland is to filter stormwater, mitigate floods, and provide a stable and diverse habitat for coastal flora and fauna. The system is unique in that it comprises both fresh and saltwater ponds, with tidal flushing. More details of this wetland are given in Section 4.3.2 as part of the instrumentation review. Unfortunately, to date the extensive monitoring program has only collected data from the inlet, so no performance information is available.

The newest addition to stormwater treated wetlands in South Australia is the Urrbrae Wetland. This wetland is still under construction but will be 4.5 hectares, and filter stormwater from a 4,600 hectare catchment (The Urrbrae Wetlands, 1996). The site is located at a secondary school, and as part of the design four small side ponds have been constructed to provide study sites of wetland ecology. No data has yet been published on the water quality improvement achieved at this site.

Further afield, the Shankland Drain Wetland in Victoria, is a constructed wetland for improvement in urban stormwater quality. Franklin *et al.* (1995) detail the monitoring of this wetland in its initial stages after construction. The wetland operates as an off-line wetland next to a stormwater drain, receiving diverted drain water via a gross pollutant trap, positioned 30 metres upstream. Inflow and outflow from the wetland were sampled for a 5 month period, 2 months after the initial filling. During this time 9 events were monitored, none intense in nature. Results were pooled from event sampling and base flow, or non event sampling. These can be viewed in Table 4-I. When monitoring event flows, Franklin *et al.* found that removal efficiencies for suspended solids improved. In base flow sampling both inflow and outflow were almost free of sediment load, which would explain the low removal percentage. Total phosphorus removal was found to be 22%, with orthophosphate reductions a large proportion of this at 14%. Nitrate levels were monitored and found to be reduced by 44% over the period, and total organic nitrogen by 10%.

Martin (1988) describes the success of a monitoring program on an urban wetland/detention basin treatment system in Orlando, Florida. The system comprises a detention pond, receiving stormwater from overland flow and kerbing, in series with a heavily vegetated wetland. Outflow from the detention pond flows over an earthen spillway into the wetland. Details on the relative sizes of these basins can be seen in Table 4-I.

During the study of the Orlando detention pond/wetland system 11 storms were monitored, 6 with sequential sampling, the remainder sampled by the composite technique. Up to 24 samples were collected in any one storm. Pond inlet velocity, measured with an electromagnetic current meter, was used as the control mechanism for sampling at the pond inlet and outlet. Frequency of sampling at the inlet was increased during periods of rapidly changing discharge. Samples were recorded every 30 minutes at the wetland outlet during periods of flow. Samples were stored in refrigeration units for preservation. Water samples were laboratory tested, no other field instrumentation was used.

Martin (1988) used three different evaluation techniques to determine the removal performance of the system. Event mean concentrations, summation of loads (load in minus load out) and a third method developed for that particular study, the linear least squares regression of inlet and outlet loads. Here each constituent was plotted, inlet versus outlet load, and a transport rate calculated as the regression coefficient. The removal efficiency was given by unity minus this transport rate. For a direct comparison to this study, however, event mean concentration results have been given in Table 4-I. In general the wetland was found to be more efficient at removing constituent loads than the detention pond. Nitrogen was found to be reduced by only 5% for the wetland alone, compared with 15% for the combined system of the detention pond in series with the wetland. Martin reports that nitrate levels were monitored but found to be close to detection limits. The little data available on nitrate indicated it increased through the wetland. Martin attributed this to the oxidation of ammonia to nitrate. Total phosphorus was found to be reduced by only 3% for the wetland, but showed a 22% improvement for the system. The reason for low phosphorus removal in the wetland was attributed to the release of soluble phosphorus from decaying plants. This forms inorganic complexes in the anaerobic sediments, and is recycled back into the water column. Orthophosphate was also monitored in the Florida study, particularly relevant to this study. Orthophosphate was found to increase at the outlet, by 22%, unlike total phosphorus which recorded a 3% reduction for the wetland alone. The dual detention pond and wetland system performed markedly better for a 2% increase, indicating an improvement in orthophosphate level in the pond effluent.

A recent study by Wu *et al.* (1996) on three wet detention ponds in Piedmont North Carolina related the removal performance of constituents such as total suspended solids, total phosphorus, and total Kjeldahl nitrogen to SAR, the surface to area ratio. SAR is defined as the ratio of the area of the detention basin to the area of the serving catchment. These three ponds, Waterford, Runaway Bay, and Lakeside were not originally constructed for water quality control and range in SAR from 0.6% to 7.5 % respectively. Results for this trial, which ran over 11 events in a 13 month period can be seen in Table 4-I. Nutrient results for Waterford have been extrapolated, using proportionality to (TSS), the only constituent measured at that site, as no direct nutrient measurements were taken.

Table 4-I : Results from other stormwater treatment wetlands

Wetland, Location	Catchment Area	Catchment Type	Wetland Volume	Wetland Area	Wetland Area as % of Catchment	Average Depth	Removal Efficiency (%)				No. of Events
	(ha)		(m3)	(ha)	(%)	(m)	TSS	TDS	TP	TN	
The Paddocks, S.A.	60	Urban 61% Imp. 39% Perv.	2600	0.8	1.3	0.3 1.0 max	80[1] 92[2]	0	50[1] 73[2]	64[2]	150 days of monitoring
Shankland Drain Wetlands, Vic.	340	160ha Urban	12000	0.8	0.24	NA	14[3] 50[4]	NA	15[3] 22[5]	44[3] 10[6]	5 months 9 events
Urban Drainage Wetland, Orlando Florida	42	Mixed Urban/Rural	3600	0.3 0.08 (Basin)	0.71	0.9-1.5 2.4-3.4 (Basin)	44[7] 15[8]	14[7] 16[8]	3[7] 22[8] -22[9]	5[7] 15[8]	11 events
Waterford, Piedmont	122.2	Urban	NA	0.73	0.6	NA	41	NA	29	22[10]	13 months 10 events
Runaway Bay, Piedmont	28.3	Urban	NA	0.23	0.8	NA	62	NA	36	21[10]	13 months 10 events
Lakeside, Piedmont	26.6	Urban	NA	2.0	7.5	NA	93	NA	45	32[10]	13 months 10 events

Notes on Table 4-I:

[1] For The Paddocks these removal efficiencies were achieved for a 5 day retention time.

[2] Efficiencies are for the wetland for the entire 150 day load analysis.

[3] Efficiencies represent the results achieved during the whole study period, largely base flows.

[4] Efficiencies are for the events monitored.

[5] The efficiency obtained for orthophosphate during the entire load study period.

[6] The efficiency obtained for total organic nitrogen during the entire load study.

[7] The wetland system in Florida included a detention pond. These efficiencies are for the wetland alone.

[8] Efficiencies for the pond and wetland in line system.

[9] Orthophosphate reduction for the wetland alone, negative indicating an addition.

[10] Nitrogen values are total Kjeldahl nitrogen (TKN).

In reference to Table 4-I, the most notable feature is the uniform report of reductions in all major constituents, TSS, TDS, total nitrogen and total phosphorus. The average performance for each study period was a positive reduction in all water quality constituents. No mention is made of individual events recording negative results except for Wu *et al.* (1996). In this study the Lakeside Wetland produced 2 negative TKN reductions and 3 negative TP reductions out of the 10 events monitored. For Runaway Bay Wetland there were 2 negative event reductions in TKN recorded, and 1 in TP. These individual results are significant as they show that wetland performance varies with event. This can be due to the magnitude of the event, or catchment and wetland conditions. This fluctuation in wetland performance can be overlooked if the details behind average performance results are not reviewed. Another notable feature of Table 4-I is the short term nature of all of the studies. The longest of them, the Piedmont study by Wu *et al.* lasted only 13 months. This is close to the minimum duration a study purporting to hold for long term behaviour could have. Seasonal fluctuations in catchment, hydrology, and aquatic vegetation growth cycles, must all be present during the period of monitoring if the term long-term can be applied to the result.

For the wetlands described in Table 4-I, there is a lack of information given on vegetation, the cover of macrophyte growth, or any other physical basin property. This reflects the engineering view point of wetlands, as sedimentation basins.

In comparison to the other wetlands in Table 4-I, The Paddocks Wetland performed best. For a SAR of 1.3% it performed better than the Lakeside Wetland with a SAR of 7.5%. This could in large be due to the influence of the grass swale, where the highest concentration of nutrients were recorded (Tomlinson *et al.*, 1993). There is a general increase in performance with increased SAR, however this is far from conclusive. The Orlando Wetland shows that for its SAR value of 0.71% it is performing poorer than Shankland Drain Wetland which has a 0.24% SAR. SAR is clearly not the only parameter worth considering for wetland design. However, having said this, it is hard to compare a wetland in Victoria, Australia directly with a more tropical wetland in Orlando, Florida. For the study of multiple wetland sites in Piedmont, Wu *et al.* (1996) found that there is a defined improvement in water quality treatment for ponds of increasing SAR, but that this gradually levels off at 2%. There was little return for sizeable increases in pond area for values of SAR greater than 2%. SAR cannot therefore be disregarded as a design aid.

4.3.2 Techniques for Monitoring Stormwater Quality

As a first step in the design and installation of a monitoring system for the Minkara Wetland a number of stormwater collection systems, primarily in South Australia, were reviewed. Descriptions of stormwater collection systems published after the installation of the Minkara Wetland monitoring network, have been included to show the current standard of field data collection systems.

A priority of any stormwater quality monitoring system is to collect and sample the desired parameters, suitable to the aims of the study, at the correct time and place. Once the sampling strategy has been defined there are many approaches leading to a suitable monitoring solution, usually constrained by time and budget. In this particular study, budget was a concern from the outset.

As detailed in Sections 2.6 and 4.2.1, the parameters required for this study were already defined, as was the type of sampling, grab sampling. The nature of the water quality constituent concerned and its source is critical in determining the sampling methodology. Concentrations of non-point source pollutants, such as those typical of an urban catchment, are likely to increase with flow, so the flow regime is another important factor in planning a sampling strategy (Burn, 1991). The Minkara Wetland catchment, as described in Section 3.4, is predominantly urban, implying a non-point source for the water quality constituents concerned. The wetland receives inflow purely from stormwater runoff, so flow occurs during events only, and these typically last for only a few hours. Given the dependence of concentration on flow, and the flow regime, sampling at times other than during events would add little to the understanding of the dynamic nature of water quality in the event flow. A logical approach to the sampling strategy was to begin with the onset of flow, so that the initial stages of the event were monitored, and continue until flow ceased. For constituents that increase in concentration with flow magnitude and are, therefore, more variable and attribute a greater percentage of load with flow, it is desirable to sample more intensely during higher flows (Burn, 1991). The cost of analysing samples, both in time and money, is a sizeable component of the entire monitoring program. Sampling frequency should be such that the total number of samples is minimised whilst still providing sufficient detailed collection to allow for accurate analysis (Kachka *et al.,* 1994). For this particular study the optimum sampling strategy was thus one which started at the onset of flow, reached a maximum frequency during the most dynamic stages, around the hydrograph peak, and continued at a reduced frequency to the conclusion of the event. The difficulty of this strategy is that this must all be achieved whilst minimising sample collection and maximising the information collected.

Formulation of the ideal sampling strategy is the first step in the process, implementation is just as important, and generally harder to achieve. Problems, such as the adjustment of sampling frequency towards the peak of the hydrograph and ensuring adequate sample cover, need to be addressed. Event flow rarely takes on the form of an idealised hydrograph, and detection of the peak is only possible after its occurrence. Many unique solutions to these and similar monitoring problems have been formulated and put into practice in other stormwater quality studies. A review is given here of many of these techniques used in implementing better sampling strategies.

As mentioned in Section 4.3.1, the Barker Inlet Wetlands are a large coastal wetland system developed as part of the MFP Australia project. A large budget has been allocated for studying the effect of these wetlands on stormwater. The University of Adelaide has been involved in this monitoring study for the past 3 years. A close association between the Minkara Wetland work and the Barker Inlet study has allowed many of the monitoring techniques to be exchanged. Williams and Daniell (1996) detail the current monitoring network for the MFP wetlands. Rainfall in the catchment is measured by nine pluviographs. Each of the four inlet channels is fitted with a broad crested weir for flow measurement. At the centre of each channel are positioned the sampler intake hoses and water quality sensors. These are mounted in a float mechanism which allow sample and probe measurements to be taken above the channel floor during flow. This is surrounded by a 3 metre long, vandalism proof, galvanised steel cage. Cables and sampler inlet hose run underneath the weir to a vandal resistant steel instrument box. In this box are housed the data loggers and water sampler. Logged at each of the sites is:

- stage height;
- turbidity;
- electrical conductivity;
- pH;
- dissolved oxygen; and
- water temperature.

These parameters are logged every ten minutes at low flows, and every 2 minutes during events. Stormwater samples are taken during events, by an automatic sampler capable of collecting 24 one litre samples. The sampler is initialised once a stage height limit has been reached. Samples are taken when stage height or turbidity increase or decrease by a defined amount. This ensures a cover of samples on all stages of the hydrograph, and allows for multiple event monitoring. By having a water quality variable other than flow controlling sampling protocol, a flush of turbid water will cause a sample to be taken which would otherwise be missed. This sample most probably contains high values of other constituents, and provides valuable event information.

As mentioned in Section 4.3.1, The Paddocks is a local, intensely monitored wetland. The study of this system has been supplying data on stormwater quality and the improvement achieved by the wetland and upstream grassed swale for 6 years. Tomlinson *et al.* (1993) detail the refinement of the data collection exercise over the period of the study. Initially sequential grab samples were taken and analysed. The triggering for the sampling was based on changes in water depth at the inlet and outlet. A 50 mm change in depth at the inlet would trigger the device to collect a set of 24 evenly spaced samples. The downstream trigger was set to collect with a change in depth of 25 mm. The method of collection was altered in 1992 to collect a proportional composite sample where a 500 ml sample was added to the composite for every 70 m^3 of inflow. The reasons given for changing to the composite sampling method were:

- sequential sampling gave a coarse sampling frequency;
- poor data continuity due to gaps after sampler was full;
- difficulty in estimating total pollutant loads; and
- expense of analysing the multiple samples from the sequential method.

Tomlinson *et al.* noted that because composite sampling was used, it was not possible to determine the improvement of individual hydrological events. Only a long term relationship could be developed. This highlights one of the drawbacks of a composite sample technique, and also the difficulties in designing a grab sampling methodology that avoids these problems.

In studying the incidence of first flush phenomenon in stormwater, Vorreiter and Hickey (1994) used a simple yet effective sampling technique. Refrigerated automatic samplers were used for sample collection. These were triggered by logged stage height sensors, when flow height exceeded 100 mm above base flow level, and sampled at a set frequency. A similar technique of sampler control was used by Somes and Wong (1996), namely level triggered time interval sampling. The idea of cooling the samplers is an important inclusion to the sampling strategy. This allows for longer time between on site sample collection and laboratory testing. Kachka *et al.* (1994) discuss the importance of quick collection, cold storage, and testing with reference to nutrients "..the labile nature of ammonia and filterable phosphorus species within water systems may lead to transformations of these nutrients between the time of sample collection and analysis". They go on to say "to preserve the microbiological characteristics of samples and to minimise the effects of bacterial activity on other determinands, samples require storage at temperatures of 1 to 4°C". Here they are referring to refrigeration at the point of collection, namely refrigerated automatic water samplers.

A clear example of removing the technology from water quality collection, Allison and Chiew (1995) describe the use of volunteers to collect gross pollutants and water samples at 5 sites in an inner city Melbourne catchment. The size and nature of the pollutant desired in the study necessitated a physical presence to place specially designed trash racks in the flow and to time the rate of debris accumulation. Water samples were taken manually at a predetermined time interval. Although the technique of manual data collection in this study solved many of the complex problems of event definition, a new and perhaps equally difficult dilemma arose in the prediction of the event to enable personnel to take up field positions. Allison and Chiew used a radar warning system which gave a warning of between 30 minutes and two hours of a rain event.

Finally, as an example of the integration of a number of triggering devices and sampling methodologies, a study by Bycroft *et al.* (1995) details the collection of stormwater quality data for the Brisbane City Council. Automatic sampling was triggered by either a defined amount of rainfall recorded in local pluviometers, or by an increase in flow. Sampling began at a high constant frequency in order to collect a large amount of information during the initial stages of flow. After 5 samples, control switched from time, to event flow volume. Samples were taken after volumes equivalent to 10% of the one year return period storm for the catchment passed by.

It can be seen from these examples that a great deal of variety exists in the sampling strategies employed. A common trend is the use of flow, or gauged stage height, as a triggering mechanism for automatic sampling (Martin, 1988; Tomlinson *et al.*, 1993; Somes and Wong, 1996; Williams and Daniell, 1996; Vorreiter and Hickey, 1994). Other triggers such as pluviometers have also been shown to be successful (Bycroft *et al.*, 1995). It is after initiation of sampling that an increase in the type of sampler controlling technique is apparent. Time interval sampling using automated samplers is still the most popular sampling method. This is because no extra hardware is required, the sampler can be set at the desired frequency, and will sample until full, after triggering. A few studies have included greater intelligence into their sampling systems, further controls to sample faster in the early stages of flow (Bycroft *et al.*, 1995; Martin, 1989). A further development is the control of the sampler by multiple water quality variables. This has only been seen in the study by Williams and Daniell (1996) on the Adelaide MFP Wetlands. Such systems are considered to offer greater flexibility, and give a better sample coverage. However, these systems are more prone to failure, due to the greater number of links in control, and require a committed team to regularly service and check the equipment.

Becoming more common with water quality surveys is the understanding that water quality constituents continue to interact within the samples, and that to obtain representative concentrations these interactions must be slowed by cooling. Collected samples are commonly retrieved and place in cooling (Martin, 1988; Williams and Daniell, 1996), although this is not strictly necessary if testing is completed within a few hours of the event (Bycroft *et al.*, 1995). The optimum solution is to refrigerate samples on collection (Vorreiter and Hickey, 1994), but this is rare and expensive.

The techniques used to sample stormwater are extremely varied. There is no single best solution, but there are better ones. Each solution is particular to the catchment concerned, the nature of the parameters, the desired outcomes of the program, and the time and money available for design and construction.

4.3.3 Comparison of Grab and Composite Sampling Techniques

Although there are a number of advantages with composite sampling, as noted in Tomlinson *et al.* (1993), the main drawback is the masking of the transient nature of any changes in water quality. This method gives only an average over the event, or series of events. This shortcoming was particularly important in the case of the Minkara Wetland where one of the primary aims of the work was to determine reaction rates for the removal of the nutrients, nitrate and phosphate.

The calculation of reaction rate is one of the tasks that can be solved using sequential sampling. It is also possible to determine other properties of the wetland from the time dependent input and output data. Levenspiel (1972) gives a number of examples of conclusions that can be drawn on the efficiency of a chemical reaction tank, based on inspection of the temporal changes in concentration at the outlet of a continuous flow system. The sorts of problems that can be diagnosed in this way include internal circulation and parallel flow paths. These operating characteristics can only be determined by collecting and analysing a series of grab samples.

Although wetlands are often considered to behave as plug flow, Kadlec *et al.* (1993) point out that this assumption is incorrect and that "design equations based upon it (the assumption of plug flow) are therefore also incorrect". Kadlec *et al.* show a number of wetlands in the U.S., where it has been possible to derive simplified models based on a combination of plug flow and continuous stirred tanks. These models are able to explain the changes in concentration through the wetland.

In order to provide data of suitable format for the calculation of reaction rates, and the description of time and flow dependent relations, grab sampling was chosen as the most suitable sampling technique.

4.4 Development of the Data Collection System at the Minkara Wetland

4.4.1 Funding Available

A proposal for funding was put together by Dr D.J. Walker and Mr T.M. Daniell of Adelaide University and presented to the Happy Valley Council Board, in March 1994. The Council considered the standard of water quality leaving their catchment and the effectiveness of their wetlands to control water nutrient and sediment levels sufficiently important to pledge $19,000 to the research work. They also expressed interest in using this work to advance design guidelines for constructed urban wetlands so that other councils could be more confident with wetland performance.

Given the extent of the system planned for Minkara Wetland, this funding covered only the costs of the off-the-shelf equipment and the materials to manufacture the purpose designed instrumentation. Laboratory equipment not already available in the department for chemical analysis of the collected water samples was also purchased with this money. Labour and engineering workshop facilities were supplied by the Department of Civil and Environmental Engineering at the University of Adelaide.

4.4.2 Existing Monitoring System at the Start of this Research

Initially, the wetland contained equipment installed as part of an earlier research project on sediment deposition. This equipment included a stage height recorder at the outlet weir which had been operational for 2 years, a turbidity meter at the inlet and a Gamet Waste Watcher automatic water sampler. The turbidity meter had developed a fault in the data logging function and was not operational. The sampler had not been installed on site, however, it had been used as a manually triggered sampler with personnel in attendance.

4.4.3 The First Phase : Initial Monitoring System, Time Interval Sampling

A second Gamet Waste Watcher automatic water sampler was purchased to add to the existing sampler. This can be seen in Table 4-I. . It was envisaged that these would work independently, one at each end of the wetland, collecting water samples from runoff, before it entered the wetland and as it left at the outlet. This required two sampling stations to be set up. These required the multiple functions of housing the automatic samplers, protecting them from vandalisation, and connecting them through secured pipes to the intake positions.

4.4.3.1 Installation of the Gamet Automatic Water Samplers

Given the size and shape of the samplers (see Table 4-I) the easiest protection solution was to sit the samplers in partially buried 200 litre drums that had been concreted into place. This process can be seen in Figure 4-2. With minor alterations to the carry handles of the samplers, these fit snugly into the drums and allowed easy access to the control panel and intake nozzles. Lockable steel plate lids were constructed to fit over the exposed lids of the drums. The intake hoses were buried and protected from crushing by electrical conduit. At the inlet sampling station the inlet hose was fitted to an intake nozzle housed in the inlet cage which evenly distributed water from 3 levels of the inflow. This nozzle was attached to a float, such that the entire nozzle rose in the water column as the level increased. The inlet cage had been constructed at the University to house a turbidity meter and pressure transducer for an earlier project. At the outlet sampling station the intake hose was fixed to the wall of the weir 100mm below the normal static water level. This was not housed in a cage or protected in any way. Being under water and hidden from general view it was considered quite safe from vandalism.

4.4.3.2 Operation of the Gamet Waste Watcher

The Gamet automatic samplers yield 24 one litre samples and can be set to sample in a number of modes. There were time, float, pulse, and level modes available, as described in Table 4-II. In time mode the sampler operates at a constant time interval after waiting the specified time delay. In float mode the operation is identical to time interval sampling except that the sampler is triggered by a float switch. Hence a sampler may sit idle for any given time, unlike in time mode where this period is specified, and begin constant time interval sampling when the float switch is closed. Whilst sitting idle or in a 'sleep' mode the sampler powers down to use a minimum of battery reserves. This is an important function when considering the extended period of time a sampler may be left fully functional in the field. In pulse mode the sampler works as slave to another sensing device, whereby a sample is taken whenever a signal is received. Again the sampler operates in a 'sleep' mode when signals are not being received. Level mode is a percentage rise and fall sampling function which requires a level converter to be fitted to the sampler.

Table 4-II : Modes of operation of the Gamet Waste Watcher automatic sampler

Mode	Description
Time	Constant time-interval sampling Initiated on time delay
Float	Constant time-interval sampling Initiated by float switch signal Operates in 'sleep' mode when not in use
Pulse	Remote signal sampling Initiated and sample taken with signal Operates in 'sleep' mode when not in use
Level	Remote signal sampling Initiated by signal Sample taken when signal indicates desired degree of change Operates in 'sleep' mode when not in use

Figure 4-1 : Automatic water sampler. Housing in foreground.

Figure 4-2 : Installation of the protective housing for the Inlet sampler

4.4.3.3 Description of the Laboratory Equipment Used

All water quality data at this time was from field collected water samples tested in the laboratory. The unit purchased for testing for nutrients was the Palintest Interface Photometer 7000 which can be seen in Figure 4-3. This was chosen as it was the cheapest unit capable of economically testing for nitrates and phosphates in large numbers. Other units on the market, although quicker and less labour intensive than the Palintest Photometer, were either more expensive or had a higher cost per test. Cost was the deciding factor for chemical laboratory equipment as hundreds of nutrient tests were planned. For total suspended solids tests the Nalgene Reusable Filter Holder 4100 unit with vacuum pump was used. Whatman GF/C 0.7 μm glass fibre filter papers were used. These were of larger pore space diameter than general practice for suspended solids removal by filtration. For this unit, however, these were the most economically viable alternatives to the standard 0.45 μm pore size. As with the chemical nutrient tests these filtrations were numerous and cost was an issue. As the aim of this research work was to monitor any changes in water quality due to the wetland, consistency with the use and size of these filter papers was most critical. Total dissolved solids tests were carried out with the Lovibond Checkit Micro hand held unit. When tested in the laboratory these units showed discrepancies between units and so a single unit was used throughout all such tests to maintain consistency.

Figure 4-3 : Palintest interface photometer, and nitrate testing kit

4.4.3.4 Operation of the Initial Monitoring System

Without any external equipment the only mode on the Gamet samplers available to the user is the time mode. As no other equipment was available at the beginning of the sampling program, both automatic samplers were used in this mode initially in order to get under way. There were many problems with this system. To collect samples which yielded useful water quality information over the entire event required a certain amount of prediction. The duration of the event needed to be predicted in order to spread the samples over the entire flow. The timing of the event was just as critical as this determined the time delay before the constant time interval sampling began. This required the user either to predict both the timing and duration of a future flow event, or to wait in the field with the sampler and switch it on when it rained. The second option defeated the purpose of having an automatic sampler. The best possible solution with such limited smart-ware was to visit the site when an event looked imminent, 40 minutes away by vehicle in this case, and start the samplers at a frequency low enough to cover any foreseeable flow duration. Usually this would mean the time delay was not required.

During the last month of winter 1994 this was the only data collection system at the Minkara wetland. A number of sample collections were made during this time. The success of these was very limited. As shown in Figure 4-4, during one particular sampling run over a period of 2 days a number of small events with 10 distinct peaks passed through the wetland and the samplers failed to collect specimens during any significant inflow. This demonstrates the hit and miss strategy of this basic system.

Use of the first basic monitoring system showed two of the biggest problems of sampling storm events, triggering the sampling equipment so as not to miss the initial flow, and sampling at various positions of the hydrograph. The stage monitoring system at the end of phase one can be seen in Figure 4-5.

4.4.4 The Second Phase: Float Triggered Externally Controlled Sampling

The cheapest and quickest way to improve the initial monitoring system mentioned above was to install a simple triggering device, a float switch. This eliminated the problem of having to predict the timing of the event, and would thus greatly improve the ability of the system to sample when an event was occurring.

4.4.4.1 Installation of the Float Switch and Underwater Cable Linking Samplers

The float switch was installed in the inlet intake cage. The cable for the float was protected from vandalism by feeding it through the existing buried conduit to the sampler.

In order to connect the two sampling stations, approximately 100 metres apart, a cable capable of carrying a minimum of 3 independent signals was needed. The shortest route from one sampling station to the other was through the deepest flow channel of the wetland. It was decided that as well as being the shortest distance to lay the cable, the water provided excellent cover and protection. This made it imperative to use water proof cable or risk malfunctions in the system due to short circuiting. Gel-filled electrical cable designed specifically for this purpose was priced at $350 for this length. The cheapest, yet still functional, alternative was to feed a telephone cable through ordinary agricultural irrigation hose to provide the water proofing. This saved $250 on the gel filled electrical cable. The only problem with this approach was that the telephone cable had to be fed through the hose in one piece to ensure water proofing. This was achieved by using compressed air to force a plug, pulling fishing line, through the hose. The line was then used to pull the cable through. This exercise was rather difficult and took a large open space to feed through the entire 100 meters. A number of pegs were then made, designed to push deep into the floor of the basin and hold the buoyant air filled hose below the surface. Laying of the hose was then achieved simply by wading through and pegging it down from one end the other. This hose, containing the telephone cable, can be seen in Figure 4-6, a photo taken during a drainage period.

Figure 4-6 : Cable linking inlet and outlet stations, during drainage period in January 1995

Having a cable linking both stations allowed the conditions at the inlet to initiate both samplers. Hence a sample could be taken at the outlet prior to flow from the current event reaching the overflow weir.

4.4.4.2 Design and Construction of a Microprocessor Controller to Distribute Sample Collection

Improvement in the spread of the samples over an event was also needed in order to record water quality information at all stages of flow. The aim was to cover both rising and falling limbs of the event adequately, by varying the sampling frequency. Experience had shown that the peak of flow occurred early on in the event. It was also clear that flow conditions changed most dynamically in the early periods. By sampling more frequently at the start of an event and until the peak, when conditions were most dynamic, information on the transient nature of the incoming water quality could be gathered.

For varied frequency sampling with the Gamet Waste Watcher samplers, external equipment was needed. It was envisaged that this would take the form of a microprocessor controlled device. This unit was designed to control both samplers independently and to be sophisticated and flexible enough to adapt to the monitoring system as it expanded. At this stage the only other field equipment to work with were the float switch at the inlet cage, and the underwater cable linking the inlet and outlet samplers. The simplest approach was to use the float switch as an flow initiation signal for the controller, which would then have the capability to control the samplers according to a predetermined timetable.

It was imperative to conserve battery power in the samplers so that performance could be guaranteed even if an event did not occur for some time after placement in the field. As mentioned in Section 4.4.3.2 the samplers, when in both float and pulse modes, have the ability to go into a 'sleep' state when not triggered. In pulse mode, however, the state of alertness of the sampler is higher, and more battery power is consumed than in float mode. This stems from the fact that the signals required to fire the sampler in each mode are quite different. In float mode the signal is of extended duration. The onset of the signal 'wakes up' the sampler which then monitors the float to see if it is still closed, for a period of one minute. Only then does it take a sample. This is to ensure that the switch has not closed due to wave or swell action, or that a piece of floating debris has temporarily fouled the switch. In pulse mode the signal is much shorter and requires immediate action from the sampler. For the field situation it was necessary to operate the samplers in float mode to conserve power. It was therefore necessary to engineer the control device to send signals imitating a float switch. These signals would switch on and off according to the time table.

The control device was designed, manufactured, and tested wholly within the Department of Civil and Environmental Engineering instrumentation workshop.

4.4.4.3 Determination of the Initial Controller Time Table

The design and construction of the controller took 5 weeks to complete. Unfortunately due to the limited number of personnel involved with the project this put the sampling program with the existing system out of action. For this reason, once the controller was complete there was an urgency for it to be placed in the field. It was early spring 1994 at this stage, and rain events were rare. The sampler controller was to be placed in the field immediately on the completion of testing in order to avoid further delays. This left little time for the time table determination, an equally important part of the controller as the electronics. Experience was used to work out a suitable sampling time table.

At this stage several storms had been monitored. Although not many had been adequately sampled, nearly all had ample flow information recorded. From experience of these events a few simple observations were used to come up with a simple yet effective initial sampling time table.

- Flow durations at the inlet were approximately 2 hours;
- Flow durations at the outlet were of the order of 1 day;
- The peak at the inlet was generally in the first hour of flow; and
- The peak at the outlet was generally in the first 2-3 hours of flow.

The timetable derived from this approach can be seen in Table 4-III.

Table 4-III : First sampler controller timetable, based on experience

Sample Number	Inlet Sample Time (mins)	Outlet Sample Time (mins)
1	0	0
2	5	20
3	10	40
4	15	60
5	20	80
6	25	100
7	30	120
8	35	180
9	40	240
10	45	300
11	50	360
12	55	420
13	60	480
14	65	600
15	70	720
16	75	840
17	80	960
18	85	1080
19	90	1200
20	95	1440
21	100	1680
22	105	1920
23	110	2160
24	115	2300
Total Duration	**1 hour 55 mins**	**38 hours 20 mins**

Note that the inlet samples in Table 4-III were at a constant interval of 5 minutes. Insufficient information was known about the rapidly changing flow at the inlet at this time to predict when to reduce the sampling frequency. Keeping it constant but quite high ensured enough information about the rising limb and peak could be attained given the flow duration was 2 hours or under at this location. Note also that the frequency of sampling at the outlet changed after 2 hours and again at 8 hours and 20 hours. This was in order to cover, with a limited number of samples, as much of the more slowly changing falling limb of the outlet flow as possible.

4.4.4.4 Sampler Operation Using a Float Switch Triggered Microprocessor Controller

Assorted teething problems and limited rain events at this time (late spring early summer 1994) meant that only two small events occurred while the float triggered control device system was operational. Both of the events were small in peak flow and total runoff. Sample times, when matched against the flows calculated using outlet stage recording, showed that the float switch at the inlet station appeared to have insufficient sensitivity at these low flow rates. Sampling had been only initiated at, or about, the peak of the hydrograph at the upstream station. The float switch level was such that the much of the flow had passed this inlet point before the level had risen sufficiently to raise the switch.

Lowering the float at this point would have yielded further problems. A float switch set just above static water level would be triggered by all flows entering the wetland, even quite insignificant ones. This would mean the sampler would be triggered with the first flow of any sort and, with no other control device, take all its 24 samples making it inoperable for later, possibly significant flows. The float for this system was set at a level considered to pick up as early as possible any flows of even minor significance and to allow the base flow through unmonitored. It would have been good to monitor even the smallest events passing through the wetland, but with only one person to collect and test the samples this was not possible.

The spread of the samples over the event was still inadequate at this stage as the event durations and the subsequent timetable had been being estimated through experience. There was a lack of information around the peak of the event. However, if the frequency of samples was increased there was a greater risk of losing the tail of the storm, or indeed a good portion of a longer event.

The addition of the float switch ensured that the samplers would only activate when an event was in progress. However, the start of the rising limb of the hydrograph was not being sampled.

Information about phenomena such as first flush effects were therefore not obtained with this system, although the timing of the automatic water samplers was greatly improved. The continued failure of the float to initiate the sampling system at the correct time, before the peak flow, indicated that a more advanced triggering mechanism was needed.

Figure 4-7 shows one such event monitored with the float trigger and controller in action. Note how the inlet samples begin just after the calculated peak of the inflow. Note also the spread of the outflow samples and how slowly conditions change there in relation to the inlet. The layout of the monitoring system at this conclusion of stage two can be seen in Figure 4-8.

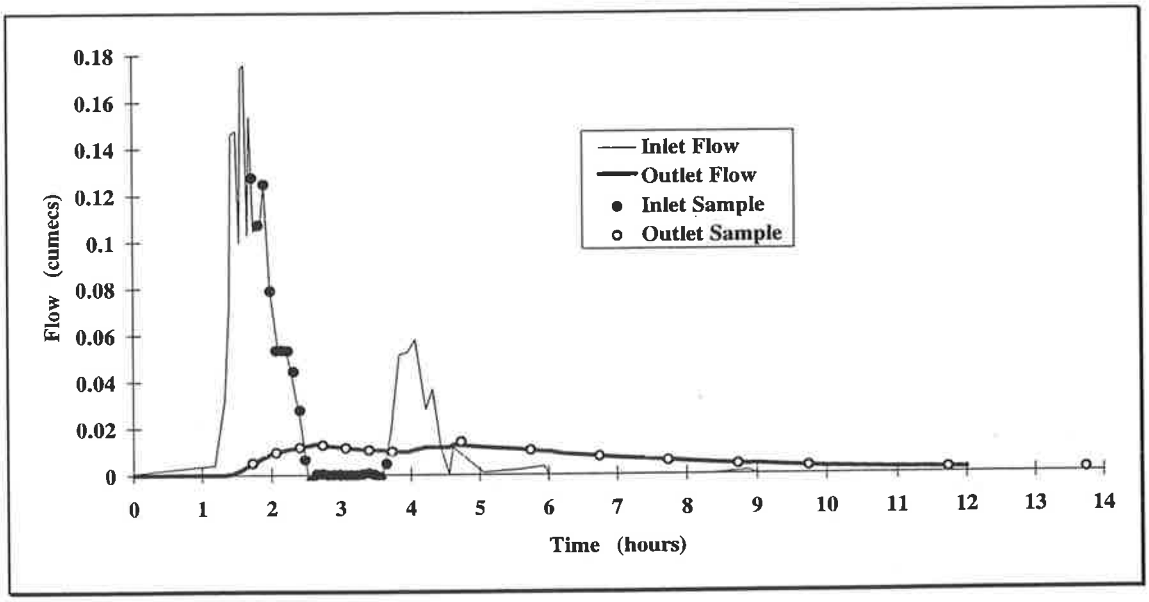


Figure 4-7 : Float triggered sampling with an external controller determining sampling frequency according to a predetermined timetable

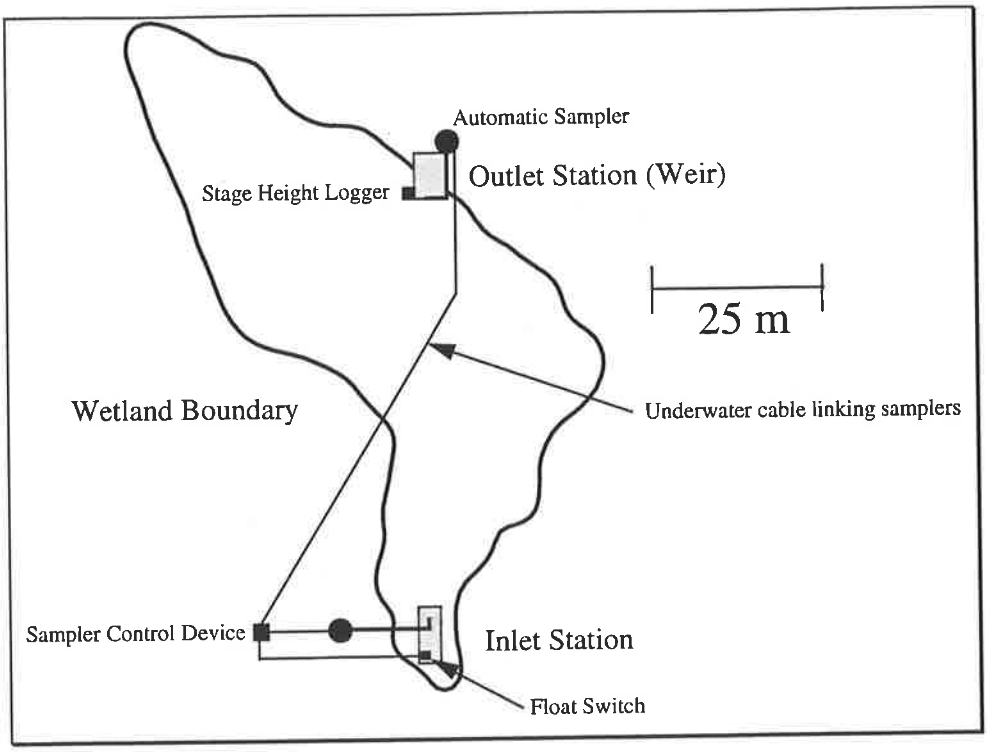


Figure 4-8 : Layout of the monitoring system at the end of phase two

4.4.5 The Final Phase : Improved Timetable and Triggering, Installation of Additional Field Sensors

With the problems of insufficient information at the onset of the event, and incorrect sample distribution in mind, a meeting of all parties involved in the project was held in December 1994. It was decided that with the remaining funds, an array of electronically logged sensors would be installed at both sampling stations. Given the parameters identified as being most useful in Section 4.2.1, the instruments selected as being most appropriate for the situation were:

- dual dissolved oxygen and water temperature sensors;
- turbidity meters; and
- pressure transducers.

Nutrient sensors were considered but found to be both too expensive and unreliable in the field. A laptop computer was purchased to handle all down loading on site, and data storage and interpretation in the laboratory. The sensors were to provide water quality data at a high frequency and without the time delays associated with the collection and testing of water samples. As well as the advantage of additional information gained from these sensors, there was also the capacity to collect and store a huge data set, evenly spread over any event. This information, when viewed with the nutrient and sediment data from automatically collected water samples would give a more complete picture of catchment and wetland processes.

4.4.5.1 Installation of the Water Quality Sensors and Loggers

Logging units were required to switch power on and off to the array of sensors, as a method of power conservation. Another crucial requirement of the loggers was to operate, or power up the sensors, at irregular time intervals. These features were not available with commercial loggers so this necessitated the construction of purpose designed units.

This delayed the installation of the new system by two and half months. This was an unfortunate delay, but was viewed as an opportunity to put into place a logging unit that could easily be adjusted as the monitoring system evolved. The Department of Civil and Environmental Engineering Logger, or DCEEL, was designed specifically for this purpose, with many of the foreseen future advances allowed for on the circuit board. A number intelligent functions were built into the DCEEL. One of these was the ability to limit the recorded data.

The DCEEL was designed to power up the sensors every minute regardless of the time of day or conditions. The reading from each channel was analysed and compared to the last respective reading. If any channel had changed by a specified amount, different for each channel, then all the sensors readings were recorded. Limiting the data stored in this way saved on the memory used by the logger and hence allowed for longer field recording durations. Although not always the deciding factor for field life, available storage memory is an issue when conditions are frequently changing such as during events, a time of great interest for the researcher. In quiescent times, battery life determined the field life of the unit. This duration was extended somewhat by the provision of a 6.5 Ah 12 volt battery for the pressure sensor and turbidity meter. This allowed for a safe functional period of 10 days with reasonable flow activity. Details of the DCEEL, as published by Woithe and Gamble (1996), can be seen in Appendix C.

The inlet station was constructed as part of a previous Masters project (as yet unpublished) at the Minkara Wetland 18 months prior to the commencement of this project. As can be seen in Figure 4-9, it consisted of an instrument protection cage, with access lid, connected to a logger box via a steel tube. The cage contained a float to which was attached a turbidity meter and the newly installed 3 nozzle sampler intake hose. The new equipment consisted of the dual dissolved oxygen / temperature probe, and the pressure transducer. A stilling well was constructed for the pressure transducer, to smooth out the readings and to remove any turbulence or flow effects. A bracket was made to hold the DO/Temperature probe. These were positioned in the cage so as not to affect the performance of the float.

No protection or sensor mounting equipment was available at the outlet station. A new cage and support structure at the weir would be needed. The aim was to monitor the outflow of the wetland, and keep the instruments in the water in times of no flow. This meant mounting them inside the wetland as near to the weir as possible. Rather than mount them on the wall of the weir itself, which would interfere with the outfall, the solution arrived at was to suspend a cage 2 metres inside the crest, as can be seen in Figure 4-10. The cage was supported on an rotatable arm that allowed the cage to be swung from the logger box to meet the weir crest. Access to the instruments for cleaning could then be gained through the top lid. The instruments themselves were mounted in a float, that slid up and down two guide poles with the rising flow level. The pressure sensor was mounted in a stilling well to the side of the cage, ensuring a stable datum. Cables were fed through the hollow support arm to the logger box where the logger itself was housed. The whole assembly was constructed in the University engineering workshop over a period of 7 weeks in January 1995.

Figure 4-9 : Inlet station, instrument protective housing and intake structure

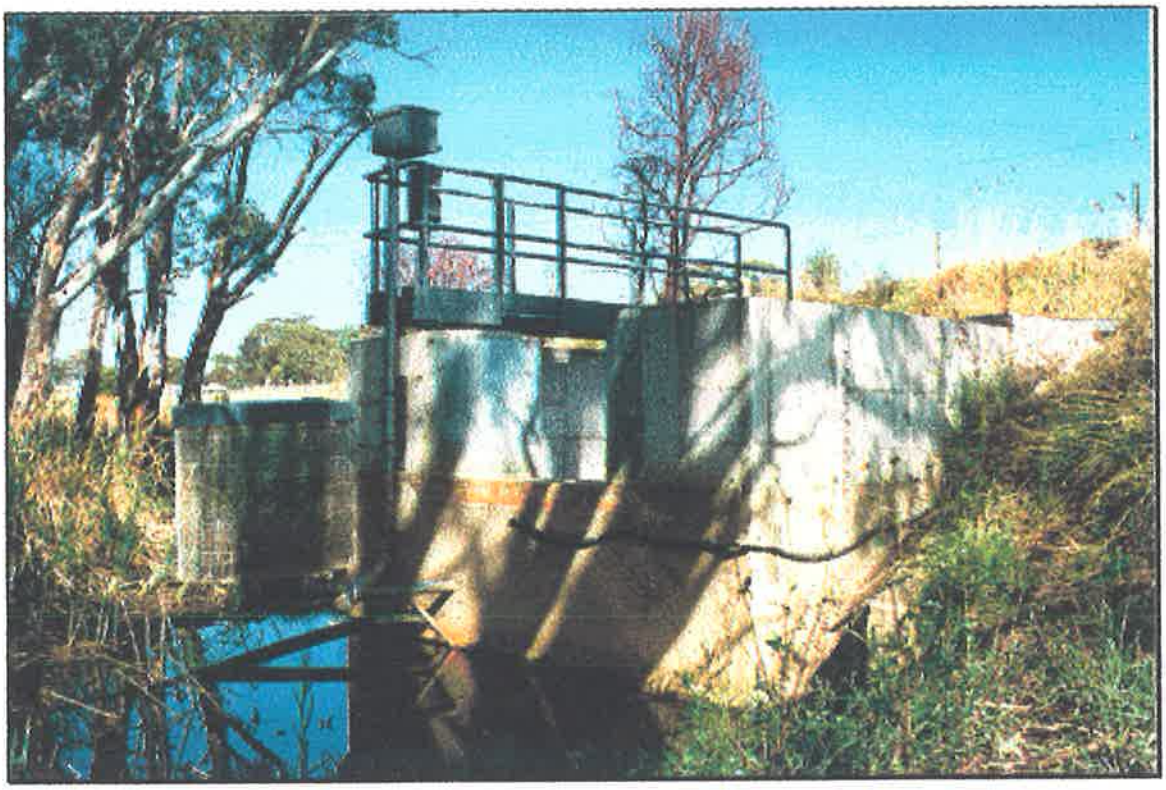


Figure 4-10 : Outlet station, instrument protective housing and intake hose

4.4.5.2 Use of Field Sensors to Trigger Sampling

The dissolved oxygen/temperature probes, pressure transducers, and turbidity sensors were seen as providing an extremely sensitive and flexible triggering mechanism for the samplers. The level of control sensitivity using a pressure transducer was much greater than when using a float switch. The pressure transducer also has the added advantage of reading the level at any given time rather than simply indicating when a particular level has been exceeded. It was decided to use the input from the inlet pressure sensor to trigger the water samplers. The pressure signal was sent via the DCEEL to the sampler control device much as the float signal had previously.

4.4.5.3 Trial of a Logic System for Sample Control

As part of the next improvement to the monitoring system, the 'continuous' level reading capabilities of the pressure transducer would be used by the controller. A system was devised whereby the controller logically initiated the samplers according to the previous few recorded levels. Details of this can be seen in Appendix D. This logic system was wholly based on inlet stage height representing flow rate. As can be seen in Figure 4-11, a plot of water levels at both inlet and outlet stations, there was not a significant difference in time or magnitude between these levels. The outlet weir was controlling the level at the inlet station even for the smaller events. The inlet station was in the back-water of the weir. A number of 'events' during the 12 day period were reverse routed and plotted against the water level at the inlet.

One of these small events can be seen plotted in Figure 4-12, showing the water level at the inlet still rising long after the peak flow has passed the station. This showed why the float switch had failed to trigger the samplers early enough in an event to enable them to capture the rising limb of the inflow hydrograph. This finding also made the pressure sensor at the inlet station obsolete as a method of controlling sampling at the inlet. The pressure sensor alone at this location would give greater triggering sensitivity than the float switch. However, in this location the pressure sensor was as ineffective as the float switch for picking up the initial stages of flow. The pressure sensor in this location was also ineffective for smarter sample distribution over the flow hydrograph when used in conjunction with the logic controller. If an improved triggering system was to be used it would mean moving the pressure sensor to a location further upstream, above the level of influence of the weir. The lack of a suitable flow calibration structure at the inlet, such as a v-notch weir, was deliberate.

A weir was not suitable, due to the wide flow front at this location and the natural aesthetic beauty of the site.

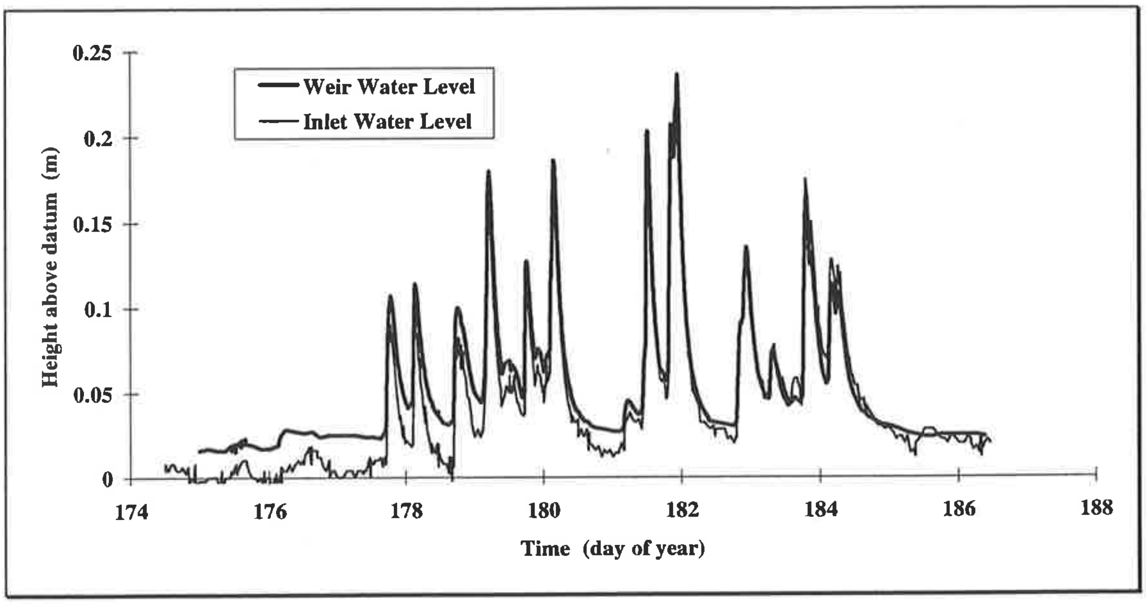


Figure 4-11 : Comparison of weir and inlet water levels for a period of two weeks

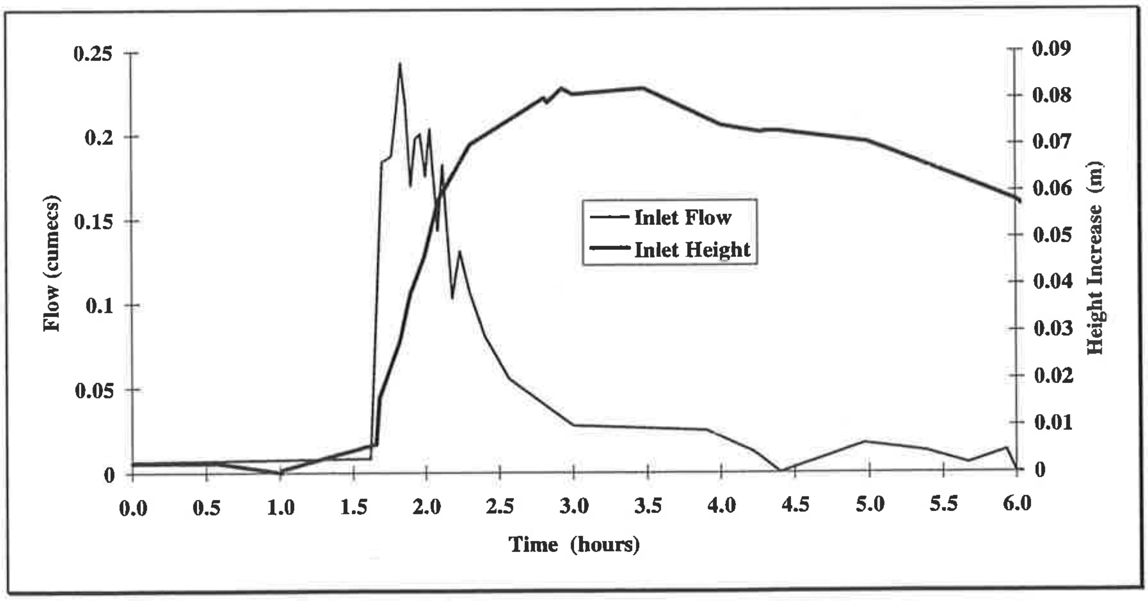


Figure 4-12 : Flow variation at inlet station with inlet water level during an event

4.4.5.4 Relocation of the Pressure Sensor Upstream

It was decided to keep the inlet pressure sensor as this was still the best available method of indicating the arrival of an event, as well as the other advantages of level indication and high sensitivity. A new pressure sensor location was found 70 metres upstream, comprising a small shallow pool in the direct flow path of any incoming event. This pool was approximately 1 metre higher in elevation than the inlet station and hence not under the influence of the weir. It was separated in elevation from the wetland itself by a small natural waterfall that can be seen in Figure 4-13. This made it a suitable location for indicating the initial stages of the event, as well as the time of the peak flow.

Figure 4-13 : Small waterfall separating the upstream pressure transducer from the inlet station level

Unfortunately relocation of the pressure sensor also meant an end to the use of the logic decision controlling scheme before it even got up and running. No survey data was available for the new pressure sensor site. Due to the depth of water at the site, negating an easy survey, and the lack of time to develop the full logic program with the new stage height/flow relationship, this path was not pursued any further. The largest fault with the previous time table system had been the pressure sensor's failure to pick up the first inflow and peak. This was now solved with the relocation of the sensor. In the interest of getting the best possible system up and running as soon as possible, the timetable option was again adopted.

The previous time table was in need of improvement as it had been based on some rather limited field experience, certainly not the best method available.

4.4.5.5 Determination of the New Controller Time Table

The new time table was determined by observing all storm events with a peak flow in excess of 0.2 cumecs, monitored at the overflow weir of the wetland in the two year record. There were 22 such events indicating the common nature of flows of this magnitude passing through the system. These were identified by using the hydrological archiving system HYDSYS (Hydsys Pty Ltd, 1994). These events were reverse routed (using the same technique described in Section 3.8.1) to determine the corresponding flow hydrographs at the inlet sampling station of the wetland. Through scaling of the plotted hydrographs the events were characterised by mean duration and time to peak, at both the inlet and outlet of the wetland, in a similar manner to that used by Kachka *et al.* (1994). Figure 4-14 and Figure 4-15 show one such storm plotted in this way, with the durations labelled. Figure 4-16 and Figure 4-17 show plots of the entire 22 characterised events, at the inlet and outlet respectively. Results of this process can be seen in Table E-I in Appendix E. Sampling durations were chosen to cover as many 'types' of event possible, from short fast peaking to longer slow peaking events. This decision was aided by plotting the parameters identified as being most crucial, time to peak and duration of flow. The sampling was split into two simple halves. The first phase, the rising limb, was designed to sample to the peak of the event. This period has long been recognised as a time when change in pollution and sediment levels is most rapid (Cullen, 1983). It has been suggested by Bedient *et al.* (1980) referenced in Kachka *et al.* (1994), that the minimum number of samples to define this phase for accurate pollution load determination is 4 samples. As a minimum of 12 samples were available for each event, allowing for 2 storms, 7 samples were used for this phase, leaving 5 for the second phase, the falling limb.

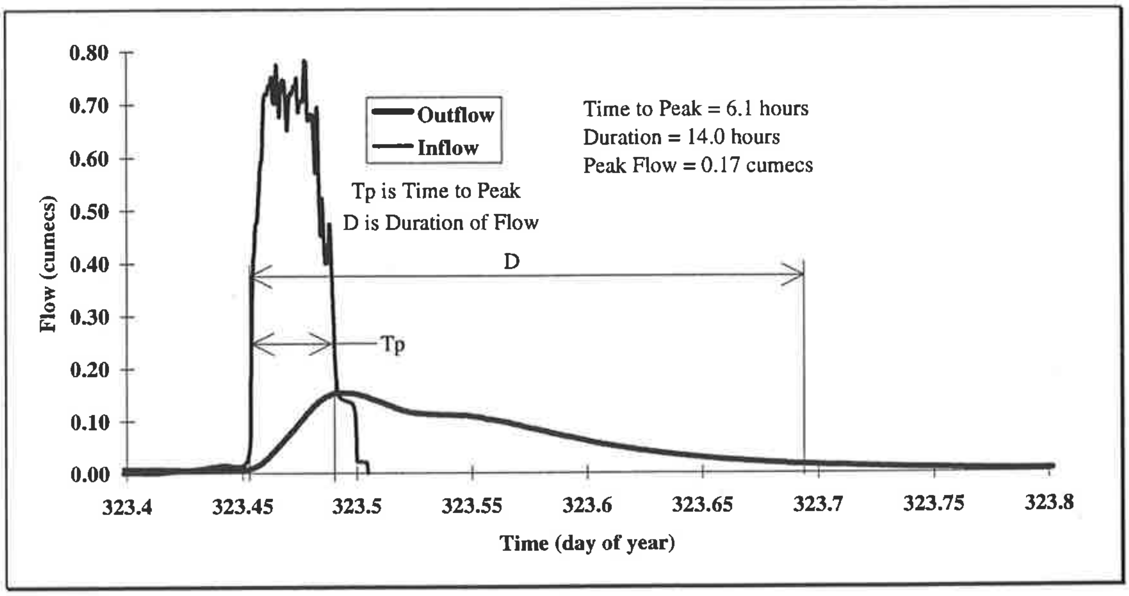


Figure 4-14 : Outlet flow example of the characterisation of an event by time to peak, and flow duration

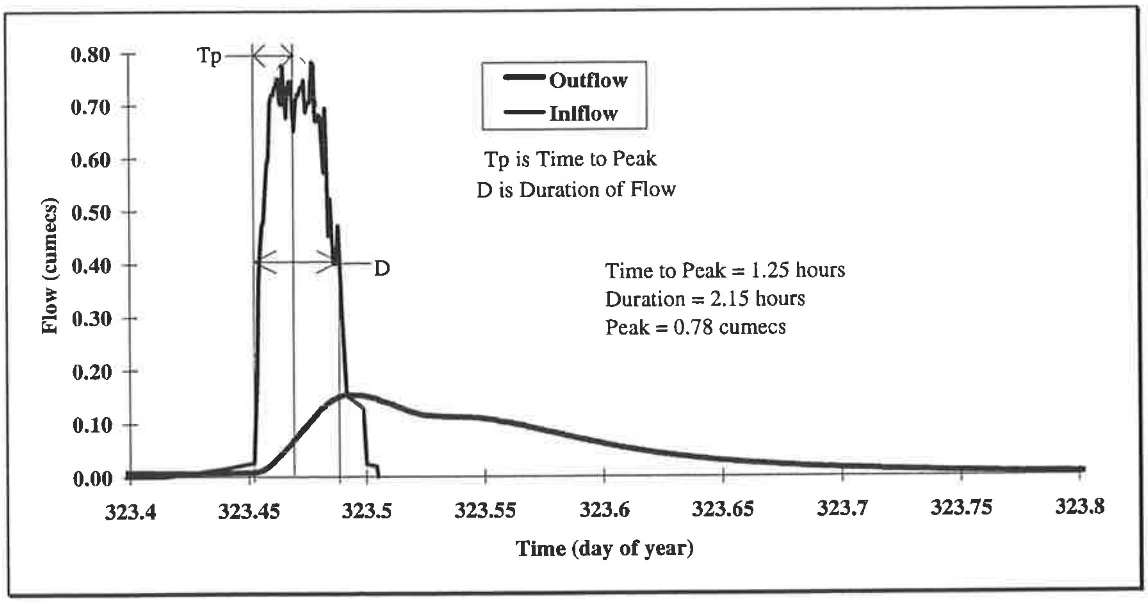


Figure 4-15 : Inlet flow example of the characterisation of an event by time to peak, and flow duration.

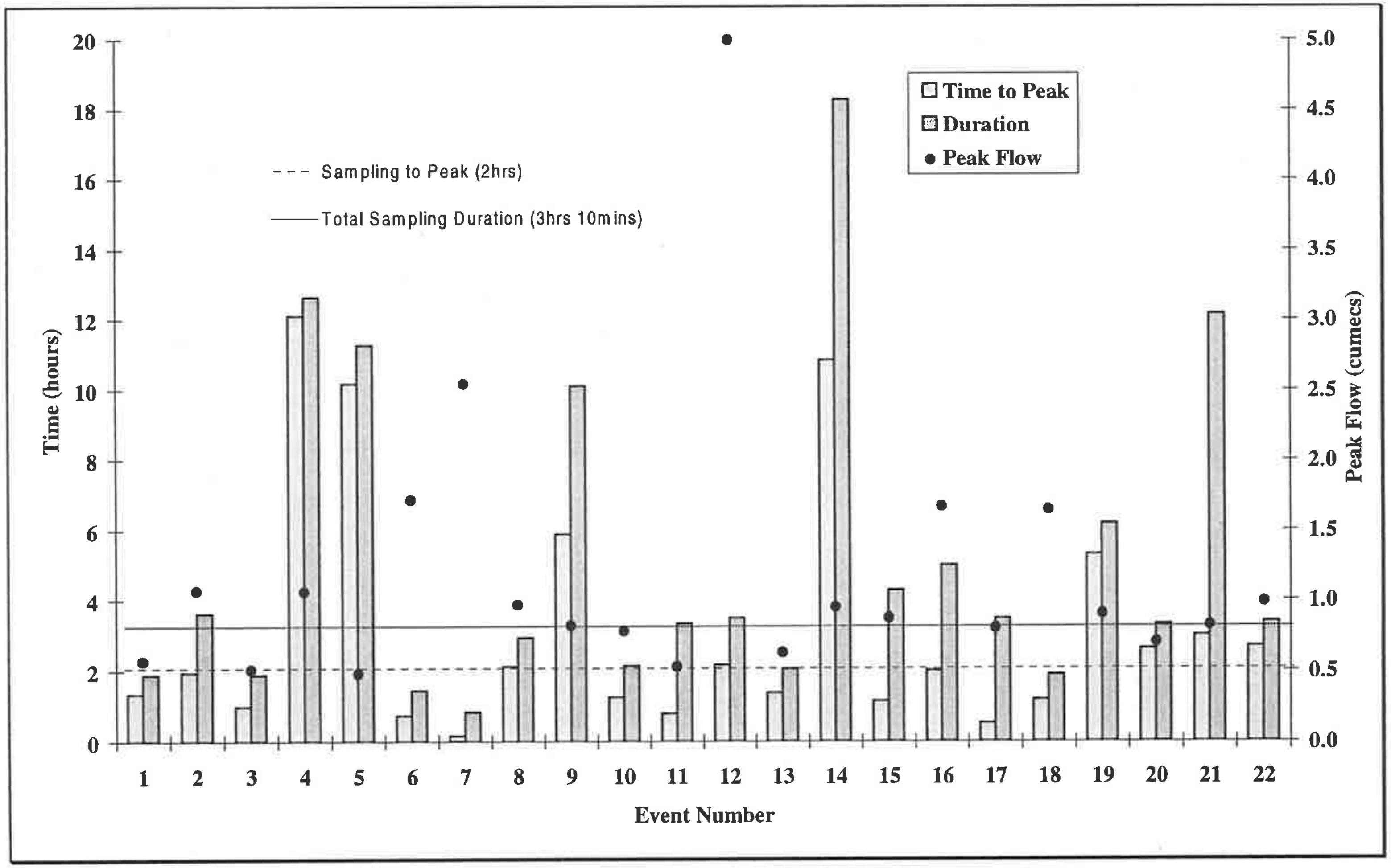


Figure 4-16 : Flow durations for the 22 inlet events with peaks ≥ 0.2 cumecs at outlet

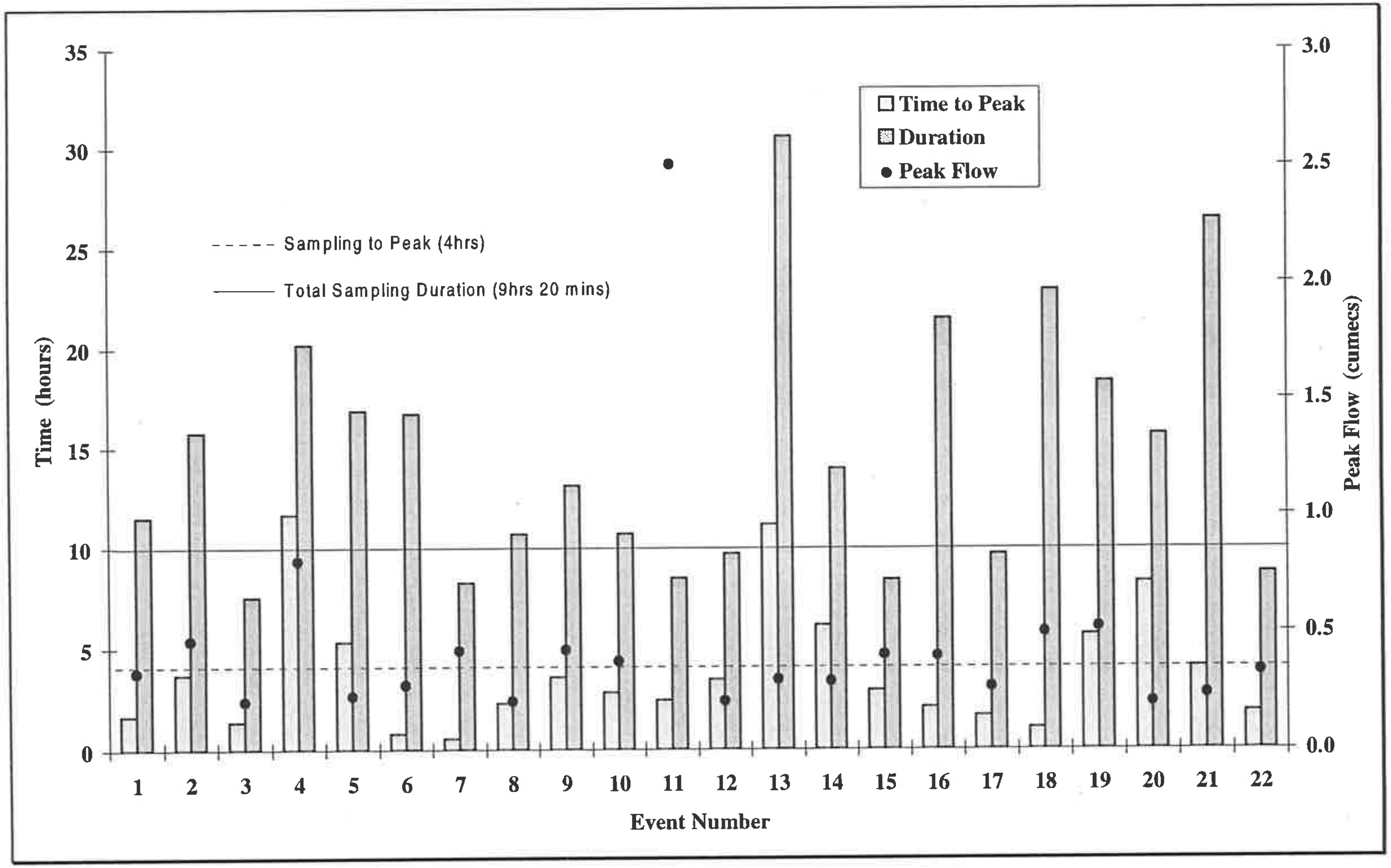


Figure 4-17 : Flow durations for 22 outlet events with peaks ≥ 0.2 cumecs at outlet

The final sampler controller timetable can be seen in Table 4-IV. Note that for the inlet station the frequency of sampling is higher than at the outlet because conditions there are more dynamic.

The timetable method relied on sampling for the longest period, with the highest frequency of sampling possible given the limited number available, in order to collect representative event flow data.

Table 4-IV : Final sampler controller timetable

Sample Number	**Inlet Sample Times First or Long Event** (mins)	**Inlet Sample Times Second Event** (mins)	**Outlet Sample Times First of Long Event** (mins)	**Outlet Sample Times Second Event** (mins)
1	0		0	
2	15		40	
3	30		80	
4	45		120	
5	60		160	
6	75		200	
7	90		240	
8	110		300	
9	130		360	
10	150		420	
11	170		480	
12	190		540	
13 (1)	210	0	600	0
14 (2)	230	15	660	40
15 (3)	250	30	720	80
16 (4)	270	45	780	120
17 (5)	290	60	840	160
18 (6)	310	75	900	200
19 (7)	30	90	960	240
20 (8)	350	110	1020	300
21 (9)	370	130	1080	360
22 (10)	390	150	1140	420
23 (11)	410	170	1200	480
24 (12)	430	190	1260	540
Total Duration	7 hours 10 mins	3 hours 10 mins	21 hours	9 hours 20 mins

Note also from Table 4-IV that the timetable still allowed for some sampling flexibility. There is the ability with such a timetable to sample two 'average' events, or one longer event.

The controller simply needed to recognise the current situation and continue on the correct table.

4.4.5.6 Operation of the Sensor Triggered System

The controller was modified to accept the pressure sensor signal. This allowed for an adjustable level to be set as the sampler trigger level. The sampler was reprogrammed with the new time table and additional decision making capabilities. The new information enabled sampling of two individual storms if the upstream water level had dropped below the trigger height between events. It also allowed a single long event to be sampled using the extended timetable if the upstream water level had not dropped below the initial trigger height after completing half of the total samples available.

All sensors had been installed and collecting data at the inlet station for a period of one month prior to the relocation of the pressure sensor, and installation of the modified controller. The inlet sensors had functioned without any fault during this period. The outlet sensors were installed at the same time as the modified controller. An example of the sampling distribution achieved with final system can be seen in Figure 4-18. Figure 4-19 shows the final field monitoring system at the conclusion of the field research. Gamble and Walker (1995) describe the systematic design and construction of the entire monitoring network.

4.5 Data Collection and Handling Techniques Used in this Study

A monitoring program had been carried out by the department of Civil and Environmental Engineering at the University of Adelaide in the Happy Valley region from July 1992. The collection of stage height data from the Minkara Wetland had been carried out as part of this for 18 months prior to the commencement of this project. With more than a ten fold increase in the amount of data being collected from the wetland a review of the data handling procedures was required, before problems arose and data were lost.

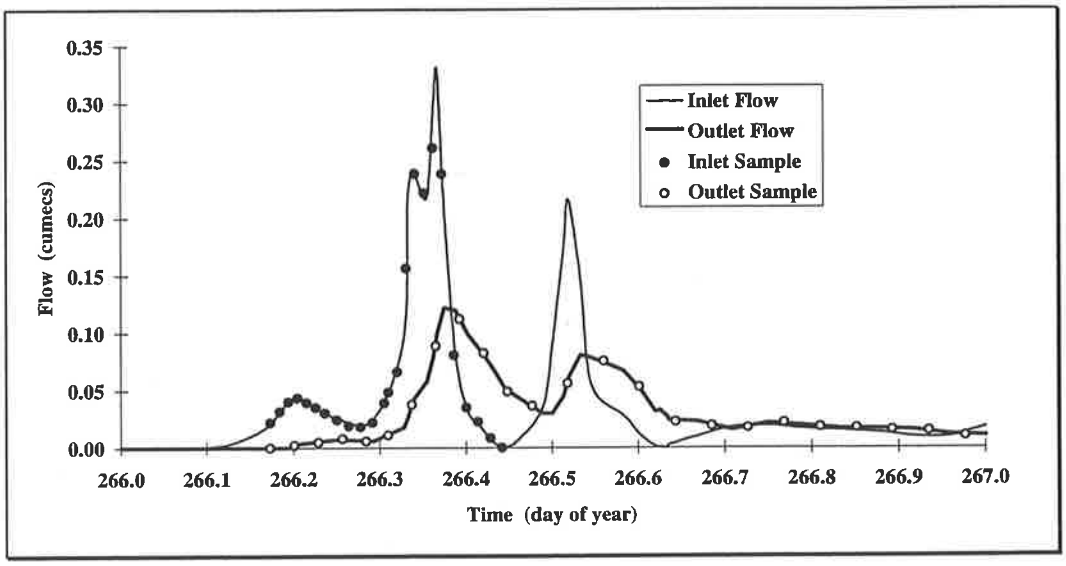


Figure 4-18 : Stage height triggered sampling with an external controller determining sampling frequency according to the final timetable, incorporating limited logic control

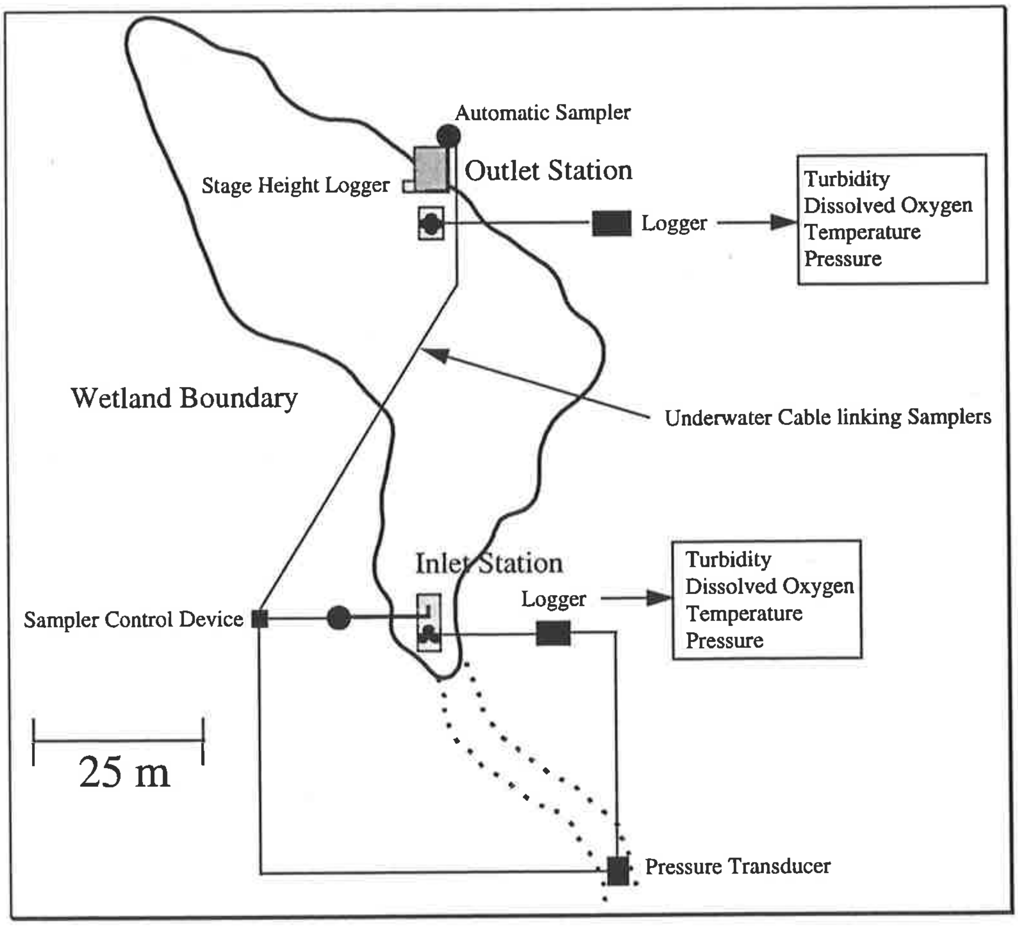


Figure 4-19 : Layout of the final monitoring system at the Minkara Wetland

4.5.1 Improvements to the Data Collection System

There were many serious errors with the previous system, due to the lack of any real systematic method of data handling, and a number of stage height files had gone missing. The first area targeted for review was the handling of data files on return from field collection. The first revision of the system was to set up a location on the engineering computer server to hold the raw data. As the information was highly important, a users group was formed, and those only closely involved with the project given access. The location was structured such that stage height files, water quality files, logger control files, and other data such as rainfall files all had defined positions.

Another problem with the old system was that backup files could not be located. As part of a house keeping exercise a series of disks were purchased and clearly labelled in appropriate categories, and a filing system used to keep track of all the data disks.

A further drawback of the previous system was that information regarding the overall coverage of the data was not easily accessible. Information as to what instruments were up and running at any particular time was available only by plotting a number of data files (not labelled by date) until the correct one was found. A computer program was written to automatically strip the essential information from the data files. It archived the logging information of each file, recording the time of field operation of the logger, and the dates when the logger was set and collected. A logger may have been initialised in the field two months previously, however, if the batteries fail after two weeks there is a large difference between the time in the field and the field operation time. This program was called "FILEARCH" for obvious reasons. By using this program, the logger failure times became far more easily seen, and solutions to the failures found earlier, resulting in a better data set. Another computer program was written to automatically add the latest data files information to a master file, containing coverage of all the previous data files. This program was called "Master".

An instruction sheet was written, detailing the procedure for backing up all data files, and updating the data coverage archives. This is shown in Appendix F, and formed part of the field book.

The next and perhaps most damaging fault of the previous system was the inadequacy of the field preparation sheets and field data collection notes. The preparation sheets contained insufficient detail on accessing the loggers and a lack of stress placed on what equipment was needed for each logger. Updating of these was needed as a matter of course to keep up with the development of the monitoring system. As can be seen in Appendix F the latest field preparation notes include information on timing procedures, now much more critical with three separate loggers at the one site. They also detailed the battery types required for each logger and sensor, and the batteries and bottles for the water samplers.

Contained within the field operation notes was information on how to access each of the 3 types of logger used in the region. Although not a problem with the loggers at the Minkara Wetland site, the rainfall loggers in the Happy Valley region require exact procedures to be followed, or risk losing the entire data file. Simplified but more precise instructions were provided with the new field operation sheets. Also added was information on how to set up the automatic water samplers, and to collect and label samples.

With the previous system a single sheet for each logger was used for the information on the timing and conditions for the collection of the data, as well as the file names of each data set. This meant a single sheet could contain all the information as to when a site was visited, the conditions of the batteries, and the file names of the previous year of record. If lost or damaged in the field there would be no record of battery performance in the last year, or indeed when the site was last visited. For the new data acquisition system, field sheets were designed for each logger or task, with a new template form to be filled out each visit. A number of these can be seen in Appendix G.

Having a separate sheet for each logger for each visit allowed greater information to be attained on the collection of the field data. This included whether there had been any problems with the downloading procedures and why, a good way to tell if the field operation notes were successful. Another addition to the collection sheets was instructions to the collector to check the functionality of the logger before leaving the site. In fact, certain settings on the loggers were detailed, and the collector was informed of their importance. Many of the faults of the previous system could be attributed to a lack of trust or confidence in the field workers. This caused data to be lost when changes were made to the logger settings without any knowledge on the part of the collector.

One problem with having a fresh form to fill out for each logger with every visit was that the new data file name was no longer at hand. A separate sheet containing all the past files names and the dates of collection was included with the field notes. This was updated every time a data file was downloaded. Another solution was to adopt a new file naming system where the filename is comprised of the collection time and date. As file collection had been under way for over a year, to maintain consistency this option was not chosen.

The field preparation sheets, logger operation sheets, individual logger collection sheets, file name sheet, and data handling sheet were all combined to form a field folder. This folder contained all the information available on the preparation, downloading, and backup of field collected data.

Folders were used to store the field collection sheets. In these were kept a backup of the file name sheet as well as the archive sheets for each logger.

As with the electronically logged field sensors, procedures were written up to detail how collection of the automatically collected water samples was to be carried out. Unlike the field probes, the water samplers had to be emptied and reset with clean bottles every day an event passed through. This called for regular visits to the wetland site. This was made less arduous when daily sampling began in September 1995.

4.6 Water Quality Testing Procedures

4.6.1 Cold Storage

The key to obtaining water quality information that accurately represents the condition of the water at any particular time is the quick sample collection, holding in cold storage, and immediate testing in the laboratory (Kachka *et al.*, 1994).

Refrigerated automatic samplers were not an option available for this sampling program due to budget constraints. Rather than disregard the idea of cooling the samples to prevent or slow changes in nutrient concentrations, a large chest freezer was purchased for sample storage in the laboratory. This was obtained as part of another wetlands water quality project at the University, and modified to keep samples at temperatures of 1 to 4°C. The aim was to collect samples as soon as practically possible from the samplers after an event and bring them back to cold storage.

The time such samples can be left in cold storage before changes in nutrient concentrations occur was investigated by Kachka *et al.* (1994). They concluded that samples for nutrient analysis should be stored under refrigerated conditions for no longer than 18 hours after collection. This information was used as a guide throughout the testing program of this research. Wherever possible samples were collected, refrigerated, and tested for phosphates and nitrates within this 18 hour time frame. Times of sample testing were recorded so that degradation in the constituents could be monitored if delays in testing occurred. Sediment tests were carried out at times exceeding this limit by up to a couple of days.

4.6.2 Nutrient Tests

As mentioned in Section 4.4.3.3 the Palintest Interface Photometer 7000 was used for all phosphate and nutrient tests. It was important that testing procedures provided repeatable results which allowed valid comparison across samples. The testing techniques themselves were the most accurate available for the project budget and can be considered to provide good indication of phosphate and nitrate concentrations.

Instructions supplied with the photometer were followed precisely. Appropriate detergents (Nalgene laboratory detergent) and cleaning products were used to ensure there was no sample contamination. Deionised water was used for rinsing purposes. Accurate timing was used for all chemical reactions. A study on the effect of incorrect timing procedure when using the photometer was carried out by vacation students under the supervision of Dr David Walker. This showed conclusively that sample concentrations varied with the time of reading. For this reason accurate timing was strictly enforced.

The Palintest photometer kit comprises of a photometer unit, a number of light transmissive test tubes, and individual chemical packs for each of the tests. These contain tablets and/or powders to be crushed and mixed with the sample to form a test solution in the test tubes. The kit may be seen in Figure 4-3. An untreated sample tube is tested for the transmission of a particular wavelength of light in the photometer unit, and this is compared to the treated sample. The concentration of the determinand is then displayed.

All through the nutrient testing program, each individual sample was read a minimum of 3 times in the photometer unit, to ensure a stable result. The problem of variation with sample reading was discovered in the study carried out by Dr David Walker mentioned above. This study showed that the same sample, when tested a number of times in the same manner, yielded different concentrations. This problem was avoided by repeatedly reading the sample until a stable value was reached. The cause of such an error may be attributed to moisture on the outside of the test tube, which should be removed, or the alignment or position of any particles in the solution reflecting the light, affecting the reading.

4.6.3 Sediment Tests

Each field collected sample was tested for total suspended solids and total dissolved solids. Unlike the nutrients the sediment water quality parameters were not considered to change considerably with short periods of time, in the order of 2-3 days. For this reason all nutrient tests were carried out before sediment tests. In addition to this, the temperature of the refrigerated samples was found to adversely affect the performance of the TDS probe. Some time was needed until a stable reading could be achieved at such a low water temperature. Concentrations would slowly rise over a period of 5 minutes, due to the rising water temperature. To avoid incorrect concentrations and delays in the reading of TDS, the samples were left out of refrigeration to achieve room temperature prior to this test, allowing quick stable readings to be obtained. When carrying out this test the probe was washed in deionised water prior to each test to prevent contamination.

TSS tests were carried out using 0.7 µm glass fibre filters and the Nalgene filtration equipment as mentioned in Section 4.5.2.3. Standard Methods (1980) were carried out during all the TSS tests. All samples were adequately mixed to ensure a uniform sediment concentrations throughout the sample. Deionised water was used to rinse out the upper tray of the filtrator, and filter papers were dried at 104 °C for sufficient time as to remove all moisture, as outlined in Standard Methods (1980). All transfers of filters were carried out with tweezers so as not to remove or deposit any further material on the filter, and also to ensure no moisture was picked up by the filter from the oven to the scales.

4.7 The Implication of Safety Issues to this Field Study

A point raised at the meeting held in December 1994 was that of the safety of personnel while undertaking data collection. It had been mandatory for a single site visitor to carry a mobile phone with them at all times since the installations began in June 1994. This was seen as an inadequate safety mechanism, since any fall off the weir structure or into the water may render the phone useless or incapacitate the carrier. Whilst working conditions on site were considered unsafe, internal guide-lines were put into place, requiring 2 personnel to attend the data collections or carry out field work. These guidelines were issued only as a short term solution to a problem that would continue until better protection devices were installed, at both the inlet and outlet sampling stations. Safety platforms were needed at both locations to enable field personnel to safely obtain access to the logging units and to clean equipment.

At the outlet station, the weir, obtaining access to the stage height logger at one corner of the weir was a safety issue. A balance act was required simply to reach the unit, with a 3 metre fall onto concrete on one side, and water on the other. Up until this research began the use of the weir as a station was so infrequent that danger to visiting personnel had not been recognised. A platform/walkway was constructed to enable the collector to safely access the stage logger and the water quality logger which at this stage was planned to sit along side it. The platform was constructed in the University engineering workshop over a period of 7 weeks from January to March 1995. There was no monitoring during this period as the wetland was drained as discussed in Section 3.6. Building the platform in-house was a great advantage when modifications were needed to integrate the outlet station monitoring equipment with the structure for access and operation reasons. A gate was positioned to allow safe access to the weir spillway via a ladder. The walkway can be seen in Figure 4-10.

At the inlet station the problem of safety was less critical. There were no high wire acts required to download data. The station was still unsafe, however, as in order to reach and open the logger box support with one hand was needed for balance. This left one hand to plug in leads and change batteries. A small platform was required to allow a safe comfortable standing position near the logger. Like the walkway this was built in the University workshop. This can be seen in Figure 4-9.

4.8 Budget

Table 4-V outlines all major expenditures over the 2 year running time of the research project. The initial funding of $19,000 donated by Happy Valley Council was sufficient to meet most of the hardware requirements. Of note, however, is the supply of a number of crucial components from other related research carried out at the University. These included an automatic water sampler, a turbidity meter, the sample storage freezer, and a stage height sensor and logger. Together these totalled approximately $7,500, a useful contribution without which the project would not have been possible. It would seem then for a project of this size, $25,000-$30,000 is necessary simply to cover the hardware and related safety and protection equipment.

Table 4-V : Budget for the research project

Instrumentation	
Item	**Cost**
Tain Electronics Turbidity Meter	$760
Greenspan Dissolved Oxygen / Temp Probe (2)	$880
Tain Electronics Pressure Sensor	$280
Gamet Waste Watcher Automatic Water Sampler	$4,750
Microbits Workstation	$3,250
Dryfit Lead Acid Batteries	$500
Microprocessor Units (3)	$250
8 Channel Recorder	$800
Total	**$12,800**
Safety Equipment	
Item	**Cost**
Padlocks	$160
Crane Hire	$130
Transport	$130
Mesh	$320
Plate	$110
Elbows	$35
Galvanised Tube	$100
Bolts and Washers	$100
Steel Tubing	$200
Total	**$1,285**
Testing Equipment	
Item	**Cost**
Palintest Interface Photometer 7000	$2,000
Test Tubes	$100
24 Gamet bottles	$110
Sediment Filters (2)	$120
Palintest Chemical Analysis Tablets	$450
Total	**$2,900**
Miscellaneous	
Item	**Cost**
Agricultural Tubing (2)	$35
Telephone Cable (2)	$50
XP-SWMM Software	$750
XP-Aqualm Software	$750
Deltagraph Software	$220
Data Storage Tape	$45
Tubing / Connectors	$100
Slides / Photos	$40
Total	**$2,075**
Grand Total	**$19,060**

was lost whilst work on these improvements was carried out, however, advancements were achieved in water quality sampling methods. Further time was lost whilst the wetland was drained in the Summer of 1994/95. With these developmental delays this left a total of 8 months for the collection of the data set. The following collection techniques were used:

- automatic event grab sampling;
- automatic field sensor logging; and
- daily grab sampling.

Throughout the research period a total of 8 events were sampled and laboratory tested. The information and the quality of this information varied depending on the state of the monitoring systems at the time of collection.

In addition to the direct water sampling of events, a system of logged field sensors was operational for a period of 4 months from June to November 1995. This provided information on temperature, dissolved oxygen, and turbidity, during both event and quiescent periods.

Table 5-I details all the event monitoring, the current stage of network development and the available data set for each event. Note the large time delay between monitoring in November 1994 and September 1995. It was during this period that the majority of the developments to the monitoring system took place, as mentioned in Section 4.4.

In addition to the event data collection, a daily sampling program was initiated in September 1995, and ran over 64 days. Grab samples were taken at the inlet and outlet stations, and further upstream above the natural channel system, at the point where the concrete stormwater network ended. The purpose of this daily grab sampling was twofold. Firstly, to allow the longer term behaviour in the period following an event of the wetland to be viewed, and secondly, to gain an understanding of the affect of the natural, heavily vegetated upstream channel.

Table 5-I : Summary of the date and available information of all collected event data

Event Number	Date	Time Delay Sampling	Float triggered preliminary timetable sampling	Pressure transducer triggered developed timetable sampling	Sediment and Nutrient Data	Field Sensors
1	24/06/94	✓			✓	
2	26/10/94		✓			
3	12/11/94		✓			
4	13/09/95			✓	✓	✓
5	23/09/95			✓	✓	✓
6	30/09/95			✓	✓	✓
7	02/10/95			✓	✓	✓
8	11/10/95			✓	✓	✓

By sampling at approximately the same time each day, and testing as soon as possible afterwards, a good picture of the time effects on nutrient and sediment concentrations was possible. These daily data were used to determine decay rates in quiescent periods for the nutrient and sediment parameters.

5.4 Data Treatment of the Automatically Sampled Events

The data obtained from the collection of event flow specimens using automatic samplers was comprised simply of an output file from the water sampler controller, and the results of the sediment and nutrient tests. The output file indicated the timing and success of each sample. The flows at both the inlet and outlet were required for the duration of the event. A weir flow calculation and reverse routing procedure was carried out for the event, as described in Section 3.8.1, yielding the inlet and outlet flow records. An example of this can be seen in Appendix B. Using spreadsheet analysis the flow at the time of each sample was calculated at both the inlet and outlet sampling points. By determining the flow at the time of sampling in the event hydrograph prior to chemical analysis, much laboratory time could be saved should the sampling time be unsatisfactory. An example of the plot created prior to laboratory work once field samples were collected, which indicates the flow at the sampling location at the time of sampling, can be seen in Figure 5-1. From a plot of this type the success of the sampling program can be viewed easily and directly. The entire set of sample time plots for the 8 events can be seen in Appendix H. Before making any strong statements as to the event performance during an event, or long term behaviour of the wetland, it was important to know when in the record the information on these observations was based.

Analysis of the water samples was then carried out as described in Sections 4.6.2 and 4.6.3, this yielded the additional constituent information desired, such as nitrate and phosphate concentrations. An example of the results of this analysis can be seen in Table 5-II for Event 5, monitored on 23/09/95. This was the first step in data analysis and interpretation.

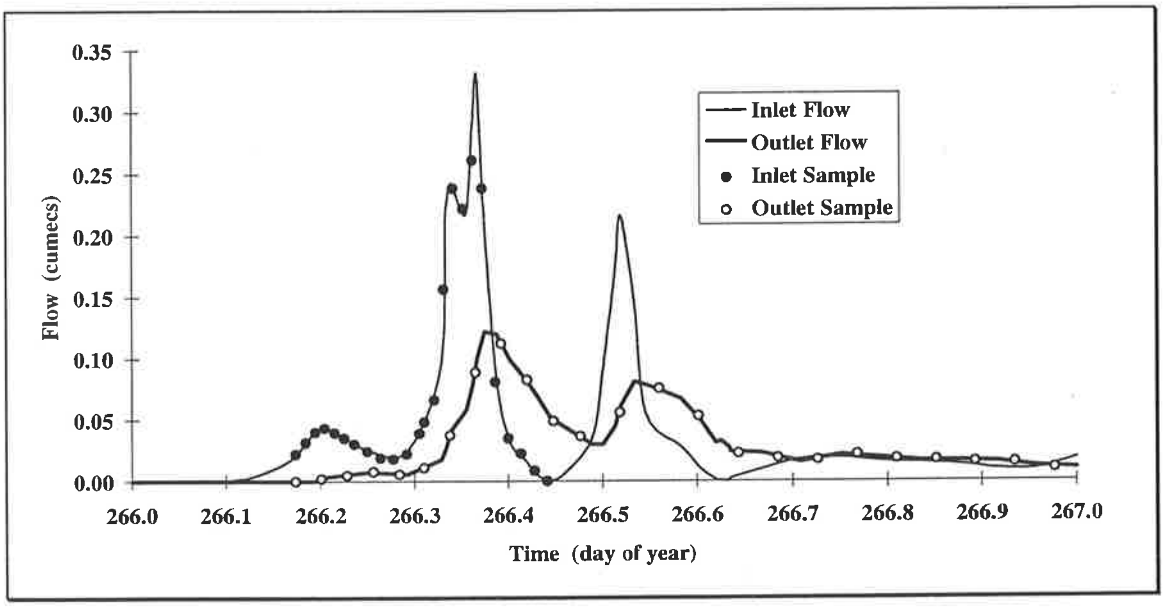


Figure 5-1 : Example plot of flow at sampling time, for Event 5, monitored on 23/09/95

Table 5-II : Water quality and flow results from Event 5, monitored on 23/09/95.

WEIR SAMPLES							INLET SAMPLES						
Time (day)	**Time YMDHM**	**Flow (L/s)**	**TDS (ppm)**	**TSS (mg/L)**	**Nitrate (mg/L)**	**Phosphate (mg/L)**	**Time (day)**	**Time YMDHM**	**Flow (L/s)**	**TDS (ppm)**	**TSS (mg/L)**	**Nitrate (mg/L)**	**Phosphate (mg/L)**
266.173	9509230409	0	550	10.22	0.00	0.05	266.173	9509230409	22	800	18.10	0.01	0.08
266.201	9509230449	2	700	4.31	0.00	0.06	266.183	9509230424	32	740	30.25	0.05	0.20
266.228	9509230529	5	830	4.69	0.00	0.07	266.194	9509230439	40	620	24.67	0.08	0.16
266.256	9509230609	8	700	4.38	0.00	0.08	266.204	9509230454	44	390	13.27	0.09	0.10
266.284	9509230649	6	690	5.19	0.00	0.08	266.215	9509230509	40	320	8.50	0.07	0.10
266.310	9509230726	11	800	5.83	0.00	0.09	266.225	9509230524	35	250	7.89	0.04	0.06
266.338	9509230806	38	900	6.07	0.00	0.08	266.235	9509230539	30	250	7.74	0.04	0.08
266.365	9509230846	88	990	6.25	0.00	0.16	266.249	9509230559	24	250	5.44	0.04	0.04
266.393	9509230926	108	850	8.30	0.02	0.12	266.263	9509230619	19	270	5.76	0.02	0.07
266.421	9509231006	82	810	9.93	0.03	0.10	266.277	9509230639	22	280	5.71	0.01	0.08
266.449	9509231046	49	820	9.38	0.01	0.09	266.291	9509230659	39	330	5.54	0.00	0.08
266.476	9509231126	36	750	8.92	0.02	0.06	266.305	9509230719	48	340	4.81	0.01	0.08
266.518	9509231226	56	850	7.32	0.01	0.04	266.310	9509230726	0	340	1.80	0.02	0.08
266.560	9509231326	75	810	7.94	0.00	0.04	266.320	9509230741	66	320	15.07	0.00	0.12
266.601	9509231426	53	550	7.64	0.00	0.08	266.331	9509230756	156	220	51.08	0.04	0.30
266.643	9509231526	22	500	6.83	0.00	0.11	266.341	9509230811	238	130	28.67	0.03	0.16
266.685	9509231626	19	480	8.89	0.00	0.08	266.351	9509230826	222	120	17.07	0.03	0.15
266.726	9509231726	17	270	15.14	0.00	0.08	266.362	9509230841	261	90	5.48	0.02	0.13
266.768	9509231826	22	180	11.15	0.00	0.08	266.372	9509230856	238	70	25.00	0.00	0.19
266.810	9509231926	18	N/A	N/A	N/A	N/A	266.386	9509230916	81	80	17.67	0.00	0.09
266.851	9509232026	17	N/A	N/A	N/A	N/A	266.400	9509230936	35	100	12.05	0.01	0.07
266.893	9509232126	15	N/A	N/A	N/A	N/A	266.414	9509230956	22	110	8.60	0.00	0.07
266.935	9509232226	15	N/A	N/A	N/A	N/A	266.428	9509231016	8	130	7.64	0.00	0.07
266.976	9509232326	10	N/A	N/A	N/A	N/A	266.442	9509231036	0	150	6.02	0.02	0.07

Plots of the sampled water quality variables against the flow record for the particular event were then constructed. This gave a good visual description of the behaviour, and was a logical first analysis step. Examples of the plots created from this spreadsheet analysis for Event 5 (monitored on 23/09/95) can be seen in Appendix I. One of the plots in this series is displayed in Figure 5-2, showing the total dissolved solids concentration at both the inlet and outlet stations throughout the event, and the flow hydrograph. This method of plotting aids in the determination of trend behaviours and identification of peak reductions, but only in a event by event context. No long term average performance criteria can be obtained directly from this form of analysis. This type of plot is also extremely helpful when carrying out further analysis such as load calculations. Discrepancies or unexpected results were easily explained when the visual aid of the flow and constituent concentration sequence was available.

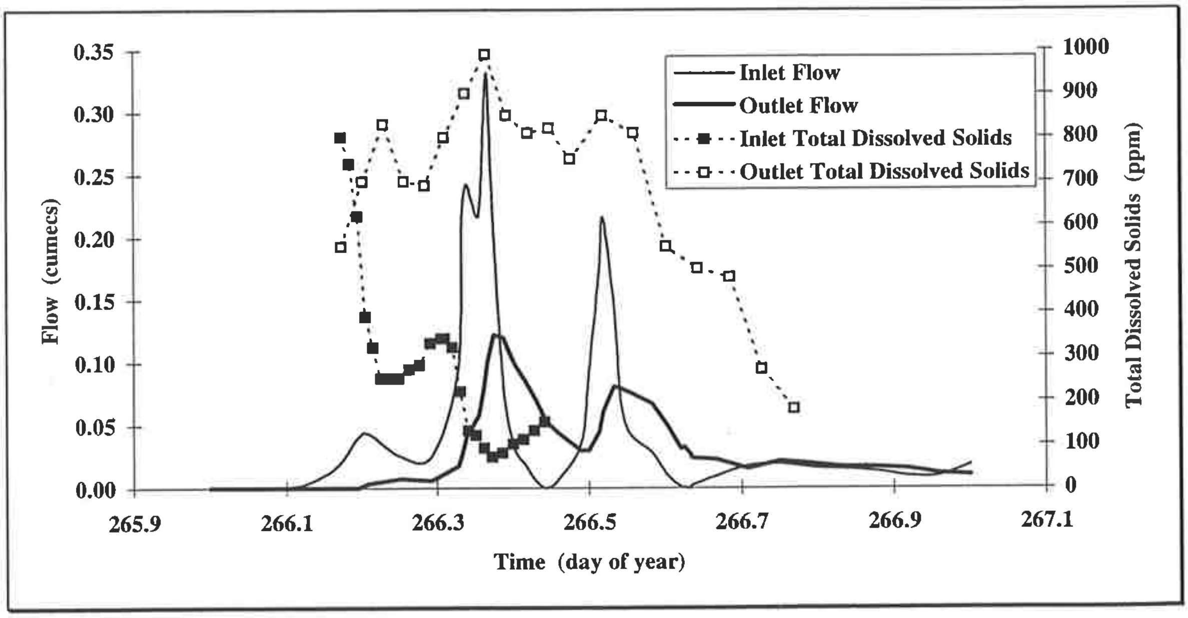


Figure 5-2 : Example of a water quality constituent plot, for Event 5, monitored on 23/09/95

5.5 Classification of Events to Aid in the Explanation of Wetland Behaviour

To aid in the detection and explanation of trends and relationships between event water quality constituents, a number of key factors were identified as being the most likely influences on behaviour. These were:

- event flow volume, relative to basin volume and catchment (ARI);
- peak flow;
- event duration;
- effluent detention time;
- rainfall conditions; and
- antecedent conditions.

Identification of the variables affecting water quality constituent concentrations was the first and most important step in the process of identifying trends in wetland behaviour. By describing the hydraulic and hydrologic characteristics of each event using these parameters the identification of atypical or outstanding events was possible. This helped in providing possible explanations for notable event results.

Definition of many of the parameters identified above involved subjective decisions. The most judgemental and wide reaching decisions were included in the event duration calculation. For this calculation, the definition of the event was set by a combination of flow and water quality record. Generally speaking the event hydrographs were shaped in a similar fashion to the idealised skewed bell curve, and were sampled adequately to enable easy determination of the water quality parameters detailed above. In three cases, however, such as Event 5 as seen in Figure 5-1, two events occurred in quick succession, such that sampling occurred over both events. A similar situation occurred for Events 3 and 8. For these events water quality information was available only at the outlet for the second peak.

To allow for analysis of a complete "event", the information collected on the second peak was discarded. As the inflow had ceased between the two peaks, the definition of the shortened events was easily observed at the inlet. The situation at the outlet was not as straight forward. Visual inspection of the hydrograph clearly indicated the sharp increase in outflow, as flow from the second peak reached the weir. An assumption as to the shape of the hydrograph without the influence of this second inflow was made, and the falling limb of the outflow hydrograph was extended to zero flow, purely for duration purposes. This extension was achieved simply using the rate of outflow prior to the influence of the second event. In this way it was not necessary to manufacture water quality data for the partially sampled inlet record, a technique that was considered to introduce greater error than shortening the outlet record. Event 5 was then treated identically to the other 6 events, the flow and duration marked by the end of the extended outlet hydrograph. An important point to note here is that the water quality information collected during the period covered by the artificial extension of the outlet hydrograph was discarded and not applied to this period. Only the data collected up to the extended period was included. Although this presented an error in the water quality load calculation this was minimised by the fact that the period of extension was not large, and that the flow during this period was low. This method was by no means ideal, however, the alternative was to analyse an incomplete event and have no direct method of determining constituent loads, or to discard the entire event. As data were scarce these were seen as less desirable options.

Initial parameter calculations identified Event 1 as particularly outstanding. This event had by far the highest flow volumes and durations. This was not due to hydrologic behaviour, rather a result of the poor monitoring system in place at this time. There was a low frequency of sampling for this event, an absence of triggering, and poor sample timing. Event 1 was not included in the analysis of the water quality constituents for these reasons. This is clearly apparent in the event sampling plot for Event 1, in Figure H-1, Appendix H.

5.5.1 Calculation of Event Flow Volumes

The calculation of event flow volume was a simple procedure, the desired accuracy of the result dependent on the technique and the quality of flow information used. As one of the prime aims of the evaluation phase was to determine event constituent loads, a method that would enable the easy verification of that calculation was selected.

Event flow, and then in turn load calculation, was carried out by a discrete summation method, due to the non-continuous nature of the data. The water quality information of each sample, flow in the case of event volume, was used as the midpoint of a time band of width equal to the time interval between consecutive samples, and applied over that time interval. For the total flow volume calculation the flow rate at the time of sampling was applied over this time band, to yield the flow volume for that duration. These individual flow volumes were then summed over the entire sample record to yield the total event flow volume. This process can be seen more clearly seen in Figure 5-3.

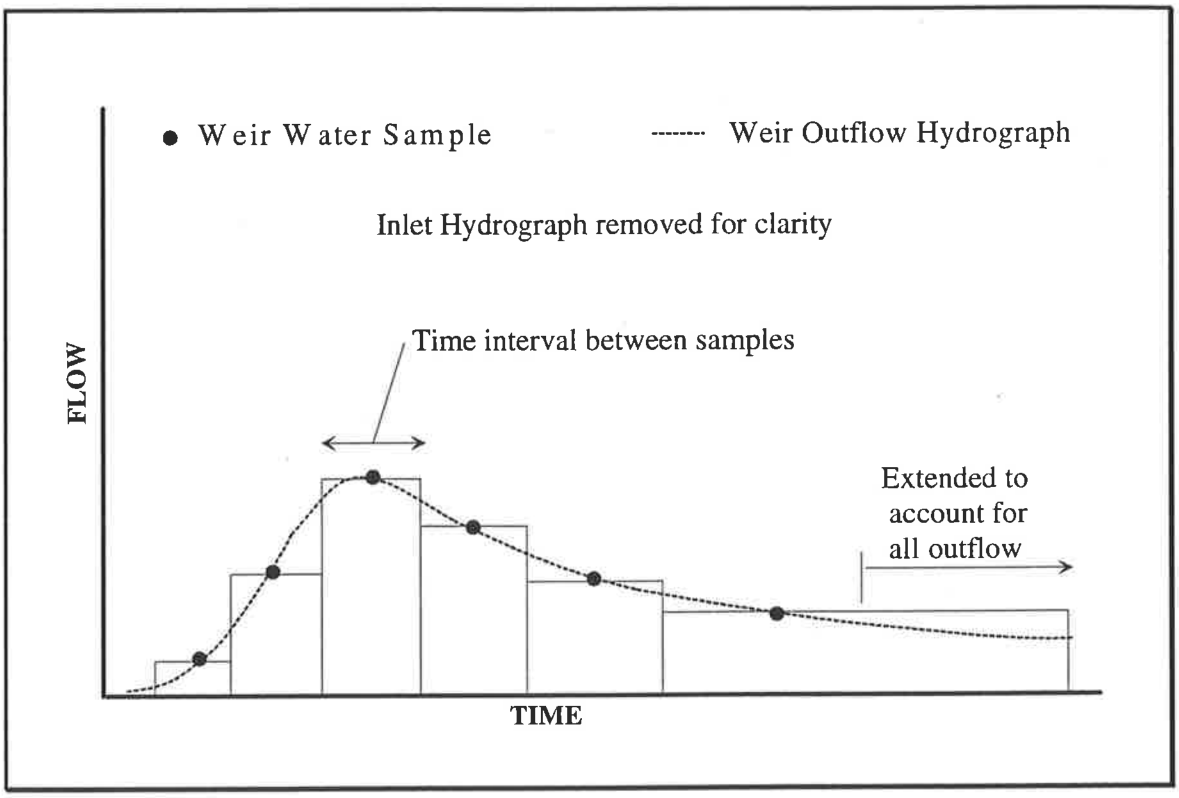


Figure 5-3 : Example of the event flow volume and load calculation procedure

The primary concern of this process was to ensure the inlet and outlet flow volumes corresponded. The basic law of conservation of volume was used to check that the hydrographs had been divided such that all of flow hydrograph was accounted for. In some cases there were no samples at the end of the hydrograph. In these instances it appeared that more flow entered the wetland than left, a nonsensical situation. The easiest and least assumptive corrective measure was to extend the final samples time of applicability such that the outflow equalled the inflow, and continuity was maintained. In one case the inflow hydrograph was not covered at the start of the event and the first samples band was extended backwards in time to include more inflow. These simple corrections were well justified but did, however, change the event volume, and hence load calculation. The error was possibly more significant in the load calculation where the water quality information obtained at the time of sampling was applied over an even greater range of time and flow. In other words, no account was made of the possible significant change in water quality constituent during the extended period of applicability. This time extension was necessary, as no other information was available as to the state of water quality during this unsampled period. It was more justified to extend length of time that a known state existed, than to falsely produce water quality data. One point to note here is that changes to water quality variables at the end of an event, when flow changes are slow and volume passing are low, are themselves slowly changing. This in some ways alleviates the inaccuracies of the extension to the duration of the sampling period.

As a comparison the discrete flow integration technique was repeated using, the higher frequency hydrograph information collected by the stage height recorder at the weir. In this case the time bands were narrower as flow data was available at a higher frequency than the water quality data. Variations between the two methods were of the order of 10-15%, an acceptable level, and not a crucial factor given a consistent approach had been used for all events allowing for a impartial comparison.

The results of the procedure can be seen in Table 5-III, the summary of the event flow volume process. Also included in this table are the percentages of wetland basin volume represented by the event flow volume and the contribution of inflow to monitored effluent. The effluent contribution percentages were calculated using results published by Walker (1996) from modelling the Minkara Wetland. Using the basin geometry of the wetland, derived from the survey work discussed in Chapter 3, a series of model runs were carried out for a range of event volumes of one hour duration. The models were run to steady state, or zero outflow, and the percentage of inflow present in the outflow calculated, yielding a coarse range of mixing, or hydraulic efficiency coefficients. Detailed modelling work carried out on the Minkara Wetland revealed that the percentage of inflow retained, and hence the amount of current basin volume displaced, is a function of event volume and basin geometry. Through carrying out several model runs of various sized events a broad range of hydraulic efficiency factors were derived. These efficiency factors relate the percentage of event runoff leaving the basin as effluent, to the flow volume, for a range of flows. With this information the *in-situ* volume displaced for each event can also be calculated. This greatly aids the determination of the relative proportion of *in-situ* and event volume in the monitored effluent, and can help explain observed behaviour.

Table 5-III : Results of the event flow volume calculation

Event Number	Event Flow Volume (m^3)	Percentage of Basin Volume (%)	Percentage of Inflow as Effluent (%)
2	615	23	20
3	552	20	20
4	2874	106	40
5	1591	59	30
6	675	25	20
7	2490	92	35
8	718	27	25

Events of greater volume contribute greater percentage of event runoff to wetland effluent, as would be expected. Due to the degree of mixing within the wetland, for the inflow to become the dominant source, event volumes of many times the available basin storage are required.

As apparent in Table 5-III, half the events monitored provided less than a third of the basin volume, and only one of the 7 events monitored, Event 4, contained more volume than the wetland basin. If plug flow conditions were assumed, Event 4 was the only event monitored where the effluent sampled originated from the current flow event, and only a small fraction of that event flow. As already highlighted by Gamble and Pannell (1993) and Walker (1996), plug flow conditions do not exist in the Minkara Wetland, however, this statement highlights the influence of *in-situ* water conditions on effluent water quality when such small events are studied. If, as is the case for the Minkara Wetland, there is both a degree of mixing of wetland and inflowing waters and a degree of short circuiting, analysis of event water quality becomes complicated. Given that the composition of the effluent for each event varies depending of event size, the contribution of *in-situ* water on water quality of the effluent varies also. The water quality characteristics of the *in-situ* water depend largely on the detention time of that storage. This is addressed in the calculation of detention time, and will be discussed in Section 5.5.4. The combined application of event flow volume and detention time in explaining wetland performance is critical, therefore, in determining the relative ~~a~~effect of each event source on the overall water quality of the monitored effluent.

In all of the events monitored the effluent was comprised in the majority of *in-situ* water. A total of 4 out of the 7 events monitored produced 25% or less of flow originating from current event runoff. It is likely, therefore, that the monitored effluent reflected the water quality of the storage volume and not the event runoff. This can result in the mis~~s~~-interpretation of the water quality of the individual event, and is a restriction on the success of event based monitoring programs. This point will be further expanded as further information on the influence of *in-situ* water is addressed.

5.5.1.1 Determination of Event Average Recurrence Intervals

This calculation was included to allow for the evaluation of the magnitude of the monitored events on a catchment scale. The calculation of an event's average recurrence interval (ARI) generally involves plotting a large series of annual or partial series flow maxima collected from the catchment concerned according to a plotting position. Where this data is not available, long term rainfall records can be substituted, provided a strong correlation can be achieved with the limited flow record over the overlapping period. In the case of the Minkara Wetland catchment, insufficient flow data was available, with less than 3 years complete record. The alternative of using rainfall for the catchment was not an option, due to the short record at both local sites, one at Happy Valley Reservoir, and one at a nearby school.

Another option was to use a technique published by Akter (1992) and Eusuff (1995) for regional flood frequency estimation in the Mt Lofty Ranges. The Minkara Wetland catchment lay within the defined area covered within the study, and was therefore sited suitably for applying this technique. The Akter and Eusuff studies involved data collected from 22 catchments with durations of 13 to 52 years, from a variety of large and small, urban and rural catchments. Through a regression analysis of events from the 22 Mt Lofty catchments studied, Eusuff (1995) produced a table of flow equations corresponding to individual ARI's. To compensate for the varied landuse types within the Mt Lofty Ranges, the catchments were divided into high and low runoff per area categories. Minkara catchment, as a highly urbanised catchment, lay within in the high runoff percentage group. In the Mt Lofty study the most urbanised catchment included was the Aldgate Creek catchment, of approximately 50% urbanisation. This indicated that the high runoff per area equations derived by Eusuff (1995) may have underestimated the flow originating from the Minkara catchment. The equations have been reproduced in Table 5-IV, along with the calculated results for the Minkara catchment.

Table 5-IV : Calculated event flow for Minkara Wetland for various ARI's using generalised equation, after Eusuff (1995)

ARI (Years)	Flow Equation (after Eusuff)	Minkara Catchment (calculated flow, Eusuff) (cumecs)
2	$Q = 0.57\ A^{0.82}$	0.69
5	$Q = 1.16\ A^{0.82}$	1.41
10	$Q = 1.64\ A^{0.81}$	1.99
20	$Q = 2.18\ A^{0.79}$	2.63
50	$Q = 3.02\ A^{0.75}$	3.61
100	$Q = 3.8\ A^{0.73}$	4.52

Given that the equations derived by Eusuff (1995) were based on a substantial data set, and that all of these catchments were of lower development than the Minkara Catchment, it is probable that this method provides a lower bound estimate of the true flows. It is quite likely, therefore, that the estimates of ARI for the Minkara Catchment using this method would exceed those calculated using actual long term at-site runoff data. As seen in Table 5-IV, no flow information was available for events with an ARI of less than a 2 years.

The estimation of the associated ARI for each monitored event was not possible without information on the peak flow.

5.5.2 Calculation of Peak Flows

The process of calculating peak flows was carried out using the reverse routing analysis as discussed in Section 3.8. Hydrograph plots were used to identify the approximate timing of the peak flow, the calculated flows were then extracted from the flow data at both the inlet and outlet. The results of this analysis can be viewed in Table 5-V.

Clearly evident from Table 5-V is the marked attenuation of peak flows achieved due to the storage provided by the Minkara Wetland basin. Also apparent is the magnitude of the peak flow for Events 4 and 7, outstanding in that they were more than double the next highest monitored event. In determining the average recurrence interval for runoff events leaving the Minkara Catchment either of the two peak flows could be used. The information used to determine flow events of various ARI's was derived from Aldgate creek, and from stream flow of a number of other catchments within the Mt Lofty ranges. For this reason the inlet peak flow was used as a comparison, as this represented the catchment runoff prior to the influence of the wetland.

Table 5-V : Results of peak flow calculation

Event Number	Peak Flow (cumecs)		ARI (estimate)
	Inlet	Outlet	(years)
2	0.185	0.024	<2
3	0.160	0.023	<2
4	0.702	0.194	~2
5	0.335	0.130	<2
6	0.337	0.074	<2
7	0.700	0.280	~2
8	0.172	0.056	<2

In examining the event with the highest peak flow, Event 4, against the range of design flows calculated for Minkara Catchment, it is evident that the ARI for even the most extreme event monitored was of the order of 2 years. As mentioned above, this is likely to be an over estimate. Events 4 and 7 can not be considered extreme on a catchment scale, however, they are of an outstanding nature compared to those monitored in this study. It would be expected that characteristics associated with peak flow, such a rainfall volume and intensity, would be outstanding also. Events other than 4 and 7, the majority of the data set, were events of low ARI. If it is accepted that the calculated flow values based on Eusuff (1995) provide lower bounds, then there is some certainty that the majority, 5 out of 7 of the events were of very low ARI, or events of more than annual occurrence.

5.5.3 Calculation of Event Durations

The calculation of event duration involved the reverse routing of the outlet flow to produce the inflow hydrograph, and plotting of the event. The start and end of the event, at both locations was then identified visually, and accurate times were obtained from the stage height record. Event duration was defined as the period in which flow remained in excess of base flow, as a result event runoff for which water quality information from automatic water sampling was available. In circumstances where the event duration exceeded the period of water quality data, the extended period was included, whether this be prior to, or after, event sampling. In this way a true representation of the event duration would be achieved, enabling a better comparison between events. The aim was to include all the flow represented in the automatic samples.

In the two cases of dual peaking hydrographs, the technique discussed in Section 5.5 was used to allow a representative duration of the fully sampled event to be determined. The results of the process appear in Table 5-VI.

Table 5-VI : Results of the event duration calculation

Event Number	Event Duration (hrs)	
	Inlet	Outlet
2	6.0	14.5
3	2.8	8.5
4	11.0	14.3
5	8.6	13.7
6	4.1	7.4
7	3.9	7.8
8	4.8	11.2

In all cases the duration was seen to be longer at the outlet, a characteristic of the flow attenuation as a consequence of the basin storage. An interesting point to note in Table 5-VI, is the difference in the duration for Events 4 and 7 given their similar volume. In turn this reflects that the flow from the shorter event passed through the basin at a higher rate. From this stems the idea of an event flow rate, or the time taken for event flow volume to pass through the wetland for any event. This parameter better defines the dynamic nature, or rate of flow-through for any event, and can be used to explain phenomenon caused by turbulence and mixing. As the same flow passes at both inlet and outlet in different times, there are inlet and outlet event flow rates, as shown in Figure 5-4. This parameter highlights that although both Event 4 and 7 had similar volumes, Event 7 flowed through far quicker, suggesting higher disturbance within the basin.

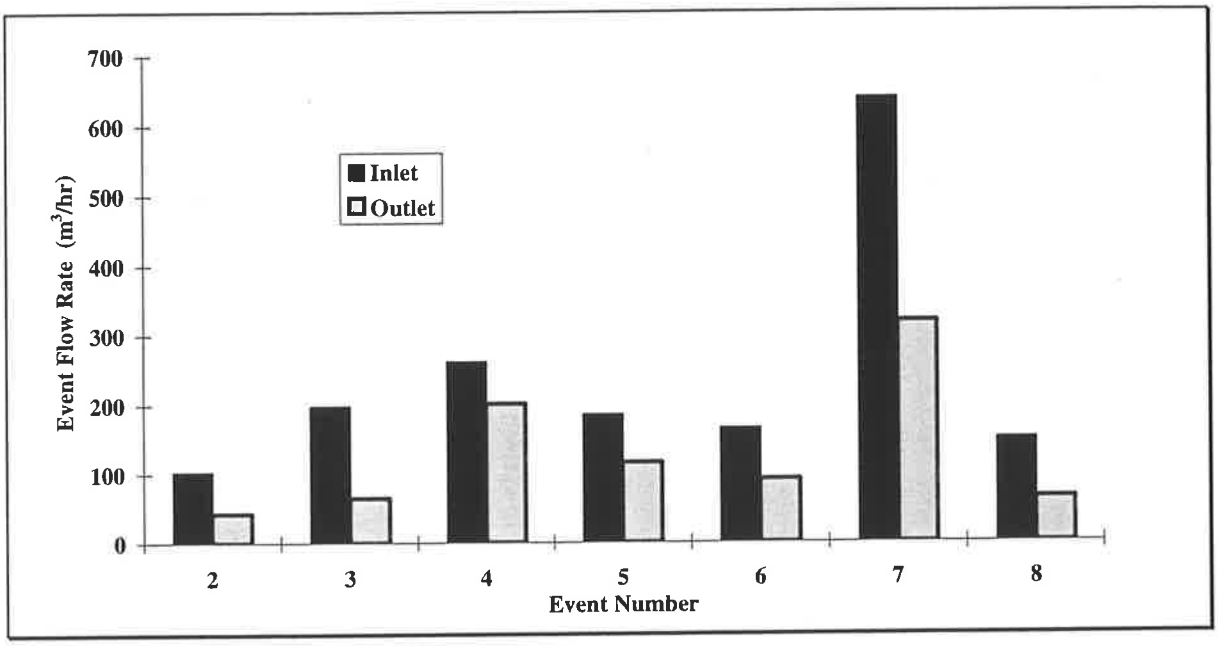


Figure 5-4 : Event flow rate for the inlet and outlet stations for the 8 monitored events

5.5.4 Calculation of Event Detention Times

Detention time, residence time, contact time or retention time, is a useful parameter in determining the ability of a wetland to detain flow. The longer this period the greater the potential for particle settling, and for chemical and biological interaction within the wetland. Detention time can be described by Equation 5.1. (Walker, 1995; Mitsch and Gosselink, 1991; Kadlec, 1989):

$$T = \frac{V}{Q} \tag{5.1}$$

where: T is detention time (days);

V is wetland basin volume (m^3);

and Q is the flow rate (m^3d^{-1}).

The definition above has useful application in the design of fixed rate treatment facilities such as wetlands for the treatment of wastewater. In these cases the detention time is the average time taken for a particle of water to flow from the entrance to the outlet of the detention basin, and a close relationship exists between this parameter and the degree of treatment achieved.

Following on from the successful application of detention time in sewage treatment, detention time has been used as a design aid in a number of stormwater wetland sizing guidelines (Phillips, 1990; US EPA, 1986; Auckland Regional Council, 1992). The significance of the calculation of a long term average detention time for stormwater wetlands has, however, been questioned, as numerical modelling has shown this to be a poor statistic in representing actual physical detention times, due to the intermittent nature of rainfall and runoff (Walker, 1996).

Irrespective of the accuracy of using a long term detention time in determining the expected performance of a constructed urban wetland, the simple definition of detention time given by Equation 5.1 is grossly inaccurate and misleading when considering individual events. This is due to the timing of runoff events and the flow patterns, or degree of mixing within the wetland. Due to the stochastic nature of rainfall and the resultant runoff, a significant percentage of the flow volume is treated for less than the long term mean detention time. Smaller volumes, those held in the basin during quiescent periods, are detained for longer durations than the large events that pass with little detention. When studying individual events careful attention must be placed on prior flow conditions, as an indicator of the detention time of the *in-situ* water, which may contribute a large fraction of the effluent sampled.

The sampling of a single event does not ensure a complete monitoring of the resulting runoff. Runoff from any one event may take a number flow periods to be displaced from the wetland. This is crucial to the performance of the wetland, the delaying or detention capability, allowing for greater water treatment. This greatly complicates the issue of event monitoring. For the runoff of any one event to be completely monitored, to be wholly accounted for in the effluent, a number of subsequent events would need to be monitored. Consequently, although the event detention time for the monitored effluent can be calculated with adequate accuracy with the aid of numerical basin modelling, this has little physical relevance to the current inflow.

Detention time calculated on an event basis is not so much a descriptor of the treatment of the current event runoff, but a measure of the treatment achieved for the wetland effluent, composed partly of displaced basin storage and event runoff.

A spreadsheet analysis was used to carry out the calculation of detention times, using a 6 hourly outlet flow volume record. As the data interval was long compared to the flow time, no reverse routing was carried out, and flow continuity was assumed, inflow being equal to outflow for the discrete period. The calculation was a two stage process.

Firstly, the average detention time of the *in-situ* water was calculated. Knowledge of the flow conditions prior to the event was required in this process. The basin volume at the time of an event was considered as being comprised of a number of individual historic 6 hourly inflow volumes. The summation of these discrete volumes being equal to the total basin volume. The number of discrete 6 hourly inflow fractions making up the basin volume at the time of the event, was derived by working backwards in time. By assigning a detention time to each of these discrete volumes contributing to the outflow, a volume weighted average effluent detention time could be determined. Before assigning a detention time to each of the 6 hour inflows, account had to be made of the fraction of each inflow contributing to pond volume at the time of the event.

Through subsequent flow activity, the volume of each 6 hour historic inflow remaining in the basin reduces through time by displacement. The fraction displaced at each time step is proportional to the volume of each subsequent 6 hour inflow, according to the hydraulic mixing coefficients for the basin. Using a spreadsheet analysis, account was made of the volume of each individual 6 hour inflow remaining in the basin after every subsequent flow. Each discrete volume was assumed to be completely mixed with the basin volume, earlier flows were not displaced preferentially. The volume of each 6 hour inflow remaining in the basin at the time of the event could then be determined. The detention of each of the basin volume fractions was determined by the differential of inflow and event times. Historical flows were included until virtually all basin volume at the time of the event was accounted for. Generally the inclusion of an event of such magnitude that the entire basin was flushed, negated the need to account for inflows previous to this time.

The average detention time for the basin storage present at the time of the event was calculated using a volume weighted approach. Each discrete volume was multiplied by the time of detention, and the sum divided by the volume of the basin. This value represented the flow weighted average detention time of the basin storage, or the *in-situ* detention time. An example in simplified format is shown in Appendix J.

Secondly, the effluent detention time was calculated from a volume weighted average of the outflow, composed of *in-situ* basin volume and event flow, in proportions according to the basin mixing coefficients. The event flow volume was considered to be detained for only a short period, equal to the event duration. Calculated in this fashion detention time is an indicator of the average detention treatment obtained by the effluent resulting from an inflow event. By weighting the results according to the volume of each effluent source, the contribution of each is taken into account. The results of this analysis can be viewed in Table 5-VII.

Table 5-VII : Results of the effluent detention calculation

Event Number	*In-Situ* Water Detention Time (days)	Effluent Detention Time (days)
2	14.2	11.5
3	7.8	6.4
4	4.8	3.1
5	4.3	3.2
6	3.7	3.0
7	4.4	3.0
8	3.9	3.0

The effluent detention time, seen in Table 5-VII, is reduced from the *in-situ* value according to the fraction of event inflow contributing to the effluent. For events of long *in-situ* detention times, this makes the magnitude of the decrease in residence quite significant, as shown by the 3 day reduction in average detention time for the effluent of Event 2. As a result of the small *in-situ* detention time for Events 4 and 7, the largest monitored events, the magnitude of the reduction in average effluent detention time is not large. However, this is significant as it occurs early on in the quiescent treatment process. As discussed in Chapter 1, Kadlec *et al.* (1993) have suggested that the decay of a number of water quality parameters, such as nitrogen and dissolved oxygen, can be represented by a first order reaction. This implies that the concentration of the constituent concerned is critical in determining the rate, and hence, the amount of decay over any given period. It follows then that the rate of decay is higher immediately following an event than many days later, and that the shortening of this period in the early stages has a greater affect on the overall improvement achieved. Even though Event 2 had a reduced effluent detention time by 3 days, due to the interaction of the inflow, it is suggested that this be of less significance to the combined effluent water quality than a reduction of 1 day earlier on in the quiescent treatment process.

It is apparent that effluent of the majority of the events monitored were of similar detention time. Events 4 through 8 had basically identical detention times. Events 4 and 7 however, contributed proportionally greater event runoff volumes to the monitored effluent. The high detention time calculated for Event 2 coupled with the low event volume, yielding a long period of residence for the effluent, indicated that the composition of effluent is strongly biased towards the *in-situ* water.

5.5.5 Calculation of Event Rainfall Conditions

Event rainfall data was available at two locations near the study site. One lay within the catchment, and was set up by the University of Adelaide for monitoring rainfall for the Minkara catchment as part of another research program. This study was in its infancy and several problems had occurred with the monitoring equipment, severely reducing the consistency and quality of continuous rainfall data collected at that site. For reasons of accuracy this data was not used in the analysis of event rainfall.

Almost equidistant to the Minkara rainfall gauge was a government funded and maintained pluviograph, at the Happy Valley Reservoir, station AW503532. This site had a reliable rainfall data set for the monitoring period concerned, the years 1994 and 1995. This information was available as incremental rainfall, however, the data was extracted as total rainfall in millimetres for 15 minute intervals. This provided sufficient accuracy to determine total event rainfalls and event rainfall intensities, whilst allowing easy manipulation in spreadsheets to carry out longer term calculations.

For the analysis of event rainfall the following parameters were identified as having the most influence on event conditions and water quality:

- total event rainfall;

- mean event intensity;
- maximum event intensity;
- duration of event rainfall;
- total annual rainfall; and
- annual cumulative rainfall to event.

A high number of parameters were investigate initially, as the methods used to produce these were easily facilitated. All parameters were calculated using spreadsheet analysis, numerical integration was used for calculating event volumes. Rainfall events were defined using a combination of flow hydrographs, to define when the runoff event occurred, the known lag time of runoff to flow of 23 minutes (Table 3-I, Williams and Smythe (1994)), and primarily, the actual rainfall data. The distinction of event rainfall corresponding directly to monitored event runoff were generally quite simple. Except for Events 5 and 8, rainfall events were clearly defined by dry periods of substantial length, of between 2.5 hours and 6 days, prior to and succeeding precipitation. Events 5 and 8, as discussed in Section 5.5, were not completely monitored as two peaks occurred in the flow hydrograph. For these events only the inlet flow hydrograph was sampled for the second peak. To extract event rainfall directly corresponding to the sampled flow, identification of the rainfall responsible for that flow was necessary. Observation of the rainfall record showed that in for both events, two clearly distinct periods of rainfall occurred, resulting in the two separate peaks in the hydrograph, delineated by a short period of low flow. These rainfall periods were separated by 1 hour and 6 hours respectively. This conforms with the suggestion by ARR (1977) that a minimum time of about twice the time of concentration for the catchment be used to define separate rainfall events, as done by Gamble and Pannell (1993).

1987?

The results in Table 5-VIII clearly show the outstanding rainfall event were Events 4 and 7. In all cases the greater majority of the years annual rainfall had fallen prior to the rainfall event monitored. This was not considered further as a significant factor in determining the water quality of event runoff. Three events stood out with regards to total event rainfall, Events 4, 5 and 7. Not surprisingly these three events contained the highest runoff volumes of those monitored.

Table 5-VIII : Results of the event rainfall analysis

Event Number	Yearly Rainfall (mm)	Yearly Total to Event (mm)	Total (mm)	Mean Intensity (mm/hr)	Maximum Intensity (mm/hr)	Duration (hrs)
2	382.6	326	3.4	0.85	2.4	4.0
3	382.6	367.0	2.2	0.52	1.6	4.0
4	590.2	488.6	9.0	1.17	7.2	7.0
5	590.2	503.2	5.4	0.74	2.4	7.0
6	590.2	525	1.6	0.91	2.4	1.5
7	590.2	527.4	8.0	3.56	4.8	2.25
8	590.2	539.2	1.4	1.4	3.2	1.0

When comparing rainfall intensity, the outstanding events were Events 7 and 4. Event 7, which exhibited an average intensity 2.5 times higher than the second highest event monitored. This positions Event 7 as clearly the most intense rainfall event overall, with the 8mm of total rainfall falling in 2.25 hours. Event 4 exhibited a low mean intensity, however, a concentrated fall of 1.8 mm in 15 minutes was expressed in the maximum intensity recorded of 7.2 mm/hr. From the rainfall data observed for the 8 events monitored, it is apparent that Events 4 and 7 are the outstanding monitored events.

5.5.6 Calculation of Event Antecedent Conditions

The antecedent conditions considered in the hydrologic description of the events were dry rainfall period, and dry flow period prior to the monitored event. These were calculated from the 15 minute rainfall and hourly flow records respectively, using a spreadsheet technique. The antecedent dry rainfall period was defined quite simply, as the total continuous time prior to an event, in which the recorded rainfall was below 0.2 mm per 15 minute interval. As rainfall values were given in 0.2 mm increments, this represented zero rainfall on the record. For flow purposes the antecedent period was defined as the total continuous time prior to an event, in which the recorded flow was below 10 L/s per hour interval. The value of 10 L/s was set as on observation of the long term flow record, this value represented the approximate baseflow condition. The results of these analyses are displayed in Table 5-IX.

Table 5-IX : Results of antecedent conditions calculation

Event Number	Dry Rainfall Period (days)	Dry Flow Period (days)
2	4.6	18.4
3	4.5	7.7
4	3.3	2.9
5	0.9	0.9
6	0.1	1.9
7	0.7	1.9
8	5.9	0.2

Events that stand out in Table 5-IX are those where the calculated dry rainfall and flow periods are not seen to correlate well. Two such events are Events 2 and 6, where the period of no flow far exceeds the zero rainfall period. That is to say that rainfall occurred far more recently than flow. Observation of the rainfall record showed that this was due to the small nature of the rainfall events. Rainfall although registering on the pluviograph, was insufficient to cause runoff, given the catchment conditions at the time. The other outstanding event according to antecedent conditions was Event 8 which exhibited a shorter dry flow than dry rainfall period. There are two possible explanations for this phenomenon. The magnitude of the flow, high enough to exceed the baseflow level of 10 L/s, but low enough not to be considered of event status, may have been derived from sources other than rainfall. Given that the wetland receives water from the stormwater drainage network, it is possible that the flow originated from an urban release. It is more likely, however, given the proximity of the rainfall gauge concerned, that localised rainfall within the catchment at that time did not fall at the site of the pluviometer. The dry rainfall period for Event 8 is, therefore, considered doubtful. Events 2 and 3, those with the highest calculated effluent detention time, were also seen to have the longest dry flow period. This would be expected given the direct link between these two parameters. The low nature of the dry periods is also reflected in the low detention times calculated. The dry periods do not directly correspond with the detention times as these incorporate the flow regime prior to this time, not simply the interval.

5.5.7 Overview of the Classification of Monitored Events

A review of the classification of the monitored events presents in a descriptive and visual format their nature and hydrologic characteristics. This aids in explaining the physical and chemical processes at work in the wetland, for individual events.

As an extension to this, the processes involved in the nutrient enrichment of stormwater runoff, interception, buildup, washoff and transport, are heavily dependent on rainfall and flow conditions, both those historically and for the current event. Interception although relying heavily on physical parameters such as vegetation and structural cover, is related to antecedent conditions, and more precisely to the wetness of the catchment. Parameters such as the dry rain period help describe conditions for interception. Similarly buildup is strongly related to the length of time between rainfall events. The greater the dry period, the greater the amount of buildup (Duncan, 1995). Washoff has been related to both rainfall intensity and event volume by numerous authors (Duncan, 1995). Transport similar in nature to washoff, relies on flow volume and rate to produce turbulence, mixing and other mass transport mechanisms. The individual mechanism for polluting stormwater can not be directly measured from event samples, due to the integrated nature of the mechanisms in urban runoff. There is, however, sufficient knowledge on these processes to provide a possible explanation for the observed water quality results, given sufficiently defined antecedent and event conditions.

Events 4 and 7 have be shown to be clearly the largest events by volume. They were the only events to provide a runoff volume closely matching that of the wetland storage, however, according to modelled hydraulic mixing coefficients, even these two events contributed less than half their volume as effluent. The majority of all effluent monitored was, therefore, *in-situ* water. It would be expected that the water quality of the monitored events would reflect this. These two events showed also that they were the most extreme flow events monitored. They exhibited peak flows at both inlet and outlet far exceeding all others. They were not, however, shown to be extreme on a catchment basis, returning a ARI of approximately 2 years. Individually they were separated by very different flow through times, or as defined, event flow rates. The rainfall analysis highlighted the difference in the these two events. Event 4, although similar in runoff volume, was longer due to the lengthy rainfall period. The magnitude of this event was largely a result of a short burst of intense rainfall, within a protracted rainfall event, compared to the consistent and medium intensity rainfall of short duration for Event 7.

Detention time was shown to be reasonably uniform across the majority of those events monitored, for both the *in-situ* and combined outflow. That would suggest that the quiescent treatment for the *in-situ* component of the effluent was similar for all but Events 2 and 3, which exhibited significantly longer detention times. As can be seen from Figure 5-5 this was shown to be heavily influenced by antecedent conditions such as dry flow and rainfall periods, as would be expected.

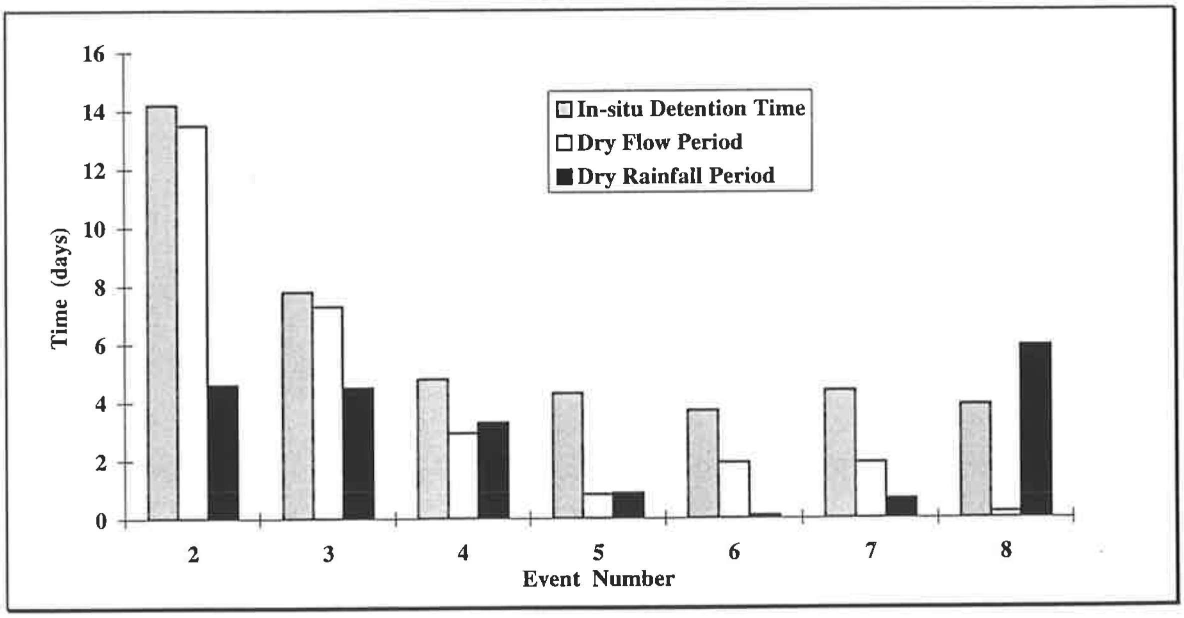


Figure 5-5 : Event antecedent conditions as related to detention time

5.5.8 Conclusions of the Event Classification Process

It has been shown that the wetland effluent resulting from a runoff event is composed of a combination of *in-situ* storage and event flow. The relative contributions of each source have been identified as being dependent on the event volume relative to the total storage volume. For the largest event monitored in this study, 60% of the sampled effluent originated from the *in-situ* storage. This volume of water has effectively no physical link to the event in progress. Its water quality is a function of the properties of the event that deposited it, and the quiescent treatment achieved since that time.

Given that in part the aim of this chapter was to evaluate the reduction in peak concentration and load in event effluent, the consequences of this finding should be noted and understood. On an event by event basis the reduction calculation has no physical relevance, as there is a limited relationship between the monitored inflow and outflow. There is no validity in calculating the water quality improvement when essentially two different sources of water are evaluated.

It cannot be denied that the presence of the wetland has an affect on the water quality of every event. The improvement achieved, be it by purely hydraulic or of biochemical nature, is attributable to the wetland. If the magnitude of this improvement is to be measured then a comparison of the water quality of the outflow must be made with the inflow. As these can not be compared directly for the event without a substantial and thorough monitoring program in conjunction with accurate computer modelling, as discussed below, the only alternative is to compare a number of pooled event inflow and outflow results. This technique excludes the calculation of an event by event wetland water quality improvement, in favour of an overall observed improvement across a range of events. Unfortunately and unavoidable, this restricts the complexity of the analysis such that wetland behaviour can not be related to individual event characteristics when considering changes in event water quality from the inflow to the outflow.

For the reduction calculations the average load and peak water quality values over all monitored events were compared between the inlet and the outlet. This was also carried out for the EMC analysis.

The effective monitoring of water quality improvement due to wetland action on an event by event basis has, therefore, not been achieved in this study. The reason for this failure may be found in the explanation of the monitoring technique considered to provide the most successful event monitoring solution. This technique is not only intensive, it offers a tenuous solution to the event monitoring dilemma.

Firstly, the issue of the quality of *in-situ* water must be addressed. By recording the water quality of the first sample in the effluent, and assuming that uniform mixing has occurred in the quiescent period, the quality of the *in-situ* storage volume can be attained. Secondly, the separation of the influence on water quality of the *in-situ* water, from that fraction of the current inflow present in the outflow, can be achieved if an assumption is made about the composition of each sample. By assuming equal volumes of *in-situ* and inflow water in each sample, the flow weighted contribution of each source can be established. The effective outflow water quality, reflecting the quality of the dynamically treated event flow can then be determined. Using numerical modelling, such as that carried out by Walker (1996), better estimates of the composition of each sample could be achieved.

The most demanding part of this monitoring strategy would come in satisfactorily accounting for the event flow detained in the storage. Again the assumption of complete mixing would be required. Also the basin the volume specifically attributed to the event in question would need to be reduced with subsequent flow, in a manner similar to the process used in the calculation of detention times in Section 5.5.4. Each post event outflow would be composed of an amount of current runoff and *in-situ* storage, of which a fraction would be the event of interest. A major limitation of this technique is that every single outflow, from the time of the original event to the time when the all volume of the event has been satisfactorily accounted for, would have to be monitored. This is a substantial barrier to the effective monitoring of event water quality, as the commitment to sampling and testing is immense. Another complexity would be the issue of subsequent events altering the condition of the *in-situ* water. This affect would have to be removed in later calculations.

Although event characteristics can not be used to explain the water quality improvement due to the wetland for individual events, this is not so for event inflows or outflows treated separately. Individually, the water quality of the event inflow or outflow is influenced by the parameters identified in Section 5.5. However, as a consequence of the possible interactions that occur in within the wetland environment, the search for explainable trends between water quality parameters is more involved in the effluent. Not only is the effluent a composition of *in-situ* water and inflow, there are the additional influences of the wetland, such as direct plant uptake and vegetative filtration.

The next process was the plotting of sampling times and event water quality constituents, and carrying out the reduction and trend analyses. The identification of influencing factors discussed here was of critical importance to promote quick and representative event calculations.

5.6 Calculation of Peak Reductions

Concentration peaks were taken from the 7 sampled event data tables as shown in Table 5-II, and Tables K-I through K-VII in Appendix K, which detail the entire event data set collected.

Peak concentrations of the water quality parameters TSS, TDS, nitrate and phosphate were taken as the highest values recorded from testing the automatically collected event water samples. Peak flow for the monitored event was derived from the reverse flow routing calculation procedure mentioned in Section 3.8.1. In using the automatically collected water samples for the nutrient and sediment parameters there were at best 24 data points available. The frequency of these samples was significant in comparison to event duration. Unfortunately due to sampling limitations, many of which are discussed throughout Chapter 4, these data points were not always at or near the peak of the hydrograph at the particular location, and did not necessarily span the entire event. The peak flow calculation, however, can be regarded as accurate, due to the high frequency of data available from the stage height data logger, at the outlet weir, and the robust nature of the reverse routing procedure.

The total reduction in peak water quality constituent concentration was calculated as the difference in average effluent and inflow concentrations, for Events 2 through 8. As discussed in Section 5.5.8, this limited the review of the analysis, as event specific explanations for pseudo event reductions were not valid.

5.6.1 Review of the Analysis of Constituent Peak Concentrations

The analysis of the peak water quality results was divided into two sections, the average reduction for the events monitored, and the presentation of distinct trends detected between constituents and other event parameters.

5.6.1.1 Overall Average Peak Reduction Performance of the Wetland

Table 5-X summarises the results of the peak concentration reduction analysis. Individual results of the entire event by event analysis can be seen in Table L-I, Appendix L.

Table 5-X : Results of peak reduction analysis

Water Quality Constituent	Average Outlet Peak (mg/L)	Average Peak Reduction (%)
Flow	NA	73
TDS	718	27
TSS	13.8	79
Nitrate	0.06	47
Phosphate	0.23	22

In general the reduction of peak water quality constituent concentration can be attributed to the low fraction of event inflow present in the effluent monitored, ranging from 20 - 40 %. Although a measure of the mixing achieved for each event was not available, it is reasonable to assume that mixing is considerable when such low volumes of inflow exit the storage basin during an event lasting a number of hours. This would point to the reduction of peak constituent concentrations by dilution with *in-situ* water of lower concentration.

In Table 5-X it can be seen that on average peak flow is reduced by 73%. Unlike the other water quality parameters, inflow and outflow rates for the same event can be directly compared without the complications of *in-situ* water contamination. This result was reasonably consistent throughout the record, as can be seen by the low deviation in the individual flow reductions in Table L-I, Appendix L. It must be remembered, however, that the inlet flow is numerically derived from the outlet flow record using a reverse routing procedure. This forces the reduction to be positive at all times. The consistency of the reduction comes about due to the identical numerical basin operation. The value of 73% peak flow reduction is very satisfactory on the basis of flood mitigation alone, one of the primary objectives of small urban stormwater wetlands, such as the Minkara Wetland.

The average reduction in peak total dissolved solids concentration of 27% was considered low given the composition of the monitored effluent. This result was not unduly weighted by any particular event, as results were reasonably consistent for the entire record. Given that significant peak concentrations were evident in the inflow this would point towards the lack of removal of TDS in the storage during quiescent periods. TSS, phosphorus and to a degree nitrogen, are generally removed from solution within the basin, through sedimentation, or complex iron formation and assimilation in the case of the nutrients. The reduction of TDS from solution relies more heavily on pH and chemical interaction, characteristics not monitored in this study. It is quite conceivable that due to conditions within the basin, TDS was not reduced, and indeed may have been produced, although this would be more easily seen in the analysis of event TDS loads.

The ability of the wetland to substantially reduce total suspended solids peaks was a notable feature, considering the variety of flow volumes encountered, from 20% to 106% of the storage volume. The result of 79% reduction in peak total suspended solids concentration reflects a hydraulically effective basin shape, with short circuiting not a major influence. The effluent registered consistently low peak concentrations of TSS. This would be due to the nature of the constituent, being extremely reliant on turbulence for suspension and the high fraction of storage volume having received quiescent treatment. Under the steadier conditions within the basin only the finer material would remain in suspension.

The average reduction in peak nitrate concentration of 47% was considered high in comparison to phosphate reduction at 27%. Given the high reduction of TSS and the common association of sediment and phosphorus, a higher level of peak phosphate reduction was expected. Inlet peak nitrate concentrations were reasonably consistent for the monitored event data set, as was inlet peak phosphate, in contrast to a high level of fluctuation at the outlet. Given the variation in event and catchment conditions and the fluctuation of sediment concentrations these were peculiar findings. The trend analysis was used to try and determine the reason for these observations.

5.6.1.2 Trends in Constituent Peak Event Concentrations

In order to detect trends in peak concentration of the water quality constituents, correlations were carried out between the water quality variables and the parameters detailed in Section 5.5 and the additional parameter of chronology, or date of event.

Obtaining clear cut findings using peak concentrations is a difficult task. Results rely on single event values, and are, therefore, open to error if outliers, or spurious data are present. Often there is no indication, other than statistically, of the validity of atypical points and a decision must be made to accept or reject them. Also, ensuring sample collection at the time of maximum concentration is impossible with the grab sampling methods used in this study. There is, therefore, a tendency for the analysis to be open to error. There is no buffering action when using peak values in the analysis, to cover measurement or processing errors. Events displaying characteristics of an atypical nature may indicate unusual performance of the wetland under specific conditions. These conditions may be unrelated to flow, and hence unmonitored in this study, such as a localised catchment condition. These limitations must be taken into account when viewing the results of such an analysis. Peak concentrations do, however, provide worthwhile information on the behaviour and performance of the wetland to improve the water quality of stormwater.

For constituents not requiring a large transport component, those less commonly associated with particulate matter, such as TDS and nitrate, it is proposed that processes such as buildup and washoff are of more importance to peak concentration than peak flow at the inlet. This would suggest factors such as dry rain and flow period as likely influences. Rainfall intensity and peak flow would be indicators of transport driven constituent concentrations, given that sufficient material was available for washoff. The time dependent variables would be expected to be related to effluent concentrations for all constituents, given the detention treatment present for the effluent.

Only those relationships showing significant correlation and strong significance, or those leading to these findings, were included and discussed below. These can be seen summarised in Table 5-XI. All significant correlations found were of a linear nature unless otherwise stated. Exponential, logarithmic, and power correlations were also trialed.

Table 5-XI : Significant correlations found in the peak water quality constituent results

Parameters	Inlet Correlation (Significance)	Outlet Correlation (Significance)
Nitrate v TDS	0.71 (0.074)	NS
Nitrate v TSS	0.67 (0.084)	NS
Phosphate v Dry Flow Period	NS	0.69 (NA)

Notes on Table 5-XI:

NS : Not Significant;

NA : Not Available;

The significance values, P, in Table 5-XI, indicate the probability that the observed correlation occurred due to a random distribution. A low significance value, generally 5% ($P = 0.05$), is considered as representing a correlation of strong significance. Significance values were only calculated for linear correlations.

It is clear from Table 5-XI that very few correlations were found for peak water quality values and event or catchment conditions. This is most likely due to the sampling and testing limitations mentioned above. A number of worthwhile observations were made.

The fluctuation of nitrate at the inlet was not able to be attributed to event specific conditions, such as peak flow or rainfall intensity, or catchment conditions such as dry rainfall period. Other significant correlations were observed, however, for nitrate and the sediment constituents. TDS and nitrate were shown to be linearly correlated. Peak inlet nitrate concentration displayed a correlation with peak inlet TDS concentration with a coefficient of 0.71 ($P = 0.074$), a reasonable indication of a link between peak nitrate and TDS inlet concentrations.

A correlation was also found between peak nitrate and peak TSS at the inlet, with a linear correlation coefficient of 0.67 ($P=0.084$). These relationships between nitrate and sediment parameters are not renowned or widely reported. This result is pleasing as although the analysis was unable to show that individual characteristics were responsible for peak inlet concentrations, this demonstrates there is a high degree of interrelation of constituents at the inlet. This would be expected given that the influence of the complex interactions within the wetland at this location were not present. The correlation of nitrate and TDS may be due to physical or chemical processes, or because both were found to be reduced at the outlet. Correlations such as this allow the monitoring of constituents such as nitrate, using easily attainable data, such as TDS from field sensors.

It is thought that the correlation between nitrate and TSS at the inlet is due to the entrapment of nitrate in the sediment by the adsorption to inorganic particulate matter. Although it is not proposed that this form provides the majority of nitrate to the wetland, as this separation was not performed in the chemical analysis, it is suggested that there is sufficient nitrate associated with particulates in the inflow, that there be a correlation between the two constituents. The high reduction of peak nitrate observed can, therefore, be strongly associated with the high reduction of TSS as a likely process behind nitrate reduction.

Similarly to nitrate, the consistent nature of peak concentrations of phosphate were not seen to be closely related to any individual characteristic of catchment of event. It is quite possible, however, if the period of buildup was sufficiently similar in all cases, defined by the dry rain period, that this limited the amount of nutrients, deposited by fallout, and readily available for transport. This can be discounted as there was a variation of approximately 3 times the smallest buildup period between the events monitored. An alternative explanation, given that all other conditions were seen to vary within the data set, is that the grass channel upstream from the wetland had a significant influence on the peak concentrations of nutrients reaching the wetland. Without event sampling upstream of the vegetated channel it is impossible to know the extent of buffering action of this feature on event transported nutrients.

Only one relationship was observed for outlet water quality and hydrologic conditions, that being between phosphate and dry flow period. A power correlation, with a coefficient of 0.69 was obtained including all events. This indicated that peak outlet phosphate concentration reduced with increasing dry flow period, as seen in Figure 5-6. In this context dry flow period represents the undisturbed quiescent treatment period for basin storage and reflects how the *in-situ* water influenced the monitored effluent water quality. As this period increases, peak phosphate tends to rapidly decline, possible due to the reduction in overall *in-situ* phosphate concentration, as a result of the process of assimilation by the biota. Algae are very efficient at removing phosphate from solution. As this process appears not to be related to sediment content this suggests the influence of the hydrolyzation of colloidal phosphorus, producing a higher percentage of soluble phosphorus within the water column. This effectively reduces the amount of particulate phosphorus, adsorbed onto inorganic complexes such as clays. As can be seen from Figure 5-6, when Event 7 was removed from the data set the correlation between phosphate and dry flow period improves considerably. The purpose of this exclusion was purely to demonstrate the possible influence of more intense and turbulent events, such as has been shown for Event 7. Turbulent conditions within water bodies are critical in the export of phosphorus from the sediments. It is suggested that Event 7 was of such a turbulent nature that there was movement phosphorus to the water column, resulting in an increased concentration in the effluent for the given quiescent flow period. These explanations are quite plausible, however, a more thorough analysis of a variety of phosphate species with a larger data set is required prior to any firm explanation of the observed behaviour. With such a small data set, and using one off peak values, it is hard to justify the exclusion of any one event to demonstrate the influence of any one contributing factor.

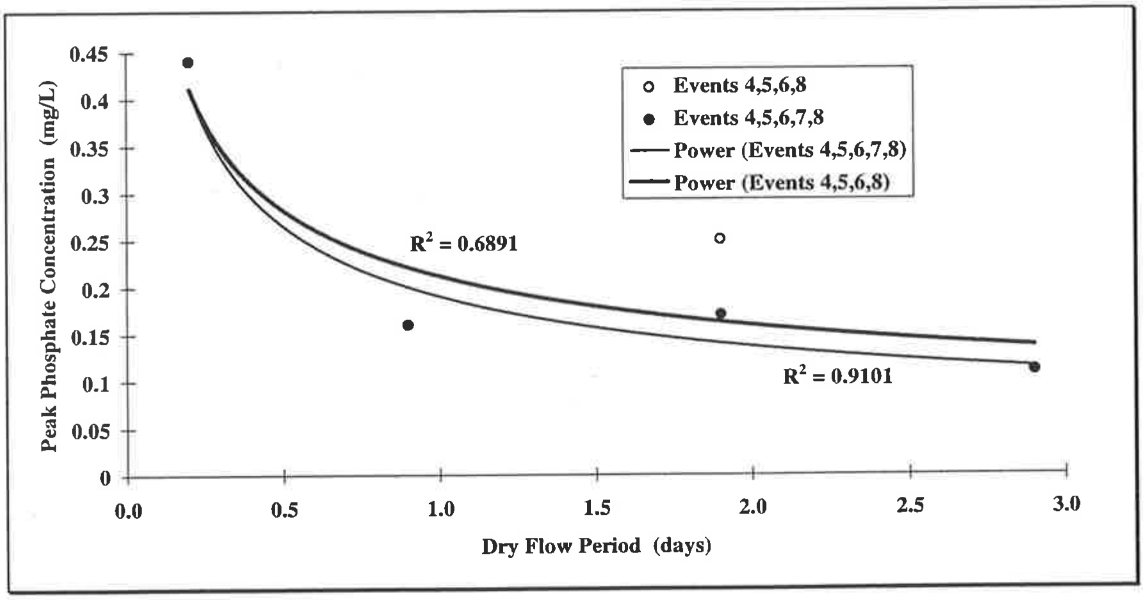


Figure 5-6 :Peak outlet phosphate concentration versus dry flow period

The low reduction of phosphate in comparison to the high average reduction in TSS could be attributed again to the increase in soluble phosphate due to hydrolyzation. Uniform peak TSS values at the outlet made the determination of a strong correlation between phosphate and TSS hard to achieve. This uniformity again reflects the *in-situ* water quality and is probably as a result of the consistent distribution of sediment particle size in the runoff. The larger fraction being settled quickly within the basin, leaving a consistent concentration of fine sediment. This material is either that kept suspended with baseflow turbulence or resuspended bedload from event disturbance.

Peak water quality concentrations were found to be unrelated to the magnitude of event peak flow at either inlet or outlet. It was surprising that the inlet did not show a correlation to peak flow, especially for TSS, a constituent heavily reliant on turbulence and flow for transport. This is quite likely due to the availability of sediment being a combination of both antecedent conditions and current flow conditions. With single peak values the interaction of these makes the determination of a correlation extremely difficult. Given the significant percentage of *in-situ* water present in the effluent, the lack of a correlation there was not unexpected at the outlet.

Insufficient spread in detention times of the monitored events made any correlation between nutrient water quality and residence, or detention time tenuous.

There were no clear findings relating peak event concentration with chronology, or the date of the event. This can be attributed to the short length of the study period, in particular with the nutrient monitored events. This issue would be addressed given a longer multi-season study.

Intensity of event alone was found to have very little impact on the occurrence of water quality peaks. This was true for rainfall and flow intensity. Again this can be attributed to the combined number of catchment and event characteristics responsible for water quality.

5.6.2 The Timing and Flow Conditions at the occurrence of Peak Water Quality Constituent Concentrations

The timing and flow conditions at the occurrence of peak concentrations in water quality constituent during an event are of great interest, particularly as an indicator of first flush. Figure 5-7 shows an example of the timing of these water quality constituent peaks. The entire set for events monitored can be viewed in Appendix M. Note in Figure 5-7 the early occurrence of peak TDS in both inlet and outlet hydrographs, and also the occurrence of peak TSS at the inlet at the start of the event, an indication of first flush. Another notable feature is the occurrence of peak phosphate at the inlet at the same time as the peak TSS, reinforcing the understanding that phosphate, being of very low solubility, is often found in particulate form, or bonded to clay particles.

Table 5-XII : Results of reviewing the plots of peak constituent concentration occurrence

	Peak Concentration Prior to Peak Flow								Dual Peak Concentrations			
	TSS		TDS		Phosphate		Nitrate		TSS and P		TSS and N	
Event	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
2	1st	x	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	1st	LH	✓	✓	NA	NA	NA	NA	NA	NA	NA	NA
4	✓	✓	✓	x	✓	✓	✓	✓	✓	x	x	x
5	✓	LH	✓	✓	✓	✓	✓	x	✓	x	x	x
6	✓	x	✓	x	x	x	✓	x	x	x	✓	x
7	✓	x	✓	✓	✓	✓	✓	x	x	x	x	✓
8	✓	LH	✓	✓	✓	LH	✓	x	✓	x	x	✓

Notes on Table 5-XII:

✓ indicates a positive result.

x indicates a negative result.

1st indicates that the first sample was taken after the peak of the inflow hydrograph, but that this sample was the peak event value for the constituent concerned.

LH indicates that there was a local high prior to the peak of the sampled hydrograph. This was not the global maximum for the event but is the maximum prior to the influence of secondary flow, arising from further rainfall shortly after the initial event.

NA indicates that these values were not available for these events.

For all water quality constituents, the peak concentration quite clearly occurs prior to peak flow at the inlet. This result was observed for 5 out of 7 events for TSS, 6 out of 7 for TDS, 5 out of 5 for nitrate, and 4 out of 5 for phosphate. This demonstrates clearly the phenomenon of first flush as discussed in Section 5.2. The peaks of the water quality constituents are observed to occur in the initial stages of flow, prior to the highest recorded flow rate.

There were fewer positive results for the outlet, indicating that the occurrence of peak concentration prior to maximum flow in the effluent were less common. This may have been due to the collection of data belonging to a later event as a result of the longer sampling time at this location. These events were, in some cases, larger in volume and peak flow than the outlet flow resulting from the sampled inlet event. Figures M-3, M-5, and M-8 show this quite clearly in Appendix M. In the case of TSS only 1 out of 7 events peaked prior to maximum flow, however, there were 3 occasions where local maxima occurred prior to secondary event influence. This was seen in 4 out of 7 events for TDS, and 3 out of 5 for phosphate, with an additional local high.

An important finding at the outlet station was the lack of peak nitrate concentration occurrences prior to maximum flow, occurring in only 1 out of 5 events. This was in stark contrast to the inflow where every monitored event returned a maximum nitrate concentration before the hydrograph peak. There is a greater number of influencing factors determining the distribution of water quality variables at the outlet. In addition to the rainfall-runoff and catchment conditions that affect the inlet flow in magnitude, form and content, there are the wetland basin conditions influencing water quality.

In order to observe the phenomena of phosphate concentration being linked to TSS levels the occurrence of both constituents achieving peak concentration in the same sample was noted. Positive results were marked as '✓'s in Table 5-XII. Phosphate and TSS occurred together in 3 out of the 5 events at the inlet. This relationship is not apparent at the outlet, however, with no positive results. Again at the outlet there are a greater number of influencing factors, not all of which would act equally on these constituents, separating the peak occurrences. A similar procedure was repeated for dual nitrate and TSS peak occurrences. This revealed that nitrate did not have as strong a link to suspended matter as phosphate at the inlet in the timing of peak concentrations. There was however a reasonable occurrence of simultaneous peak nitrate and TSS concentrations at the outlet, with 2 out of 5 event recording this result. No positive results were recorded for phosphate and TSS at the outlet so this is significant in that regard. As discussed above this could be due to the higher concentrations of soluble phosphorus in the effluent. This result further indicates that this hypothesis provides a potential and realistic explanation for the observed behaviour.

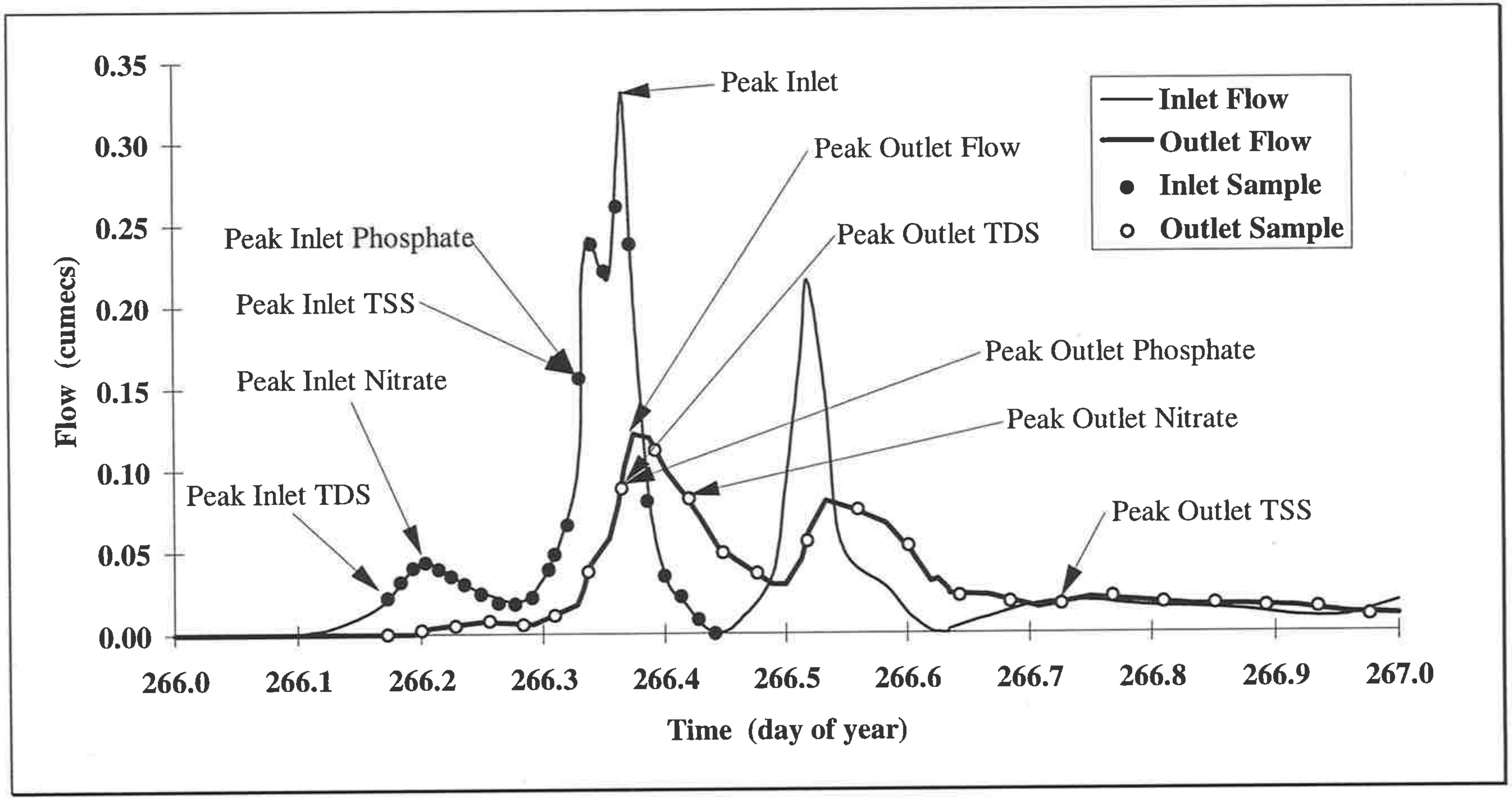


Figure 5-7 : Example of peak water quality constituent concentration occurrence, during Event 5, monitored on 23/09/95

5.6.3 Comparison of Event Peak Water Quality Results to ANZECC (1992) Guidelines

Of importance to receiving waters of the Minkara Wetland, is the event outlet peak concentration of the water quality constituents, as it is the maximum outlet concentration that determines the nature of any threshold exceedence effects in downstream waters. ANZECC (1992) guidelines outline the range of maximum concentrations for freshwater streams for a number of water quality variables. These guidelines are, as stated in ANZECC (1992), "provided as an indication of levels at or above which problems have been known to occur, depending upon a range of variables". They do not represent absolute cut-off values above which problems such as eutrophication occur in every aquatic ecosystem. As stated in the guidelines "it is strongly recommended that site specific studies be undertaken to determine the potential for undesirable plant growths occurring in each particular system". That is to say these values represent only a general guide to the levels observed in other healthy freshwater systems in Australia and New Zealand, and should be noted as such. The guidelines give the following recommendations for the water quality constituents of interest in this study:

• Total Nitrogen (including Nitrates)	0.10 - 0.75 mg/L;
• Total Phosphorus (including Phosphates)	0.01 - 0.10 mg/L;
• Total Dissolved Solids	< 1000 mg/L; and
• Total Suspended Solids	< 10% change from seasonal average.

Considering nitrate first, it can be seen from Table 5-X that the average maximum concentration of nitrate in wetland effluent of 0.06 mg/L, was well below the maximum recommended value. Peak phosphate concentrations, however, were more than twice the healthy limit, at 0.23 mg/L. As an average event peak value, this is not as critical in the long term as a flow weighted mean concentration, however, this indicates that phosphate values at the outlet are not always reduced to acceptable levels. Enrichment could occur in collecting waters should this excess of phosphate build up in a downstream basin over time. Given that outlet waters have the potential to cause enrichment further down the catchment, it is reasonable to say that with the collection of phosphate observed in the wetland itself, there is the potential for eutrophication at the Minkara Wetland site over time.

Total dissolved solids recommended limits were satisfied comfortably, even with the low reduction in peak concentrations.

In order to determine the total suspended solid criteria, the seasonal average TSS concentration needed to be calculated. The average Spring level of TSS leaving the Minkara Wetland was derived from a combination of the daily grab sampling program and the event samples. Using the daily flow record for the 3 month grab sampling program, the volume weighted average concentration for each water quality constituent under baseflow, or non event conditions, was determined. These were combined with the individual event mean concentrations, and averaged according to contributing volume. The result was a flow weighted average, of event, quiescent and low flow concentrations for the entire period.

Average Seasonal TSS Concentration (Spring)	11.30 mg/L
ANZECC (1992) TSS Range	10.17 - 12.43 mg/L

Maximum observed TSS levels leaving the Minkara Wetland were in exceedence of the recommended range, at 13.8 mg/L. With such a low percentile range allowed, and specified as a flow weighted long term average, there was little hope of satisfying this guideline, given that the TSS value was an average maximum event result.

5.7 Calculation of Load Reductions

Event loads calculation was carried out in conjunction with the event flow volume calculation as discussed in Section 5.5.1, by the discrete summation method. Inflows and outflows were calculated and then adjusted according to the sampler coverage of the particular event.

Once inlet and outlet flow volumes for the 8 events were matched as closely as possible without distortion to the applicability of the samples, the water quality constituent load calculation was carried out. Results are included for the load calculation procedure in Table L-II, Appendix L.

Loads were calculated for the water quality variables of total suspended solids, total dissolved solids, nitrate and phosphate. The total load was achieved in two simple steps. Firstly, by taking the flow volume for the interval concerned and applying the constituent concentration applicable to that flow volume, to yield individual sample loads. Secondly, these were summed up over the entire sample record, to yield the total event load, already knowing that the flow volume satisfied continuity and took account of all of the hydrograph. Results for Events 2 through 8 were averaged. Results from this analysis can be seen in Table 5-XIII.

5.7.1 Review of the Analysis of Constituent Loads

The analysis of event loads can be viewed in two ways, as an overall average behaviour of the wetland system in improving water quality, and as a number of individual events to see if any trends are apparent in either the inflow or the effluent.

5.7.1.1 Overall Average Load Reduction Performance of the Wetland

Results of the load analysis carried out on the event data can be seen in Table 5-XIII. Performance of the wetland being judged in an identical fashion to the peak concentration analysis.

Table 5-XIII : Results of the load analysis

Water Quality Constituent	Average Removal (%)
Total Dissolved Solids	-170
Total Suspended Solids	61
Nitrates	24
Phosphates	23

On average there was a strong addition of total dissolved solids to the wetland effluent. Here, the load analysis showed an increase in TDS of 170%. This addition of almost two times the total dissolved matter in the effluent was unexpected. A possible explanation for the increase of TDS in the effluent was concentration of the *in-situ* water due to evaporation. This possibility was checked by carrying out a simple water balance analysis for the events monitored. Actual evaporation loss from the wetland could not be calculated through summation of inflows and outflows, as no direct measurement of inflow was undertaken during the study. Monthly evaporation data was obtained from the Bureau of Meteorology at the closest available site, Adelaide. The technique used was simple, however, it allowed for an estimate of the magnification of *in-situ* TDS concentration, for the effluent of each event.

The evaporation losses were applied to the average detention time of the effluent. The level of the wetland remained at weir level, due to a small baseflow overflow, providing a constant evaporation surface area. The concentration of inflow during the detention time of the effluent was assumed as equal to the initial basin concentration, allowing the increase in concentration purely from volumetric evaporative means to be determined. Results indicated for the event with the longest effluent detention time, Event 2 with 11.5 days, the concentration due to evaporation was of the order of 8%. This was not sufficient to fully explain the observed increase in TDS concentration.

It was, therefore, likely that other actions were responsible for this behaviour. The observed increase was possible if there was a release of dissolved solids from within the wetland, from biological interaction, or if matter entering the wetland dissolved into solution. As will be seen later, there was also the possibility of TDS being deposited during base flows, or ground water flows, increasing the *in-situ* concentration, and then being flushed out of the system during events. This would give the impression that TDS production was occurring from within the wetland, as monitored event inflows would not highlight this activity.

It was undeniable from the load analysis that there was a removal of total suspended solids load from the wetland effluent. TSS removal averaged 61% and can be attributed to the settling and vegetative filtration achieved within the wetland basin and the fact that the majority of effluent was composed of *in-situ* water.

Nitrate removal averaged 24% for the events studied. This represents almost half the reduction in the peak nitrate concentration as recorded in the analysis of peak event concentrations. From this evidence, it could be argued that the action responsible for reducing the higher concentrations of nitrate reduces at lower concentrations and possibly over time, such as sedimentation, where the majority of the load is reduced in a short period. The reduction of nitrate in the water column is commonly achieved by 3 mechanisms. By plant or algae assimilation, to form proteins and amino acids, through denitrification, or the bacterial oxidation of organic matter to form ammonia, and by adsorption of nitrate in particulate matter and sedimentation. Unfortunately, as ammonia was not measured in this study, it is impossible to tell whether the process behind the reduction of nitrate load is due to assimilation, denitrification or sedimentation. This is a short coming of low budget studies, where the lack of chemical analysis hinders the understanding of the processes at work in improving stormwater quality.

As discussed in Section 5.6.1.2, the large majority of the reduction of peak nitrate was attributed to a high reduction in TSS, as these constituents exhibited a linear correlation at the inlet. As the reduction in TSS and nitrate loads were lower than those recorded in the analysis of peak concentrations, the argument that sedimentation was responsible for the removal of nitrate still holds merit. High rates of denitrification are found only under anaerobic conditions, and these are unlikely to have been achieved in such a shallow and frequently recycled wetland such as the Minkara Wetland. The DO record at the wetland, although infrequent due to equipment problems, shows this to be the case. It is quite likely, therefore, that the level of nitrate load reduction was influenced primarily by sedimentation and assimilation. Another factor in this process is the production of nitrate within the wetland through nitrification, or the bacterial oxidisation of ammonia by the nitrosomonas. This action is far more time dependent and, therefore, less likely to have been responsible for significantly increasing the concentration of nitrate in the peak analysis, which as a single maximum value is weighted in favour of the current inflow. Given the correlation between peak TSS and nitrate at the inlet, it is quite possible that nitrification within the wetland was responsible for the decline in nitrate load reduction when compared to that achieved for TSS.

Phosphate reductions were lower than expected at 23%, given the good improvement in the total suspended solids load and the accepted relationship between the two constituents. The value achieved was almost identical to the peak concentration reduction. The fact that phosphate reduction was not seen to decline on a load basis when TSS removal was reduced, indicates other processes at work, as would be expected within a biological system. The observation of two events with increases in phosphate export from the wetland reinforced this assessment.

There is a strong link between the removal of particulate matter and phosphorus due to the low solubility of the phosphorus compounds and their adsorptive nature. O'Neill (1985) gives a detailed discussion as to the geochemical nature of this relationship and this has been shown in field studies. A preliminary study by Allison and Chiew (1995), where events were grab sampled at 4 different sized urban subcatchments, and at the catchment outlet, showed a correlation of between 0.65 and 0.95 between TSS and total phosphorus. The correlation between sediment and phosphate is widely accepted, Sivakumar and Jahromi (1995) used turbidity and TDS as indicators to model phosphorus transport in a river system. The measurement of such sediment parameters is continuous and inexpensive compared to nutrient monitoring. It would be expected then that a correlation be observed for TSS and phosphate loads at the Minkara Wetland. The trend analysis of phosphate loads was used to aid in the explanation for the observed phosphate reduction.

5.7.2 Trends in Constituent Event Loads

Correlations were carried out between the event constituent loads and the flow, time, and water quality parameters mentioned in Section 5.5 and Section 5.6.1.2. As with the peak concentration analysis, only the relationships showing significant correlation and strong significance, or those leading to these findings, were included and discussed below. These can be seen summarised in Table 5-XIV. The correlations in Table 5-XIV are linear in nature, unless otherwise stated. Exponential, logarithmic and power correlations were also trialed.

The correlation of event constituent load and event runoff volume was removed from the load trend analysis, as these two variables are not totally independent of each other. Given similar catchment conditions, an increase in load of a water quality constituent with event flow volume would be expected to occur.

Firstly, one point of note is that there are a greater number of reasonably strong relationships between individual water quality variables and hydrologic factors than with peak concentrations. This could be attributed to the fact that the load analysis takes account of all the event water quality results, so an event is not misrepresented by a single value.

Table 5-XIV : Significant load analysis trend correlations

Parameters	Inlet Correlation (Significance)	Outlet Correlation (Significance)
TSS v Max Rainfall Intensity	0.74 (0.013)	0.91 (0.001)
TDS v Max Rainfall Intensity	0.89 (0.002)	0.78 (0.020)
Nitrate v Max Rainfall Intensity	0.90 (0.014)	0.85 (0.027)
Phosphate v Max Rainfall Intensity	0.82 (0.035)	NS
Phosphate v Rainfall Dry Period	NS	0.85[1] (0.120)
TDS v TSS	NS	0.92 (0.003)
TDS v Phosphate	0.91 (0.012)	NS
TSS v Nitrate	0.74 (0.063)	0.89 (0.016)
TSS v Phosphate	0.88 (0.019)	NS

Notes on Table 5-XIV:

[1] Indicates the linear correlation coefficient when Event 8 is excluded from the correlation.

All constituents were seen to be linearly correlated with rainfall intensity at the inlet. At the outlet all constituents except for phosphate were correlated. For the inlet this result reinforces that reported by Duncan (1995), that rainfall intensity has a strong influence in the washoff of pollutant loads in stormwater. However, given that point sources and erosion were not measured in this study, pollutant load can not be said to be solely reliant on the process of washoff. It is most likely that all three mechanisms were increased with higher maximum rainfall intensity. When the differential in the buildup time over the event data set is considered, a period of between 6 and 18 days using either rainfall or flow dry period, this suggests the process of washoff was the controlling factor in the production of pollutant loads at the inlet. This again agrees with the suggestion by Duncan (1995), that buildup is often not a limiting factor to washoff.

The relationship at the outlet is more complex. As only a small fraction of runoff from the event concerned reaches the outlet, a maximum of 40% for the events monitored, processes within the wetland are heavily involved in influencing the load exported in the effluent. The correlation between maximum rainfall intensity and effluent pollutant load may be due to a number of factors.

Inlet load has already been shown to correlate well with maximum rainfall intensity, thought to be due to increased washoff, erosion and point source loads. If the improvement in water quality achieved within the wetland during the quiescent period was of sufficient benefit that the inflow load still dominated the effluent, maximum rainfall intensity would still be an influence. Factors such as buildup would, therefore, still be relevant influences. An absence of change in *in-situ* water quality during an event would also explain this result, as in-situ water would provide nothing other than a constant base load.

Given the relationship between rainfall and load at the inlet and the correlation at the outlet, this indicates that a large inlet load is conveyed to a large effluent load. This was shown to be the case with good correlations between inlet and outlet loads, ranging between 0.75 and 0.88, between all constituents types, except phosphate for Event 7. This indicates that wetland mechanisms did not have a great impact on effluent loads for the events monitored. However, due to the similarity in the effluent detention time for the nutrient monitored events, those constituents most affected by contact time, the influence of this factor was not able to observed. The similarity of such a variable between events, effectively negated the possibility of observing its influence on the load reduction performance of the wetland due to biological means.

Event 7 exhibited a larger load than would be expected for its maximum rainfall intensity, and the removal of Event 7 for phosphate resulted in a correlation coefficient of 0.97 between inlet and outlet for that constituent. Unfortunately due to the similarity in the detention times, the trend in the phosphate load could only be attributed to physical mechanisms rather than biochemical means, such as the re-suspension of phosphates adsorbed to particulates. If this were the case, however, it would be expected that evidence of this, in the form of an increased TSS load for event would be present also and this was not observed. It is suggested as a possible explanation for this irregularity that the material disturbed within the wetland during this more extreme event was particulate material containing a higher phosphate content, such as fine colloidal matter, of small enough particle size to have little affect on the total TSS load. This hypothesis could have been tested if phosphate was accounted for in dissolved and solid forms, which unfortunately was not the case.

Phosphate load at the outlet was the only constituent observed to correlate well with dry rainfall period. Given the similarity in detention time this could indicate the importance of buildup to phosphate accumulation within the catchment. As discussed above this process is still considered to be of importance at the outlet if loads were dictated by the inflow conditions, be that due to low *in-situ* levels, or due to similar biological treatment between events.

Figure 5-8 shows the strong linear correlation found between outlet TSS load and outlet TDS load. The correlation coefficient of 0.92 ($P = 0.003$) and the significance value indicates that this relationship, even with limited data points, was not of a random nature. There were no atypical events on this plot, indicating that the type of event, magnitude and intensity, had little affect on this relationship. There was no such clear correlation at the inlet. This was considered to be due to the influence of the vegetated channel upstream of the wetland. At the outlet, there is an relatively abundant supply of solids from the unvegetated basin floor. At the inlet, flow must pass through a densely vegetated channel, most likely reducing the TSS load through filtration, more so than the TDS load.

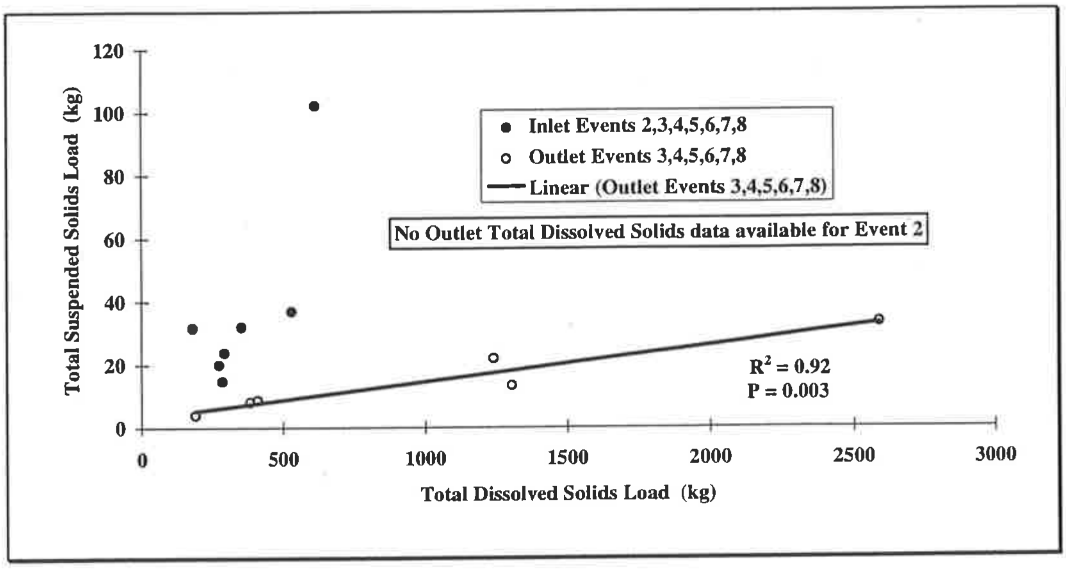


Figure 5-8 : Variation of event TSS load with event TDS load

Phosphate load returned quite a strong positive correlation to TDS load at the inlet station, with a correlation coefficient of 0.91 (P=0.012). Phosphate also returned a good correlation to TSS at the inlet, as seen in Figure 5-9. The existence of this relationship between phosphates and solids has been shown in other studies (Somes and Wong, 1996; Kerr and Eyre, 1995; Sivakumar and Jahromi, 1995). As discussed in Section 2.4 a link between TSS and phosphates is as a result of the insoluble nature of phosphates. The outlet did not show such a clear correlation, probably due to the influence of the wetland at that point. Processes such as plant assimilation, uptake of phosphates by phytoplankton, consumption by rotifers and crustaceans, do not directly affect TSS concentrations. The influence of detention time within the wetland, a measure of the biological contact time, is consequentially dissimilar for the two constituents. These time dependant processes have the effect of removing the associated relationship between the two constituents. An explanation for the observed increase in phosphate load at the outlet for two events was unable to be obtained with the trends analysis. It is thought, however, that this was due to an increase in phosphate due to decomposition of the biota, or through hydrolyzation of colloidal phosphorus and release from the sediments. This second action was not expected to be as significant as it was unlikely that anaerobic conditions were present.

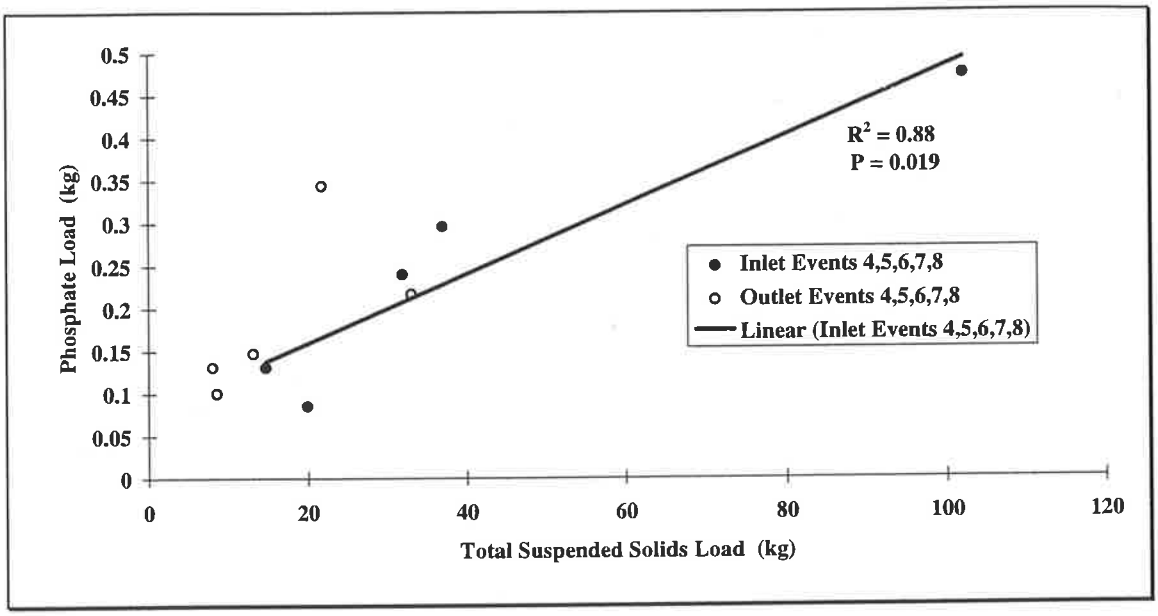


Figure 5-9 : Variation of event phosphate load with event TSS load, inlet and outlet stations

A linear relationship between total nitrogen and TSS in stormwater has been shown to exist (Bycroft *et al.*, 1995). Correlations carried out between nitrate and TSS loads in this study showed that a good linear relationship existed at both the inlet and outlet stations. This result can be viewed in Figure 5-10.

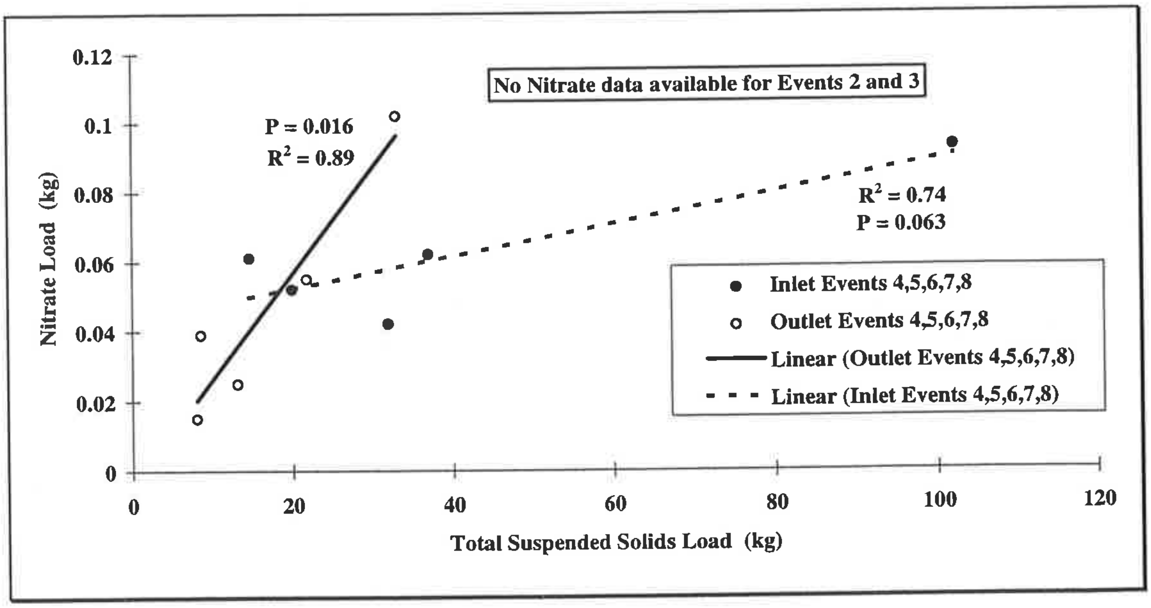


Figure 5-10 : Variation of nitrate load with TSS load

The use of correlations of TSS with nutrient constituents has been used to extend the information of wetland surveys (Wu *et al.*, 1996). These results were significant in that it agreed with such larger studies.

Detention time showed no correlation with water quality loads. Like the peak analysis this was due to the limited range of variation in detention times for the events monitored. This was especially true of the nutrient monitored storms.

Chronology correlated poorly with constituent load, due to the short the 3 month nutrient data set.

5.8 Calculation of Event Mean Concentrations

Event mean concentration (EMC) is defined as the flow volume or load weighted average concentration, for a particular constituent for a particular event. It is the sum of the flow weighted concentrations divided by the event flow volume. Using this parameter, concentrations from individual samples are weighted according to their contribution to the entire event volume, not simply on their value. Results of this analysis can be seen in Table 5-XV.

Table 5-XV : Results of Event Mean Concentration analysis

Water Quality Constituent	Inlet Average EMC	Outlet Average EMC
Total Dissolved Solids (ppm)	316	548
Total Suspended Solids (mg/L)	30	12.5
Nitrate (mg/L)	0.055	0.037
Phosphate (mg/L)	0.171	0.147

In Table 5-XV, it should be noted that average wetland removal efficiencies have not been included. These are identical to those calculated in the event load analysis by virtue of the same flow weighting. The values quoted in Table 5-XV differ from earlier findings published in Walker and Gamble (1995) as results there represented average event concentrations, not event mean concentrations.

5.8.1 Comparison of Event Mean Concentration Water Quality Results to ANZECC (1992) Guidelines

As mentioned in Section 5.6.3, the Australian and New Zealand Environment and Conservation Council Guidelines, outline water quality standards for marine and freshwater ecosystems. These guidelines have been based on studies carried out in both countries, and the figures presented represent the limits associated with healthy systems.

The findings of this study show that nitrate levels of waters leaving the Minkara Wetland are well below these accepted ANZECC (1992) guidelines. Phosphate concentrations, however, exceed the range regarded as consistent with healthy aquatic ecosystems. Although reduction in phosphate does generally occur within the wetland, this reduction appeared insufficient to lower the phosphate EMC to the level considered safe. The exceedence was almost 50% above the higher limit.

As can be seen from Table 5-XV, the TDS guideline was easily met with EMC values almost half this at 548 mg/L. From the results of this study it was clear that even though there was an increase in total dissolved solids concentrations during events from inlet to outlet of the wetland, the average was still below levels considered undesirable by the ANZECC (1992) guidelines.

For TSS solids the seasonal average calculated for the Spring period, as mentioned in Section 5.6.3.

Average Seasonal TSS Concentration (Spring)	11.30 mg/L
ANZECC (1992) TSS Range	10.17 - 12.43 mg/L

Given such a low average seasonal TSS, the range of acceptable conditions was narrow, and hard to satisfy. However, the TSS EMC value at the outlet, as shown in Table 5-XV, does close to meeting this criteria at 12.5 mg/L. Given the error associated with the calculation of the seasonal average concentration with daily grab and intermittent event sampling can be regarded as satisfying ANZECC (1992) guidelines.

5.8.2 Comparison of Inflow Event Mean Concentrations With Published Values for Urban Stormwater

Typical concentrations of the water constituents concerned in this study were presented in Section 2.5. These represent values collected from a number of urban catchments, from stormwater sources, similar in nature to the inflow source of Minkara Wetland.

The average inflow EMC for nitrate of 0.055 mg/L was well below the common values for urban stormwater reported in Table 2-II, ranging from 0.48 - 1.0 mg/L. This could be attributed to some degree to the location of sampling for this comparison. As will be discussed in Section 5.9, the existence of the heavily vegetated upstream channel is suspected to have influenced the water quality at the inflow sampling location. This could only have been proven if another sampling station had been located further upstream.

The average phosphate EMC for the inflow of the monitored events of 0.171 mg/L, lies within the typical range reported in Table 2-ZZ, of 0-1.5 mg/L. Although appearing extremely low in comparison, when account is made of the greater number of phosphorus species included in the reported values, the fraction of phosphorus as phosphate within that range would be lower.

The lower nitrate and phosphate loads found in this study, compared to those reported in the literature, could be attributed to a number of properties of the catchment. The lack of development within the Minkara Catchment, the absence of any industrial point nutrient sources, or a number of other influences, such as geology or vegetative cover, could all be responsible to some degree.

5.9 Calculation of the Decay Rates for the Water Quality Constituents

The aim in determining a rate of decay of pollutants removed in stormwater effluent passing through the wetland, was to calculate both the quiescent, or non-event decay rate, and the dynamic, or event decay rate. Calculation of these rates involved very different data. The quiescent decay rate, relied on daily records, during periods of no flow, so that the same volume of water could be monitored over a period of time. The dynamic decay rate required high frequency event data, taken shortly before, during, and just after the event. Each of these was a separate process.

5.9.1 Calculation of Constituent Quiescent Decay Rates for Minkara Wetland

As mentioned in Section 5.1, a daily grab sampling program was in operation for a period of 64 days during the monitoring period. Samples were taken at approximately midday each day at the inlet and outlet of the wetland, and upstream prior to the heavily vegetated inflow channel. This data was used to observe trends in water quality constituent behaviour during the quiescent periods, or baseflow, and also to calculate the decay rate of each of the 4 water quality constituents. The daily sampling data can be seen in Appendix N.

The decay rate calculation involved obtaining a daily flow volume record of the wetland and identifying the quiescent periods within the sampling program duration. When flow equivalent to an event occurred (there was some base flow during most days) the wetland was considered as flushed, and the quiescent decay process as ceased. Daily decay rates were calculated as the difference between the inlet concentration and the outlet concentration one day later. Samples taken during events were not included. The daily differences for the remaining record were averaged, to yield the wetland quiescent decay rates, as seen in Table 5-XVI.

Table 5-XVI : Wetland quiescent decay rates

Water Quality Constituent	**Decay Rate** (mg/L/day)
Total Dissolved Solids	125
Total Suspended Solids	0.8
Nitrate	0.008
Phosphate	0.015

One outstanding result from Table 5-XVI was the low decay rate of total suspended solids at 0.8 mg/L/day. The reason for such a low decay rate of TSS is clear in Table N-I in Appendix N. This indicates that TSS concentrations in quiescent times are very low at both the inlet and outlet locations, of the order of 5mg/L. This points to a quick and very substantial reduction in TSS immediately following an event. TSS levels were almost stagnant during quiescent times of the daily sampling program. Cordery (1976) found that up to 85% of suspended solids settle in the first 15 minutes following an event, and up to 90% in the first hour. Settling of suspended matter to this time-frame cannot be said to occur at this location, as the sampling methodology was not in place to show this behaviour. However, it does highlight that immediately following an event, during the initial quiescent period, there is a high removal rate of suspended solids due to settling, removing the greater percentage of the suspended load. Given the consistent nature of the daily TSS results it is likely the remaining wash load was too fine to settle under the slightest turbulence apparent during base flows, or thermal convection action.

Another interesting result in Table 5-XVI was the positive decay rate of total dissolved solids, given the finding of increased TDS load during dynamic periods in Section 5.7.1. In periods of low turbulence and low flow it appeared the wetland worked to reduce TDS concentrations, by either the uptake of salts in plant life, the formation of precipitates, or dilution. It was likely that in dynamic situations there was sufficient turbulence to allow the TDS which may be precipitated, or contained in higher concentrations lower in the water column, to redissolve (in the case of the suspended material) and mix with the event effluent. There was possibly sufficient base flow concentration to load the basin with TDS, and that during dynamic conditions the removal of this build up resulted in an observed negative load reduction from inlet to outlet of the wetland.

Decay rates of nitrate and phosphate were low, 0.008 mg/L and 0.015 mg/L respectively, and this would be expected on viewing the entire daily sample data set. Values of both nutrient constituents were low at both inlet and outlet locations. Small fluctuations were seen but these could be attributed to analysis error, given the low recorded values, or temperature or other effects. Minor fluctuations on a day to day basis would be expected in any natural system. The low nitrate decay rate was largely due to the almost untraceable amounts of nitrate in the wetland outflow. Phosphate levels were of the order of 4 times higher, averaging 0.12 mg/L.

To determine the affect of the heavily vegetated channel, that extended approximately 400 metres upstream from the inlet of the wetlands to the concrete stormwater network, the decay rate calculation was repeated using the upstream and outlet daily samples. The results of this can be seen in Table 5-XVII.

Table 5-XVII : Quiescent decay rates including the vegetated channel and wetland

Water Quality Constituent	**Decay Rate** (mg/L/day)
Total Dissolved Solids	510
Total Suspended Solids	0.8
Nitrate	0.093
Phosphate	0.215

Of note in Table 5-XVII is the marked increase in the decay rate of TDS including the vegetated channel, from the wetland decay rate alone. Including the vegetated channel resulted in a 4 fold increase in this decay rate, from 125 to 510 mg/L/day. This suggests strongly that the upstream channel plays an important role in reducing TDS levels from the stormwater system outlet to the wetland outfall. However, no observed increase in the decay rate calculated for TSS was observed. Again this was a direct result of the levels of TSS being low during quiescent times at the upstream sampling location. The reliance on event flow for TDS transport through the vegetated channel is lower than that for TSS, due to the nature of the constituents.

Inclusion of the vegetated channel has shown an increase of a magnitude of 10 in both nutrient constituent decay rates. The decay rate for nitrate rose from 0.008 to 0.098 mg/L/day including the vegetated channel, and phosphate from 0.015 to 0.215 mg/L/day. Again this strongly points to a large contribution by the upstream channel during quiescent times.

Given the results in Table 5-XVI and Table 5-XVII, it is clear that during quiescent or low flow periods the vegetated channel plays an important role in the reduction of the water quality variables considered. This has been observed in other urban stormwater water wetlands. Tomlinson *et al.* (1993), reported significant improvement to water quality in stormwater flowing through a grassed swale prior to the wetland basin. The highest concentrations of nutrients were detected in this vegetated channel. Given this result it would be extremely helpful to obtain samples from upstream of the vegetated channel during events to observe the contribution during dynamic times.

5.9.2 Calculation of Constituent Dynamic Decay Rates for Minkara Wetland

Initially the calculation of the dynamic decay rate was to yield a first order reaction rate, reliant on the concentration of the constituent in question. The data required for such a derivation was not available, and so this was not possible. To enable the calculation of a first order reaction rate requires high frequency sampling at both stations simultaneously, in order to compare the change in concentration over the same time period. This was not achieved, as samples were spread at the outlet station in order to obtain as much information as possible at this location, where flow lasts considerably longer than the inlet. Instead, a zero order decay rate was derived. This was simpler, and entailed the change in event mean concentration for the constituent over the duration of the event, and as a result was independent of concentration. As this was designed to be for long term modelling use, the decay rate was represented as a function of flow, where shown to be appropriate. By including flow an account was made of the mixing of inflow and *in-situ* storage. This removed the need to express the influence of the varied composition of the effluent on a separate basis.

As can be seen in Table 5-XVIII, all rates were found to be logarithmic, except phosphate which showed no relation to event flow rate, displaying a uniform rate of decay. Decay was highest during the lowest flow rate events, indicating that contact time with the wetland was an important factor. Decay rates for TDS were negative, due to the addition of TDS in event effluent.

Table 5-XVIII : Dynamic decay rates for Minkara Wetland

Variable	Decay Rate for Variable (mg/L/hr)
TSS	-0.721Ln(x) + 4.94 (0.70 - 2.5)
TDS	-19.5Ln(x) + 62.8 (-3.5 - -51.5)
Nitrate	-0.003Ln(x) + 0.017 (-0.0006 - 0.007)
Phosphate	0.001

Notes on Table 5-XVIII:

(x) is the event flow rate, decay rates valid for x larger than 30 and smaller than 350 m^3hr^{-1}.
Values in brackets represent the range of decay rates for which the logarithmic equations hold.

Comparison between the dynamic and quiescent decay rates including the vegetated channel, shown in Table 5-XVII, reveals that dynamic decay rates for phosphate and TDS were significantly lower. Phosphate decayed approximately 9 times slower during events, and TDS changed from a positive to negative decay rate in dynamic times. Nitrate decay rates were similar for dynamic and quiescent periods for low flow rate events, the higher events returning lower rates of nitrate decay than the quiescent periods. TSS decayed up to 80 times faster during events, however, this was due to there being sufficient flow during these times to carry a suspended load, and the reductions were subsequently higher. This comparison shows the importance of time on the decay of nitrate, phosphate and total dissolved solids, and also on flow for the transport of suspended matter. As an extension to this, it is clearly desirable to design wetlands that detain stormwater for as long as possible, and to slow down the flow of water to allow for sediment deposition, as it is during this time when the great majority of load is transported.

No information was available to determine the affect of the upstream vegetated channel during events, so the change in the dynamic decay rate including this feature was not possible.

5.10 Evidence of First Flush Phenomena in the Minkara Wetland Catchment

As mentioned in Section 5.2, first flush effects were considered as increases in water quality constituents prior to the peak of the flow hydrograph. Particularly of interest was the export of a large percentage of the load in the early stages of flow with particular reference to TSS and turbidity. Figure 5-11 shows the field data collected from *in-situ* turbidity meters at both inlet and outlet stations for Event 4, plotted with flow. It is clear from this figure that there was a substantial increase in turbidity at the inlet station at the onset of flow. This occurred well before peak flow, some 2.4 hours prior, although the peak of turbidity was not reached until 30 minutes before maximum flow. The outlet change was not as significant, but it can be seen that the level of turbidity here was already elevated due to prior flow. This is indicated by the drop off in outlet turbidity soon after the event. However, the maximum turbidity was achieved at the outlet prior to peak flow at that location. The magnitude of turbidity at the outlet, being greater than the inlet, points towards an export of suspended matter from the wetland. As this was not seen to occur in any of the sampled events this is unlikely. A few possible causes of the elevated outlet turbidity values include dirty lenses, low powered batteries, or different meter calibrations. For the observation of first flush characteristics, the importance is not on the magnitude but on the timing of the change, and this is not affected by these faults. In Figure 5-12 inclusion of the TSS data suggests that although turbidity increased rapidly very early in the flow of this event, TSS did not begin to increase until just before the peak of the hydrograph. This suggests two things, that high levels of TSS require significant flow for transport, and that turbidity is not linearly correlated to TSS over all values. As far as the first flush is concerned both TSS and turbidity showed increases and attained peak concentrations prior to peak flow, indicating a flushing of these water quality constituents with the first stages of event flow.

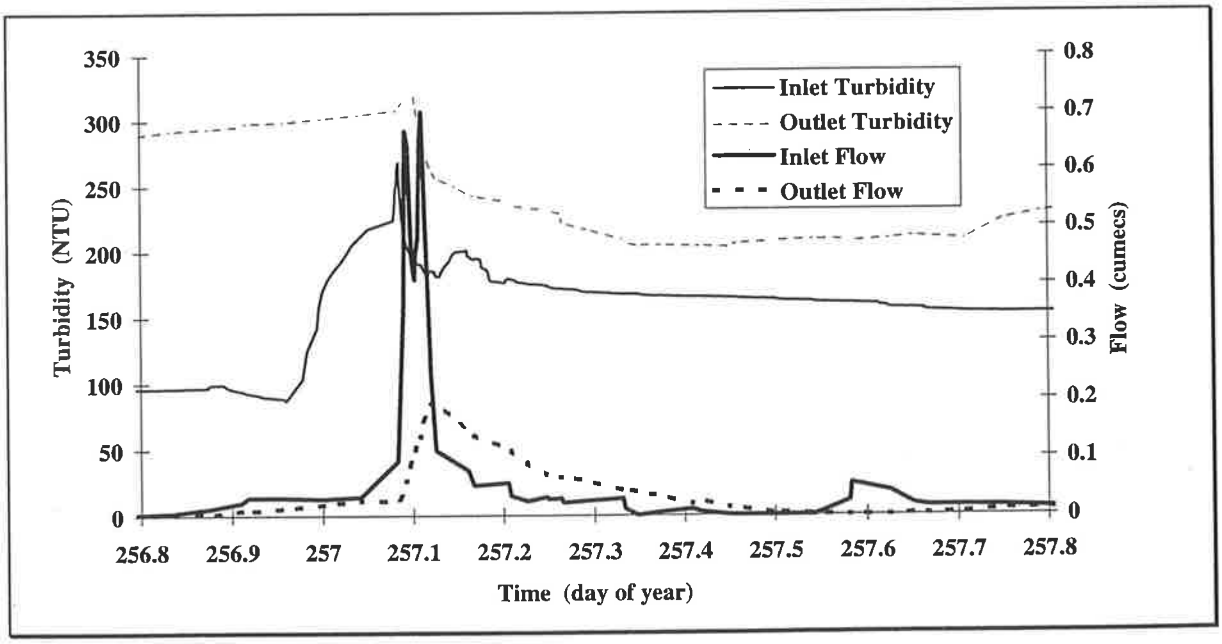


Figure 5-11 : Variation of turbidity and flow, for Event 4, monitored on 13/09/95

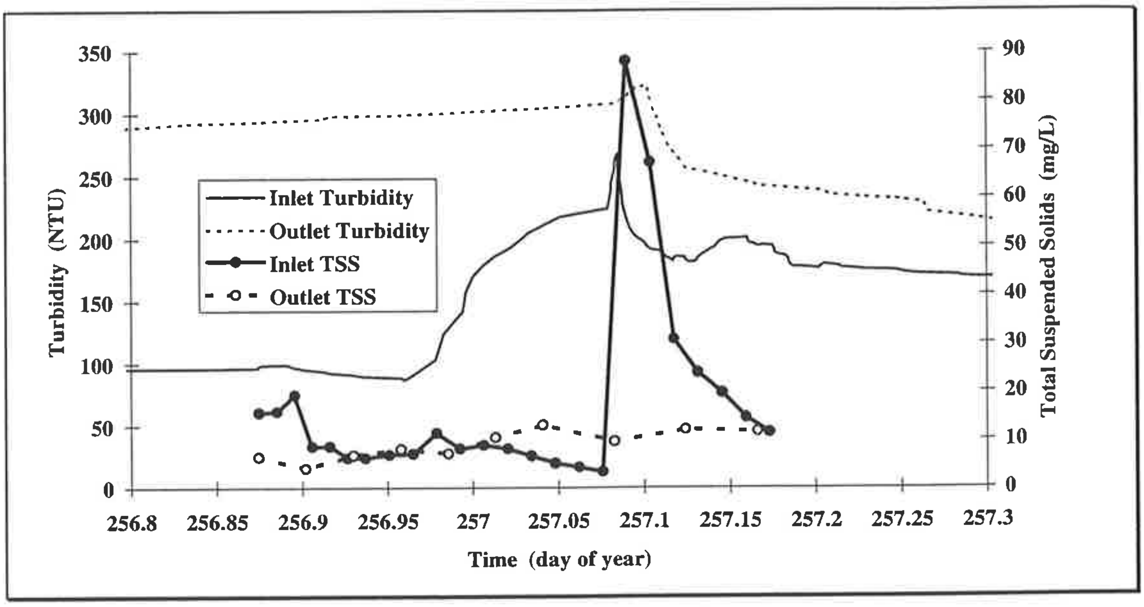


Figure 5-12 : Variation of turbidity and TSS, for Event 4, monitored on 13/09/95

Figure 5-13 shows inlet and outlet turbidity plotted with flow for Event 5. A similar pattern to Event 4 emerged. The inlet again showed more clearly the phenomenon of first flush. Turbidity there was again increasing early in the flow, and achieved a maximum value prior to peak flow. This situation was more complex than Event 4 due to the influence of a second event shortly afterwards. Turbidity did not reduce at the inlet station before the onset of the second flow, causing another slight increase. The turbidity record at the outlet is almost completely stable, probably due to the more stable flow conditions there, and also the influence of mixing. Again looking at the TSS and turbidity plot for Event 5, in Figure 5-14, it can be seen that suspended solids increased and achieved a maximum prior to peak flow, an indication of the flushing of this material in the early stages of flow. TSS at the outlet did not change significantly. The high suspended solid values achieved early in the flow record can be attributed to a small event occurring just prior to the Event 5, not shown in Figure 5-13.

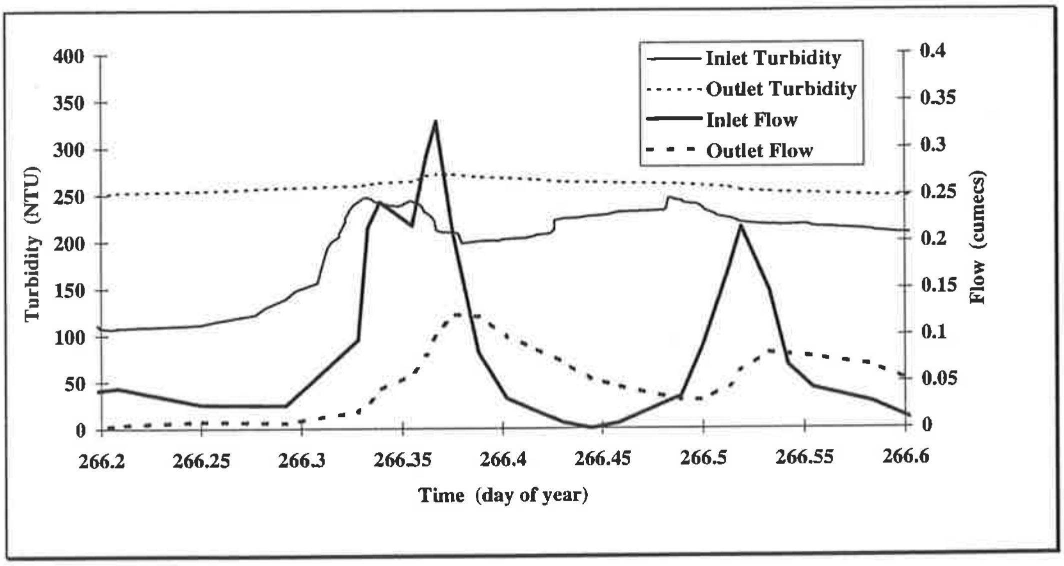


Figure 5-13 : Variation of turbidity and flow, for Event 5, monitored on 23/09/95

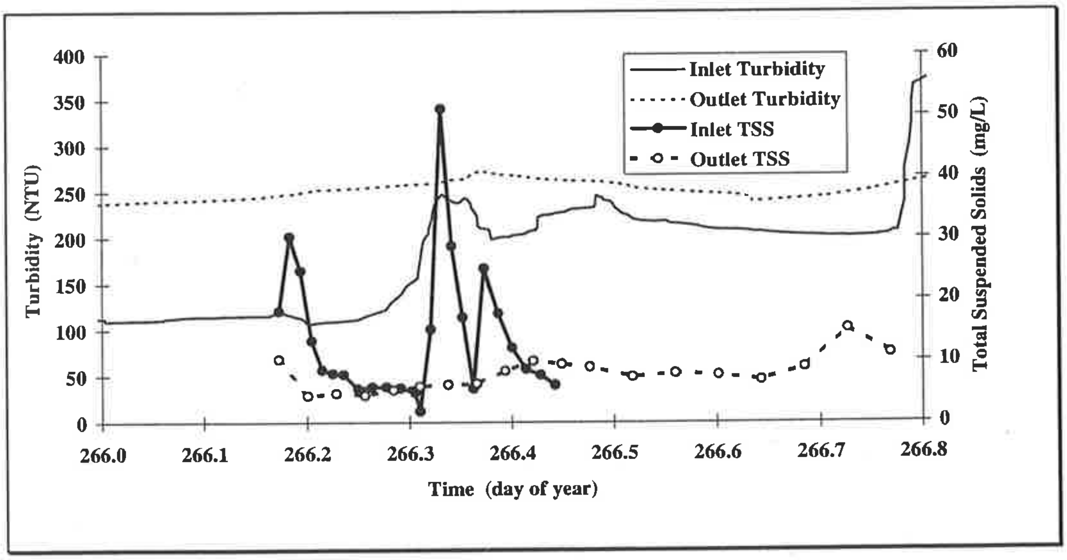


Figure 5-14 : Variation of turbidity and TSS for Event 5, monitored on 23/09/95

As a final demonstration of the flushing of suspended material in the early stages of flow, Figure 5-15 shows the inlet turbidity from an event on 01/07/95. This event was monitored only by the field sensors, so no TSS information is available. In this particular event the peak of turbidity and flow coincide, however it is quite visible that a large proportion of load has passed before the main flow of the event occurs.

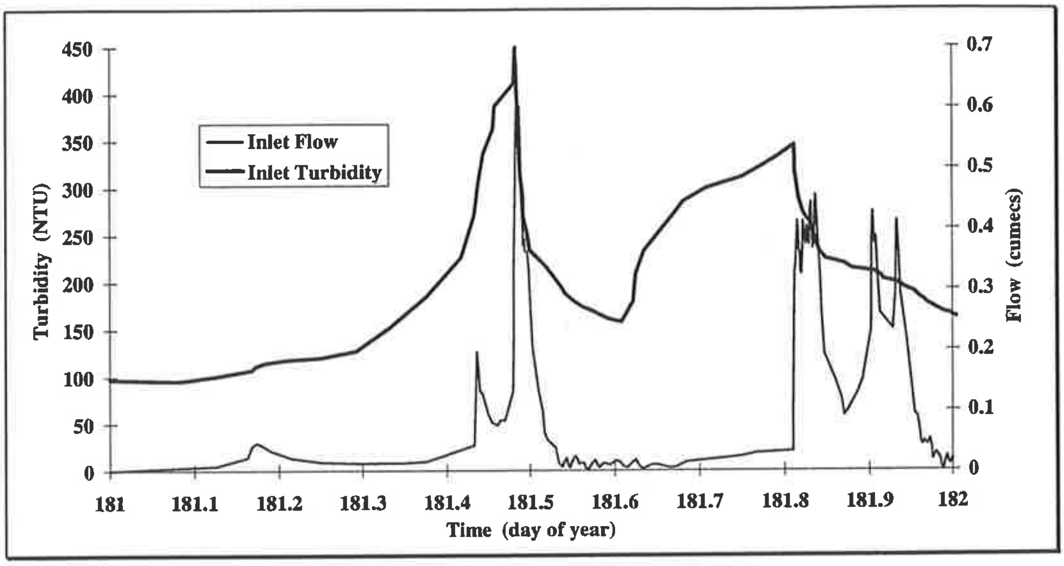


Figure 5-15 : Variation of turbidity and flow, for event monitored on 01/07/95

Chapter Six

Conclusions and Recommendations

6.1 Outcomes of the Monitoring Program

The conceptual design, construction, installation, and operation of this wetland monitoring study are all considered to have been achieved with success.

The main aim, however, to calculate the improvement in stormwater water quality on a individual event basis was not accomplished. As discussed in Section 5.5.8, it is the author's view that it is impractical to attempt to determine the event specific changes in constituent concentrations or loads, when a significant percentage of effluent monitored does not originate from the event concerned. This problem is compounded in that a complete discrete account of the event is not possible as a result of mixing within the wetland storage basin. Without substantial numerical modelling, and an intense field monitoring program, successful purely event by event based monitoring is not attainable.

Another failure of this work, was the absence of a sufficient range of laboratory tests performed on event samples. This was due in part to the lack of funding and staff on the project, the limitations of the equipment, and the shear number of tests that could reasonably be carried out within the time constraints. Given greater knowledge of the influence of many of the constituents not monitored in this study, a better understanding of the system may have been possible. Further effort to obtain additional information, in particular total and particulate fraction concentrations of the nutrients of interest, would have been advantageous. Information on the concentration of nutrient species in rainfall would also have been a great benefit to the project.

Having said this, it is still thought that for all the above constraints, the monitoring program yielded valuable results. The monitoring of inlet and outlet water quality and the analysis of 7 sampled events enabled, the calculation of:

- the average performance of the wetland to improve effluent water quality;
- relationships between selected water quality constituents under dynamic conditions;
- decay rates of constituents during quiescent and dynamic periods; and
- a comparison between wetland effluent peak and event mean concentrations and ANZECC guidelines.

Valuable information about the Minkara Wetland was also obtained during this study. Volume and surface area relationships of the basin were derived, as were flow calculation and reverse routing procedures. These have already been used in other research work at the University of Adelaide.

As part of this work, an extremely useful research resource has been put into place. It will continue to supply new and important knowledge of wetland action in improving stormwater quality. Flexibility has been designed into this system that will enable it to grow with new developments in technology, and new insights into wetland behaviour.

6.1.1 Advances Achieved in Wetland Monitoring

This study has improved the current standard of stormwater monitoring in a number of areas. Limited budget and support staff made this extremely difficult, but new developments were achieved. By the end of the study the system was a stage height triggered, time sequence sampling strategy, similar to many programs currently in operation (Tomlinson *et al.*, 1993; Vorreiter and Hickey, 1994). However, it is believed that innovations were made that will enable improvements in future wetland monitoring possible. The use of an external microprocessor and logger, to control and record multiple automatic sampler performance is one development as yet unseen by the author in this field. The application of this technology was not extended in this study, and with larger networks and software upgrades, intelligent control of multiple monitoring devices is possible. Woithe and Gamble (1996) have published the development of this control device, so other applications may occur in the future. In future studies at this site it is envisaged that this feature will be developed to include control from further field sensors, such as turbidity and dissolved oxygen probes.

The process of installing a stormwater monitoring network, although already carried out elsewhere around the world, was not without its problems. This is an area rarely discussed in the literature reviewed by this author. Such a focus is placed on the results of wetland monitoring studies that little attention is given to the methods and strategies used to produce the findings. This is a problem for the first time field researcher. The only way to learn these pitfalls is, unfortunately, to get caught by many of them. This causes delays, and in some instances a drop in the quality or quantity of data obtained. There is the lack of detail in published literature as to sampling techniques used. It is hoped that the work described here may be used to help future researchers, new to the area of stormwater monitoring.

6.1.2 Observed Performance of the Minkara Wetland

Analysis was carried out to determine the overall water quality improvement achieved by the wetland, and also to uncover any trends evident between the water quality variables.

6.1.2.1 Overall Water Quality Improvement Achieved by the Minkara Wetland

The combination of collected data from the 7 sampled events yielded the following information in Table 6-I. The following points summarise the observed performance of the Minkara Wetland:

- TSS and nitrate loads were found to be reduced by 61% and 24% respectively;
- TDS load was found to increase in wetland effluent by 170%;

  This finding was not encountered by the author in the literature on longer term studies. Single events, however, have returned this result in other wetlands. Tomlinson *et al.* (1993), although reporting no overall change observed in TDS loads, indicated that mean TDS values at the outlet were approximately double the inlet readings in the sequential samples for some events.

- phosphate load was reduced by 23%, higher than expected given the reduced improvement between TSS peak concentration and load, and given the correlation of these constituents at the inlet;

This was attributed to the different processes responsible for the availability within the water column of the two constituents. Phosphate, once in contact with the wetland is involved in a number of time and biological dependent actions, not common to TSS.

- when compared with ANZECC (1992) guidelines all constituents, except phosphate, were below recommended safe values for both event peak and event mean concentrations in the effluent. Phosphate exceeded ANZECC guidelines by 100% in event peak concentration, and 50% in event mean concentration;

The Minkara Wetland was found, therefore, to be improving stormwater quality to a standard acceptable for release into freshwater systems, for all constituents other than phosphate.

- first flush was found to be occurring in the Minkara Wetland catchment. This phenomenon was observed at the inlet of the wetland, and specifically related to TSS, phosphate and nitrate;
- dynamic decay rates, except for phosphate, were found to be logarithmic in nature, related to event flow rate. Phosphate was found to decay at a uniform rate under dynamic conditions;
- quiescent decay rates were found to be much higher when the influence of the highly vegetated inlet channel was included;

The vegetated channel provided conditions comparable with overland filtered flow. Tomlinson *et al.* (1993) showed the effectiveness of a grass swale in filtering sediment from flow and removing a large percentage of nutrients. This appeared to be the case with the Minkara Wetland inlet channel also.

- dynamic decay rates for phosphate and TDS were found to be lower than the quiescent, indicating the importance of time in the lowering of these constituents. However, quiescent TSS decay rates were substantially lower than the dynamic rate, approximately 80 times lower. This highlights the importance of flow for sediment transportation, and the reduction of stormwater flow rate for sediment removal. A similar finding was also made by Franklin *et al.* (1995).

Table 6-I : Summary of the overall wetland performance to improve water quality, results of the monitoring study on Minkara Wetland

	TSS	**TDS**	**Nitrate**	**Phosphate**
Load Reduction (%)	61	-170	24	23
Inflow EMC (mg/L)	30	316	0.055	0.171
Outflow EMC (mg/L)	12.5	548	0.037	0.147
Quiescent Decay Rate (mg/L/hr)	0.03 (0.03)[1]	21.3 (5.21)[1]	0.0039 (0.0003)[1]	0.0089 (0.00063)[1]
Dynamic Decay Rate (mg/L/hr)	0.70 - 2.5	-3.5 - -51.5	-0.0006 - 0.0007	0.001

Notes on Table 6-I:

[1] Values in brackets represent decay rates for constituents neglecting the influence of the vegetated inlet channel.

With only 7 data sets, or events to work with, and the incomplete nature of some of these sets, it was to extremely difficult to derive accurate long term predictions of stable wetland behaviour with respect to water quality constituent reduction. It is doubtful that a stable condition exists, with changes to plant growth and season altering the ability of the wetland to improve water quality in time. Given this, the results of analysing the data set have been presented purely on the basis of the short term findings of this study, and not as the long term predicted behaviour of the wetland. During this study there were variations in the improvement in water quality obtained. Any wetland or basin that performs at a certain level for the average event should be expected to perform worse for larger flows and better for smaller ones (Driscoll, 1982). There is a high degree of variability in urban runoff contamination, depending highly on site specific factors, and rainfall characteristics (Wu *et al.*, 1996). It is unlikely that this study was extensive enough to represent the average performance of the Minkara Wetland in the long term. In short, more event sampling needs to be carried out, and throughout all seasons of the year, if long term predictions can be made. At this location this will be highly unlikely due to the required drawn down period for maintaining the health of the resident River Redgums.

6.1.2.2 Summary of the Trends Observed in Event Water Quality Data

Trends were identified between many of the water quality constituents and flow variables, such as rainfall conditions, detention time and event volume, and also between the constituents themselves. Only the significant results of this correlation analysis for event peak concentrations and event load have been shown in Table 6-II. The majority of these correlations were linear in nature, although logarithmic, polynomial, and exponential trends were trialed. Correlations are linear unless otherwise stated.

Table 6-II : Significant trend correlations

Peak Concentration Parameters	Inlet Correlation (Significance)	Outlet Correlation (Significance)
Nitrate v TDS	0.96 (0.074)	NS
Nitrate v TSS	0.84 (0.084)	NS
Phosphate v Dry Flow Period	NS	0.69
Load Parameters	**Inlet Correlation (Significance)**	**Outlet Correlation (Significance)**
TSS v Max Rainfall Intensity	0.74 ()	0.91 ()
TDS v Max Rainfall Intensity	0.89	0.78 ()
Nitrate v Max Rainfall Intensity	0.90	0.85
Phosphate v Max Rainfall Intensity	0.82	NS
Phosphate v Dry Rainfall Period	NS	0.85
TDS v TSS	NS	0.92 (0.003)
TDS v Phosphate	0.91 (0.012)	0.92 (0.042)
TDS v Nitrate	0.74 (0.063)	0.89 (0.016)
TSS v Phosphate	0.88 (0.019)	NS

Notes on Table 6-II:
NS Not Significant.

A number of findings were of great interest in Table 6-II. Points of note include:

- peak concentrations displayed fewer clear correlations to flow variables;

  This was attributed to possibility of singular nature of the peak concentration data miss-representing the entire event.

- TDS correlated well with nutrient constituents, nitrate and phosphate both in peak concentrations and event loads;

  This finding has implications in all stormwater and wetland monitoring studies. The use of TDS instruments in field conditions, is a far cheaper alternative to the collection of grab samples for laboratory testing. Given sufficient calibration trials within the study catchment, the option of using cheaper, electronically logged sensors, could become a viable monitoring option.

- maximum rainfall concentration correlated very well with constituent loads;

  This result agreed with other published work, that washoff is a primary influence on pollutant load in urban stormwater. It is also suggested, given the lack of a correlation with antecedent conditions at the inlet, that buildup was the not the limiting process in the loads observed for the events monitored.

  Correlation of maximum rainfall intensity at both inlet and outlet could lead to the conclusion that wetland mechanisms were not a significant influence on loads. However, due to almost uniform detention times for the nutrient events, this premise would be misleading.

- phosphate at the outlet was the only constituent to correlate with the antecedent and detention describing parameters dry flow and dry rainfall period.

  This is significant as this indicates that catchment conditions and time dependent processes within the wetland are influential on phosphate concentrations in the effluent. This would be expected, however this was the only result that showed direct evidence of this.

6.2 Comparison of the Minkara Wetland Observed Performance and other Urban Constructed Stormwater Wetlands

Discussed in Section 4.3.1 were the findings of other studies on constructed urban wetland water quality improvement performance. The wetlands in question varied in size, location, and the surface to area ratio (SAR), identified by Driscoll (1982) as an important variable in performance.

Having identified the limitations of this particular study above, with regards to using the data collected and applying it to the long term, it is timely now to compare the results of this research to these other studies. The information from Table 4-I has been reproduced here and that gained from Minkara Wetland has been added, creating Table 6-III.

The first point that needs to be made here is the comparison of the duration of monitoring, or the number of events the results of these studies have been based on. The longest study carried out lasted for 13 months, the Piedmont study. This can hardly be said to represent the long term for a system subject to annual cycles.

Table 6-III : Comparison of Minkara Wetland observed performance and other constructed urban stormwater wetlands

Wetland Location	Catchment Area	Catchment Type	Wetland Volume	Wetland Area	Wetland Area as % of Catchment	Average Depth	Removal Efficiency (%)				No. of Events
	(ha)		(m3)	(ha)	(%)	(m)	TSS	TDS	TP	TN	
The Paddocks S.A.	60	Urban 61% Imp. 39% Perv.	2600	0.8	1.3	0.3 1.0 max	80[1] 92[2]	0	50[1] 73[2]	64[2]	150 days of monitoring
Shankland Drain Wetlands, Vic.	340	160ha Urban	12000	0.8	0.24	NA	14[3] 50[4]	NA	15[3] 22[5]	44[3] 10[6]	5 months 9 events
Urban Drainage Wetland Orlando Florida	42	Mixed Urban/Rural	3600	0.3 0.08 (Basin)	0.71	0.9-1.5 2.4-3.4 (Basin)	44[7] 15[8]	14[7] 16[8]	3[7] 22[8] -22[9]	5[7] 15[8]	11 events
Waterford Piedmont	122.2	Urban	NA	0.73	0.6	NA	41	NA	29	22[10]	13 months 11 events
Runaway Bay Piedmont	28.3	Urban	NA	0.23	0.8	NA	62	NA	36	21[10]	13 months 11 events
Lakeside Piedmont	26.6	Urban	NA	2.0	7.5	NA	93	NA	45	32[10]	13 months 11 events
Minkara Wetland, Adelaide	127	Urban	2720	3500	0.28	0.5	61	-170	23[11]	24[12]	7 events

Notes on Table 6-III :

[1] For The Paddocks these removal efficiencies were achieved for a 5 day retention time.

[2] Efficiencies are for the wetland for the entire 150 day load analysis.

[3] Efficiencies represent the results achieved during the whole study period, largely base flows

[4] Efficiencies are for the events monitored.

[5] The efficiency obtained for orthophosphate during the entire load study period.

[6].The efficiency obtained for total organic nitrogen during the entire load study.

[7] The wetland system in Florida included a detention pond. These efficiencies are for the wetland alone.

[8] Efficiencies for the pond and wetland in line system.

[9] Orthophosphate reduction for the wetland alone, negative indicating an addition.

[10] Total nitrogen values are given as total Kjeldahl nitrogen (TKN).

[11] Total phosphorus values given are phosphate.

[12] Total nitrogen values given are nitrate.

It is extremely difficult to compare different studies of nutrient removal from wetland systems when the constituents reviewed vary. A direct comparison cannot be made between a removal of total nitrogen and nitrates, each quite different, one a subset of the other. The only absolute known is that phosphate and nitrate make up a percentage of total phosphorus and total nitrogen respectively. Complications arise when certain phosphorus or nitrogen species show positive reductions and others negative. This can be hidden in the overall total elemental reduction.

With this in mind a comparison will now be made between Minkara Wetland and those reviewed in Table 4-I.

As a method of comparing two different wetlands, the surface area of the basin to catchment area ratio, SAR can be used. Shankland Drain Wetland and Minkara Wetland have very similar SAR values. TSS reductions in Minkara Wetland correspond very well with Shankland Drain Wetland, indicating a good correlation between sediment performance and SAR. Shankland Drain Wetland also performed almost identically in the removal of phosphate 22% to 23%. However, Shankland Drain outperforms Minkara Wetland in the removal of nitrogen, quite significantly. The Orlando Wetland with an SAR value twice that of Minkara recorded a negative reduction of phosphate of 22%. This highlights the variability of wetland performance with SAR.

Using the SAR value, as an indicator for water quality improvement by wetlands, came about through the US EPA's Nationwide Urban Runoff Program of 1978. This parameter has been demonstrated by Wu *et al.* (1996) to be a reliable parameter for the design of wet detention ponds for stormwater quality improvement. Unfortunately the basis for the use of the SAR parameter is one of a stormwater detention basin for sedimentation, a settling tank, not a wetland, as discussed by Driscoll (1982). For this reason, SAR is only a reliable indicator for wetland performance for suspended solid pollutants, the only constituent genuinely governed by hydraulic considerations. Work has been done to correlate the removal of sediment and nutrients (Somes and Wong, 1996; Bycroft, 1995; Tomlinson, 1993; O'Neill, 1986), including this research work, and some good correlations have been found. These studies have focussed on the correlation between TSS and TP. The reason for a good correlation between these two constituents stems purely from the particulate nature of many of the forms of phosphorus. As detailed in Chapter 2, not all forms of phosphorus important to plant growth and waterbody enrichment are insoluble. Orthophosphate, the most important form of phosphorus for plant nutrition is a form of soluble phosphorus. The wetland study by Martin (1989) showed that although reductions in TSS and TP were apparent, there was a marked increase in orthophosphate for the wetland. This would indicate an increase in the readily available supply of phosphorus in the effluent, even though at first glance this would not be apparent.

Generally speaking the Minkara Wetland performed well in comparison with the other similar SAR sized wetlands and wet detention ponds in Table 6-III for TSS and nutrient removal. The performance of the wetland to remove TDS, or in this case, to export TDS from the wetland, was peculiar to this wetland only. This has been explained by the flushing of dissolved solids built up in times of base flow, during events.

6.3 Recommendations for Future Research

It is strongly recommended that further research is carried out at the Minkara Wetland site, using the monitoring network designed and constructed as part of this work. This would enable a true long term wetland study to be carried out, over a number of years. A common weakness of literature on wetland studies is the shortness of their duration, driven in part by the cost of running a monitoring study in the long term, the length of postgraduate research degrees and the eagerness to publish. Through the continued involvement of the Department of Civil and Environmental Engineering, future research projects at the Minkara Wetland site could yield lead to significant insights into the performance of wetland in improving stormwater quality.

References

Akter, S. (1992). 'Regional Flood Estimation Method for the Mt Lofty Ranges', *University of Adelaide*, Master of Engineering Science Thesis.

Allison, R.A., and Chiew, F.H.S. (1995). 'Monitoring of stormwater pollution from various landuses in an urban catchment', *The Second International Symposium on Urban Stormwater Management*, Melbourne, Australia, 11-13 July, pp 511-516.

Allison, R.A., Essery, C.I., McMahon, T.A., (1994). 'How Gross is Pollution? - its occurrence and measurement in stormwater channels within Australian cities', *Water Down Under '94*, Adelaide, Australia, 21-25 November, pp 281-286.

Andoh, R.Y.G. (1994). 'Urban Runoff: Nature, Characteristics and Control', *Journal of the Institution of Water and Environmental Management*, Vol 8. No.4.

Auckland Regional Council (1992). 'Stormwater Treatment Devices: Design Guideline Manual', Prepared by Beca Carter Hollings and Ferner Ltd for the Environmental planning Division of Auckland Regional Council, First edition.

Australian Rainfall and Runoff (1977). *A Guide to Flood Estimation.* The Institution of Engineers, Second Edition, Volume 1.

Australian and New Zealand Environment and Conservation Council (1992). *Australian Water Quality Guidelines for Fresh and Marine Waters.*

Bedient, P.B., Lambert, J.L., and Springer, N.K. (1980). 'Stormwater pollutant load-runoff relationships', *Journal of Water Pollution Control Federation*, Vol. 52, No. 9, pp 2396-2404.

Bos, M.G. (1989). *Discharge Measurement Structures*, International Institute for Land Reclamation and Improvement, Wangeningen, 3rd edition.

Boyd, M. J., Pilgrim, D. H., Knee, R. M., and Budiawan, D. (1989). 'Reverse Routing to Obtain Upstream Hydrographs', *Hydrology and Water Resources Symposium*, Christchurch N.Z., 23-30 November, pp 372-376.

Brezonik, P.L. (1976). 'Nitrogen: Sources and Transformations in Natural Waters', *Nutrients in Natural Waters*, Allen, H.E., and Kramer, J.R. eds, John Wiley and Sons.

Burn, E.H. (1991). 'Water Quality Sampling for Nutrient Load Estimation', *Water Pollution: Modelling, Measuring and Prediction*, Wrobel, L.C., and Brebbia, C.A. eds, Computational Mechanics Publications, Elsevier Applied Science, Southampton.

Bycroft, B., Mack, P., and McAlister, T. (1995). 'Stormwater Data Water Collection Program for the Brisbane City Council', *The Second International Symposium on Urban Stormwater Management*, Melbourne, Australia, 11-13 July, pp 483-487.

Cordery, I. (1976). 'Evaluation and Improvement of Quality Characteristics of Urban Stormwater', *Water Research Laboratory*, UNSW, No. 147, October, 1976.

Cowardin, L.M., Carter, V., Golet, F.C., La Roe, E.T., (1979). 'Classification of wetlands and deepwater habitats in the United States', U.S Dept of the Interior, Fish and Wildlife Service Report FWS/OBS-79/31.

Cullen, P. (1983). 'Research into Nutrient Exports from Land Surfaces', *Workshop on Non-Point Sources of Pollution in Australia*, Monash University, Melbourne 7-10 March 1983, Australian Government Publishing Service, Canberra, pp 123-135.

Daniell, T.M., McCarty, D.J. (1994). 'Sedimentation in Artificial Urban Wetlands in Happy Valley, South Australia', *Water Down Under 94, International Hydrology and Water Resources Symposium*, IEAust Australia, Adelaide 21-25 November 1994, pp 341-346.

Daniell, T., McCarty, D. (1996). 'Retrofitting Wetlands for Water Quality Control', *National Conference for Wetlands for Water Quality Control*, James Cook University, Townsville, 25 - 29 September, pp 415-424..

Dowling, R.M., Stephens, K.M. (1995). 'The Use of Wetland Plants in Artificial Wetlands in Queensland', *National Conference for Wetlands for Water Quality Control*, James Cook University, Townsville, 25 -29 September, pp 135-141.

Driscoll, E.D. (1982). 'Analysis of Detention Basins in EPA NURP program', *Conference on Stormwater Detention Facilities-Planning, Design, Operation and Maintenance*, New York, pp 21-32.

Duncan, H.P. (1995). 'A Review of Urban Stormwater Quality Processes', *Cooperative Research Centre for Catchment Hydrology*, Monash University, Report 95/9.

Eusuff, T.H. (1995). 'A Regional Flood Frequency Approach to the Mt Lofty Ranges', *University of Adelaide*, Master of Engineering Science Thesis in Hydrology and Water Resources.

Faulkner, S.P., Richardson, C.J. (1989). 'Physical and Chemical Characteristics of Freshwater Wetland Soils', *Constructed Wetlands for Wastewater Treatment*, D.A. Hammer ed., Lewis Publishers, Chelsea.

Franklin, J.M., Pettigrove, V., and Mason, B. (1995). 'Shankland Drain Wetland - An Off-line Wetland for Improvement of Urban Drainage Water Quality', *The Second International Symposium on Urban Stormwater Management*, Melbourne, Australia, 11-13 July, pp 375-380.

Gamble, S., and Pannell, J. (1993). 'A Review of the 1986 EPA Report: "Methodology for analysis of Detention Basins for Control of Urban Runoff Quality".' *Department of Civil and Environmental Engineering,* Final Year Research Project.

Golterman, H.L. (1975). *Physical Limnology: An Approach to the Physiology of Lake Ecosystems*, Elsevier Scientific Publishing Company, New York.

Harper, D. (1992). *Eutrophication of Freshwaters: Principles, problems and restoration*, Chapman and Hall, London.

Harrison, R.M., and Wilson, S.J. (1985). 'The Chemical composition of highway drainage waters : Majors ions and selected trace metals.' *The Science of the Total Environment*, 42, pp 63-77.

Hill, P. I., Fleming, N. S., and Daniell, T. M. (1993). 'How bad is your RORB Modelling?: Sensitivity fitting - An innovation.' *Proceedings of the International Conference on Environmental Management, Geo-Water and Engineering Aspects*, Wollongong, New South Wales, Australia, 8-11 February 1993, pp 431-439.

Howard-Williams, C., (1985). 'Cycling and retention of nitrogen and phosphorus in wetlands: a theoretical and applied perspective', *Freshwater Biology*, 15, pp 391-431.

Hutchinson, G.E. (1970). Introduction to 'Eutrophication: Causes, consequences, correctives', *Proceedings for the International Symposium on Eutrophication 1967*, National Academy of Sciences, Washington.

Jelliffe, P.A. (1995). 'Wetlands as a Water Quality Management Tool in Unsewered Residential Areas', *National Conference for Wetlands for Water Quality Control*, James Cook University, Townsville, 25 -29 September, pp 169-176.

Kachka, A. M., Mackay, S. M., and Simeoni, M. A. (1994). 'Sampling Methodology for the Assessment of Nutrient and Bacterial Loads in Stormwater', *Water Down Under 94, International Hydrology and Water Resources Symposium*, IEAust Australia, Adelaide 21-25 November 1994, pp 327-334.

Kadlec, R.H. (1989) 'Hydrologic Factors in Wetland Water Treatment', *Constructed Wetlands for Wastewater Treatment,* D.A. Hammer ed., Lewis Publishers, Chelsea.

Kadlec, R.H., Bastiaens, W., and Urban, D.T. (1993). 'Hydrological Design of Free Water Surface Treatment Wetlands', *Constructed Wetlands for Water Quality Improvement*, ed. G.A. Moshiri., Lewis.

Kadlec R.H., and Knight, R.L. (1996). *Treatment Wetlands*, Lewis Publishers, Boca Raton.

Kerr, G., and Eyre, B. (1995), 'Stormwater Quality in Lismore, NSW, a Regional Urban Centre', *The Second International Symposium on Stormwater Management*, Melbourne, Australia, 11-13 July, pp 543-548.

Kramer, J.R. (1972). 'Phosphorus: Analysis of Water, Biomass, and Sediment', *Nutrients in Natural Waters*, Allen, H.E., and Kramer, J.R. eds, John Wiley and Sons, New York.

Kuo, C.Y., and Zhu, J. (1989). 'Design of a Diversion System to manage the First Flush.' *Water Resources Bulletin*, Vol 25 No. 3, pp 517-525.

Leopold, L.B., (1968). 'Hydrology for urban land planning: a guidebook on the hydrologic effects of urban landuse'. *US Geological Survey Circular 554.*

Livingston, E.H. (1989). 'Use of Wetlands for Urban Stormwater Management', *Constructed Wetlands for Wastewater Treatment,* D.A. Hammer ed., Lewis Publishers, Chelsea.

Levenspiel, O. (1972). *Chemical Reaction Engineering*, Second edition, John Wiley and Sons, New York.

Maier, H.R., and Dandy, G.C. (1994). 'Blue green algae in the River Murray', *Department of Civil and Environmental Engineering, The University of Adelaide*, General Report No. G25, December 1994.

Martin, E.H. (1989). 'Effectiveness of an Urban Runoff Detention Pond-Wetlands System.' *Journal of Environmental Engineering*, Vol 114, No. 4, pp 810-827.

Mason, C. F. (1991), *Biology of Freshwater Pollution*, Second edition, Longman Scientific and Technical, New York.

Miller, G. T. Jnr, and Armstrong, P. (1982), *Living in the Environment : concepts, problems and alternatives*, International Edition, Wadsworth International Group, Belmont, California.

Mitsch, J.W., and Gosselink, J.G. (1986). *Wetlands*, Van Nostrand Reinhold, New York.

Morse McVey and Associates, (1993). 'Soil and Water Management for Urban Development.' *NSW Dept of Housing*, 2nd edition, Sydney.

O'Malley, C., and Sheldon, F. (1990). 'Chowilla floodplain biological study.', *Nature Conservation Society of South Australia*, Adelaide.

O'Neill. (1985). *Environmental Chemistry*, George Allen and Unwin, London.

Rosich, R.S., Cullen, P. (1982). 'Nutrient Runoff', *Water Quality Management: Monitoring Programs and Diffuse Runoff.* Ed. Hart, B.T. Water Studies Centre, Chisolm Institute of Technology and Australian Society for Limnology, Melbourne.

Silverman, G.S. (1989). 'Treatment of Non-point Source Pollutants - Urban Runoff and Agricultural Wastes', *Constructed Wetlands for Wastewater Treatment,* D.A. Hammer ed., Lewis Publishers, Chelsea.

Sivakumar, M., and Musavi, S.H. (1995). 'Analysis of Phosphorus in the Nepean River Using Turbidity and Electrical Conductivity', *The Second International Symposium on Stormwater Management*, Melbourne, Australia, 11-13 July, pp 503-508.

Somes, N.L.G., and Wong, T.H.F. (1996). 'Characterisation of Stormwater in the Lance Creek Catchment', *23rd Hydrology and Water Resources Symposium*, Hobart, Australia, 21-24 May, pp 223-228.

'The Urrbrae Wetlands' (1996), *Urban Wastewater Management Workshop and Wetlands Tour,* Draft Report.

Thomas, E.A. (1970). 'The Process of Eutrophication in Central European Lakes', *Proceedings for the International Symposium on Eutrophication 1967,* National Academy of Sciences, Washington.

Tomlinson, G.W., Fisher, A.G., and Clark, R.D.S. (1993). 'The Paddocks', *E&WS Report No 93/11.*

Sakadevan, K., Ryan, G., Roser, D., Starrett, J., Bavor, J., Osborne, P. (1995). 'Phosphorus and Nitrogen Budgets for Five Experimental Constructed Wetland Systems', *National Conference for Wetlands for Water Quality Control*, James Cook University, Townsville, 25 - 29 September, pp 103-109.

Standard Methods for the Examination of Waters and Wastewaters (1980), 15th edition, APHA-AWWA-WDCF, pp 94.

Uren, J., and Price, W.F. (1978). *Surveying for Engineers*, Macmillan Education, Basingstoke.

U.S. Environmental Protection Agency (1986). 'Methodology for Analysis of Detention Basins for Control of Urban Runoff Quality', *440/5-87-001, US EPA*, Washington D.C.

U.S. Soil Conservation Service (1991). 'National List of Hydric Soils', National Technical Committee for Hydric Soils, *U.S. Department of Agriculture*, Washington, D.C.

Vorreiter, L., and Hickey, C. (1994). 'Incidence of First Flush Phenomenon in Catchments of the Sydney Region', *Water Down Under 94, International Hydrology and Water Resources Symposium*, IEAust Australia, Adelaide 21-25 November 1994, pp 359-364.

Walker, D. J., and Gamble, S. (1995), 'Minkara Wetland Water Quality Assessment Preliminary Report', *Department of Civil and Environmental Engineering*, The University of Adelaide.

Walker, D.J. (1996). 'Basin Geometry and its Effect on Flow Patterns in Constructed Wetlands', *Research Report No. R135*, Department of Civil and Environmental Engineering, The University of Adelaide.

Weibel, S.R., Weidner, R.B., Christianson, A.G., and Anderson, R.J. (1966). 'Characterization, Treatment and Disposal of Urban Stormwater', *Advances in Water Pollution Research, Proceedings of the Third International Conference*, Munich, Vol. 1, Water Pollution Control Federation, pp 329-352.

Wetzel, R. G. (1983), *Limnology*, Second edition, W. B. Saunders Company, New York.

Whitehill, T. (1995). *Report of site inspection of the Minkara Wetland on 11th August*, Botanic Gardens of Adelaide and State Herbarium 1995.

Williams, B., and Smythe, C. (1994). 'Modelling Rainfall Flows into Urban Wetlands at Happy Valley, South Australia, using RAFTS-XP.' *1994 Department of Civil and Environmental Engineering Final Year Research Project.*

Williams, B.G., and Daniell, T.M. (1996). 'Characterisation of Urban Stormwater Runoff entering the MFP Wetland, Wingfield, South Australia', *International Conference on Water Resources and Environmental Research: Towards the 21st Century,* Kyoto, Japan.

Willunga Constructed Wetland System (1996). *Urban Wastewater Management Workshop and Wetlands Tour,* Draft Report.

Woithe, S., and Gamble, S. (1996) 'The Microprocessor Control of Water Samplers Located at the Inflow and Outflow Points of a Small Wetland', *Instrumentation and Control Exhibition Symposium*, Melbourne, 30 July - 1 August 1996.

Wood, G. (1975). 'An Assessment of Eutrophication in Australian Inland Waters', *Australian Water Resources Council*, Research project No. 72/45

Wu, Jy.S., Holman, R.E., and Dorney, J.R. (1996). 'Systematic Evaluation of Pollutant Removal By Urban Wet Detention Ponds', *Journal of Environmental Engineering*, Vol. 122, No. 11, November, pp 983-988.

APPENDIX A

Stadia Surveying

Stadia Surveying

Stadia surveys are carried out using a staff and a theodolite. No tape to measure horizontal distances is needed. Instead the horizontal distance (D) is calculated from reading the coverage of the stadia hairs on the staff (s). The stadia coverage is determined by taking 3 readings on the staff, the top, centre, and bottom stadia hairs. Stadia coverage (s) is simply the difference in elevation between the top and bottom hairs. Elevations are calculated from the centre stadia staff reading (m) and the vertical angle (θ), is read off the theodolite. The relationship for determining horizontal distance with a theodolite is shown in Equation A.1, (Uren and Price, 1978).

$$D = Ks + C \tag{A.1}$$

where: D is horizontal distance;
K is multiplying constant;
s is stadia hair coverage on staff;
and C is additive constant.

Modern theodolites are designed such that the multiplying constant is 100 and the additive constant is 0. This simplifies Equation (A.1) to:

$$D=100s \tag{A.2}$$

Equation (A.2) will hold, given that the angle of elevation of the theodolite is no greater than 10 degrees, and D is no less than 10 metres. These restrictions were adhered to during the stadia survey of the wetland basin.

Calculation of the elevation of the position of the staff is a little more involved. Referring to Figure A-1, adapted from Uren and Price (1978), the equation of the relative elevation of a survey point (RL_x) using the stadia technique is:

$$RL_x=RL_p+h_i \pm V-m \tag{A.3}$$

where h_i is height of theodolite;
m is height of staff centre stadia;
RL_p is relative level of theodolite;
and V is vertical component between theodolite and base of staff, given by Equation (A.4).

$$V= \tfrac{1}{2}(Ks.\sin \theta) \tag{A.4}$$

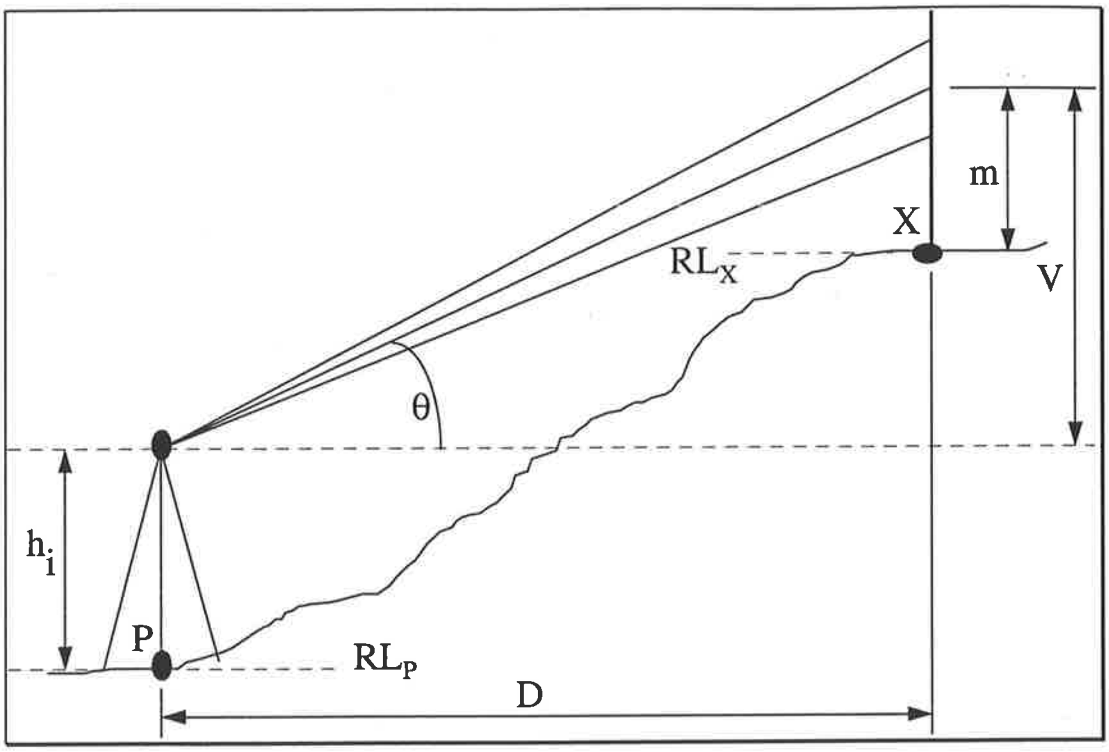


Figure A-1 : Stadia Surveying on an incline, adapted from Uren and Price (1978)

APPENDIX B

Example of Reverse Routing Procedure

Table B-I : Example of reverse routing spreadsheet analysis

Coefficients for Cv		Coefficients for Cd	
ccv	0.999902	ccd	0.833820095
ccv1	0.069933	ccd1	0.261462623
ccv2	-0.619104	ccd2	-1.5841918
ccv3	5.415045	ccd3	3.909235717
ccv4	-19.80493	ccd4	-3.941793738
ccv5	40.64155	ccd5	1.70070799
ccv6	-42.24627	ccd6	-0.16723822
ccv7	17.47164	ccd7	-0.050310697

Coefficients for Volume	
xx0	-294.059
xx1	5679.608
xx2	-35987.4
xx3	106193
xx4	-169334
xx5	161948.3
xx6	-95514.8
xx7	34883.81
xx8	-7649.22
xx9	918.8747
xx10	-46.3031

Coeffs for Cross-Area	
zz0	16.5189324
zz1	43.15628278
zz2	27.29431776
zz3	-1.693918

Weir Geometry		
Weir Crest Length	L	0.67
Weir Crest Width	bc	1.25

Time (days)	**Stage Height** (m)	**Time Increment** (hrs)	**Height Over Weir H1** (m)	**Height Above Base** (m)	**A1** (m^2)	**H1/L**	**Drag Coefficient** Cd	**Vel Head Coefficient** Cv	**Weir Outflow** (cumecs)	**Storage Volume** (m^3)	**Wetland Inflow** (cumecs)	**Smoothed Inflow** (cumecs)
266.167	0.229	0	-0.019	1.45693	15.7	0.0000	0.8338	0.9999	0.000	2609	0.03	0.031
266.194	0.249	0.648	0.001	1.47693	16.6	0.0015	0.8342	0.9999	0.000	2724	0.04	0.044
266.208	0.264	0.336	0.016	1.49193	17.2	0.0239	0.8392	1.0000	0.004	2811	0.06	0.043
266.25	0.274	1.008	0.026	1.50193	17.7	0.0388	0.8418	1.0000	0.008	2871	0.01	0.026
266.292	0.27	1.008	0.022	1.49793	17.5	0.0328	0.8408	1.0000	0.006	2847	0.02	0.025
266.328	0.294	0.864	0.046	1.52193	18.6	0.0687	0.8455	1.0001	0.018	2992	0.04	0.095
266.333	0.308	0.12	0.06	1.53593	19.2	0.0896	0.8471	1.0001	0.027	3078	0.27	0.216
266.339	0.329	0.144	0.081	1.55693	20.2	0.1209	0.8484	1.0002	0.042	3210	0.28	0.242
266.355	0.349	0.384	0.101	1.57693	21.2	0.1507	0.8487	1.0002	0.058	3339	0.14	0.217
266.362	0.372	0.168	0.124	1.59993	22.3	0.1851	0.8485	1.0003	0.079	3490	0.31	0.291
266.367	0.394	0.12	0.146	1.62193	23.4	0.2179	0.8479	1.0003	0.101	3638	0.41	0.328
266.375	0.414	0.192	0.166	1.64193	24.4	0.2478	0.8475	1.0004	0.122	3775	0.19	0.211
266.388	0.412	0.312	0.164	1.63993	24.3	0.2448	0.8475	1.0004	0.120	3761	0.06	0.081

Table B-II : Example of reverse routing spreadsheet analysis, continued

Time (days)	**Stage Height** (m)	**Time Increment** (hrs)	**Height Over Weir H1** (m)	**Height Above Base** (m)	**A1** (m^2)	**H1/L**	**Drag Coefficient** Cd	**Vel Head Coefficient** Cv	**Weir Outflow** (cumecs)	**Storage Volume** (m^3)	**Wetland Inflow** (cumecs)	**Smoothed Inflow** (cumecs)
266.402	0.392	0.336	0.144	1.61993	23.3	0.2149	0.8480	1.0003	0.099	3624	0.02	0.032
266.417	0.378	0.36	0.13	1.60593	22.6	0.1940	0.8483	1.0003	0.085	3530	0.02	0.018
266.43	0.363	0.312	0.115	1.59093	21.8	0.1716	0.8486	1.0003	0.071	3430	0.00	0.006
266.444	0.343	0.336	0.095	1.57093	20.9	0.1418	0.8487	1.0002	0.053	3300	0.00	0.000
266.458	0.333	0.336	0.085	1.56093	20.4	0.1269	0.8485	1.0002	0.045	3236	0.00	0.005
266.489	0.313	0.744	0.065	1.54093	19.4	0.0970	0.8475	1.0001	0.030	3109	0.02	0.035
266.5	0.313	0.264	0.065	1.54093	19.4	0.0970	0.8475	1.0001	0.030	3109	0.10	0.089
266.513	0.333	0.312	0.085	1.56093	20.4	0.1269	0.8485	1.0002	0.045	3236	0.14	0.172
266.519	0.353	0.144	0.105	1.58093	21.3	0.1567	0.8487	1.0003	0.062	3365	0.30	0.216
266.533	0.374	0.336	0.126	1.60193	22.4	0.1881	0.8484	1.0003	0.081	3503	0.11	0.147
266.542	0.372	0.216	0.124	1.59993	22.3	0.1851	0.8485	1.0003	0.079	3490	0.06	0.067
266.554	0.369	0.288	0.121	1.59693	22.1	0.1806	0.8485	1.0003	0.076	3470	0.04	0.043
266.583	0.359	0.696	0.111	1.58693	21.6	0.1657	0.8487	1.0003	0.067	3404	0.04	0.028
266.603	0.339	0.48	0.091	1.56693	20.7	0.1358	0.8486	1.0002	0.050	3274	0.00	0.010
266.62	0.315	0.408	0.067	1.54293	19.5	0.1000	0.8477	1.0001	0.031	3122	0.00	0.001
266.625	0.317	0.12	0.069	1.54493	19.6	0.1030	0.8478	1.0002	0.033	3135	0.00	0.001
266.634	0.308	0.216	0.06	1.53593	19.2	0.0896	0.8471	1.0001	0.027	3078	0.00	0.000
266.635	0.304	0.024	0.056	1.53193	19.0	0.0836	0.8467	1.0001	0.024	3053	0.00	0.002
266.667	0.302	0.768	0.054	1.52993	18.9	0.0806	0.8465	1.0001	0.023	3041	0.01	0.009
266.708	0.29	0.984	0.042	1.51793	18.4	0.0627	0.8449	1.0001	0.015	2967	0.02	0.018
266.75	0.3	1.008	0.052	1.52793	18.8	0.0776	0.8463	1.0001	0.021	3029	0.02	0.019
266.792	0.296	1.008	0.048	1.52393	18.7	0.0716	0.8458	1.0001	0.019	3004	0.01	0.016
266.833	0.292	0.984	0.044	1.51993	18.5	0.0657	0.8452	1.0001	0.017	2980	0.01	0.010

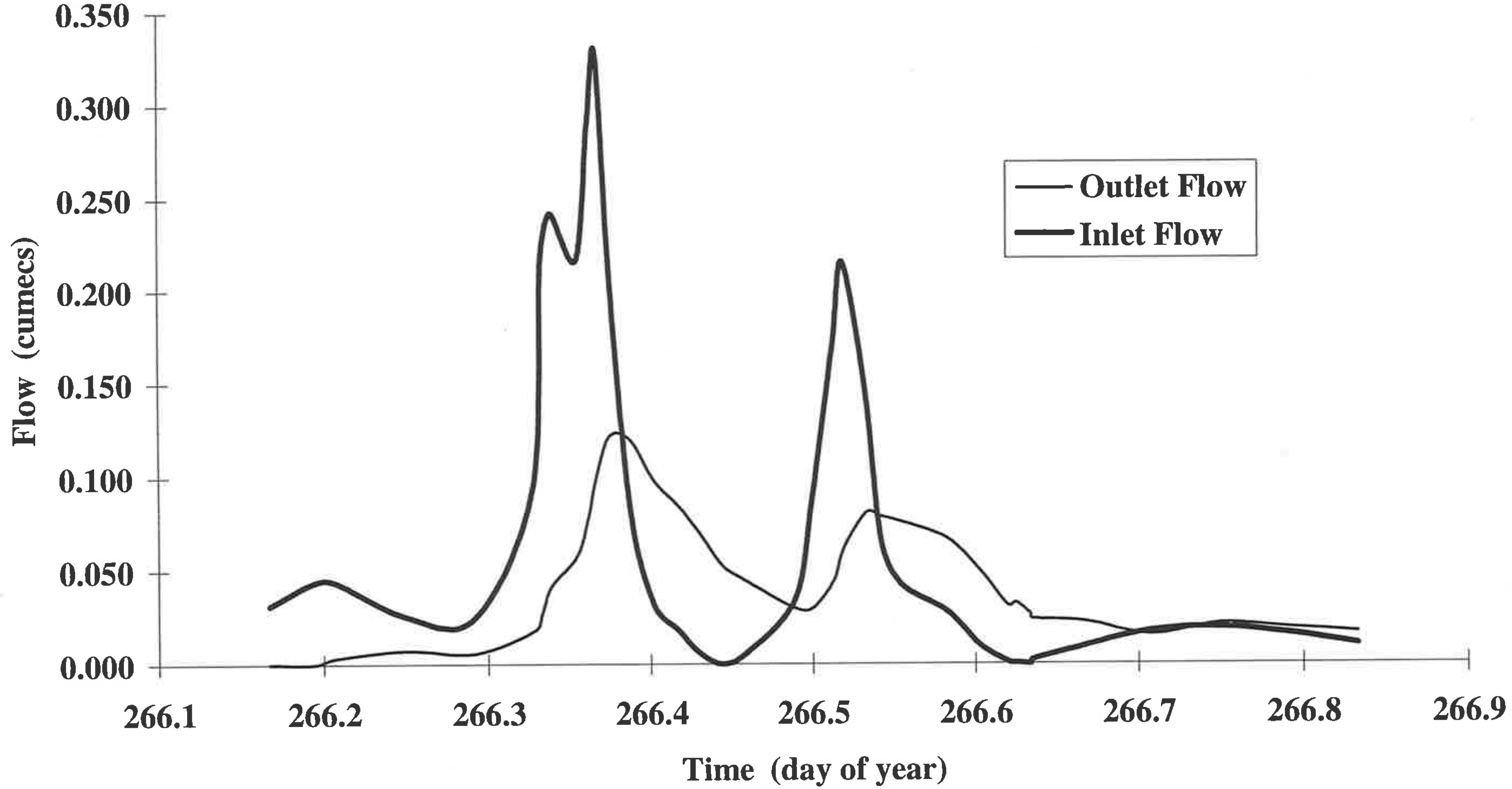


Figure B-1 : Plot of reverse routing example, inlet flow derived from outlet flow

APPENDIX C

Details of the Automatic Sampler Controller

(Woithe and Gamble, 1996)

The Microprocessor Control of Water Samplers Located at the Inflow and Outflow Points of a Small Wetland

Stan Woithe
Technical Officer, Department of Civil and Environmental Engineering, University of Adelaide
Simon Gamble
Postgraduate Student, Department of Civil and Environmental Engineering, University of Adelaide

Abstract

Research into the effectiveness of small wetlands for the treatment of urban runoff has been conducted by the University of Adelaide Department of Civil and Environmental Engineering for some time. One of the studies involved the monitoring of the water quality at both the inflow and outflow points of an artificial wetland located within the Adelaide suburb of Happy Valley. Commercially available water samplers sample at fixed time intervals with an adjustable number of more frequent samples being taken after the predetermined trigger event. However, this was considered to be too inflexible for this application. A special microprocessor based controller was therefore built to control the water samplers, with a water level sensor already used at the site providing the trigger signal. This micro-controller operated two water samplers as required, storing the date, time and number of each sample in memory for later downloading to a portable computer. Lookup tables in the program EPROM were used to vary the interval between samples based on the time elapsed from the start of the event. Different lookup tables were derived for each of the samplers. These were based on information obtained from earlier studies and took into account the propagation delay of the water through the wetland and the probable length of the rain event. The microprocessor firmware was flexible enough to either fill all 24 bottles of each sampler during a long rain event, or fill 12 bottles of each sampler during each of two smaller rain events.

1. INTRODUCTION

Serious study of wetlands has only started in relatively recent times, and is a multi-disciplined activity. In times past, wetlands were only considered useful by many people after they were drained and filled in. Fortunately, this is no longer the case, and wetlands have been constructed within urban areas for the control and treatment of stormwater runoff. However, more research needs to be carried out in order to broaden the understanding of wetland dynamics. An integral part of this is the collection of field data, which necessitates the development and use of suitable instrumentation.

2. MINKARA WETLAND STUDY

The Department of Civil and Environmental Engineering at the University of Adelaide has been involved in the study of wetlands for some time. In 1992 the Department constructed the Minkara wetland with financial assistance from the Happy Valley Council. This wetland is situated on the eastern side of the Happy Valley Reservoir on the natural water course which is channelled around the reservoir. It is approximately 80 metres long and is less then 2 metres deep in its deepest part, which makes it small by most standards. However, small wetlands like this one are worth studying because Councils are more likely to find space to build many small wetlands within their Council areas, than one large one.

The aim of this study was to monitor the quantity and quality of the water at the inflow and outflow points of the Minkara wetland. Some equipment was already installed at the site prior to the start of this study. This consisted of a stage height recorder at the outlet weir and a Gamet automatic water sampler that could be positioned at either the inlet or outlet. The water sampler, capable of taking 24 one litre samples, had to be manually triggered at the start of each rain event.

A second water sampler was purchased to enable simultaneous sampling at both the outlet (weir) and inlet of the wetland. Partially buried 200 litre drums set in concrete were used to house the samplers and protect them from the elements. The inlet hoses were placed in electrical conduit and buried. At the inlet, the sample pipe nozzle was attached to a float mechanism which allowed the water take-up point to rise with the water level. At the outlet sampling point, the intake hose was fixed to the wall of the weir some 100 mm below the normal weir water level.

At this stage, the only way the samplers could be operated was in the manually triggered time mode. This was totally unsatisfactory, because, although the time interval between samples could be set in the sampler, the start of the event could not be predicted. It was very much a hit and miss affair. Results were obtained during the last month of the 1994 winter, but these were not very useful. For example, in Figure 1 most of the samples were taken at a time when there was no flow over the weir.

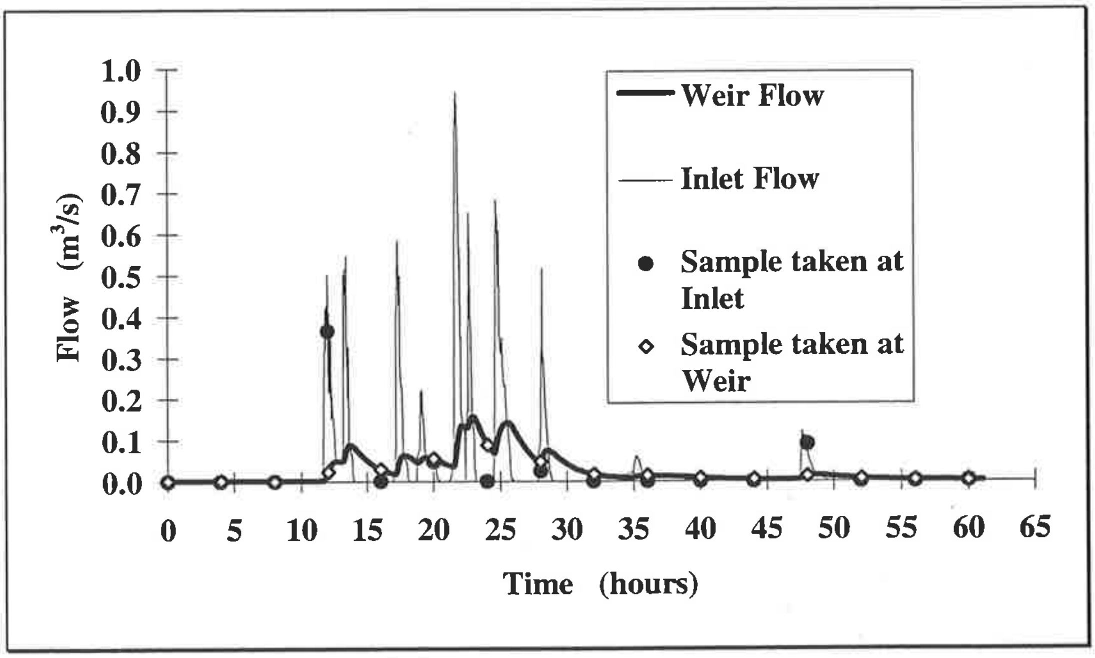


Figure 1 : Time Interval Sampling with no trigger device

While the manual triggering system was in use, work was progressing on a method to control the operation of both water samplers from the inlet station using a float mechanism and a purpose built microcomputer based controller. The decision to build the controller was made on the grounds of flexibility, and this proved to be a very useful feature as the project progressed. The two sites were connected by a four core telephone cable which was placed inside a 90 metre length of black polyethylene irrigation pipe to prevent water ingress. It was attached to the floor of the wetland with steel pegs. Three of the four wires in the telephone cable were used to control the water sampler at the weir.

There was no reason why the samplers could not have been operated using the float switch as a trigger without the purpose built controller. Indeed, this was contemplated as an alternative if the controller failed to live up to expectations. The disadvantages of the simple float switch triggering system were that the time log of each sample would not be available, and there would be less control over the time interval between samples. As it turned out, the controller was ready to install at about the same time as the cable laying and float switch installation on site were completed. Since the controller proved to be reliable in service from the day it was installed (apart from a few minor software bugs), there was no need to try the simple float switch trigger.

The results from the controller based sampling system were encouraging but not ideal. A look at Figure 2 shows that the rising limb of the hydrograph was not sampled by the inlet sampler, and that the first sample was taken at least half an hour after the start of the rain event. This was first thought to be because the float switch was not sensitive enough, so the decision was made to use the output from the existing inlet pressure sensor as the trigger signal instead. The pressure sensor was used together with turbidity, dissolved oxygen, and temperature sensors, to record continuous water quality parameters at both the inlet and outlet of the wetland, using separate loggers.

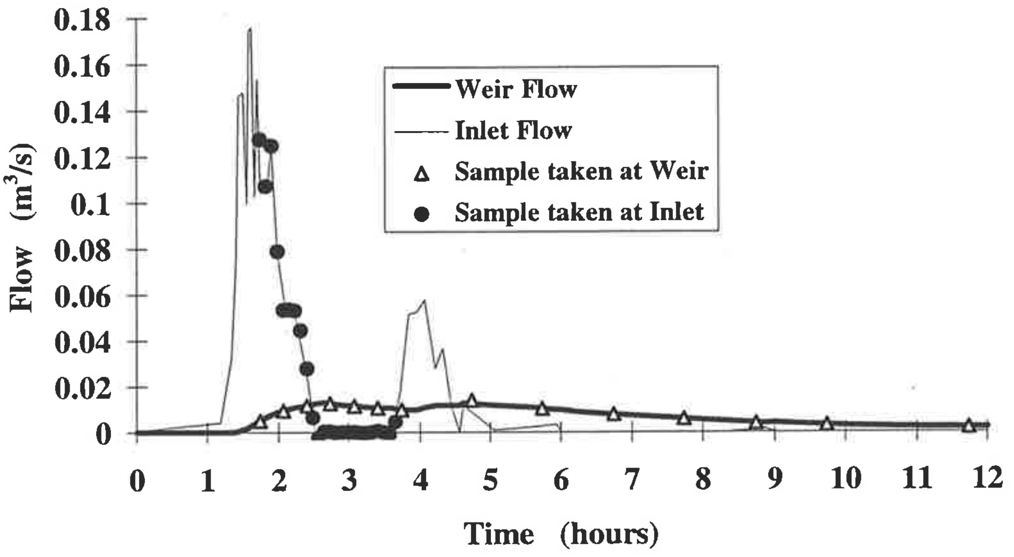


Figure 2 : Time Interval Sampling with Float Switch trigger device

An interface circuit was designed and built to produce a trigger pulse at an adjustable pressure. However, a comparison of the data obtained from the water quality loggers in Figure 3 clearly shows that there is little difference in the water level between the inlet and exit points of this wetland during rain events. In other words, the increased sensitivity offered by the pressure sensor trigger would offer little improvement over the previously used float switch. Since the pressure sensor at the inlet was more or less redundant, as this level was controlled by the downstream weir, it was decided to relocate the sensor further upstream, away from the influence of the wetland water level. In this way, the samplers were made to start sampling at a water height proportional to the flow rate, and not by the change in height of the wetland water level. A site was chosen about 70 metres upstream from, and about one metre higher than the inlet. Here the pressure sensor was installed within a specially made protective cage. Looking back with hindsight, it is most likely that a relocated float switch could have achieved the same results as the pressure sensor. However, adjustment of the trigger point for the float switch required physically shifting its position, while the pressure sensor could be adjusted with a screw driver.

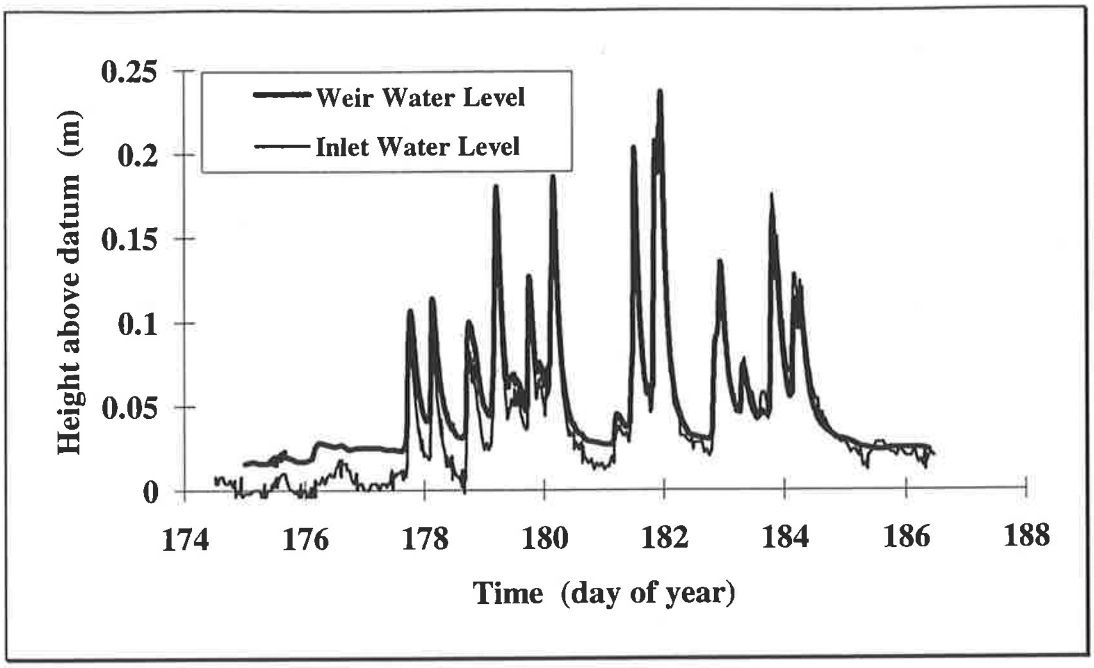


Figure 3 : Comparison of Inlet and Outlet water levels during events

Before and during the relocation of the pressure sensor, an examination of the recorded data from previous rain events at the wetland took place to determine the optimum sampling time table for both samplers. This resulted in Table I, which was transferred into the revised operating code for the microcomputer. Notice that Table I is effectively two tables - one for short events and the other for long events. Extra logic was incorporated into the operating code to stop sampling after the first 12 bottles if the flow rate had fallen below the trigger level. Both Samplers commenced from number 1 when the flow rate again exceeded the trigger level. However, if the flow rate was still above the trigger point after the twelfth bottle was filled at the inlet site, sampling would continue according to the long time table until all bottles in both samplers were filled. In this way it was possible to collect samples from either one long rain event or two short rain events using a single set of 24 bottles in each sampler.

Although the final system as described was only in operation for a short time, enough data was collected to enable the post graduate to complete the data collection phase. Typical data are illustrated in Figure 4, which shows that samples were collected during the rising limb of both the short rain events.

3. THE MICROCOMPUTER

Commercial loggers were considered for use as the controller for these samplers, but were rejected on the grounds of cost. However, the post graduate concerned did have some experience in building electronic equipment, and agreed to build the controller using a design similar to one developed for use at other water sampling monitoring sites. The controller is based around a general purpose microcomputer (type 80C552) which can be looked upon as a component consisting of just two parts. These are the Input/Output (or I/O) section and the Microcomputer section.

Table I : Time table used by the microprocessor controller

Sample Number	Inlet Sample Times First or Long Event (mins)	Inlet Sample Times Second Event (mins)	Outlet Sample Times First or Long Event (mins)	Outlet Sample Times Second Event (mins)
1	0		0	
2	15		40	
3	30		80	
4	45		120	
5	60		160	
6	75		200	
7	90		240	
8	110		300	
9	130		360	
10	150		420	
11	170		480	
12	190		540	
13 (1)	210	0	600	0
14 (2)	230	15	660	40
15 (3)	250	30	720	80
16 (4)	270	45	780	120
17 (5)	290	60	840	160
18 (6)	310	75	900	200
19 (7)	30	90	960	240
20 (8)	350	110	1020	300
21 (9)	370	130	1080	360
22 (10)	390	150	1140	420
23 (11)	410	170	1200	480
24 (12)	430	190	1260	540
Total Duration	7 hours 10 mins	3 hours 10 mins	21 hours	9 hours 20 mins

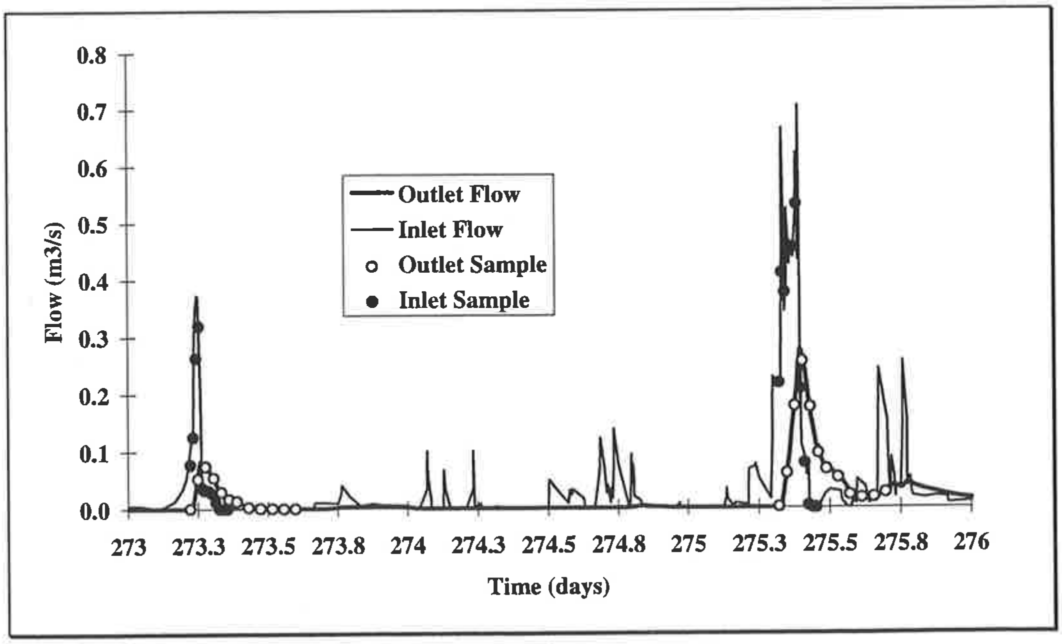


Figure 4 : Microprocessor controlled pressure sensor triggered sampling

Referring to Figure 5, the input/output section is simply the interface to the outside world, and essentially consists of a number of "on" or "off" function lines. Consider the input line used by the float switch or level trigger as an example. The state of this line is used by the microcomputer to decide the next course of action in relation to the output lines controlling the water samplers. Hence the I/O section gives the microcomputer the ability to perform and respond to external functions.

The Microcomputer section is more complicated but for simplicity can be divided into three smaller sections; Read Only memory (ROM), Random Access Memory (RAM) and the Central Processing Unit (CPU).

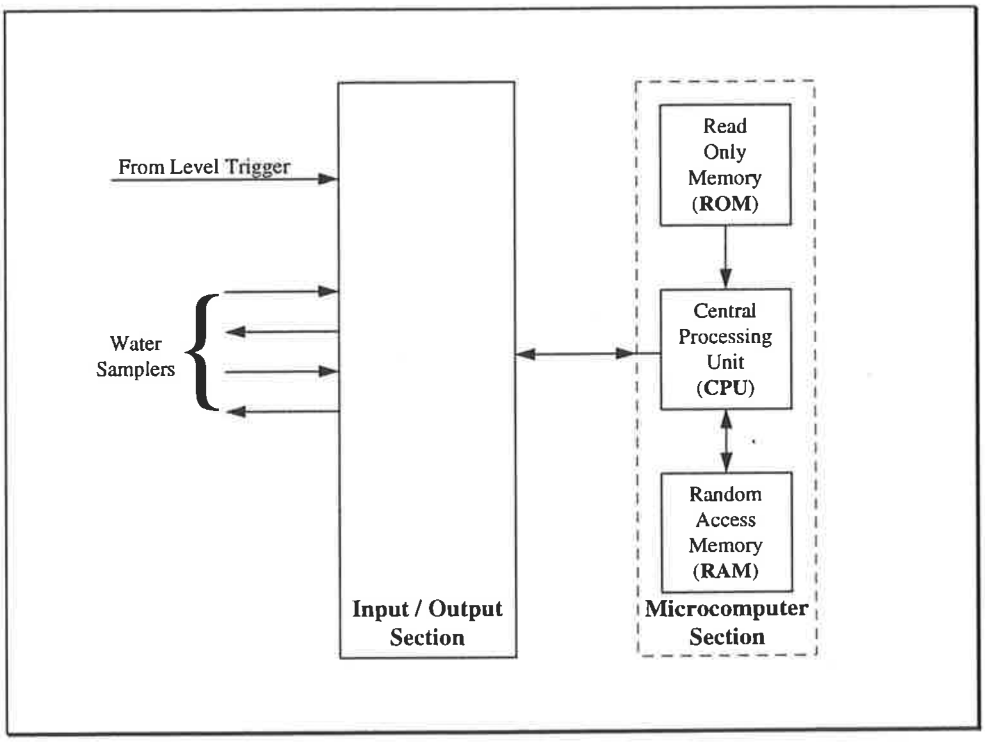


Figure 5 : Conceptual diagram of microcomputer components

3.1 Read Only Memory

This contains the code required by the microcomputer to do its allotted task. Under normal conditions, the code is fixed in the device and cannot be erased. For this application the ROM is actually an ultra-violet Erasable Programmable Read Only Memory (EPROM) device, which can be erased and reprogrammed by using an ultra-violet light source and an EPROM programmer. In this way, changes to the operation of the microcomputer can be easily made. As an example, no wiring changes were made when the controller was modified to respond to small rain events by filling only 12 of the 24 bottles; this was achieved by simply changing the operating code in the EPROM.

3.2 Random Access Memory

The microcomputer uses the RAM for the temporary storage of values during normal operation. These values are lost when power is removed.

3.3 Central Processing Unit

This section of the microcomputer does all the work according to the instructions it receives from the operating code, usually contained in the ROM (EPROM in this case). Note that the data or code coming from or going to all the other sections must pass through the CPU. This is the way that most computers operate. For example, data from the ROM cannot go straight to the RAM or vice-versa.

The microcomputer used in this water sampler controller is a single chip which contains all the sections described above except for the EPROM. There is a single chip device available which also contains the EPROM, but that was not cost effective for this project. A standard 32K by 8 bit EPROM chip is included to complete the microcomputer.

4. SAMPLER CONTROLLER BLOCK DIAGRAM

All external components except for the Real Time Clock (RTC) chip use the I/O section as the interface to the microcomputer. These will now be described using Figure 6 (the sampler controller block diagram) as a reference.

4.1 Water Pressure Sensor

As already mentioned, a low cost pressure sensor (manufactured by Tain Electronics in Melbourne) was in use at the inlet of the wetland to measure and record inlet water height. This was relocated further upstream in order to measure stream flow instead of inlet water height. The output from the pressure sensor is an analog voltage between 5 volts and 2.5 volts, representing a pressure between zero and 2.5 metres of water height. This signal was connected directly to the data recorder for logging and to an adjustable comparator complete with a sensitive Schmidt trigger input (trigger interface) to produce the on-off trigger signal for the water sampler controller. Tests conducted before installation showed that the on to off water height differential of the trigger interface was less than 5 mm and that the trigger point could be set anywhere within the 2.5 metre range of the sensor. However, in this application, the adjustment range was limited to between zero and 500 mm in height. A single input line of the microcomputer was used to sense the state of the height trigger point as either an on or off signal.

4.2 Water Samplers

Both the water samplers used at the Minkara wetland were manufactured and supplied by Gamet Equipment of Armadale NSW. However, the second unit purchased was a later model, and came with a number of extra features. One of these features was the fast sample mode. This may be used with the constant time interval sampling mode to take a number of samples at the start of a rain event using a faster time interval. As an example, the time interval between samples could be set to (say) 20 minutes, but after triggering occurs, the first 5 samples could be taken at the faster rate of (say) 5 minute intervals. In other words, the first samples would be taken in 21 minutes and the next 19 samples would be taken at intervals of 20 minutes there after. This goes some of the way to achieving what the look up table did in the sampler controller, but would not be as flexible. Triggering the water samplers into operation was done via the 'float trigger line' on each of the samplers. This was carried out by using the output lines from the microcomputer, with each of the samplers using a separate line. If the sampler responded correctly, the 'chart recorder line' from the sampler would switch from zero to 12 volts. This was connected through the interface to one of the input lines of the microcomputer as an indication that the sampler was active. In this way the microcomputer would know that the sampler had responded correctly and would act accordingly.

4.3 Serial Port

Like many other brands of microcomputer chip including the 80C552, some of the output lines may be used for special functions such as a serial port. This may be set up during the initialisation procedure by writing to special locations within the chip. As a result, any computer with a serial port and equipped with a terminal program (Zap, Telix etc) may communicate with this water sampler controller. In this way, the sampler controller was able to be set up, and the time and date of each sample downloaded into a file after the rain events. A third line from the computer, the data terminal ready (DTR) line, is used to turn on the serial interface and if required, to wake up the microcomputer as well. To save power the serial interface is switched off when not in use.

4.4 Reset and CPU Control

Most of the time, the microcomputer is turned off with only the RAM remaining powered up. This keeps the power consumption very low, but requires some external circuitry to power up the unit when required. The 'reset' line may be classified as an input line of the microcomputer with a dedicated purpose. When activated, it forces the microcomputer to restart operation from the beginning of the operating code. In this way, the reset and CPU control circuit can bring the microcomputer out of the power down mode and into the active mode. While the serial interface is operating, the microcomputer remains powered up.

4.5 Status LED

One of the output lines from the microcomputer controls the state of the "status" light emitting diode (LED) indicator. This may be used in the field to determine that the controller is functioning correctly without having to use a portable computer connected to the serial port. The state of the LED is solely under the control of the operating code and can be turned on or off by just one instruction.

4.6 Real Time Clock (RTC)

This is the only external component not associated directly with any of the input or output lines because it can be accessed in the same way as ROM or RAM by the central processing unit. The RTC device works much the same as the time/date clock in a personal computer, and is set up by the operating code to produce a pulse at the end of each second. This pulse is used by the reset and CPU control section to kick the microcomputer out of the sleep mode, and into doing something useful. When the serial port is active, steering logic in the Reset and CPU Control section uses the interrupt line to inform the microcomputer that there is a timing pulse to take care of. The serial port must be used to set the RTC to the actual time of day and date.

4.7 Data Store

A single small Electrically Erasable and Programmable Read Only Memory (EEPROM) device accessed serially by three Input/Outputs lines by the microcomputer is used as the data store. On each occasion that a sample is taken by either water sampler, the date/time of the sample, the location and the sample number is recorded in this serial EEPROM. The data can then be downloaded into a portable laptop computer at the site after an event via the serial port, and used to produce a listing as illustrated in Figure 7. Erasing of the EEPROM after the download, is also performed through the laptop.

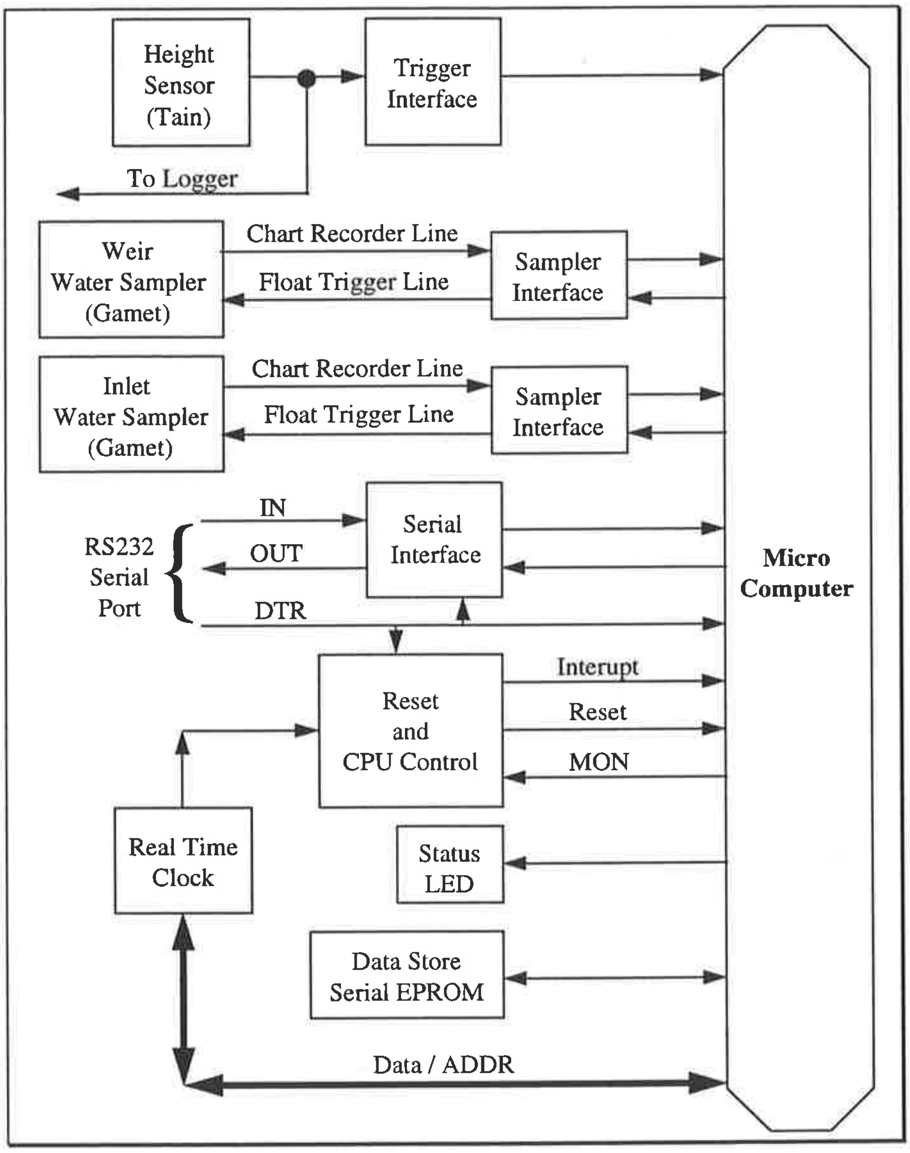


Figure 6 : Sampler controller block diagram

```
Minkara Creek Samplers
29/09/95 11:22:51
02/10/95 16:43:01
S1 01 950930052100
S2 01 950930052100
S1 02 950930053600
S1 03 950930055100
S2 02 950930060100
.
.
.
.
S2 21 951002134200
S2 22 951002144200
S2 23 951002154200
S2 24 951002164200
FFFF
```

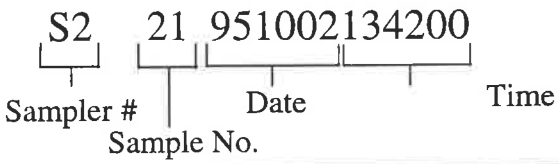


Figure 7 : Example of output from the controller, detailing time of sampling

5. THE OPERATING CODE

The firmware for this water sampler controller was written using Intel 8051 assembly language which was loaded into an EPROM using an EPROM programmer after compilation into operating code. In this way small changes to the operating code were easily made. The operating code is not particularly advanced, and indeed most of it was copied from other microcomputer based devices previously made in the Department. About the only part of it that was new was the special logic sequences for the water sampling procedure, and these make up less then 20% of the entire operating code. An overall view of the operating code follows with reference to Figure 8.

Most of the time, the microcomputer is in the "sleep" mode in order to save power, and a reset is required to wake it up. After the reset, the initialisation procedure is entered, where the input/output lines are set as required and other minor house keeping tasks are performed. However, when the power is applied for the first time after the battery was disconnected for a while, a special initialisation sequence takes place. This is done to prevent operation of the water sampler controller before the correct date and time has been set, and the data store set up correctly. What happens under this condition is that the status LED is turned on and off by the operating code at one second intervals - nothing else. This will continue until the controller is accessed through the serial port when the date, time and data memory are correctly set up.

Following initialisation, operation continues in the water sampling procedure, where the operation of the water samplers is managed. The sample lookup time table is used as required by this procedure. During normal operation, this procedure is entered every second, but nothing happens until a zero is detected in the 'seconds' register of the real time clock. At this time the status LED is turned on, and various tests are carried out to determine the next course of action. For example, if all the sample bottles have been filled, or the height trigger is not active, nothing more is done except turn off the status LED.

On the other hand, if the code determines that this is the time for either or both of the samplers to take a sample, the appropriate output line/lines are turned on. Almost immediately the sampler will acknowledge this by turning on its 'chart recorder' line to inform the microcomputer that a water sample is about to be taken. The code takes note of this by setting a flag which is stored with the date and time data record in the data store. Note that this same flag is cleared if the 'chart recorder line' did not turn on. Therefore, the state of the sampler for each sample taken will clearly show up in the downloaded data.

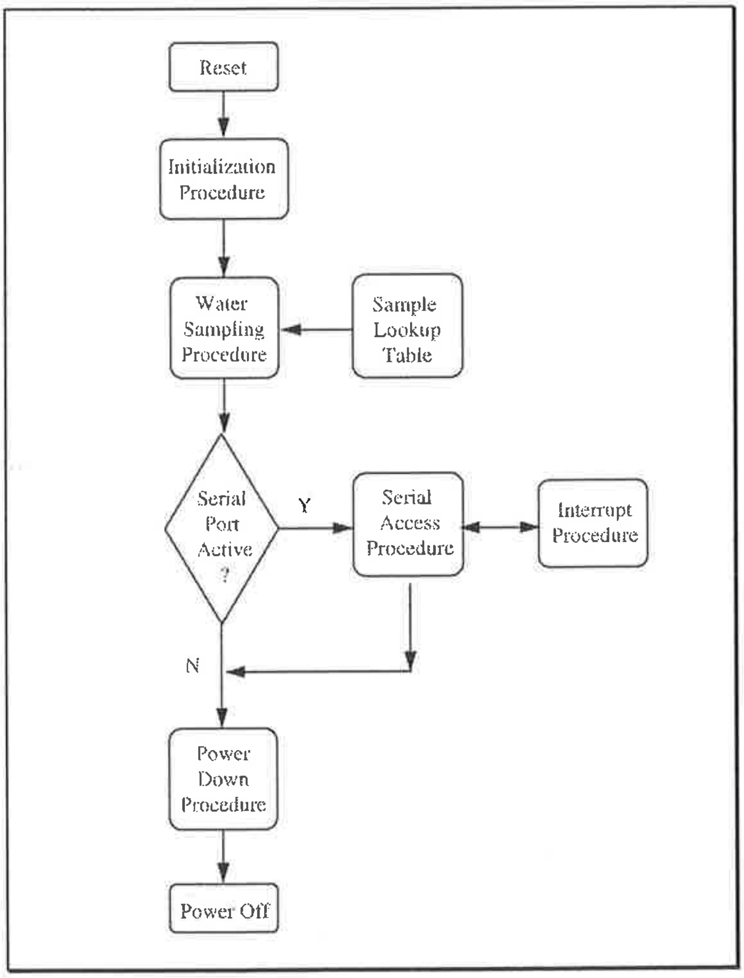


Figure 8 : Firmware flow diagram

The time required by the sampler to complete a sampling cycle is typically one and a half minutes. During this time the microcomputer monitors the state of the 'chart recorder line', and remains active until the water controller turns this line off, about 15 seconds before the sampler cycle is completed. Once this happens the code turns off the status LED and exits the water sampler procedure.

After the water sampling procedure is finished, the code checks for an active serial port by looking at the DTR line. When this is low the serial port is not active, and the microcomputer is shut down in a controlled manner using the power down procedure. As already explained, a reset is required to bring the microcomputer out of the power down mode.

Alternatively, if the code finds that the serial port is active, the serial access procedure is entered, and the microcomputer remains powered up. The code sets the port for RS232 serial communications at 9600 bits per second. At this stage, the microcomputer can respond to a number of single character commands from the controlling terminal. These commands are able to do such things as read and download the data store, erase the data store, set the date and time in the real time clock, and display a monitor screen. Most of the time, the operating code sits in a loop waiting for a character from the terminal. However within this loop, the interrupt from the RTC will be taken care of and the DTR line is checked. The only way out of the serial access procedure is by turning the monitor off or removing the serial cable, thus turning off the DTR line. This will allow the microcomputer to shut down until the next reset.

While the serial port is active, the interrupt procedure deals with the one second time intervals from the RTC. The code does this by using one of the input lines (which can be configured as an interrupt) to sense the time interval. When the interrupt is sensed, the operating code goes to the interrupt procedure which consists of the water sampling procedure and some program status saving and restoring code instructions. At the conclusion of the interrupt procedure, the code returns to where it left off in the serial access procedure.

6. CONCLUSION

The sampling and determination of water quality from urban runoff events is an involved and arduous task. The advent of automatic samplers has made the collection phase of this process much easier. However, for an accurate picture of the constituents contained within event runoff the principle factor for success of the entire sampling process is the timing of water collection. The analysis of samples is simply too time consuming to blanket the entire event with high frequency samples, and the limited capacity of the samplers prevents this without great expense. The design and use of a microprocessor controller in the time interval sampling of dynamic flow events has been shown to be successful. Improvements to the quality of data obtained and the time saved using this device is substantial. The additional flexibility offered by such a device allows the user to custom fit the controller to the desired task without worrying about major hardware changes.

Since the installation described here was completed further work has been carried out on this and other similar controllers. With additional input lines a number of field instruments can be used for threshold triggering, and these signals can be continually monitored to activate the sampler. Currently 6 such controllers are in operation using pressure and or turbidity signals for triggers. These controllers monitor both signals and trigger the sampler when either signal reaches a sensor specific threshold value, or at a given frequency when the signal remains above the threshold for some time. Further work continues in the Department to advance these sampler controllers.

APPENDIX D

A Logic Method for Automatic Sampler Control

A Logic Method for Automatic Sampler Control

As an attempt to regulate both automatic water samplers, a system was devised whereby the controller logically initiated the samplers according to the previous flow record. A software routine was devised to allow the controller to logically spread out the 24 samples over the entire hydrograph, yielding more information on the rising limb and peak, a weakness of the other system. This routine worked simply on the premise that the inlet station was positioned in an open channel, and as an open channel the rate of flow was determined by the height, and hence cross-sectional area of the flow volume. In order to calculate a flow area the pressure signal needed to be converted to a channel cross-sectional area. This relationship was easily achieved using the survey data from Section 3.6.

The basis of the system was to consider any hydrograph as comprising of 4 distinct stages:
- Rising Limb;
- Peak;
- Falling Limb; and
- False Starts (small insignificant events).

Each of these stages is then identified and treated separately. Firstly the continuum of flow rates is discretised into 15 distinct flow areas, $A_1 \ldots\ldots A_{15}$. These flow areas are spread evenly from the smallest significant flow (A_1), to the largest reasonably expected flow (A_{15}). On the basis of these flow areas, identification proceeds as follows:

Rising Limb

Rising limb sampling sequence starts when flow area $\geq A_S$, where S may be 1-3. Take a sample at A_S, A_3, A_5, A_7, A_9, A_{11}, A_{13}, **OR** 1 sample every ***R*** minutes if the next trigger cross-sectional area is not reached. Once 6 samples have been taken wait for peak.

Peak

Peak is signified by ***P*** consecutive drops of water level (pressure), **OR** when there is a fall of a discrete area. With pressure being read every minute this means consecutive drops in water level over ***P*** minutes.

Falling Limb

Note the nearest maximum discrete cross-sectional area A_{max} to the maximum area of flow recorded, and the number of samples left, ***L*** (maximum 5). Sample at $A_{(max-max/L)}$, $A_{(max-2*max/L)}$,......, $A_{(max-L*max/L)}$, where (max/***L***) is the rounded integer, **OR** every ***F*** minutes.

False Starts

Signified when A_S is reached, hence a sample is taken, and the next ***S*** pressure values are not all increasing (***S*** minutes of record). Reset and go back to Rising Limb mode. Allow for 1 false start per event (maximum of 2 events). The second false start occurs only when the first event sampling sequence is complete, that is all samples have been taken and $A_i \leq A_S$.

The maximum number of samples allowed for any one storm with this system is 12, half the total number available using the automatic water samplers. The aim of the system was to sample either 2 separate events, or 2 events where the intervening flow does not drop below the initial trigger level. The first alternative is simple to achieve, the system simply resets and waits for another rise above the trigger level. The second requires another decision, as the level is rising during the falling limb of the first event. In effect, the situation is a long event with 2 rising limbs.

Rising Limb 2
If ***R*** level increases occur in succession in falling limb mode on the first sampled event, switch to rising limb 2. Sample at A_3, A_5, A_7, A_9, A_{11}, A_{13}, A_{15} as before (up to 6 samples), starting at the next A_i, **OR** every ***R*** minutes as before.

A flow diagram of the logic sample distribution can be seen in Figure D-1.

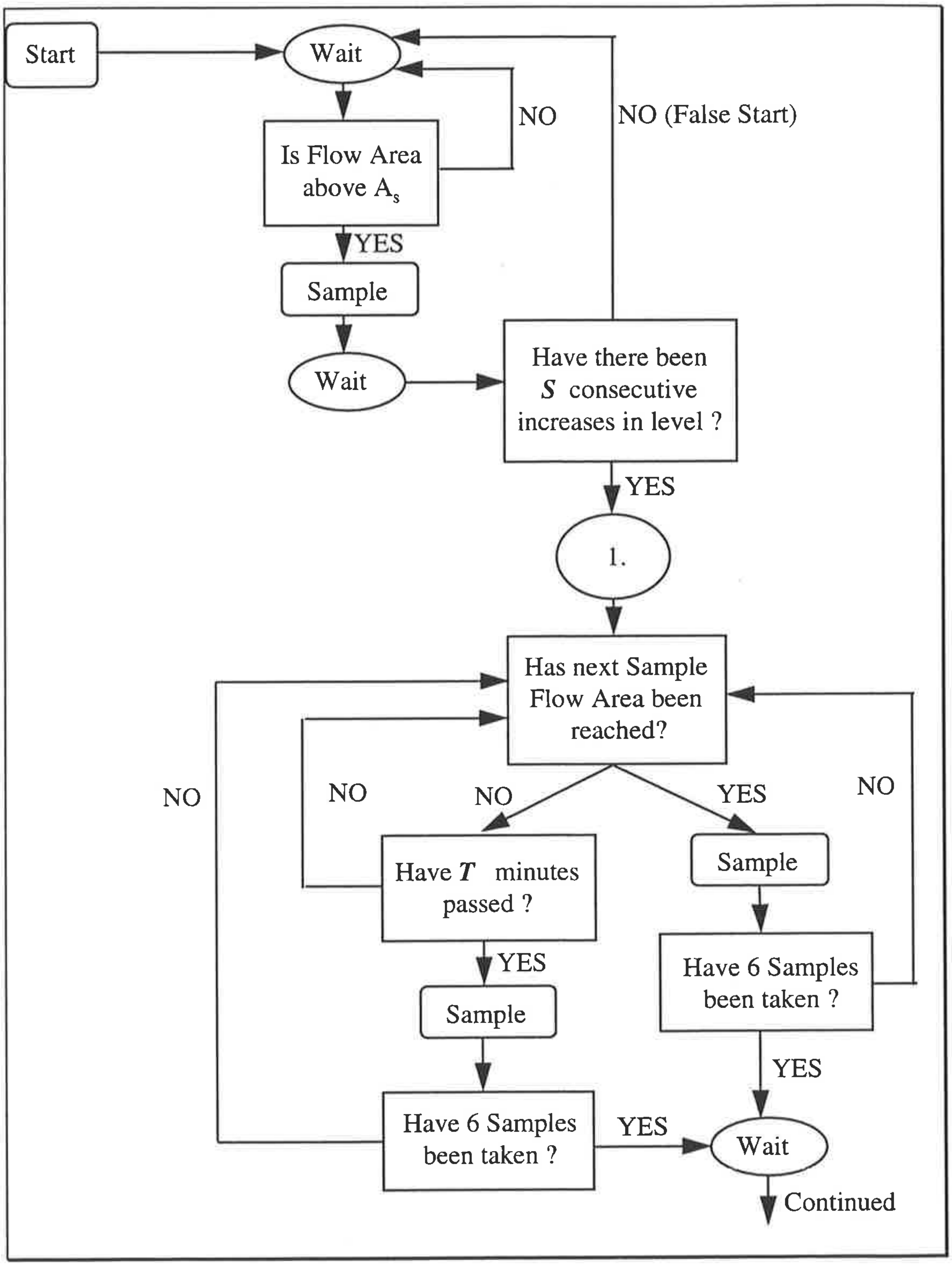


Figure D-1 : Flow diagram of logic sample distribution system

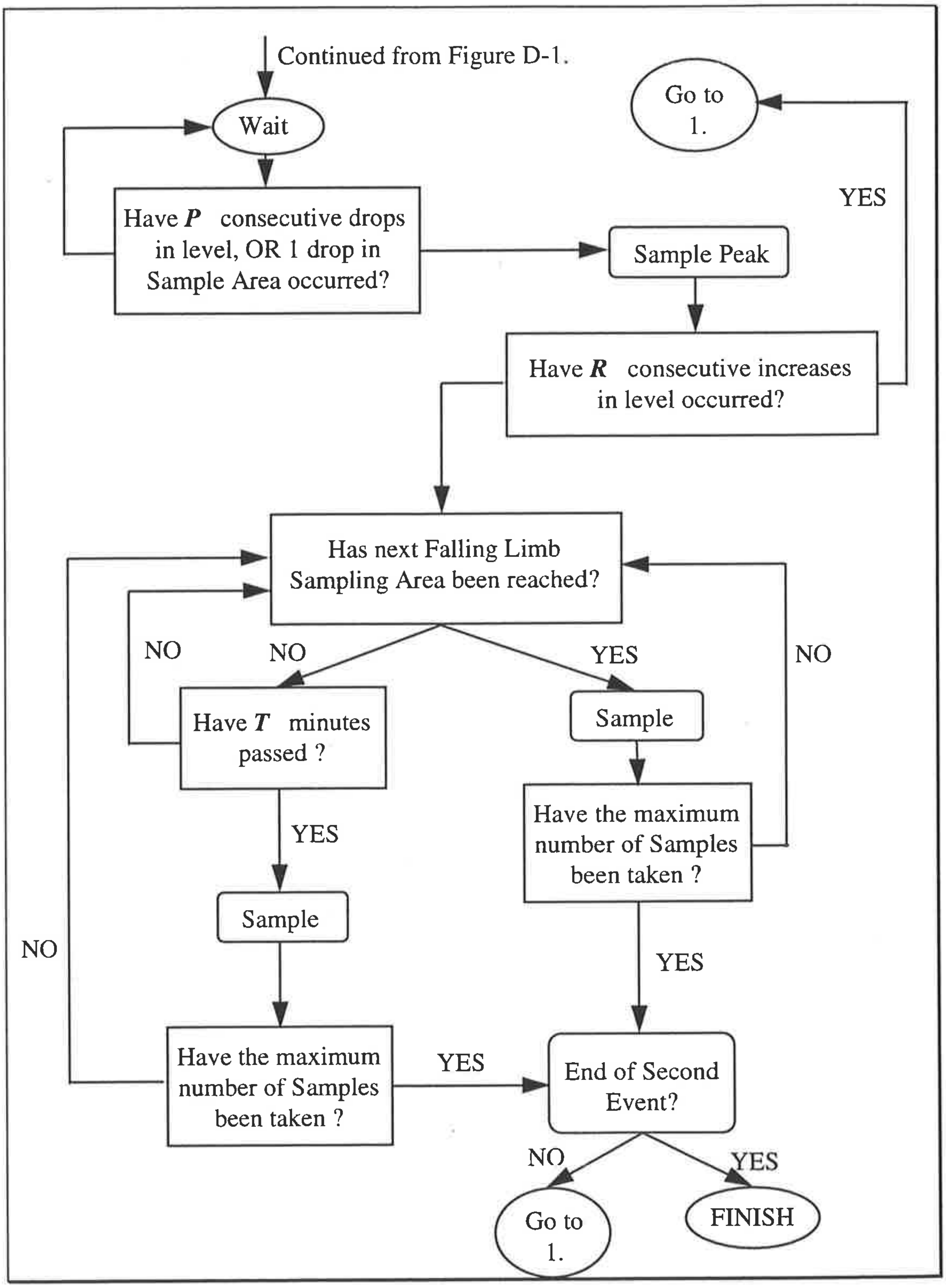


Figure D-2 : Flow diagram of logic sample distribution system, continued

APPENDIX E

Results of Parameter Analysis of Event Record for Minkara Wetland

Table E-I : Results of the parameter analysis of all recorded events at Minkara Wetland with peak flows greater than 0.2 cumecs

Storm Number	Date	Time		Peak cumecs	Peak m	Time to hrs	Time to mins	Duration (hrs)	D05 (hrs)	D1 (hrs)	D2 (hrs)	D3 (hrs)	D4 (hrs)	D5 (hrs)	D10 (hrs)	D20 (hrs)	Inflow TP	Inflow Peak	Inflow D
0	25/05/93	11:42		0.327	10.517	1.676	100	11.51	7.24	3.30	1.46	0.54					81	0.57	113
1	06/09/93	14:39		0.463	10.593	3.704	222	15.78	9.04	5.33	3.19	2.52	1.93				117	1.07	217
2	06/11/93	14:18		0.205	10.433	1.368	82	7.51	2.95	1.79	0.04						60	0.51	113
3	07/07/93	19:52	*	0.798	10.744	11.664	699	20.19	16.15	14.13	12.11	8.08	7.18				726	1.06	758
4	18/09/93	20:54		0.228	10.45	5.329	319	16.90	11.29	8.61	2.13						611	0.48	676
5	19/09/93	12:21		0.275	10.483	0.789	47	16.74	3.24	1.74	1.03						44	1.72	87
6	17/10/93	9:36		0.419	10.57	0.538	32	8.23	4.39	2.62	1.50	0.92	0.39				10	2.55	50
7	18/10/93	9:27		0.207	10.45	2.301	138	10.69	5.75	2.96	1.89						127	0.97	176
8	28/10/93	9:19		0.423	10.572	3.582	214	13.10	9.43	6.00	3.19	2.14	0.80				353	0.82	607
9	19/11/93	11:48	*	0.29	10.493	6.13	367	13.96	4.76	3.46	1.76						75	0.78	128
10	12/11/93	13:08		0.376	10.546	2.85	171	10.70	5.60	4.30	2.90	1.30					48	0.53	200
11	14/12/93	1:34		2.503	11.231	2.462	147	8.46	7.62	6.77	6.08	5.54	5.15	4.85	3.62	0.62	130	5	209
12	01/07/94	12:52		0.207	10.435	3.484	209	9.68	4.45	2.52	0.19						83	0.63	123
13	25/06/94	15:16	*	0.297	10.498	11.143	668	30.57	19.00	16.14	4.57						651	0.95	1097
14a	29/07/94	13:39		0.403	10.561	2.93	175	8.37	7.40	5.30	3.91	2.79					69	0.87	257
14b	29/07/94	21:17		0.396	10.55	2.093	125	21.48	9.63	7.67	3.77	0.84					120	1.67	300
15	08/12/94	16:52		0.267	10.478	1.667	100	9.67	5.25	3.75	2.17						32	0.8	208
16	10/02/94	6:55		0.497	10.61	1.0712	64	22.93	16.93	15.64	2.68	1.61	0.86				71	1.65	113
17	10/04/94	4:13		0.518	10.62	5.657	339	18.34	9.69	5.06	2.91	1.80	0.94	0.43			318	0.9	372
18	10/07/94	0:19	*	0.202	10.431	8.268	496	15.69	4.54	1.83							157	0.7	198
19	11/01/94	16:10		0.236	10.456	4.082	244	26.47	13.98	10.76	1.61						180	0.82	729
20	02/05/95	3:13		0.333	10.521	1.878	112	8.74	4.74	3.10	1.55	0.61					161	0.99	203
	Average			0.449	10.556	3.848	230.455	14.80	8.32	6.04	2.89	2.39	2.46	2.64	3.62	0.62	192.0	1.18	315.2
	Average *				11.143	2.977	178.167	14.40	7.96	5.59	2.44						149.4	1.30	271.2

Notes on Table E-I :

*	Events ignored due to unusually long durations to peak
D05	Durations over 0.05 cumecs
D1	Duration over 0.1 cumecs
D2	Duration over 0.2 cumecs
D3	Duration over 0.3 cumecs
D4	Duration over 0.4 cumecs
D5	Duration over 0.5 cumecs
D10	Duration over 1.0 cumecs
D20	Duration over 2.0 cumecs

APPENDIX F

Instruction Sheets for the Downloading of Field Instrumentation and the Collection of Water Samplers

UNIVERSITY OF ADELAIDE

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

HAPPY VALLEY PROJECT INSTRUMENTATION

FIELD INSTRUCTIONS FOR ACCESSING THE DATA LOGGERS AT THE MINKARA WETLAND

LAST CHANGED : 08/06/95

BACKGROUND

Three types of loggers are used in the Happy Valley project for gathering information. These are:-

1. Wesdata model 692 loggers connected to Wesdata rain gauges;
2. Mindata model 3000 loggers connected to Mindata water level pressure sensors on loan from the E&WS.
3. Department of Civil and Environmental Engineering Loggers (DCEELs).

At this time, there are three rain gauging sites, two water level gauging sites, and two water quality stations installed in the Happy Valley area. All may be accessed using the battery powered PC-4741 laptop computer or the Microbits Laptop, which are loaded with the appropriate programs for the three logger types. Data collected from the loggers in the field is saved on the computer's hard disk for further action back in the department.

FIELD TRIP PREPARATION

Before going out in the field, the following checks should be carried out:-

- Make sure that the laptop computer battery is charged. If there is some doubt about the state of charge of the battery, then leave the computer on charge for at least three hours before leaving.
- Make sure that the spare batteries for the loggers and rain gauges are charged. Note that there are three sizes of lead-acid batteries required.

Timing Procedures

- All loggers and computers must have the same date and time so that data may be cross referenced.
- The time to be used is **Central Standard Time**

Prior to leaving:
- Check the time on the computer to be used for the data collection. If this is out by more than 1 second change it by;
  a) phoning 1194;
  b) using the ***time*** and ***date*** commands in DOS.

Other Equipment

As well as the laptop computer, the following equipment should also be taken:-

The mobile phone must be taken for safety reasons. Make sure it is charged prior to leaving. If battery is low charge it in the van on the trip.

1. A **voltmeter** for measuring the condition of the logger and rain gauge batteries.
2. A small phillips head **screwdriver** for gaining access to the rain gauge loggers.
3. A small shifting **spanner** to remove/replace the rain gauges when necessary.
4. 3x fully charged 1.2AH lead-acid batteries for the rain gauges.
5. 4x fully charged 2.2AH lead-acid batteries for the water level loggers.
   - Two for stage height recorders, one at Minkara, one at Saubier;
   - Two for water quality loggers at Minkara Wetland.
6. 4x fully charged 6.5AH lead-acid batteries
   - Two for turbidity sensors at Minkara Wetland;
   - Two for Gamet automatic water samplers.
7. A new spare alkali 9 Volt battery for the Wesdata loggers.
8. The **key** for the padlock to gain access to the water level loggers.
9. The RS232 interface cable for the Wesdata laggers.
10. The RS232 interface cable for the Mindata loggers.
11. **Field Folder** contains all station summary sheets for all the logger sites.
12. Step **ladder** to reach rain gauges.
13. Repair equipment.

ACCESSING THE WATER LEVEL SENSOR, WATER QUALITY LOGGERS AND AUTOMATIC SAMPLER CONTROLLER

Two sites are equipped with Mindata pressure sensors connected to Mindata loggers for measuring water level. The two loggers are slightly different from each other. However, apart from changing the battery, the access procedure is identical. Care must be exercised when bringing the loggers out of their protective enclosures before access, because of the two metre high concrete wall top that must be traversed. Note that the wall top may be quite slippery after rain. After arriving at the site, access the logger using the portable computer, by doing the following:-

1. Switch on the laptop. For the PC4741, press the green power button on the right hand side, and wait until the dos prompt appears. For the Microbits laptop, power up with the switch just above the keyboard on the left side, and then select item 2 from the DOS Menu ("Wetland")
2. For the PC4741 type in "**HV<Enter>**". For the Microbits laptop type "**CD DOWNLOAD<Enter>**" and then "**STERM B<Enter>**". This will load a serial terminal program called "STERM" into the computer, for accessing the Mindata loggers.
3. **Press the 'F3'** key to place the computer in terminal mode.
4. Plug the RS232 cable for the Mindata loggers into the serial connector on the left hand side of the computer.
5. Unlock the logger enclosure and gently remove the logger with enough cable to reach the portable computer. Take note of the CAUTION note above when carrying out this procedure. Note also that spiders and insects may like to make their home inside the logger housing.
6. Place the logger along side the computer, and plug in the RS232 cable.
7. **Press any key** on the computer. This will cause the logger to send the 'logger Ready' message.
8. **Press 'M'** for "monitor" screen. This will place various logger information values on the screen, including date/time, current water level, amount of memory used, battery voltage, etc.
9. **Press 'S'** for the "set" menu. **Press 'S' 3 times** to stop the logging process. Now **press the 'Space Bar'**, and the message "The system is not logging" will appear at the bottom of the screen.
10. **PRESS 'R'** for the "read" menu then **PRESS 'O'** to enter the "Output data" menu. After the 'O' key is pressed, a window asking for the down load file name will appear. Refer to the appropriate site summary sheet for the naming convention being used, and **type in the file name with an extension of ".RAW"** then type '<Enter>'. **PRESS 'A'** to start the download process.
11. 'FFFF' will appear at the end of the download. When this occurs, **press any key** to return to the 'Logger Ready' prompt.
12. **PRESS '<ALT-X>'** to exit program.
13. Check data file using Norton Editor. **TYPE "NE *FILENAME*"** to view file. To quit Norton Editor **PRESS 'F3-Q'**.

14. For the PC4741 **TYPE 'HV<Enter>'** to reload program, for the Microbits **TYPE 'STERM B<Enter>'. Press 'F3' then '<Space Bar>'**. If data is good **PRESS 'R'** for the "read" menu and then **PRESS 'E'** to enter the 'Erase data memory' menu. **WAIT** for memory length check. **Press 'Y' TWICE** (yes). **WAIT** for memory clearing to complete. If data file is not good (not there) then follow steps 10 - 14 again.

15. When erasure of data is complete disconnect RS232 cable then remove lid of logger to replace battery. (When a site visit occurs only a few days after the last one, changing the battery may not be necessary). **CAUTION: FOR MINKARA CREEK THE BATTERY SHOULD NOT BE DISCONNECTED FOR MORE THAN A SECOND. CHANGE BATTERIES OVER QUICKLY**. In the event that the message "...... " appears simply reset the logger by setting the time / date / ....

16. Replace the lid and reconnect the RS232 cable. **Press any key** to bring up the 'Logger Ready' prompt, then**PRESS 'S' 4 times** to restart recording.

17. **PRESS 'M'** for the Monitor screen. Wait up to one minute for the first record to be stored. **PRESS 'M'** again to update screen to check that the logger is working correctly.

18. Unplug the RS232 cable from the logger and place it back into the enclosure. Lock the enclosure.

19. Exit out of 'STERM' by **pressing <ALT + X>** and switch off the computer (PC4741 by pressing the green button on the right hand side).

DATA HANDLING ON RETURN

1) Backup all files on appropriate 3.5" floppy diskettes. Disks are kept in the instrumentation lab.

2) Download data files to appropriate directories on HYDRA.

3) Automatically archive all the "**.RAW**" files using ***filearch*** and ***master*** (see instructions below). This automatically updates the master archive file(s) which contain information on time of collection, and the period of record collected. ***filearch* operates ONLY ON ".RAW" FILES.**

   Instructions for using ***Filearch***

   Description: ***Filearch*** automatically strips the following information from the raw data file;
   - The time the logger was stopped for downloading;
   - the time the logger was started at the beginning of this data set;
   - the time the logger stored its first value;
   - the time the logger stored its last value for this file.

   To use the program simply **type *filearch*** then a **space**, then the **data file names** you want to "strip" each **separated by a space**, and then the name of the **text file** you want this information to be placed in.

   e.g. if the files form your collection are "hubdl45.raw", "hvdl45.raw", "mwq23.raw" and the text file you wish to put the information into is "datarun1.txt" then you would type;

   ```
   filearch hubdl45.raw hvdl45.raw mwq23.raw datarun.txt
   ```

   Instructions for using ***Master***

   Description: Master automatically adds additional "stripped" files to an archive file that contains information on all previously collected and collated data files (.RAW only).

   To use the program simply **type *master*** then a **space** then the **existing archive name** of the already created "master" archive file, and then another **space** and the **"stripped" file name** you wish to add the archive.

   e.g. if the "master" archive file was called "hvmaster.txt" and the file you wished to add to this was "datarun1.txt" then you would type;

   ```
   master hvmaster.txt datarun1.txt
   ```

4) Print the information gained from the latest collection. This can be done by loading the master archive text file into Word for Windows (best with two columns). File the sheet(s) in the folder(s) kept in the instrumentation lab at the end of the archive.

5) Update the master file sheet(s) (page with the history of all data files collected) and photocopy the latest page(s).

6) Place a complete set of data collection sheets as well as the copy of the latest master file sheet in the field folder.

APPENDIX G

Plots of Sampling Times for All Monitored Events

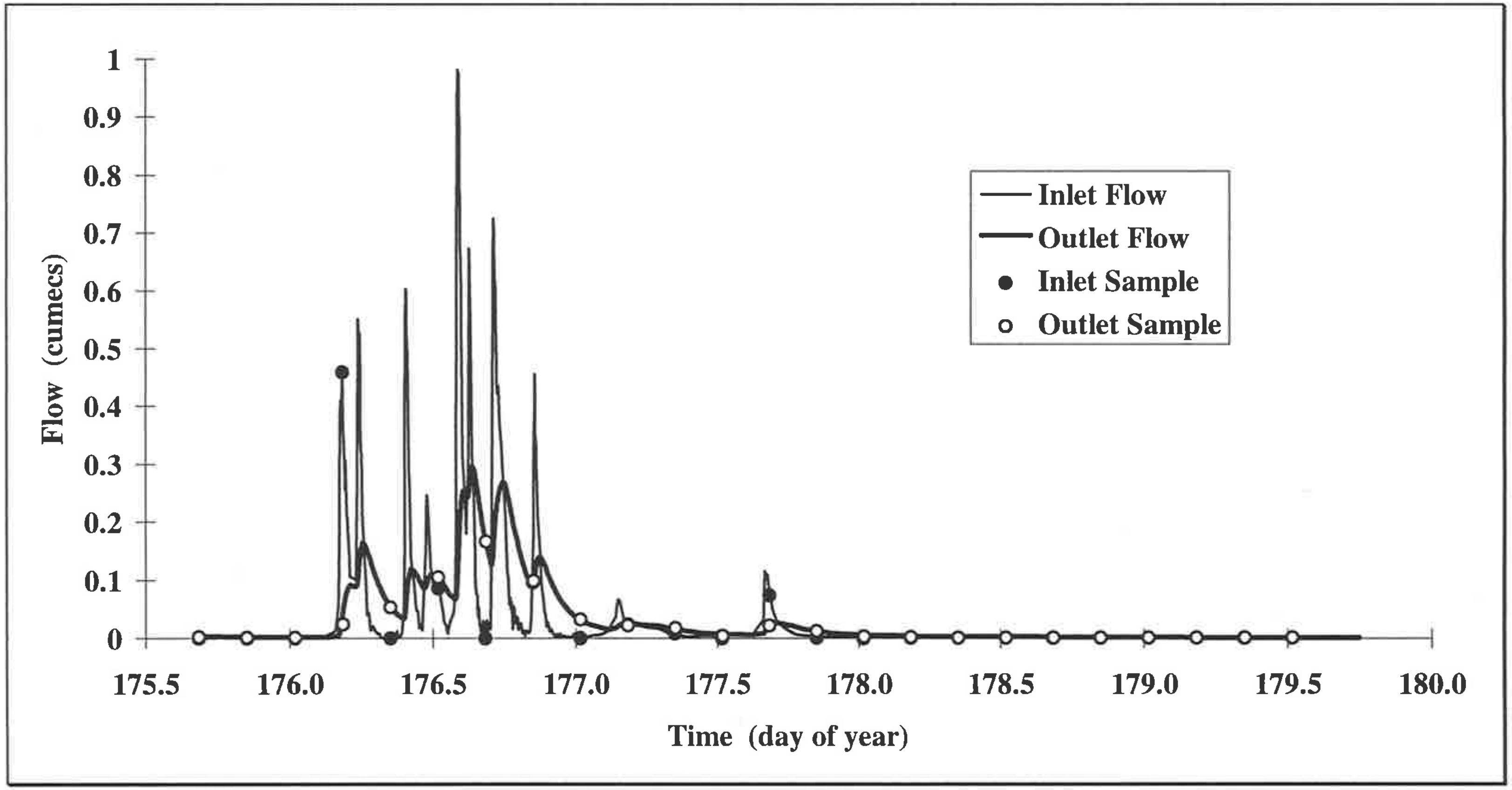


Figure G-1 : Sample times for Event 1, monitored on 24/06/94

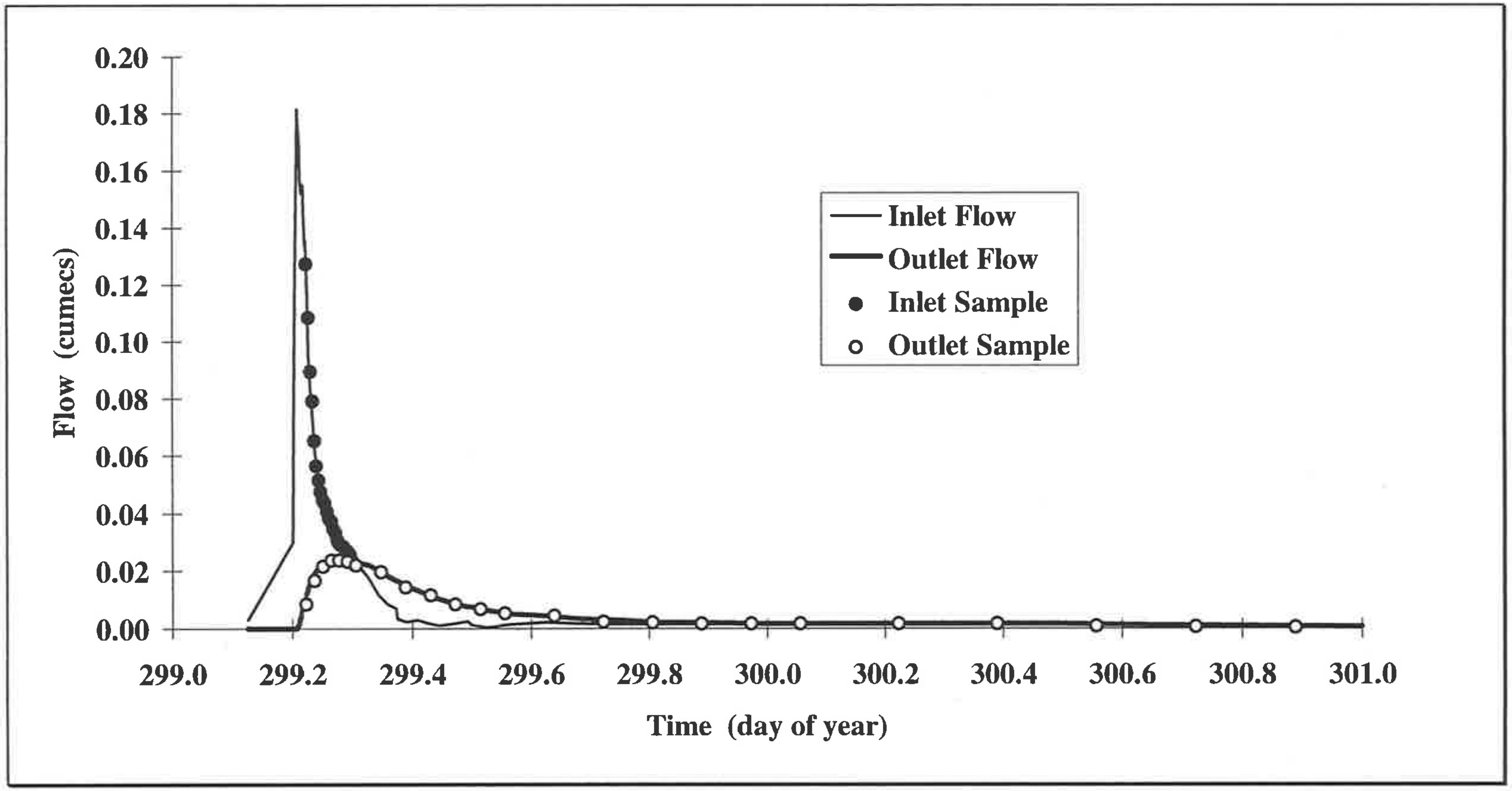


Figure G-2 : Sample times for Event 2, monitored on 26/10/94

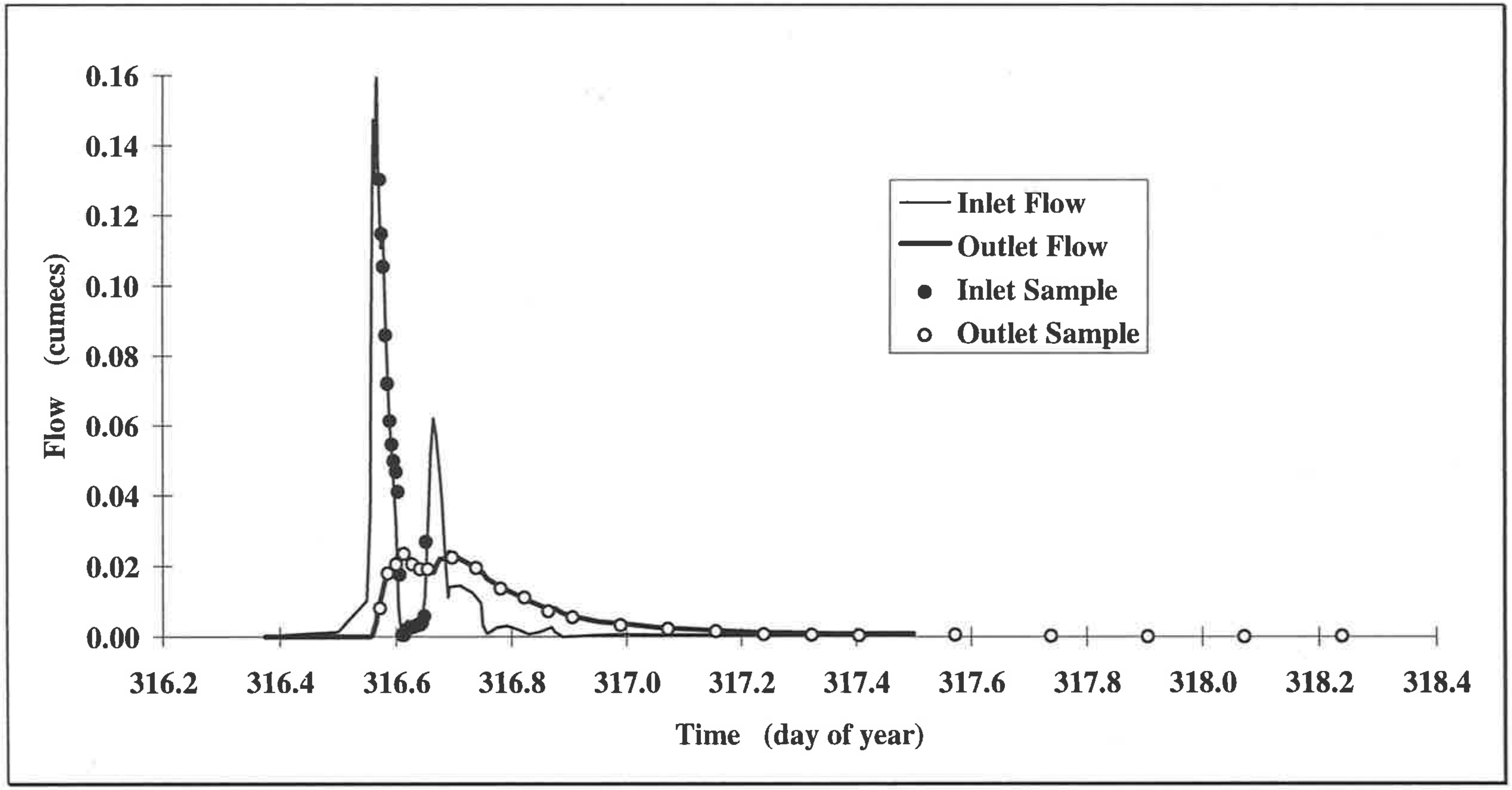


Figure G-3 : Sample times for Event 3, monitored on 12/11/94

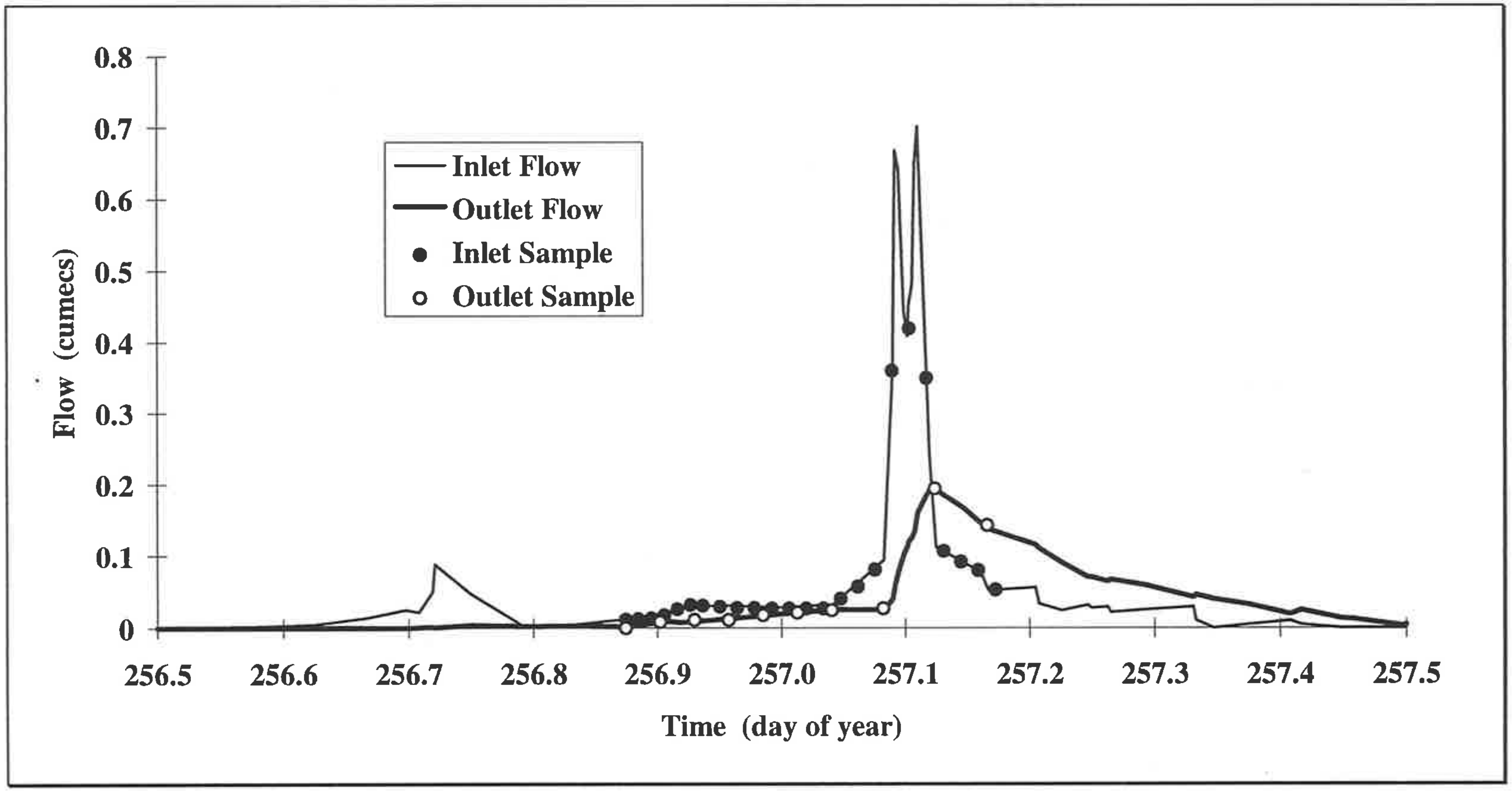


Figure G-4 : Sample times for Event 4, monitored on 13/09/95

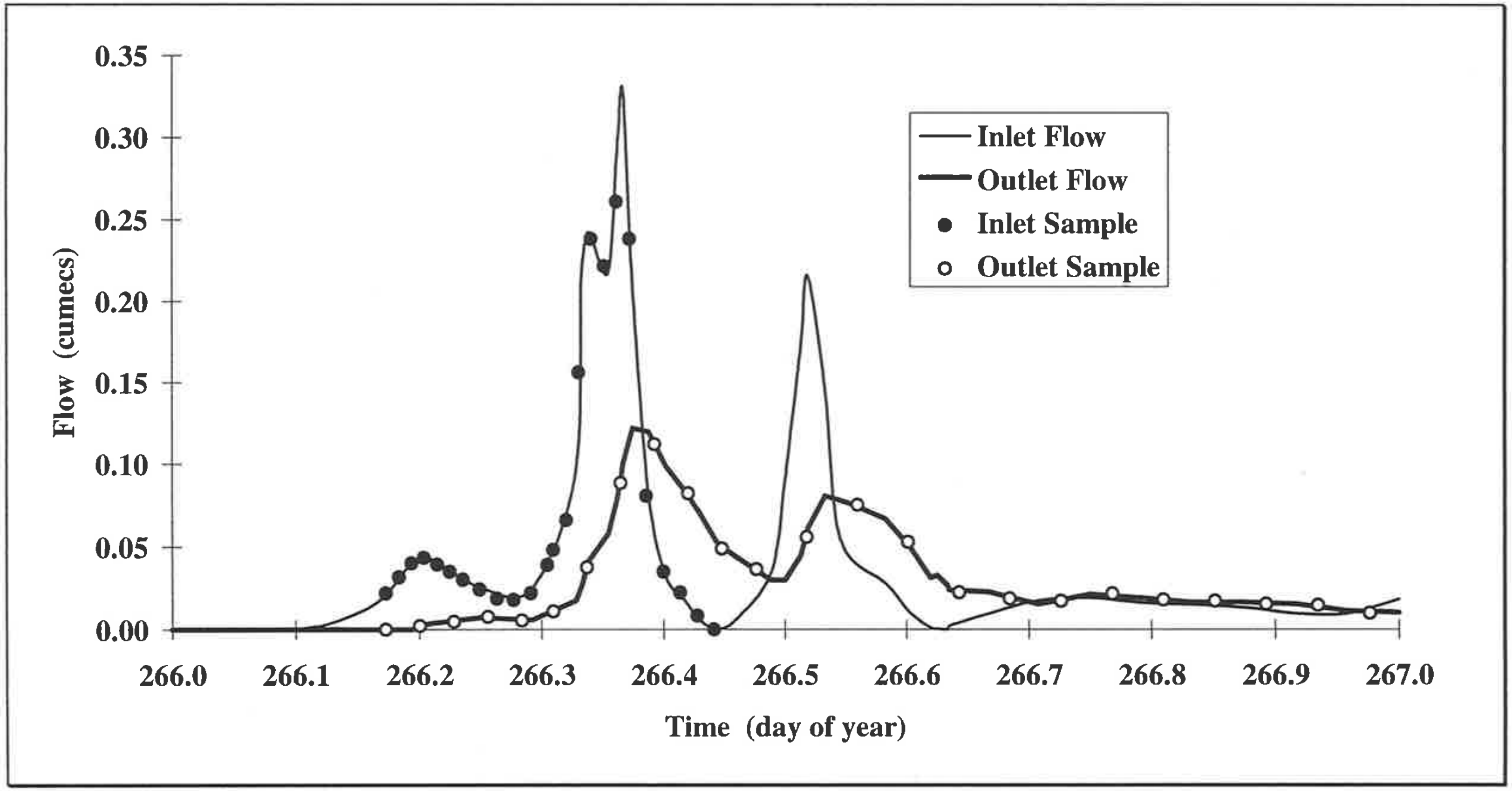


Figure G-5 : Sample times for Event 5, monitored on 23/09/95

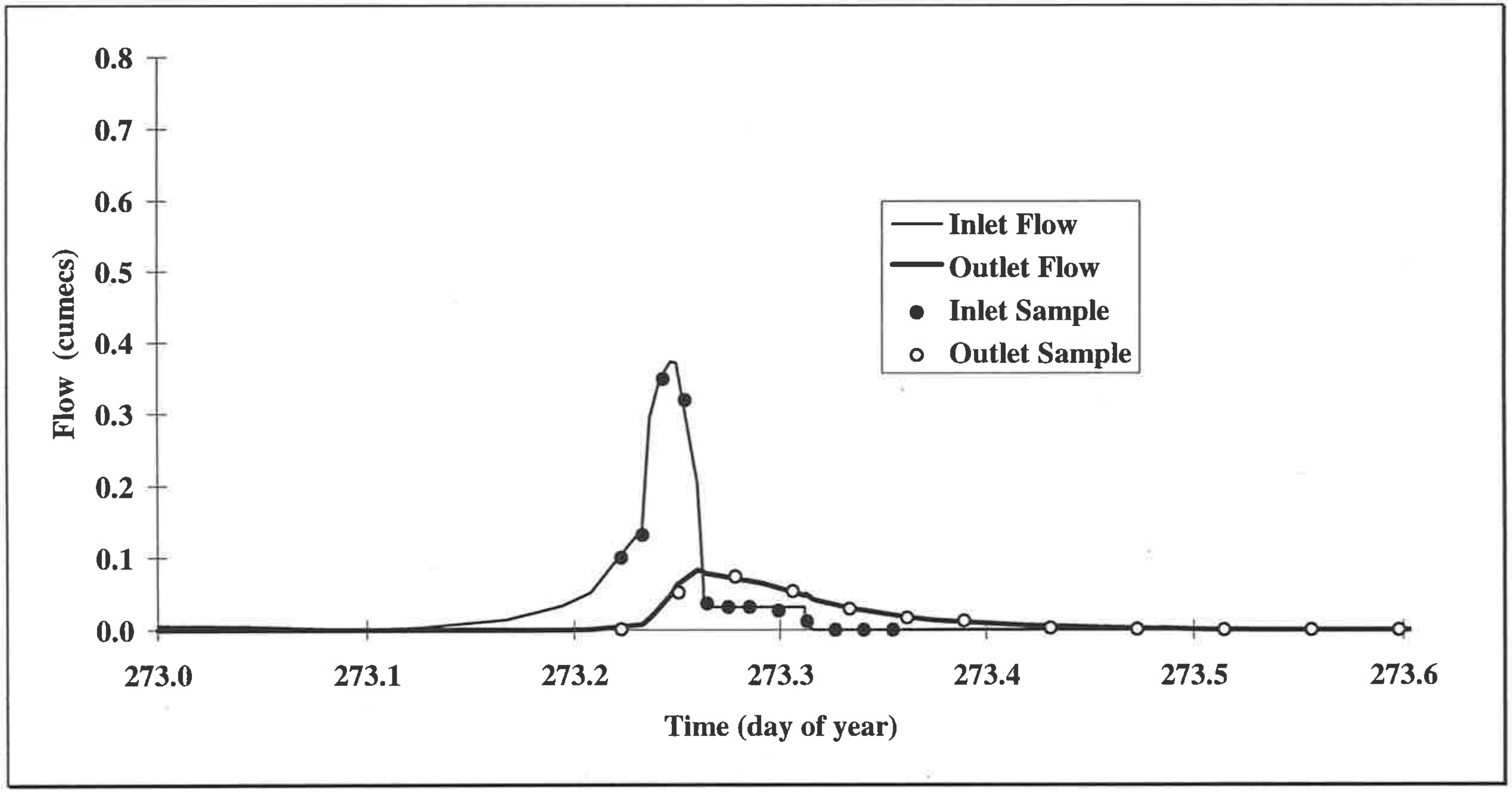


Figure G-6 : Sample times for Event 6, monitored on 30/09/95

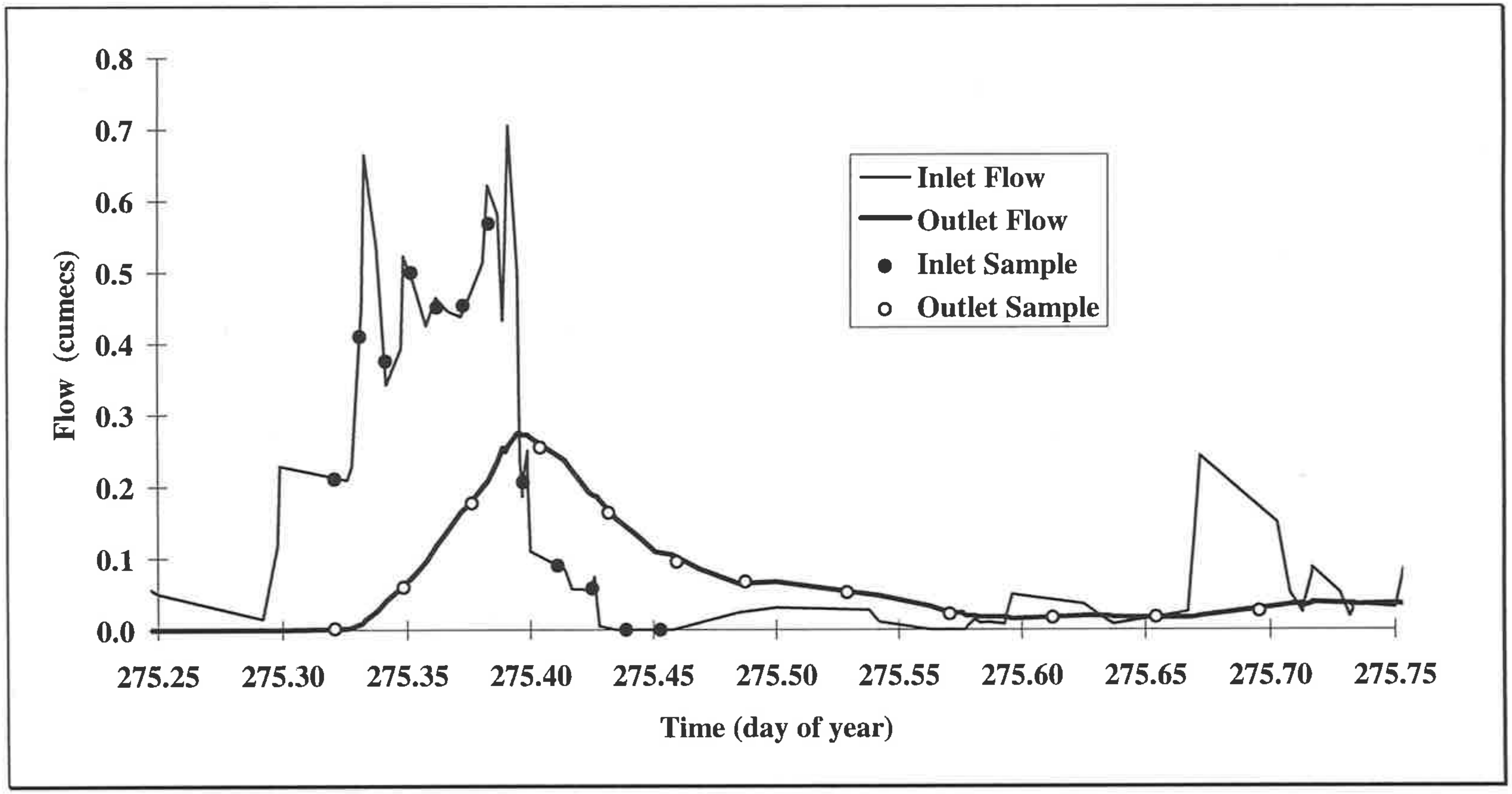


Figure G-7 : Sample times for Event 7, monitored on 02/10/95

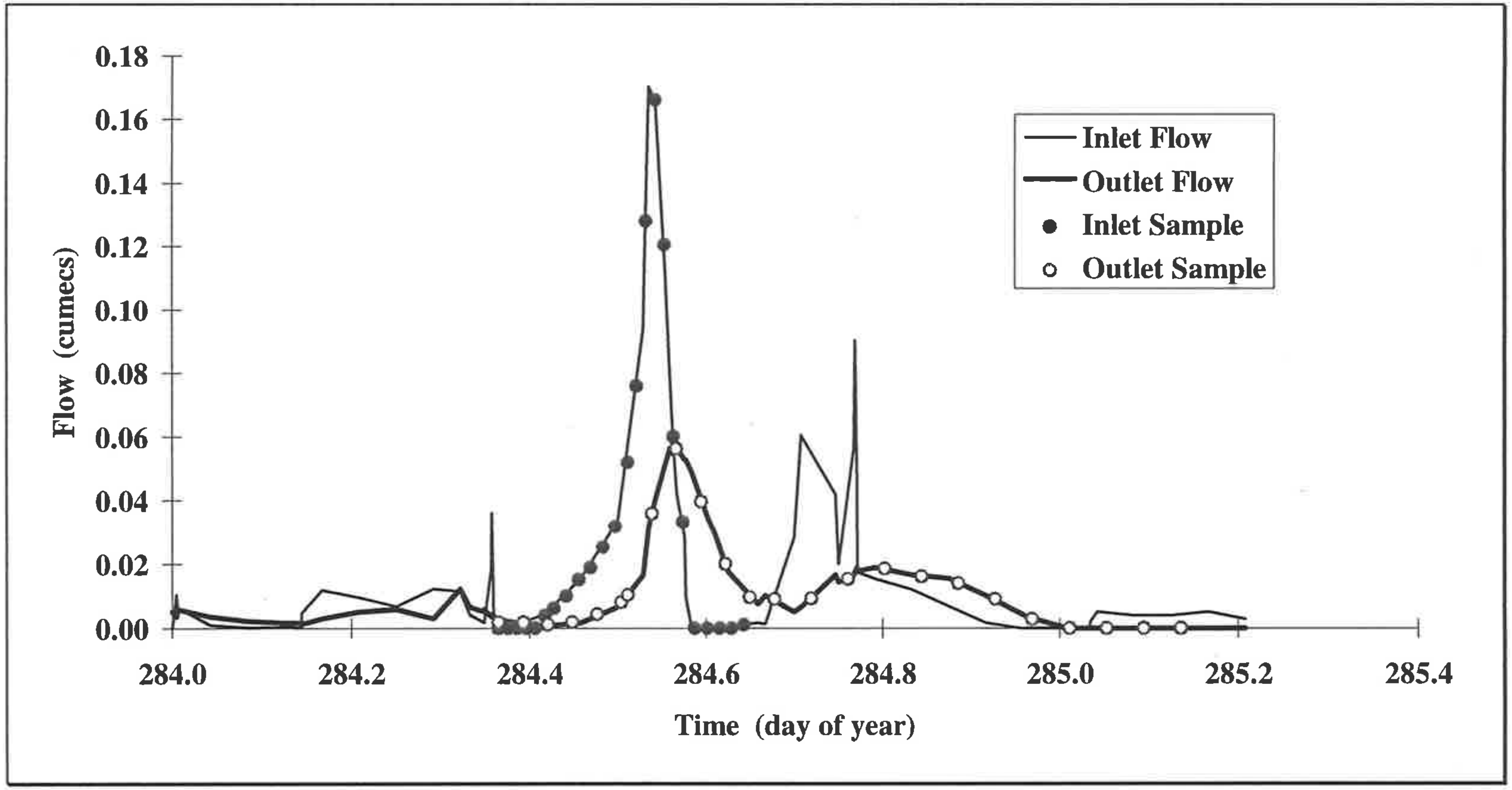


Figure G-8 : Sample times for Event 8, monitored on 11/10/95

APPENDIX H

Examples of Field Sheets Used for Field Data Collection and Record Keeping

Minkara Wetland (Happy Valley Drive) Weir Stage Height

Hydsys Station No. AU503101

Data Collection Sheet

- Please Print
- Return to Instrumentation Laboratory and file in appropriate folder
- If you have any problems phone the instrumentation lab on 303 4621

INITIALS OF COLLECTORS : ______________
DATE : __________
WEATHER (Short Description): ____

TIME LOGGER STOPPED : _________________

FILENAME (See filename sheet) : _______________ **Update filename sheet**

LOGGING DURATION OF THIS FILE :____________________
(See filename sheet e.g. 12/03/94-24/03/94)

WAS THE DOWNLOADING SUCCESSFUL : Yes / No

IF NO, WHY ? WHAT WAS THE ERROR ?

____

____

BATTERY VOLTAGE : ________________ **CHANGE IF BELOW 12 VOLTS**

WAS THE BATTERY REPLACED ? : Yes / No NEW BATTERY VOLTAGE _____

STAGE HEIGHT ON STAFF : ___________________

TIME LOGGER STARTED AFTER DOWNLOAD PROCEDURE : _____________

HAVE YOU CHECKED THE LOGGER IS FUNCTIONING AGAIN ?

CHECK

DATE, TIME, SCANNING RATE, PERIOD, VARIATION, AND IF A VALUE HAS BEEN RECORDED

- **Scanning rate must be 1 minute.**
- **Period must be 3 hours.**
- **Variation must be 10 mm.**

OTHER COMMENTS : ____

____

Minkara Wetland (Happy Valley Drive) Weir Water Quality

Hydsys Station No.

Data Collection Sheet

- Please Print
- Return to Instrumentation Laboratory and file in appropriate folder
- If you have any problems phone the instrumentation lab on 303 4621

INITIALS OF COLLECTORS : ________________
DATE : ____________
WEATHER (Short Description): ____

TIME LOGGER STOPPED : ___________________

FILENAME (See filename sheet) : _________________ **Update filename sheet**

LOGGING DURATION OF THIS FILE :______________________
(See filename sheet e.g. 12/03/94-24/03/94)

WAS THE DOWNLOADING SUCCESSFUL : Yes / No

IF NO, WHY ? WHAT WAS THE ERROR ?

____

____

LOGGER BATTERY VOLTAGE :____________ **CHANGE IF BELOW 12 VOLTS**
WAS THE BATTERY REPLACED ? : Yes / No NEW BATTERY VOLTAGE ______

TURBIDITY BATTERY VOLTAGE :__________ **CHANGE IF BELOW 12 VOLTS**
WAS THE BATTERY REPLACED ? : Yes / No NEW BATTERY VOLTAGE ______

TIME LOGGER STARTED AFTER DOWNLOAD PROCEDURE : _______________

HAVE YOU CHECKED THE LOGGER IS FUNCTIONING AGAIN ?

CHECK

DATE, TIME, SCANNING RATE, PERIOD, VARIATION, AND IF A VALUE HAS BEEN RECORDED

- **Scanning rate must be 1 minute.**
- **Period must be 1 hours.**
- **Variation must be 10 mm.**

OTHER COMMENTS : ____

____

Minkara Wetland (Happy Valley Drive) Inlet Control Device

Hydsys Station No.

Data Collection Sheet

- Please Print
- Return to Instrumentation Laboratory and file in appropriate folder
- If you have any problems phone the instrumentation lab on 303 4621

INITIALS OF COLLECTORS : ________________
DATE : ____________
WEATHER (Short Description): ____

TIME LOGGER STOPPED : ___________________

FILE NAME (See file name sheet) : _________________ **Update filename sheet**

LOGGING DURATION OF THIS FILE :______________________
(See filename sheet e.g. 12/03/94-24/03/94)

WAS THE DOWNLOADING SUCCESSFUL : Yes / No

IF NO, WHY ? WHAT WAS THE ERROR ?

____

____

BATTERY VOLTAGE : __________________ **CHANGE IF BELOW 12 VOLTS**

WAS THE BATTERY REPLACED ? : Yes / No NEW BATTERY VOLTAGE ______

TIME LOGGER STARTED AFTER DOWNLOAD PROCEDURE : ______________

HAVE YOU CHECKED THE LOGGER IS FUNCTIONING AGAIN ?

CHECK

DATE, TIME.

OTHER COMMENTS : ____

____

____

Minkara Wetland (Happy Valley Drive)
GAMET AUTOMATIC SAMPLER COLLECTION

Data Collection Sheet

- Please Print
- Return to Instrumentation Laboratory and file in appropriate folder
- If you have any problems phone the instrumentation lab on 303 4621

INITIALS OF COLLECTORS : ________________
DATE : ____________
WEATHER (Short Description): ____

TIME SAMPLES COLLECTED AT INLET: ____________________

TIME SAMPLES COLLECTED AT WEIR:_____________________

FILENAME OF SAMPLE TIMES(See file name sheet) : __________________

DID THE SAMPLER FUNCTION CORRECTLY: Yes/No ?

If No, WHAT WAS THE ERROR ?

____

____

BATTERY VOLTAGE (**INLET**):_____________ **CHANGE IF BELOW 12 VOLTS**

WAS THE BATTERY REPLACED ? : Yes / No NEW BATTERY VOLTAGE_______

BATTERY VOLTAGE (**WEIR**):_____________ **CHANGE IF BELOW 12 VOLTS**

WAS THE BATTERY REPLACED ? : Yes / No NEW BATTERY VOLTAGE_______

OTHER COMMENTS : ____

____

____

Spence School Rainfall Gauge

Hydsys Station No. AU503105

Gauge No. RG 1073

Data Collection Sheet

- Please Print
- Return to Instrumentation Laboratory and file in appropriate folder
- If you have any problems phone the instrumentation lab on 303 4621

INITIALS OF COLLECTORS : ________________

DATE : ____________

WEATHER (Short Description): ____

TIME LOGGER STOPPED : ___________________

FILENAME (See filename sheet) : _________________ **Update filename sheet**

LOGGING DURATION OF THIS FILE :______________________
(See filename sheet e.g. 12/03/94-24/03/94)

WAS THE DOWNLOADING SUCCESSFUL : Yes / No

IF NO, WHY ? WHAT WAS THE ERROR ?

____

____

LOGGER BATTERY VOLTAGE :____________ **CHANGE IF BELOW 9 VOLTS**
WAS THE BATTERY REPLACED ? : Yes / No NEW BATTERY VOLTAGE ______

RAIN GAUGE BATTERY VOLTAGE :________ **CHANGE IF BELOW 12 VOLTS**
WAS THE BATTERY REPLACED ? : Yes / No NEW BATTERY VOLTAGE ______

TIME LOGGER STARTED AFTER DOWNLOAD PROCEDURE : _______________

OTHER COMMENTS : ____

____

____

APPENDIX I

Example of Event Water Quality Constituent Plots
(Event 5 : 23/09/95)

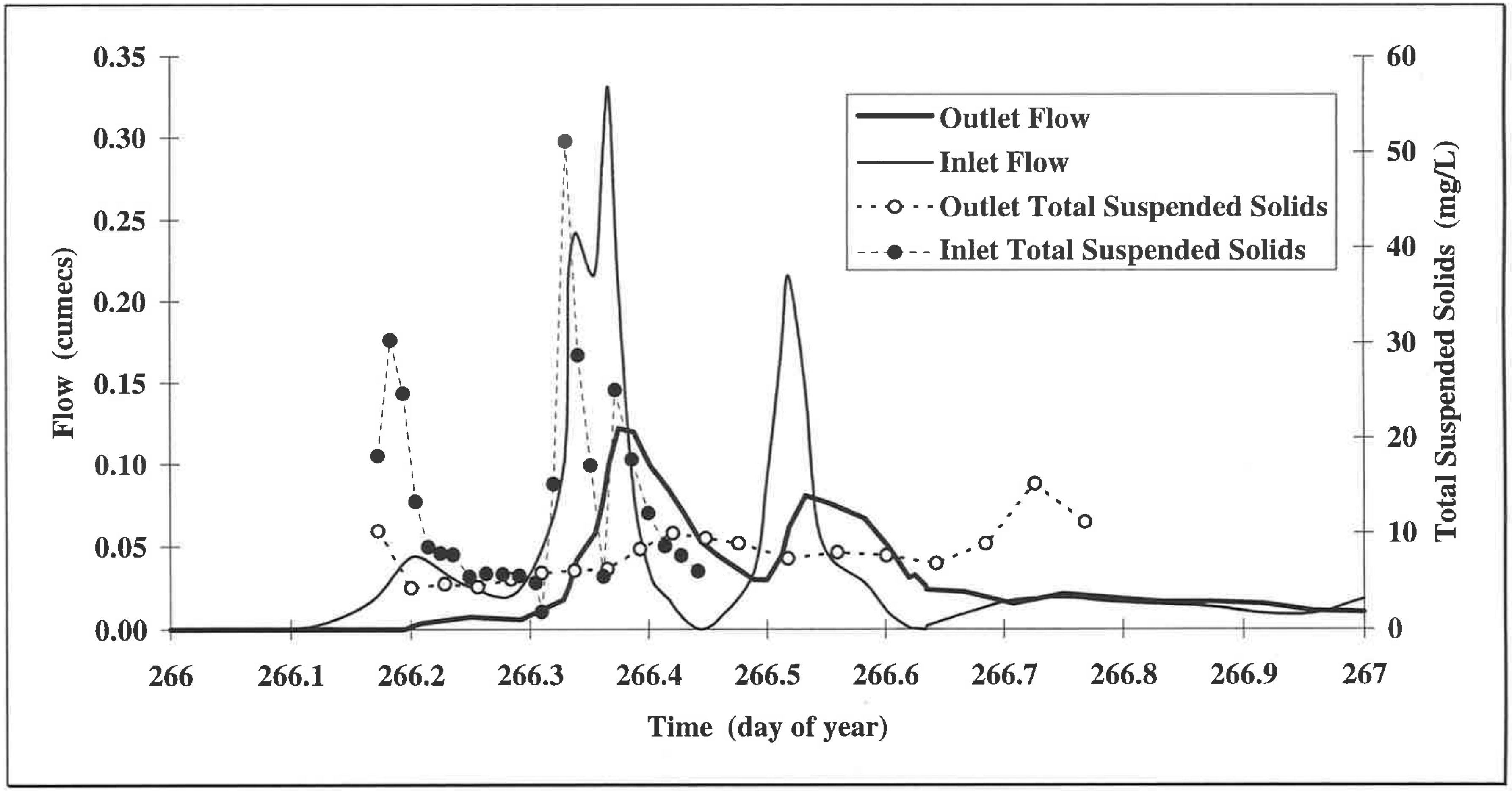


Figure I-1 : Total suspended solids versus flow for Event 5, monitored on 23/09/95

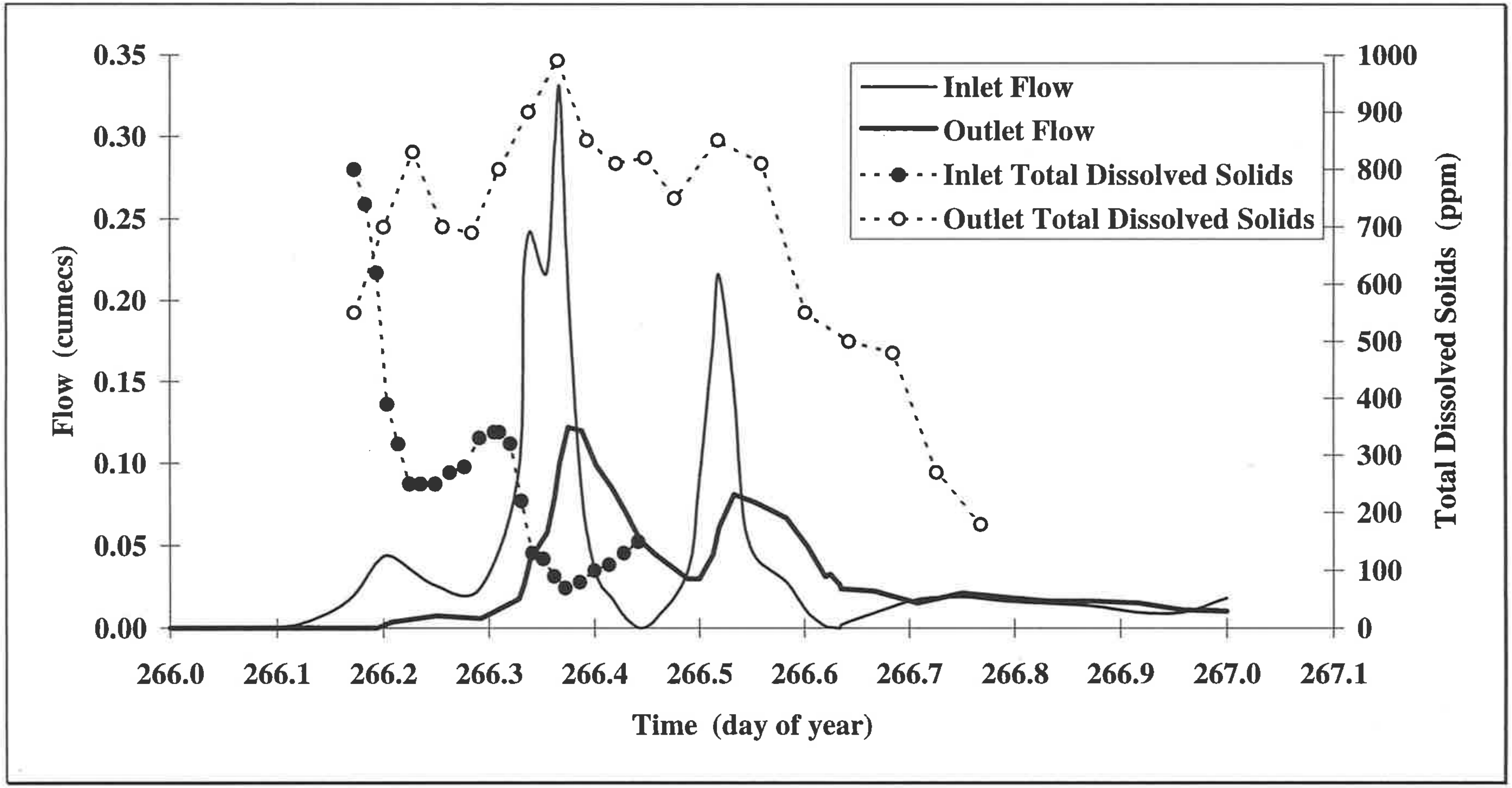


Figure I-2 : Total dissolved solids versus flow for Event 5, monitored on 23/09/95

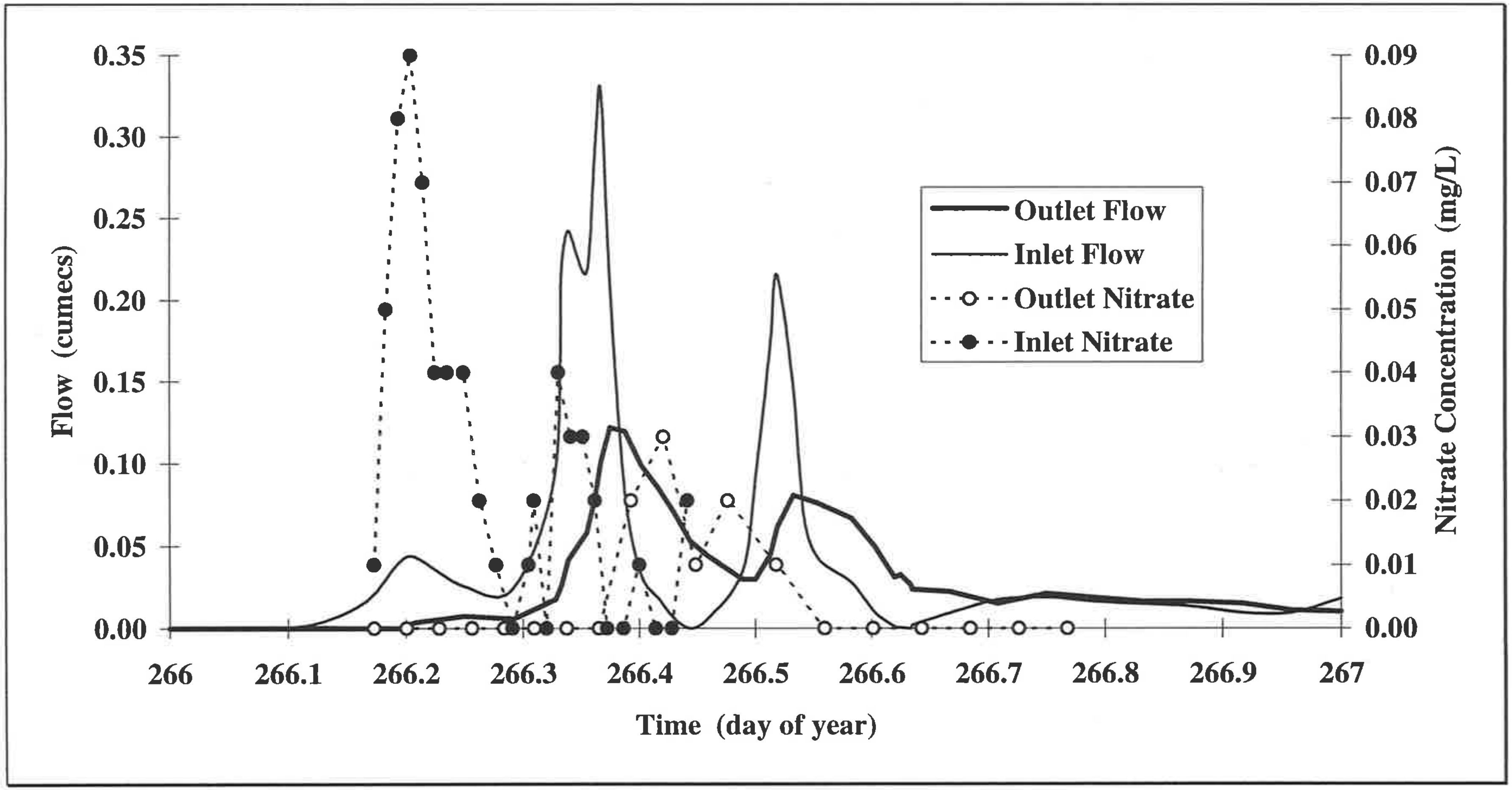


Figure I-3 : Nitrate concentration versus flow for Event 5, monitored on 23/09/95

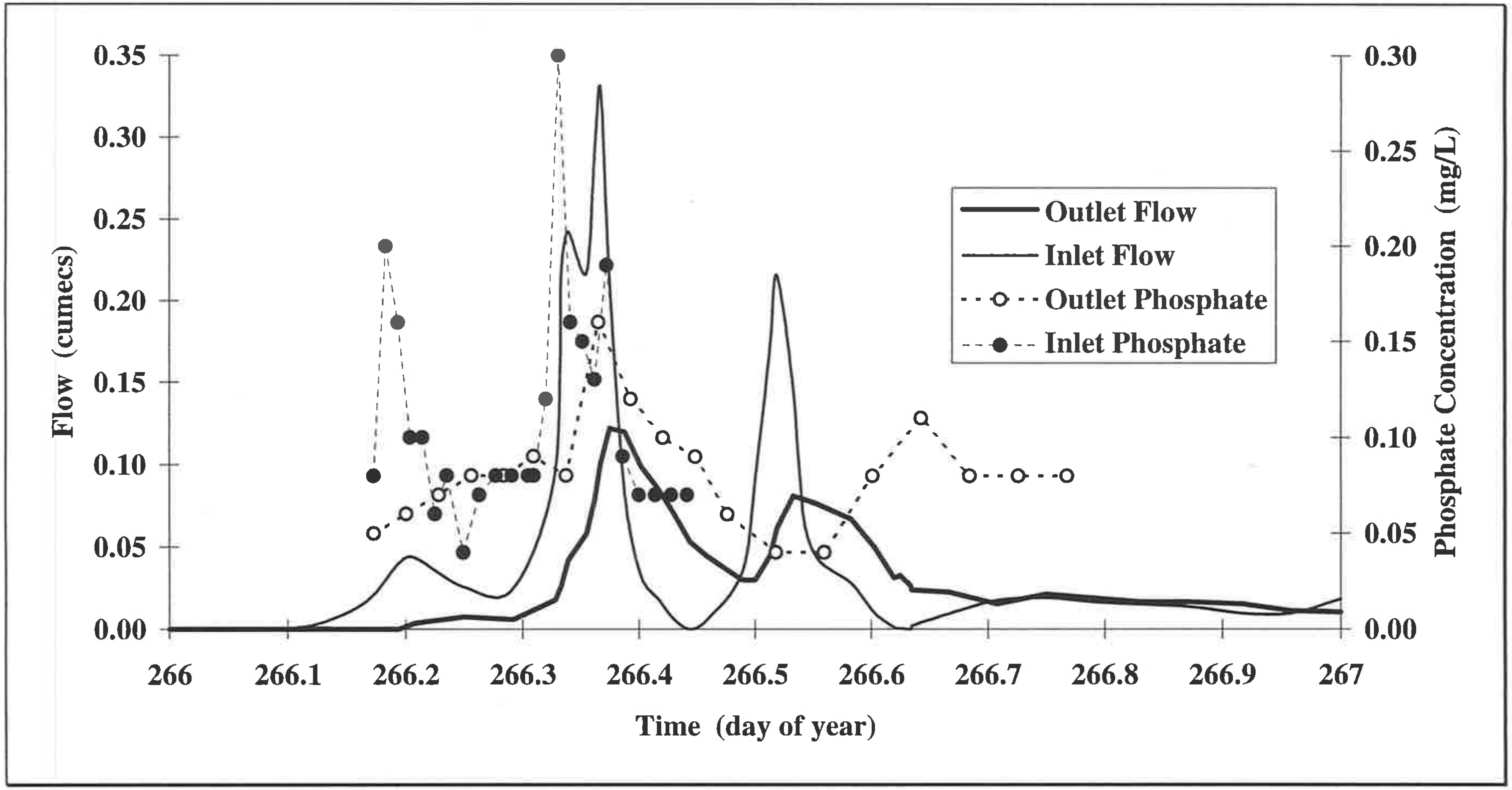


Figure I-4 : Phosphate concentration versus Flow for Event 5, monitored on 23/09/95

APPENDIX J

Example of the Calculation of Effluent Detention Time

Table J-I : Example of spreadsheet analysis used to calculate effluent detention times, for Event 3 12/11/94

Time	t-24	t-18	t-12	t-6	Event (t=0)		
				Volume of Basin (V)		Detention Time (DT)	DT.V
Historic Flow	I_4	I_3	I_2	I_1			
I_4 Remaining	I_4	$I_4(1-I_3/PV)$	$I_4(1-I_3/PV)(1-I_2/PV)$	$I_4(1-I_3/PV)(1-I_2/PV)(1-I_1PV)$		24	
I_3 Remaining		I_3	$I_3(1-I_2/PV)$	$I_3(1-I_2/PV)(1-I_1/PV)$		18	
I_2 Remaining			I_2	$I_2(1-I_1/PV)$		12	
I_1 Remaining				I_1		6	
				$\sum V$			$\sum DTV$

Notes on Table J-I:

Continue backwards until $\sum V$ = Basin Volume

Average Detention Time of storage = $\sum DTV$/Basin Volume

APPENDIX K

Monitored Event Water Quality Data

Table K-I: Results from Event 1, monitored on 24/06/94

WEIR SAMPLES							INLET SAMPLES						
Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)
175.685	9406241624	0	180	9.5	0.02	0.18	175.6847	9406241624	0	400	56.3	0	0.2
175.851	9406242026	0	180	N/A	N/A	N/A	175.8514	9406242026	0	410	N/A	N/A	N/A
176.018	9406250026	0	180	N/A	N/A	N/A	176.0181	9406250026	0	410	N/A	N/A	N/A
176.185	9406250426	24	230	N/A	N/A	N/A	176.1847	9406250426	460	190	N/A	N/A	N/A
176.351	9406250826	53	190	N/A	N/A	N/A	176.3514	9406250826	0	170	N/A	N/A	N/A
176.518	9406251226	105	180	40.9	0.02	0.23	176.5181	9406251226	85	110	19.5	0	0.21
176.685	9406251626	166	100	N/A	N/A	N/A	176.6847	9406251626	0	110	N/A	N/A	N/A
176.851	9406252026	99	100	N/A	N/A	N/A	176.8514	9406252026	96	190	N/A	N/A	N/A
177.018	9406260026	32	120	N/A	N/A	N/A	177.0181	9406260026	0	180	N/A	N/A	N/A
177.185	9406260426	22	130	N/A	N/A	N/A	177.1847	9406260426	24	330	N/A	N/A	N/A
177.351	9406260826	18	220	10.4	0.25	0.28	177.3514	9406260826	8	300	10	0.46	0.25
177.518	9406261226	4	150	N/A	N/A	N/A	177.5181	9406261226	0	300	N/A	N/A	N/A
177.685	9406261626	3	180	N/A	N/A	N/A	177.6847	9406261626	73	470	N/A	N/A	N/A
177.851	9406262026	2	190	N/A	N/A	N/A	177.8514	9406262026	0	310	N/A	N/A	N/A
178.018	9406270026	0	190	N/A	N/A	N/A	178.0181	9406270026	0	300	N/A	N/A	N/A
178.185	9406270426	0	210	N/A	N/A	N/A	178.1847	9406270426	0	310	N/A	N/A	N/A
178.351	9406270826	0	200	N/A	N/A	N/A	178.3514	9406270826	0	320	N/A	N/A	N/A
178.518	9406271226	0	200	9.4	0.22	0.3	178.5181	9406271226	0	360	27.3	0	0.13
178.685	9406271626	0	200	N/A	N/A	N/A	178.6847	9406271626	0	380	N/A	N/A	N/A
178.851	9406272026	0	210	N/A	N/A	N/A	178.8514	9406272026	0	410	N/A	N/A	N/A
179.018	9406280026	0	210	N/A	N/A	N/A	179.0181	9406280026	0	430	N/A	N/A	N/A
179.185	9406280426	0	220	N/A	N/A	N/A	179.1847	9406280426	0	440	N/A	N/A	N/A
179.351	9406280826	0	230	N/A	N/A	N/A	179.3514	9406280826	0	460	N/A	N/A	N/A
179.518	9406291226	0	230	7.5	0.11	0.29	179.5181	9406291226	0	480	6.6	0.01	0.09

Table K-II: Results from Event 2, monitored on 26/10/94

WEIR SAMPLES							INLET SAMPLES						
Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)
299.223	9410260521	8	N/A	6.3	N/A	N/A	299.223	9410260521	127	510	68.53	N/A	N/A
299.237	9410260541	17	N/A	3.45	N/A	N/A	299.226	9410260526	108	460	26.5	N/A	N/A
299.251	9410260601	22	N/A	3.35	N/A	N/A	299.230	9410260531	90	440	21.83	N/A	N/A
299.265	9410260621	24	N/A	5.45	N/A	N/A	299.233	9410260536	80	420	15.38	N/A	N/A
299.278	9410260641	23	N/A	10.87	N/A	N/A	299.237	9410260541	65	400	15.11	N/A	N/A
299.292	9410260701	22	N/A	12.3	N/A	N/A	299.240	9410260546	57	400	14.63	N/A	N/A
299.306	9410260721	20	N/A	9.44	N/A	N/A	299.244	9410260551	51	400	15.42	N/A	N/A
299.348	9410260821	14	N/A	8.56	N/A	N/A	299.247	9410260556	47	400	13.11	N/A	N/A
299.390	9410260921	12	N/A	5.17	N/A	N/A	299.251	9410260601	45	400	12.5	N/A	N/A
299.431	9410261021	8	N/A	4.72	N/A	N/A	299.254	9410260606	43	400	10.1	N/A	N/A
299.473	9410261121	7	N/A	10.92	N/A	N/A	299.258	9410260611	41	400	11.39	N/A	N/A
299.515	9410261221	5	N/A	3.52	N/A	N/A	299.261	9410260616	38	400	10.48	N/A	N/A
299.556	9410261321	4	N/A	3.46	N/A	N/A	299.265	9410260621	37	400	10.27	N/A	N/A
299.640	9410261521	2	N/A	1.53	N/A	N/A	299.268	9410260626	35	410	10.09	N/A	N/A
299.723	9410261721	2	N/A	3.51	N/A	N/A	299.272	9410260631	33	420	8.26	N/A	N/A
299.806	9410261921	0	N/A	3.32	N/A	N/A	299.275	9410260636	31	420	10.45	N/A	N/A
299.890	9410262121	0	N/A	4.09	N/A	N/A	299.278	9410260641	30	420	9.7	N/A	N/A
299.973	9410262321	0	N/A	5.11	N/A	N/A	299.282	9410260646	29	410	8.37	N/A	N/A
300.056	9410270121	0	N/A	3.67	N/A	N/A	299.285	9410260651	29	400	8.62	N/A	N/A
300.223	9410270521	0	N/A	3.9	N/A	N/A	299.289	9410260656	28	400	7.95	N/A	N/A
300.390	9410270921	0	N/A	4.09	N/A	N/A	299.292	9410260701	27	390	9.62	N/A	N/A
300.556	9410271321	0	N/A	3.69	N/A	N/A	299.296	9410260706	26	380	6.09	N/A	N/A
300.723	9410271721	0	N/A	2.93	N/A	N/A	299.299	9410260711	24	380	4.64	N/A	N/A
300.890	9410272121	0	N/A	3.6	N/A	N/A	299.303	9410260716	22	390	2.852	N/A	N/A

Table K-III: Results from Event 3, monitored on 12/11/94

WEIR SAMPLES							INLET SAMPLES						
Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)
316.572	9411121344	6	350	8.43	N/A	N/A	316.572	9411121344	130	360	104.92	N/A	N/A
316.586	9411121404	18	330	5.51	N/A	N/A	316.576	9411121349	115	360	39.17	N/A	N/A
316.600	9411121424	21	370	8.25	N/A	N/A	316.579	9411121354	105	330	30.27	N/A	N/A
316.614	9411121444	23	340	5.18	N/A	N/A	316.583	9411121359	86	310	26.18	N/A	N/A
316.628	9411121504	21	350	6.88	N/A	N/A	316.586	9411121404	72	290	24.65	N/A	N/A
316.642	9411121524	19	340	4.8	N/A	N/A	316.590	9411121409	61	280	21.43	N/A	N/A
316.656	9411121544	19	350	6.3	N/A	N/A	316.593	9411121414	55	260	17.25	N/A	N/A
316.697	9411121644	22	340	5.91	N/A	N/A	316.597	9411121419	50	250	15.58	N/A	N/A
316.739	9411121744	20	340	9.45	N/A	N/A	316.600	9411121424	47	250	13.68	N/A	N/A
316.781	9411121844	15	340	6.82	N/A	N/A	316.603	9411121429	41	250	15.01	N/A	N/A
316.822	9411121944	11	340	5.01	N/A	N/A	316.607	9411121434	18	250	17.24	N/A	N/A
316.864	9411122044	7	350	13.92	N/A	N/A	316.610	9411121439	0	250	13.67	N/A	N/A
316.906	9411122144	6	330	9.03	N/A	N/A	316.614	9411121444	0	250	15.05	N/A	N/A
316.989	9411122344	3	340	5.02	N/A	N/A	316.617	9411121449	0	250	14.71	N/A	N/A
317.072	9411130144	2	340	4.33	N/A	N/A	316.621	9411121454	2	250	12.28	N/A	N/A
317.156	9411130344	0	350	6.76	N/A	N/A	316.624	9411121459	2	260	12.13	N/A	N/A
317.239	9411130544	0	350	4.84	N/A	N/A	316.628	9411121504	3	260	15.06	N/A	N/A
317.322	9411130744	0	350	9.26	N/A	N/A	316.631	9411121509	3	260	12.81	N/A	N/A
317.406	9411130944	0	360	12.4	N/A	N/A	316.635	9411121514	3	260	10.24	N/A	N/A
317.572	9411131344	0	360	4.88	N/A	N/A	316.638	9411121519	3	270	10.38	N/A	N/A
317.739	9411131744	0	360	5	N/A	N/A	316.642	9411121524	3	280	11.73	N/A	N/A
317.906	9411132144	0	360	4.66	N/A	N/A	316.645	9411121529	4	280	7.45	N/A	N/A
318.072	9411140144	0	360	4.08	N/A	N/A	316.649	9411121534	6	290	6.94	N/A	N/A
318.239	9411140544	0	N/A	N/A	N/A	N/A	316.652	9411121539	27	300	7.08	N/A	N/A

Table K-IV: Results from Event 4, monitored on 13/09/95

WEIR SAMPLES							INLET SAMPLES						
Time (day)	**Time YMDHM**	**Flow (L/s)**	**T.D.S (ppm)**	**T.S.S (mg/L)**	**Nitrate (mg/L)**	**Phosphate (mg/L)**	**Time (day)**	**Time YMDHM**	**Flow (L/s)**	**T.D.S (ppm)**	**T.S.S (mg/L)**	**Nitrate (mg/L)**	**Phosphate (mg/L)**
256.8743	9509132059	0	710	6.39	0.00	0.08	256.8743	9509132059	11	910	15.58	0.02	0.09
256.9021	9509132139	8	700	4.00	0.00	0.04	256.8847	9509132114	12	920	15.83	0.02	0.09
256.9299	9509132219	11	710	6.74	0.00	0.04	256.8951	9509132129	13	1050	19.24	0.08	0.19
256.9576	9509132259	11	710	8.05	0.00	0.03	256.9056	9509132144	17	1110	8.55	0.11	0.24
256.9854	9509132339	18	760	7.12	0.00	0.03	256.916	9509132159	26	1020	8.60	0.13	0.19
257.0132	9509140019	21	810	10.42	0.00	0.04	256.9264	9509132214	32	940	6.16	0.15	0.15
257.041	9509140059	24	790	13.10	0.01	0.04	256.9368	9509132229	30	880	6.17	0.15	0.12
257.0826	9509140159	27	770	9.59	0.00	0.03	256.9507	9509132249	29	730	6.82	0.1	0.12
257.1243	9509140259	194	860	12.06	0.04	0.11	256.9646	9509132309	28	580	6.99	0.1	0.11
257.166	9509140359	143	940	11.61	0.04	0.07	256.9785	9509132329	28	460	11.34	0.07	0.1
N/A	N/A	N/A	N/A	N/A	N/A	N/A	256.9924	9509132349	27	390	8.10	0.1	0.09
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.0063	9509140009	27	360	8.84	0.08	0.12
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.0201	9509140029	27	320	8.08	0.08	0.12
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.034	9509140049	27	310	6.57	0.06	0.08
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.0479	9509140109	40	340	5.03	0.05	0.08
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.0618	9509140129	57	370	4.20	0.04	0.08
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.0757	9509140149	81	410	3.26	0.04	0.09
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.0896	9509140209	360	260	88.00	0.04	0.29
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.1035	9509140229	419	110	67.15	0.03	0.23
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.1174	9509140249	350	70	30.73	0.02	0.15
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.1313	9509140309	107	80	23.83	0.00	0.13
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.1451	9509140329	92	100	19.60	0.01	0.12
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.159	9509140349	80	100	14.48	0.01	0.11
N/A	N/A	N/A	N/A	N/A	N/A	N/A	257.1729	9509140409	53	120	11.46	0.01	0.11

Table K-V: Results from Event 5, monitored on 23/09/95

WEIR SAMPLES							INLET SAMPLES						
Time (day)	**Time YMDHM**	**Flow (L/s)**	**T.D.S (ppm)**	**T.S.S (mg/L)**	**Nitrate (mg/L)**	**Phosphate (mg/L)**	**Time (day)**	**Time YMDHM**	**Flow (L/s)**	**T.D.S (ppm)**	**T.S.S (mg/L)**	**Nitrate (mg/L)**	**Phosphate (mg/L)**
266.173	9509230409	0	550	10.22	0.00	0.05	266.173	9509230409	22	800	18.10	0.01	0.08
266.201	9509230449	2	700	4.31	0.00	0.06	266.183	9509230424	32	740	30.25	0.05	0.20
266.228	9509230529	5	830	4.69	0.00	0.07	266.194	9509230439	40	620	24.67	0.08	0.16
266.256	9509230609	8	700	4.38	0.00	0.08	266.204	9509230454	44	390	13.27	0.09	0.10
266.284	9509230649	6	690	5.19	0.00	0.08	266.215	9509230509	40	320	8.50	0.07	0.10
266.310	9509230726	11	800	5.83	0.00	0.09	266.225	9509230524	35	250	7.89	0.04	0.06
266.338	9509230806	38	900	6.07	0.00	0.08	266.235	9509230539	30	250	7.74	0.04	0.08
266.365	9509230846	88	990	6.25	0.00	0.16	266.249	9509230559	24	250	5.44	0.04	0.04
266.393	9509230926	108	850	8.30	0.02	0.12	266.263	9509230619	19	270	5.76	0.02	0.07
266.421	9509231006	82	810	9.93	0.03	0.10	266.277	9509230639	22	280	5.71	0.01	0.08
266.449	9509231046	49	820	9.38	0.01	0.09	266.291	9509230659	39	330	5.54	0.00	0.08
266.476	9509231126	36	750	8.92	0.02	0.06	266.305	9509230719	48	340	4.81	0.01	0.08
266.518	9509231226	56	850	7.32	0.01	0.04	266.310	9509230726	0	340	1.80	0.02	0.08
266.560	9509231326	75	810	7.94	0.00	0.04	266.320	9509230741	66	320	15.07	0.00	0.12
266.601	9509231426	53	550	7.64	0.00	0.08	266.331	9509230756	156	220	51.08	0.04	0.30
266.643	9509231526	22	500	6.83	0.00	0.11	266.341	9509230811	238	130	28.67	0.03	0.16
266.685	9509231626	19	480	8.89	0.00	0.08	266.351	9509230826	222	120	17.07	0.03	0.15
266.726	9509231726	17	270	15.14	0.00	0.08	266.362	9509230841	261	90	5.48	0.02	0.13
266.768	9509231826	22	180	11.15	0.00	0.08	266.372	9509230856	238	70	25.00	0.00	0.19
266.810	9509231926	18	N/A	N/A	N/A	N/A	266.386	9509230916	81	80	17.67	0.00	0.09
266.851	9509232026	17	N/A	N/A	N/A	N/A	266.400	9509230936	35	100	12.05	0.01	0.07
266.893	9509232126	15	N/A	N/A	N/A	N/A	266.414	9509230956	22	110	8.60	0.00	0.07
266.935	9509232226	15	N/A	N/A	N/A	N/A	266.428	9509231016	8	130	7.64	0.00	0.07
266.976	9509232326	10	N/A	N/A	N/A	N/A	266.442	9509231036	0	150	6.02	0.02	0.07

Table K-VI: Results from Event 6 and Event 7, monitored on 30/09/95

WEIR SAMPLES							INLET SAMPLES						
Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)
273.22	9509300521	0	220	7.80	0.00	0.08	273.22	9509300521	85	1010	4.13	0.02	0.05
273.25	9509300601	52	650	6.21	0.00	0.15	273.23	9509300536	139	810	62.11	0.09	0.21
273.28	9509300641	74	690	12.40	0.05	0.13	273.24	9509300551	337	260	33.33	0.08	0.11
273.31	9509300721	54	560	19.22	0.11	0.16	273.25	9509300606	367	150	23.15	0.08	0.08
273.33	9509300801	29	540	18.25	0.13	0.17	273.26	9509300621	37	150	13.94	0.05	0.08
273.36	9509300841	17	460	13.92	0.04	0.17	273.28	9509300636	32	180	9.19	0.05	0.07
273.39	9509300921	13	400	9.66	0.04	0.17	273.29	9509300651	32	210	7.61	0.07	0.07
273.43	9509301021	2	340	9.75	0.06	0.12	273.30	9509300711	27	260	5.52	0.07	0.06
273.47	9509301121	0	290	6.97	0.06	0.08	273.31	9509300731	24	300	4.00	0.04	0.34
273.51	9509301221	0	270	6.85	0.08	0.08	273.33	9509300751	0	340	1.76	0.04	0.09
273.56	9509301321	0	220	4.89	0.04	0.11	273.34	9509300811	0	380	2.41	0.03	0.07
273.60	9509301421	0	210	5.80	0.04	0.11	273.35	9509300831	0	410	2.22	0.05	0.07
275.32	9510020742	2	300	7.53	0.00	0.08	275.32	9510020742	217	660	3.19	0.00	0.05
275.35	9510020822	60	670	6.17	0.00	0.25	275.33	9510020757	410	580	2.27	0.08	0.22
275.38	9510020902	177	670	7.96	0.00	0.17	275.34	9510020812	376	270	17.87	0.07	0.14
275.40	9510020942	255	560	12.06	0.04	0.14	275.35	9510020827	455	140	12.58	0.02	0.08
275.43	9510021022	175	570	8.56	0.02	0.14	275.36	9510020842	451	100	17.58	0.01	0.13
275.46	9510021102	95	540	8.39	0.03	0.15	275.37	9510020857	454	70	17.38	0.01	0.11
275.49	9510021142	67	310	7.39	0.03	0.13	275.38	9510020912	531	60	17.40	0.01	0.08
275.53	9510021242	52	240	7.29	0.03	0.09	275.40	9510020932	207	60	13.78	0.00	0.07
275.57	9510021342	22	220	7.21	0.02	0.01	275.41	9510020952	78	80	11.01	0.00	0.08
275.61	9510021442	17	190	6.36	0.01	0.08	275.43	9510021012	4	110	10.73	0.01	0.08
275.65	9510021542	18	190	7.05	0.02	0.08	275.44	9510021032	0	150	7.92	0.01	0.08
275.70	9510021642	26	210	6.54	0.01	0.07	275.45	9510021052	0	180	5.76	0.01	0.08

Table K-VII: Results from Event 8, monitored on 11/10/95

WEIR SAMPLES							INLET SAMPLES						
Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Time (day)	Time YMDHM	Flow (L/s)	T.D.S (ppm)	T.S.S (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)
284.37	9510110846	0	380	7.42	0.00	0.13	284.37	9510110846	0	810	7.05	0.00	0.14
284.39	9510110926	0	390	5.12	0.00	0.15	284.38	9510110901	0	960	34.09	0.00	0.25
284.42	9510111006	0	390	4.51	0.00	0.18	284.39	9510110916	0	1120	7.97	0.05	0.24
284.45	9510111046	0	390	3.44	0.00	0.19	284.40	9510110931	0	1140	8.60	0.12	0.18
284.48	9510111126	4	390	2.22	0.00	0.16	284.41	9510110946	0	1100	5.63	0.11	0.22
284.50	9510111206	8	390	4.13	0.00	0.18	284.42	9510111001	4	1050	4.78	0.09	0.18
284.51	9510111216	10	390	4.80	0.00	0.17	284.43	9510111016	6	1000	3.95	0.09	0.18
284.54	9510111256	36	650	5.90	0.00	0.24	284.44	9510111036	10	940	3.17	0.09	0.15
284.57	9510111336	56	650	12.13	0.00	0.20	284.46	9510111056	15	900	2.85	0.08	0.13
284.59	9510111416	40	570	8.14	0.00	0.20	284.47	9510111116	19	870	1.29	0.06	0.13
284.62	9510111456	20	530	10.30	0.01	0.16	284.48	9510111136	25	850	2.50	0.06	0.15
284.65	9510111536	10	460	14.90	0.05	0.16	284.50	9510111156	32	840	3.31	0.06	0.12
284.68	9510111616	9	410	9.57	0.01	0.16	284.51	9510111216	52	840	3.04	0.06	0.15
284.72	9510111716	9	390	5.50	0.00	0.12	284.52	9510111231	76	520	67.12	0.13	0.30
284.76	9510111816	15	390	5.69	0.00	0.11	284.53	9510111246	128	240	21.43	0.14	0.22
284.80	9510111916	19	380	7.27	0.00	0.15	284.54	9510111301	166	160	27.40	0.07	0.19
284.84	9510112016	16	380	7.85	0.00	0.13	284.55	9510111316	121	160	18.71	0.08	0.17
284.89	9510112116	14	380	5.94	0.00	0.16	284.56	9510111331	60	190	12.50	0.06	0.13
284.93	9510112216	9	380	6.74	0.00	0.44	284.57	9510111346	33	210	8.38	0.05	0.13
284.97	9510112316	3	360	7.01	0.01	0.17	284.59	9510111406	0	260	7.35	0.05	0.12
285.01	9510120016	0.00	370	7.05	0.00	0.14	284.60	9510111426	0	310	7.16	0.04	0.11
285.05	9510120116	0.00	360	6.63	0.00	0.13	284.62	9510111446	0	350	3.40	0.03	0.12
285.09	9510120216	0.00	350	6.67	0.02	0.13	284.63	9510111506	0	390	4.39	0.02	0.08
285.14	9510120316	0.00	340	7.22	0.03	0.10	284.64	9510111526	0	430	4.61	0.00	0.10

APPENDIX L

Results of Event Water Quality Data Analysis

Table L-I : Results of peak concentration analysis

Storm		**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Average**
Date		**26/10/1994**	**12/11/1994**	**13/09/1995**	**23/09/1995**	**30/09/1995**	**02/10/1995**	**11/10/1995**	**%**
Duration (hrs)	Inlet	6.00	2.80	10.97	8.57	4.13	3.93	4.80	**5.15**
	Outlet	14.50	16.40	14.30	13.70	7.43	7.83	11.17	**12.19**
Flow Vol.	(m^3)	615	552	2874	1591	675	2490	718	**1359**
Effluent Detention Time	(days)	11.5	6.4	3.1	3.2	3.0	3.0	3.0	**4.7**
Peak Flow (L/s)	Inlet	185	160	702	335	337	700	172	**370**
	Outlet	24	23	194	130	74	280	56	**112**
Peak TDS (ppm)	Inlet	NA	360	1110	800	1010	660	1140	**847**
	Outlet	NA	370	940	990	690	670	650	**718**
Peak TSS (mg/L)	Inlet	68.53	104.92	88	51.08	62.11	17.87	67.12	**66.7**
	Outlet	10.92	13.92	13.1	15.14	19.22	12.06	12.13	**13.8**
Peak Nitrate (mg/L)	Inlet	NA	NA	0.15	0.09	0.09	0.08	0.14	**0.11**
	Outlet	NA	NA	0.04	0.03	0.13	0.04	0.05	**0.06**
Phosphate (mg/L)	Inlet	NA	NA	0.29	0.3	0.34	0.22	0.3	**0.29**
	Outlet	NA	NA	0.11	0.16	0.17	0.25	0.44	**0.23**

Table L-II : Results from Load Analysis

Storm **Date**		**2** **26/10/1994**	**3** **12/11/1994**	**4** **13/09/1995**	**5** **23/09/1995**	**6** **30/09/1995**	**7** **02/10/1995**	**8** **11/10/1995**	**Average** **(%)**
Duration (hr:mins)	Inlet Outlet	6.0 14.5	2.8 8.5	11.0 14.3	8.6 13.70	4.1 7.4	3.9 7.8	4.8 11.2	**5.2** **11.0**
Effluent Detention Time	(days)	11.5	6.4	3.1	3.2	3.0	3.0	3.0	**4.7**
Total Flow (m^3)	Inlet Outlet	640 615	552 552	2874 2874	1591 1591	740 675	2700 2490	718 718	**2400**
TDS (ppm)	Inlet Outlet	290 NA	180 189	616 2587	352 1304	273 408	530 1240	284 382	**608.9** **910.8**
TSS (kg)	Inlet Outlet	23.7 3.7	31.6 3.9	102 33	31.9 13.2	19.9 8.63	36.9 21.8	14.7 8.1	**57.2** **46.8**
Nitrate (kg)	Inlet Outlet	NA NA	NA NA	0.093 0.102	0.042 0.025	0.052 0.039	0.062 0.055	0.061 0.015	**0.13** **0.10**
Phosphate (kg)	Inlet Outlet	NA NA	NA NA	0.474 0.217	0.24 0.147	0.085 0.1	0.296 0.344	0.131 0.131	**0.44** **0.37**

Table L-III : Results from event mean concentration analysis

Storm Date		**1 24/06/1994**	**2 26/10/1994**	**3 12/11/1994**	**4 13/09/1995**	**5 23/09/1995**	**6 30/09/1995**	**7 02/10/1995**	**8 11/10/1995**	**Average (%)**
Flow Vol.	(m^3)	8249	615	552	2874	1591	675	2490	718	**1359**
Effluent Detention Time	(days)	NA	11.5	6.4	3.1	3.2	3.0	3.0	3.0	**4.7**
TDS (ppm)	Inlet Outlet	284 143	472 NA	326 342	214 900	221 820	404 604	213 498	396 532	316 548
TSS (mg/L)	Inlet Outlet	23.9 34.2	38.5 6.0	57.2 7.1	35.5 11.5	20.1 8.3	29.5 12.8	14.8 8.8	20.5 11.3	30.0 12.5
Nitrate (mg/L)	Inlet Inlet	0.085 0.069	NA NA	NA NA	0.032 0.035	0.026 0.016	0.077 0.058	0.025 0.022	0.085 0.021	0.055 0.037
Phosphate mg/L)	Inlet Outlet	0.282 0.242	NA NA	NA NA	0.165 0.076	0.151 0.092	0.126 0.148	0.119 0.138	0.182 0.182	0.171 0.147

APPENDIX M

Plots of Peak Water Quality Constituent Occurrence

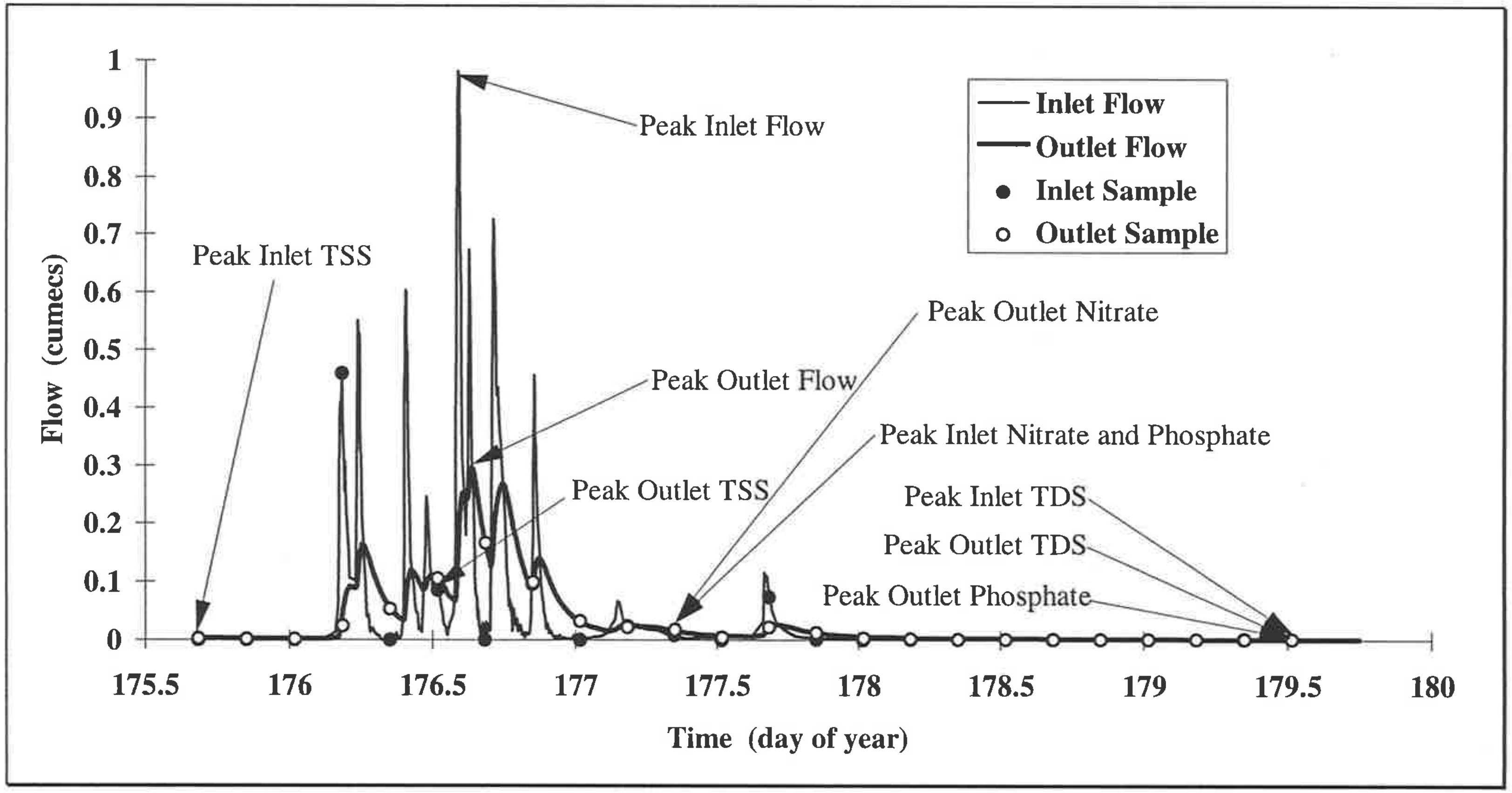


Figure M-1: Times for individual parameter peak occurrence for Event 1, monitored on 24/06/94

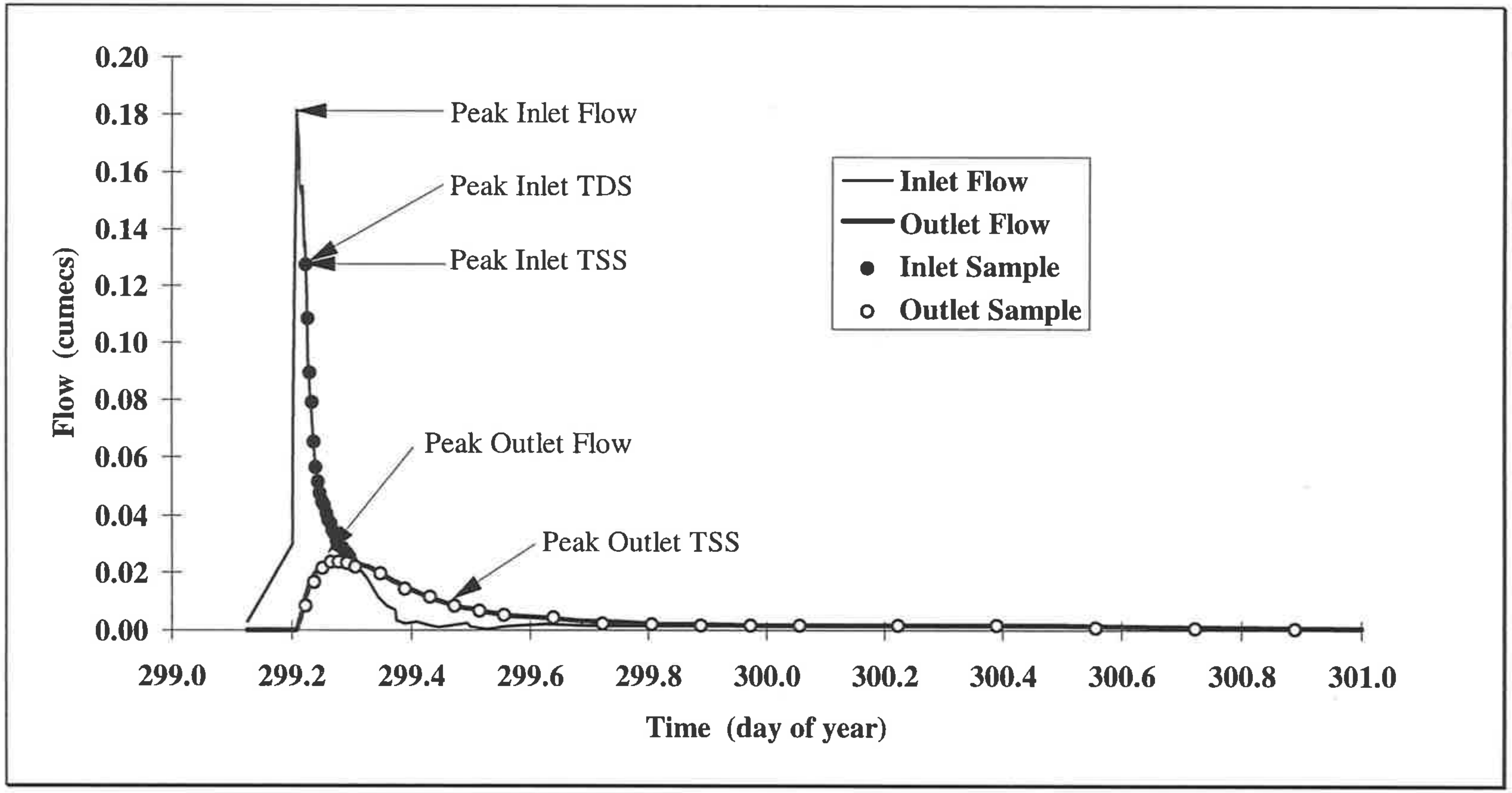
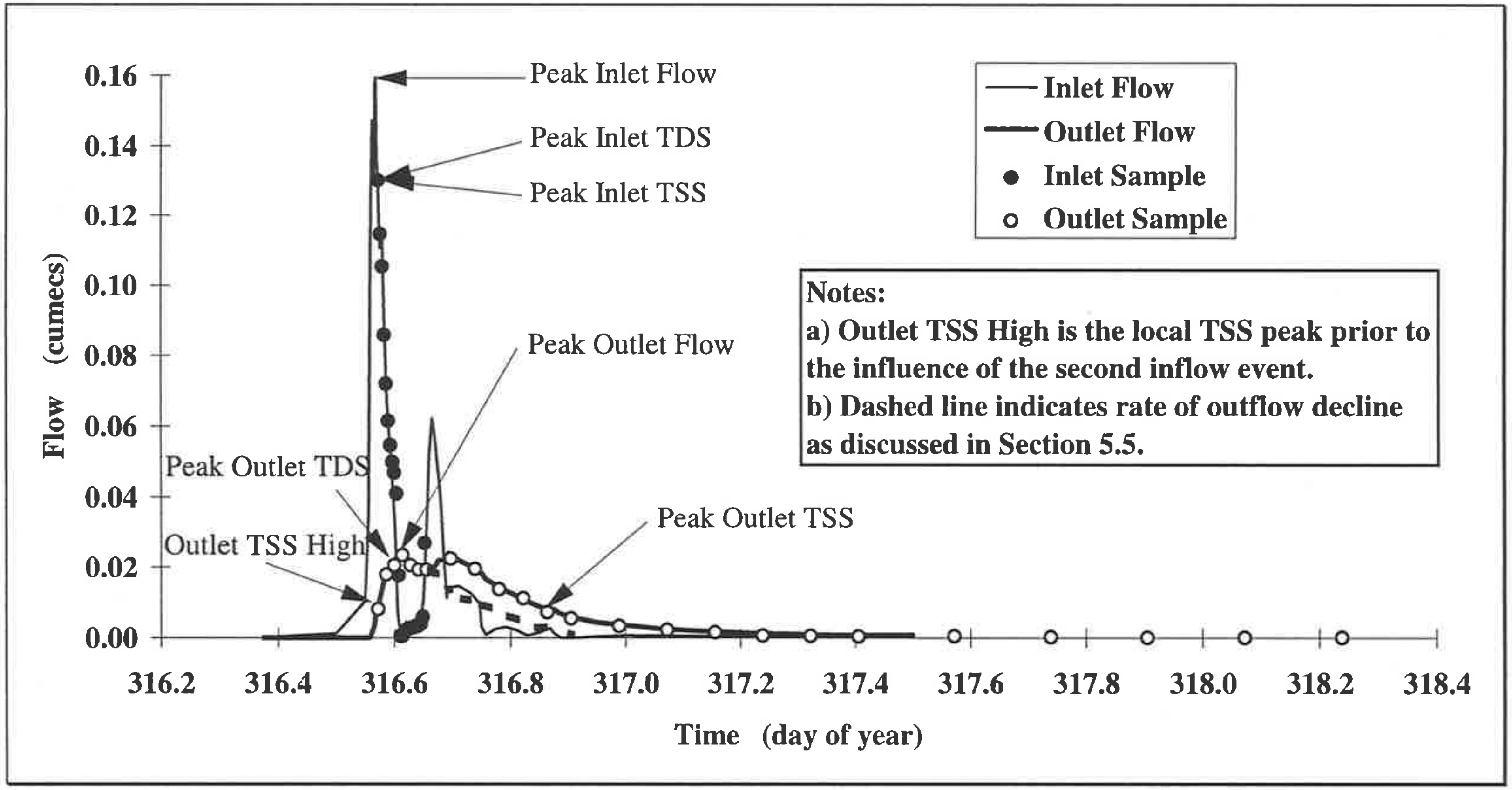


Figure M-2: Times for individual parameter peak occurrence for Event 2, monitored on 27/10/94



Notes:
a) Outlet TSS High is the local TSS peak prior to the influence of the second inflow event.
b) Dashed line indicates rate of outflow decline as discussed in Section 5.5.

Figure M-3: Times for individual parameter peak occurrence for Event 3, monitored on 12/11/94

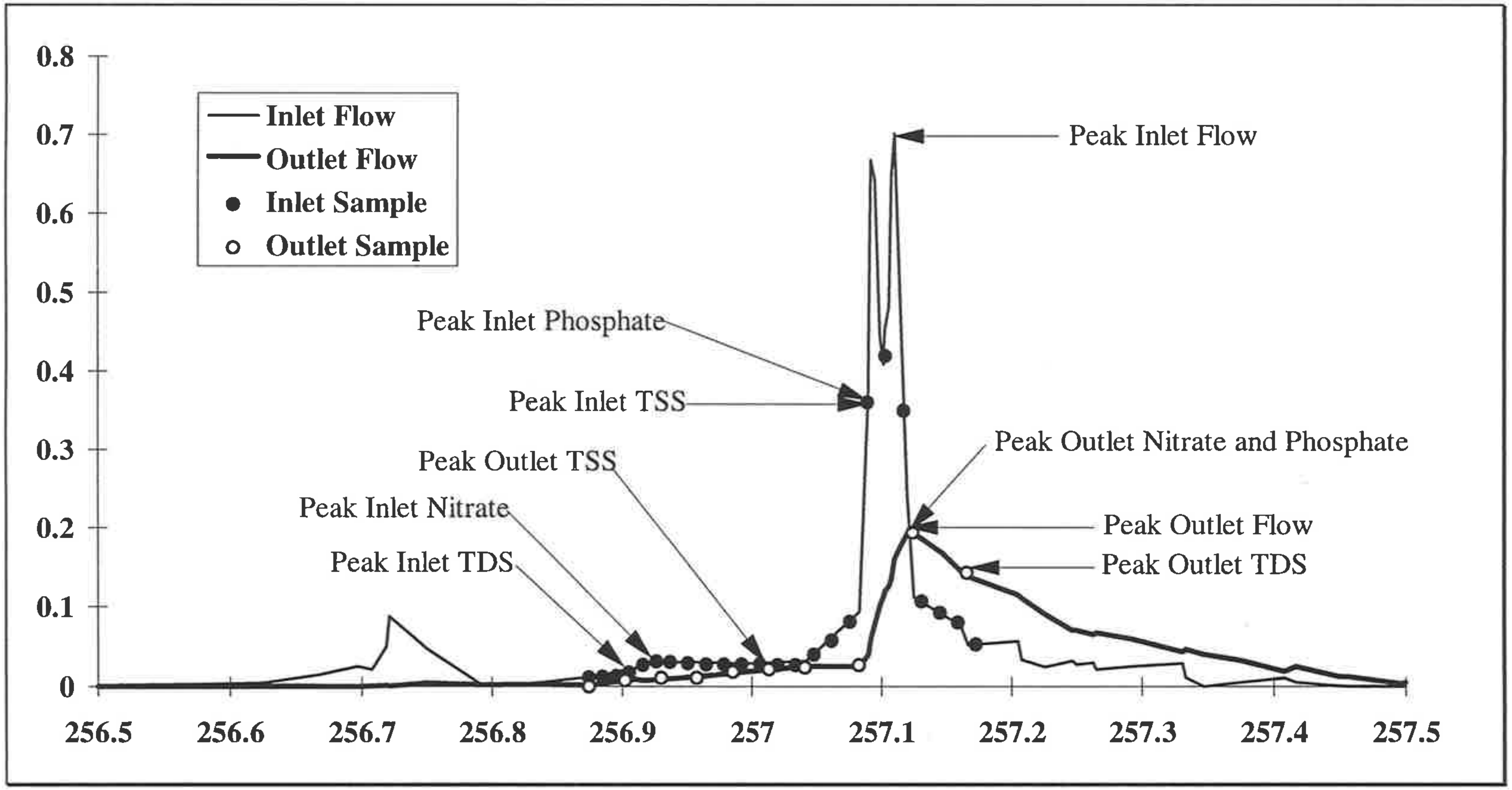


Figure M-4: Times for individual parameter peak occurrence for Event 4, monitored on 13/09/95

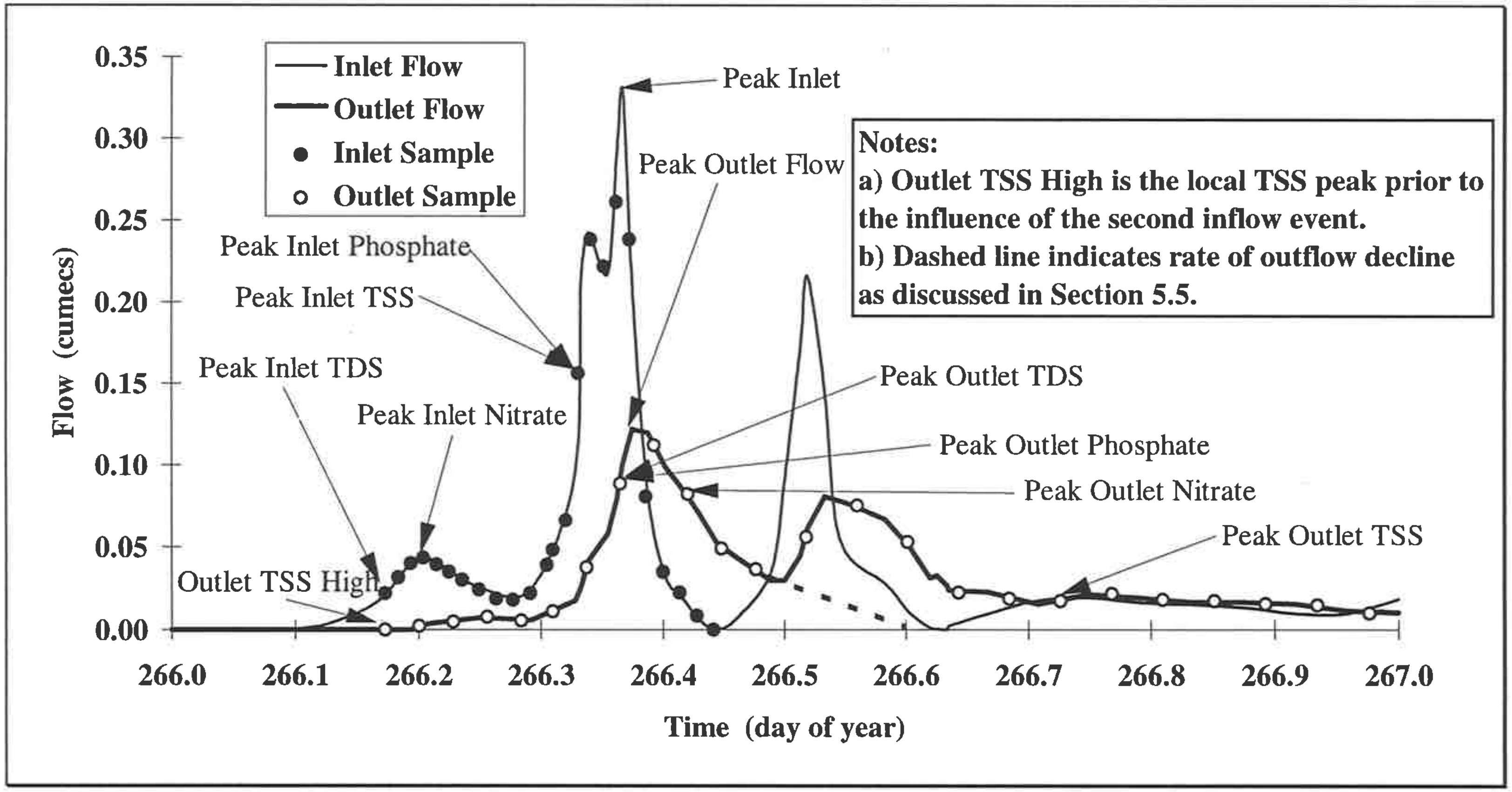


Figure M-5: Times for individual parameter peak occurrence for Event 5, monitored on 23/09/95

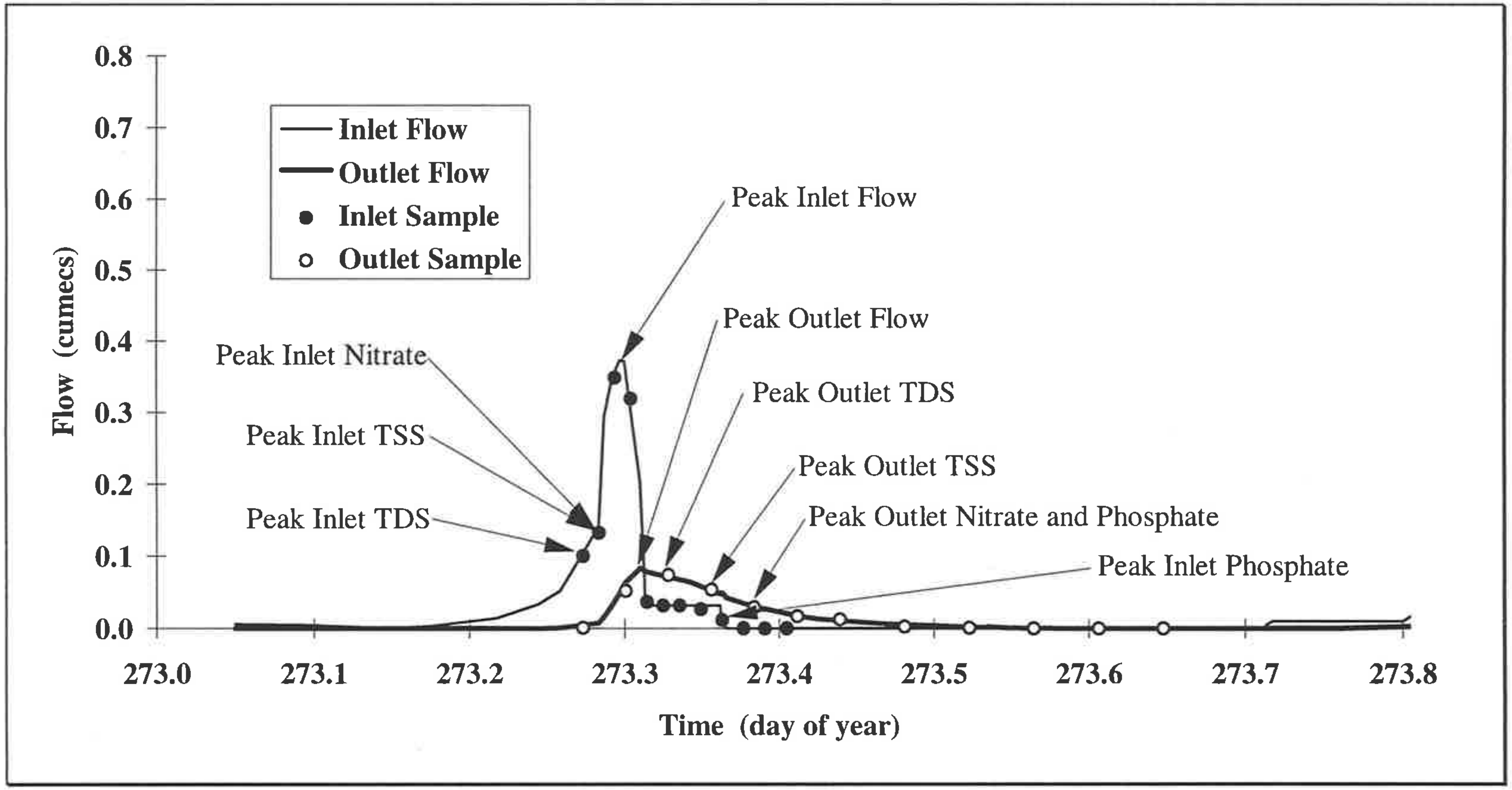


Figure M-6: Times for individual parameter peak occurrence for Event 6, monitored on 30/09/95

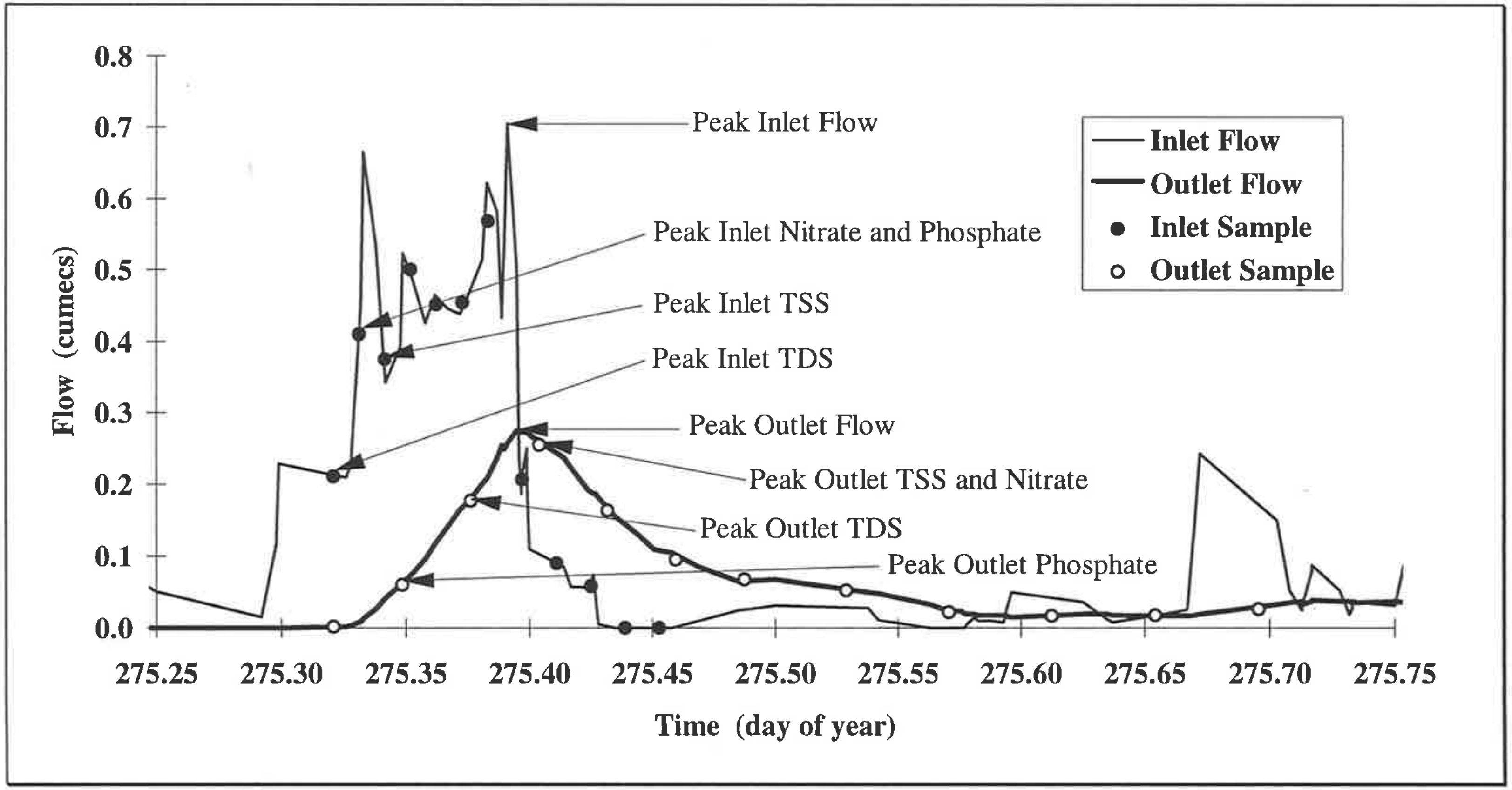


Figure M-7: Times for individual parameter peak occurrence for Event 7, monitored on 02/10/95

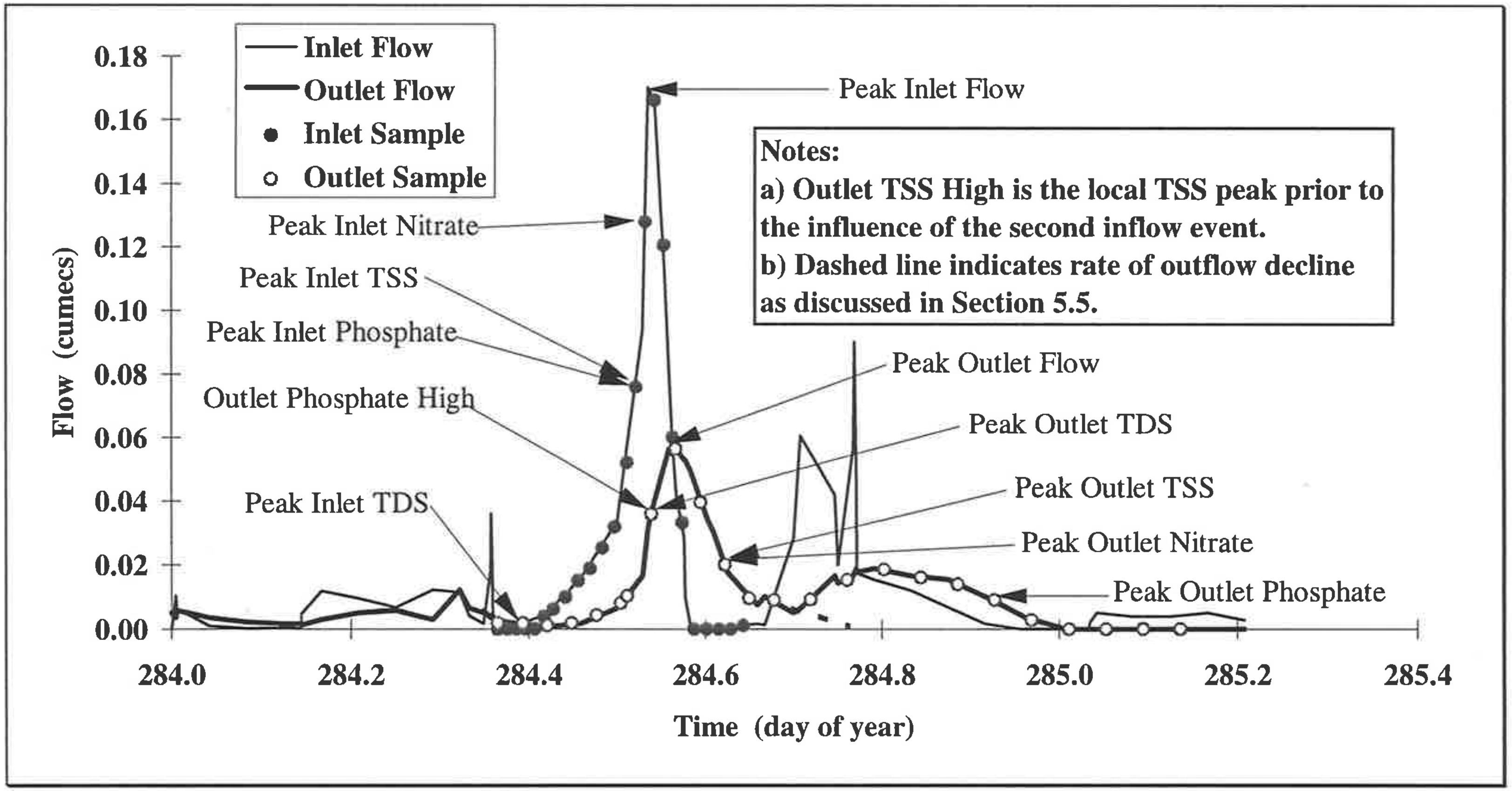


Figure M-8: Times for individual parameter peak occurrence for Event 8, monitored on 02/10/95

APPENDIX N

Daily Sampling Data for Quiescent Decay Rate

Table N-I : Quiescent decay rate , daily sampling data

		Days since	Outlet Station				Inlet Station				Upstream of Vegetated Channel			
Date	Day	Flow	T.S.S	T.D.S	Phosphate	Nitrate	T.S.S	T.D.S	Phosphate	Nitrate	T.S.S	T.D.S	Phosphate	Nitrate
			(mg/L)	(ppm)	(mg/L)	(mg/L)	(mg/L)	(ppm)	(mg/L)	(mg/L)	(mg/L)	(ppm)	(mg/L)	(mg/L)
01/09/95	1	1	1.12	1080	0.45	0.39	0.95	790	0.19	0	6.87	530	0.2	0.02
04/09/95	4	0	5.06	680	0.08	0	2.63	410	0.25	0.08	16.27	120	0.33	0.07
05/09/95	5	1	3.76	550	0.34	0.01	0.4	720	0.1	0.03	1.74	680	0.17	0.19
06/09/95	6	2	5.43	600	0.08	0	0.2	790	0.15	0.02	0.43	930	0.23	0.11
07/09/95	7	3	3.49	620	0.08	0	0.24	860	0.13	0	1.57	1290	0.25	0.31
08/09/95	8	4	4.32	640	0.08	0	4.17	930	0.16	0	1.81	1280	0.27	0.26
11/09/95	11	1	2.05	610	0.05	0	0.24	740	0.08	0	1.58	1050	0.23	0.14
12/09/95	12	2	3.13	670	0.04	0	0.25	850	0.04	0	0.99	1400	0.21	0.25
13/09/95	13	3	2.61	720	0.03	0	0.25	960	0.08	0	1.04	1380	0.32	0.24
14/09/95	14	0	3.12	180	0.08	0.01	2.91	390	0.08	0.01	1.54	300	0.14	0.07
15/09/95	15	1	3.56	240	0.08	0	16.3	470	0.04	0	0.76	1180	0.27	0.21
18/09/95	18	4	2.1	340	0.04	0	4.41	430	0.08	0	1.78	1310	0.43	0.07
19/09/95	19	5	5.19	390	0.05	0	9.1	970	0.3	0.1	8.97	320	0.08	0.06
20/09/95	20	6	0.82	370	0.29	0	2.89	580	0.12	0.01	0.98	1050	2.5	0.08
21/09/95	21	7	0	440	0.07	0	2.34	500	0.08	0	0	1060	0.57	0.08
22/09/95	22	8	4.17	440	0.07	0.01	1.46	630	0.08	0	0	380	0.14	0.05
25/09/95	25	1	3.93	170	0.13	0	30.79	500	0.08	0	1.98	1200	0.28	0.18
26/09/95	26	2	7.09	200	0.09	0	5.08	190	0.11	0	0.8	1270	0.38	0.14
27/09/95	27	3	3.66	200	0.12	0	13.62	280	0.2	0	1.63	1340	0.21	0.16
28/09/95	28	4	3.54	210	0.12	0.01	15.09	270	0.12	0	2.81	1360	0.28	0.09

Table N-II : Quiescent decay rate daily sampling data, continued

		Days since	Outlet Station				Inlet Station				Upstream of Vegetated Channel			
Date	Day	Flow	T.S.S	T.D.S	Phosphate	Nitrate	T.S.S	T.D.S	Phosphate	Nitrate	T.S.S	T.D.S	Phosphate	Nitrate
			(mg/L)	(ppm)	(mg/L)	(mg/L)	(mg/L)	(ppm)	(mg/L)	(mg/L)	(mg/L)	(ppm)	(mg/L)	(mg/L)
29/09/95	29	5	2.65	210	0.14	0	3.36	850	0.14	0	4.11	1300	0.48	0.07
03/10/95	33	0	4.06	220	0.08	0	0.56	460	0.07	0	0.74	720	0.14	0.09
04/10/95	34	1	1.77	240	0.07	0	4.59	290	0.14	0	0.45	1180	0.17	0.09
05/10/95	35	0	1.9	270	0.1	0	2.46	470	0.07	0.01	4.28	230	0.1	0.03
06/10/95	36	1	1.88	310	0.08	0.04	4.2	470	0.09	0	1.12	1220	0.18	0.11
09/10/95	39	3	1.88	370	0.1	0	2.08	570	0.16	0	1.24	1330	0.25	0.09
10/10/95	40	4	2.44	360	0.11	0	1.92	580	0.15	0	0.88	1340	0.32	0.07
11/10/95	41	0	2.59	370	0.19	0.01	4.03	820	0.14	0.07	52.63	60	0.24	0.08
12/10/95	42	1	6.06	390	0.13	0.02	1.98	510	0.07	0	2.63	1250	0.09	0.1
13/10/95	43	2	3.2	420	0.2	0.01	1.56	650	0.12	0	2.25	620	0.18	0.03
16/10/95	46	5	3.1	470	0.11	0	2.78	480	0.13	0	0.92	1210	0.35	0.05
17/10/95	47	6	2.12	470	0.13	0	2.25	500	0.18	0	0.72	1240	0.3	0.05
18/10/95	48	7	2.01	450	0.13	0	3.17	500	0.22	0	0.65	1160	0.43	0.01
19/10/95	49	8	2.92	530	0.15	0	4.71	680	0.23	0	1.08	1290	0.25	0.03
20/10/95	50	9	3.81	540	0.2	0	3.95	910	0.09	0	1.94	410	0.16	0.02
25/10/95	55	3	2.9	560	0.16	0.74	0.74	710	0.13	0	1.22	1140	0.25	0.03
26/10/95	56	4	2.42	560	0.12	0	3.17	570	0.14	0	1.31	1290	0.3	0.03
31/10/95	61	5	4.2	600	0.18	0	3.23	780	0.15	0	1.09	1430	0.35	0.03
01/11/95	62	6	4.13	600	0.16	0	2.86	630	0.14	0	0.87	1420	0.27	0.03
02/11/95	63	7	3.84	590	0.14	0.01	1.89	650	0.19	0.02	7.11	190	0.31	0.11
03/11/95	64	8	3.8	590	0.14	0.01	4.33	590	0.22	0	5.17	570	0.37	0.03