5 Simulation results of potential management scenarios and Discussion

This chapter attempts to address the second hypothesis of whether a simplified generic wetland model can be used to answer “what if” questions. The two degraded wetlands for which there is adequate data to simulate effectively, Lock 6 and Reedy Creek wetlands, are used to test simulation effectiveness of potential management strategies. In the management simulations of Lock 6 and Reedy Creek wetlands, WETMOD 2 was used to explore potential management strategies. Both wetlands are considered permanently inundated and one was additionally severely degraded due to excessive nutrient inflow from irrigation drainage.

**Lock 6 wetland**

Table 6 displays the potential percentage reduction in the outflow of PO$_4$-P, NO$_3$-N and phytoplankton biomass as a consequence of three different management scenarios. Figure 40 and Figure 41 represent the impact, on nutrient concentration and macrophyte, zooplankton and phytoplankton biomass respectively, due to potential management of turbidity reduction through the introduction of wetland dry periods in Lock 6 wetland. To illustrate the status quo, the monitored concentrations and biomass of PO$_4$-P, NO$_3$-N and phytoplankton, and the standard error, are also displayed.

The scenarios during the months of February, March and April reflect the anticipated wetland response to turbidity management (see section 3.4) during the macrophyte growth period. The sedimentation rate of PO$_4$-P, NO$_3$-N and phytoplankton during the months of March and April was constant for all scenarios (see Box). During this period, the reduction in both PO$_4$-P and NO$_3$-N wetland concentrations is therefore a direct result of the reduction in turbidity and improved uptake of nutrients by the wetland, Figure 40A and B. This is reflected in the increase in macrophyte and zooplankton growth seen in Figure 41A and B. The nutrient reduction success during this period improves with each increment of turbidity reduction management, as can clearly be seen in Figure 40A and B. The improvement in wetland condition can also be seen in the dramatic increase in macrophyte growth, first at the 50% turbidity reduction management scenario, and then at the 75% turbidity reduction scenario, as
Regional Scale Modelling of the lower River Murray wetlands

shown in Figure 41A. The 75% reduction in turbidity (Figure 41A) demonstrates a healthy growth phase of macrophytes, which reduces in the cooler months. The zooplankton population growth seen during March and April for the 75% turbidity scenario is a consequence of the assumed improved habitat conditions provided by the macrophytes. The reduction in phytoplankton during this time is a consequence of the competition with macrophytes for underwater light. The initial growth spurt of phytoplankton for the 75% turbidity reduction scenario during February, is caused by the improved underwater light conditions, and reduced competition due to, an expected, lag in macrophyte growth. The zooplankton growth during February also shows a slight increase as a consequence of the improved nutrient source (phytoplankton), followed by a slight reduction in its population during the transition from phytoplankton to macrophyte dominant phase.

The 50% reduction in turbidity (Figure 41A) signifies the first real improvement in macrophyte growth, with a corresponding wetland nutrient load reduction. However, as expected, the macrophyte growth is not as pronounced as that of the 75% turbidity reduction scenario. The 50% reduction in turbidity scenario also shows some of the February increase in phytoplankton growth prior to macrophyte competition, as well as a slight improvement in the zooplankton. The 25% turbidity reduction scenario shows minimal improvement in macrophyte growth, reflected mainly in the slight improvement in the uptake of nutrients (PO₄-P and NO₃-N) during March and April.

When the turbidity is below that of the sedimentation threshold of 70 NTU, there is a reduction in sedimentation of both PO₄-P and NO₃-N. This is apparent during a short, but clear, high turbidity event in February for the 0% turbidity reduction scenario where the wetland concentration of both PO₄-P and NO₃-N show a sudden and substantial reduction, as seen in Figure 40. This trough in PO₄-P and NO₃-N concentration is due to a rise in turbidity above the sedimentation threshold of 70 NTU that, in the unmanaged scenario, causes a sudden increase in nutrient sedimentation. More significantly, there is an early drop in nutrient concentration for the 0% scenario at the beginning of May (Figure 40), which continues for the remainder of the simulation period. The 25% simulation, where the turbidity was reduced by 25%, has a similar but more drastic drop in nutrient concentration at the end of May, followed by the 50% scenario at the end of June. The 75% scenario has only a small drop in nutrient concentration for a relatively short period of time as in
this scenario the turbidity only surpasses the 70 NTU sedimentation threshold for a short period of 7 days (28th August 1997 to 3rd September 1997).

In summary, due to the management simulation of turbidity reduction, the period of time where the turbidity remained below that of the calibrated sedimentation threshold steadily increased for each improved management scenario, i.e. each increase in turbidity reduction. Accordingly, the sedimentation rate reduced for each increasing turbidity reduction scenario until, at the 75% turbidity reduction scenario, only 7 days remained where turbidity within the wetland exceeded 70 NTU. Consequently, Lock 6 wetland progressively lost modelled sink (adsorption) capacity for both PO$_4$-P and NO$_3$-N with each increase in turbidity reduction. This does however not accurately account for any resuspension of nutrient highlighting one discrepancy in a generic model.

Phytoplankton was also affected by the sedimentation change, the phytoplankton threshold being calibrated to 95 NTU. The phytoplankton maintained a longer growth period both due to the reduction in turbidity with its inherent increased light availability and a low sedimentation rate (Figure 41C, June onwards). This growth period was extended with each improved management scenario, until the phytoplankton sedimentation is absent in the 75% turbidity reduction scenario (Figure 41C). The augmented phytoplankton availability resulted in an increased phytoplankton outflow from the wetland as can be seen in Table 6, with the 50% turbidity reduction scenario showing the highest amount of phytoplankton in the outflow. The increase in macrophytes and zooplankton in the 75% turbidity simulation, during March and April, reduced the phytoplankton growth that can be seen in the lower phytoplankton outflow in Table 6 as well as in Figure 41C. The zooplankton growth increased as a consequence of, and proportionally to, the extended phytoplankton growth, as can be seen in Figure 41B.

**Table 6: Lock 6 wetland Percentage Outflow Reduction**

<table>
<thead>
<tr>
<th></th>
<th>25% Turbidity Reduction</th>
<th>50% Turbidity Reduction</th>
<th>75% Turbidity Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO$_4$-P</td>
<td>% Reduction in-17.1 Outflow</td>
<td>-34.1</td>
<td>-47.7</td>
</tr>
<tr>
<td>NO$_3$-N</td>
<td>% Reduction in-17.2 Outflow</td>
<td>-18.0</td>
<td>9.1</td>
</tr>
</tbody>
</table>
Figure 40: Lock 6 impacts on Nutrient concentration due to Turbidity reduction
Figure 41: Lock 6 impacts on Macrophyte, Zooplankton & Phytoplankton due to Turbidity reduction
Reedy Creek wetland

Figure 42A and B and Figure 43C show the management scenarios for Reedy Creek wetland and the impact on wetland biomass and nutrient concentrations as a result of the management scenarios of successful reduction of irrigation drainage. Table 7 shows the percentage reduction of the total inflow (irrigation drainage and river concentrations) versus the percentage outflow reduction due to different management scenarios for Reedy Creek wetland.

The Reedy Creek wetland is adjacent to dairy farms whose pasture areas are situated on reclaimed swamps. The irrigation runoff from the dairy pastures is pumped from the adjacent farms into the wetland. This irrigation drainage has heavily influenced Reedy Creek wetland and caused substantial degradation. One potential management strategy that can be applied to Reedy Creek wetland is the nutrient reduction of irrigation drainage load through the use of constructed wetlands. Wen (2002a; 2002b), who contributed his data to this project, conducted preliminary trials of constructed wetlands on Basby farm, which is a dairy farm immediately adjacent to Reedy Creek wetland. His findings were that PO₄-P could potentially be reduced by 50% to 90%. Based on his findings, three scenarios of management were performed. The management scenarios represented increasing reductions of 25%, 50% and 75% of PO₄-P, NO₃-N and phytoplankton irrigation drainage loads, the time-series of which can be seen in Figure 42A and B and Figure 43C. The percentage reduction in the wetland outflow concentration compared with the reduction in inflow concentration can be seen in Table 7. In Table 7 the effective percentage of reduction of the total nutrient inflow is labelled as %RI and is displayed for each of the irrigation drainage reduction scenarios. The ensuing percentage reduction in outflow is labelled %RO (see section 3.4.1). The management scenarios of increasing reductions in nutrient inflow to the wetland are controlled through the irrigation nutrient reduction option of the model.

Each of the PO₄-P simulations, for increased nutrient removal capacity, shows the same trend, and for a large time period a virtually identical wetland concentration. However, in October and again in February, as seen in Figure 42A, the simulated wetland PO₄-P concentration shows a reduction as a result of the management. The NO₃-N reduction can also be seen in Table 7. The high phytoplankton biomass is due to a high phytoplankton inflow load from the irrigation drainage. There is a major
Regional Scale Modelling of the lower River Murray wetlands

reduction of phytoplankton during the January, February and March periods. The phytoplankton reduction was successful, as clearly seen in Figure 43C, particularly during the months of January, February and March. The reduction in percentage inflow versus reduction in percentage outflow is most extreme for phytoplankton, as seen in Table 7. This indicates that through a minor reduction in irrigation nutrient inflow, there can be a substantial impact on the outflow concentration of nutrients and phytoplankton from the wetland. Drop in phytoplankton growth phase 19th to 27th March is due to a spike in turbidity. The zooplankton growth follows the phytoplankton concentration, with a similar reduction due to management.

The high turbidity of the wetland, which restricts the Secchi depth to an estimated depth of 0.2 m, severely limits the macrophyte growth within the wetland. The degradation of the wetland macrophyte concentration from the initial starting level adopted for the model is a consequence of this macrophyte growth restriction. Therefore, despite the positive impact that simulated management (irrigation nutrient reduction) has on outflow nutrient reduction, the lack of macrophyte growth hampers an increase in the nutrient retention capacity of the wetland. The impact that the reduction of turbidity, as a second management strategy, may have on macrophyte growth and therefore nutrient retention is examined below.
Figure 42: Reedy Creek wetland impacts on Nutrient concentration due to irrigation drainage reduction
Figure 43: Reedy Creek wetland impacts on Macrophyte, Zooplankton & Phytoplankton due to irrigation drainage reduction
Table 7: Reedy Creek wetland Percentage Inflow reduction vs. Percentage Outflow Reduction

<table>
<thead>
<tr>
<th></th>
<th>0% Nutrient Reduction</th>
<th>25% Nutrient Reduction</th>
<th>50% Nutrient Reduction</th>
<th>75% Nutrient Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO4-P %RI</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>%RO (Irrigation Reduction Only)</td>
<td>0</td>
<td>1.2</td>
<td>2.8</td>
<td>4</td>
</tr>
<tr>
<td>NO3-N %RI</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>%RO (Irrigation Reduction Only)</td>
<td>0</td>
<td>0.7</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td>Phytoplankton %RI</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>%RO (Irrigation Reduction Only)</td>
<td>0</td>
<td>4.1</td>
<td>8.2</td>
<td>12.2</td>
</tr>
</tbody>
</table>

Reedy Creek wetland twin management strategies

For Reedy Creek wetland a combination of both management strategies was simulated. This was in an attempt to assess the cumulative impact of intensive management of one large and severely degraded wetland. The high irrigation drainage reduction scenarios of 85, 90 and 95% were used to assess the impact of potential full restoration of the wetland.

Figure 44 and Figure 45 represent the concentrations in the open water of Reedy Creek wetland when the turbidity is modelled at 75% reduction and the nutrients are reduced by 25%, 50% and 75% successively. Whereas, Figure 46 and Figure 47 represent the concentrations in the open water of Reedy Creek wetland when the irrigation drainage nutrient reduction scenario is maintained at 95% and the turbidity reduction scenarios are at 25, 50 and 75% respectively. Figure 44, Figure 45 and Figure 46, Figure 47 are plotted separately to distinguish between the impacts of various turbidity reduction scenarios at the best possible nutrient reduction scenario, and the impact of the nutrient reduction scenario at the best turbidity reduction scenario. Note, in Figure 44, Figure 45, Figure 46 and Figure 47 the monitored irrigation drainage concentration and the monitored concentration in the wetland are those monitored for Reedy Creek wetland. Figure 48, Figure 49 and Figure 50 show the percentage reduction in outflow load from Reedy Creek wetland as a consequence of the double management strategies. In these figures the results from all simulated combinations are presented.
The reduction irrigation drainage inflow has also reduced the wetland outflow of nutrients and phytoplankton. This can be seen in the gradual increase in “% Reduction in wetland nutrient outflow compared to status quo” in Figure 48 for PO₄-P, Figure 49 for NO₃-N and Figure 50 for phytoplankton. In Figure 48 to Figure 50 the percentage reduction in wetland nutrient outflow is related back to the status quo, i.e. without management scenarios.

With the exception of NO₃-N each increment of reduction in turbidity results in a “drop in the percentage reduction” in wetland PO₄-P outflow, and phytoplankton outflow, see Figure 49, Figure 48 and Figure 50 respectively, i.e. PO₄-P and phytoplankton outflow increase. The reason for the comparatively increased nutrient outflow, despite the management strategy of “reduction in irrigation” remaining the same at 95%, is related back to the decrease in the sedimentation rate, i.e. the turbidity simulated at below 70 NTU for nutrients, and 95 NTU for phytoplankton. The NO₃-N wetland retention, seen in Figure 49, as a general trend improves, however the NO₃-N retention reduces again for the 75% turbidity reduction as the turbidity passes below the sedimentation threshold (discussed for Lock 6 wetland above). That is, the 75% turbidity reduction scenario has a higher NO₃-N outflow due to the loss of sedimentation of nutrients (Figure 44B). This can be seen as an increase in NO₃-N wetland concentration, i.e. decreased nutrient retention, and is visible during September in Figure 46. The scenarios with minimal turbidity reduction display a higher NO₃-N retention, attributed to higher sedimentation of NO₃-N in more turbid wetlands. This again raises the question whether the model needs an improvement to account for sedimentation resuspension.

An improvement in PO₄-P retention is observable in the irrigation nutrient scenarios; however the turbidity reduction scenarios cause a steady drop in the PO₄-P retention (Figure 48). The turbidity reduction scenarios reduce the PO₄-P sedimentation as they do the NO₃-N sedimentation. The difference between NO₃-N and PO₄-P is that the PO₄-P concentration is very low during the period that has such a great influence on NO₃-N, i.e. September see Figure 44A. Therefore, the variability in wetland concentration for PO₄-P during September becomes negligible.

There is an early low macrophyte biomass for turbidity reduction scenarios which is not as apparent in nutrient reduction and status quo scenarios, which can be seen in Figure 45A and Figure 47A for the periods July 2000 to January 2001. This fast drop
in macrophyte biomass for the turbidity reduction scenarios is a model artefact with negligible repercussions. It is caused by the minimum fixed macrophyte gross primary productivity being slightly higher than the calculated, when the turbidity is below the 70 NTU threshold and the macrophyte growth is restricted due to other causes. The trend of macrophyte growth and its peak is due to the underwater light availability as well as nutrient availability during the simulation period. This can be seen in Figure 45A when compared to Figure 44 where initially the underwater light for macrophyte growth is limited. The macrophyte growth is again restricted, this time by NO₃-N limitation in late May 2001, see Figure 44B, which causes the rapid macrophyte dieback seen in Figure 45A. The same limitations caused by underwater light and NO₃-N can be seen in Figure 47A for the scenario of 75% turbidity reduction and 95% nutrient reduction when compared to Figure 46A and B. However, in this instance the macrophyte biomass is at its lowest for a 75% turbidity reduction scenario, compare macrophytes at Figure 45A on page 153 and Figure 47A. Effectively the higher macrophyte biomass growth is seen in the high turbidity reduction scenario (75%) with an incremental increase in biomass with each successive nutrient reduction scenario, seen in Figure 45A.

Phytoplankton retention improves with each irrigation drainage reduction (Figure 50). However, with the decrease in turbidity (Figure 50) and the late start of the macrophyte growth season discussed above, the phytoplankton has ample opportunity to increase its biomass (Figure 50, Figure 45C and Figure 47C). Therefore, the turbidity reduction scenarios actually contribute to the phytoplankton growth for Reedy Creek twin management scenarios. As seen previously the zooplankton growth trend, Figure 45B and Figure 47B, follows that of its food source the phytoplankton seen in Figure 45C and Figure 47C.
Figure 44: Reedy Creek wetland impacts on Nutrient concentration due to irrigation drainage reduction and 75% turbidity reduction
Figure 45: Reedy Creek wetland impacts on Macrophyte, Zooplankton & Phytoplankton due to irrigation drainage reduction and 75% turbidity reduction
Figure 46: Reedy Creek wetland impacts on Nutrient concentration due to 95 % irrigation drainage reduction at 25, 50 and 75% turbidity reduction
Figure 47: Reedy Creek wetland impacts on Macrophyte, Zooplankton & Phytoplankton due to 95% irrigation drainage reduction at 25, 50 and 75% turbidity reduction
Figure 48: Reedy Creek wetland PO4-P % reduction in outflow

Figure 49: Reedy Creek wetland NO3-N % reduction in outflow
5.1.1 Implications for Management

Lock 6 wetland

The improvement in nutrient uptake during the macrophyte growth period, March and April, shows that management scenarios, particularly the 75% turbidity reduction scenario, are extremely successful in nutrient reduction. Scenarios of increasing management success, represented by increased percentage of reduced turbidity, demonstrate gradual improvement in nutrient retention, with 75% turbidity reduction showing a drop in almost a third of wetland nutrient load. During the winter period, where the poorest performance of managed wetlands can be seen, nutrient sedimentation rate exceeds the nutrient uptake of macrophytes, phytoplankton and zooplankton. As a result, the mass balance seen in Table 6 shows the turbid state to be a more effective nutrient and phytoplankton sink. Although the macrophyte growth of March and April indicated an improvement due to turbidity reduction the main concern to wetland management was the dramatic reduction in the sedimentation of PO$_4$-P and NO$_3$-N. This reduction of sedimentation of PO$_4$-P and NO$_3$-N was as a direct consequence of the reduced turbidity, which is mainly apparent during the periods of May through to late September. This does however not adequately consider any potential resuspension of nutrient, which could be a future model enhancement. The excess nutrient availability and lack of macrophyte competition in the cooler
months led to an increased phytoplankton growth, and therefore a possible resultant degradation of water quality for the river. However, when the 50% turbidity management scenario is studied in detail, it responds to macrophyte growth and has the lowest nutrient load during most of the winter period. This, along with the healthy macrophyte growth of the 75% turbidity reduction scenario, indicates that the optimal wetland state will be found in a balance between maintaining as high a sedimentation rate as possible with some suspended sediment inflow and therefore slightly turbid waters (effectively a sedimenting wetland).

Comparing the nutrient mass balance of the different management strategies shows that the increasing macrophyte growth could not compete with the loss in nutrient sedimentation in the management scenarios, the exception being the Lock 6 wetland NO₃-N retention in the 75% turbidity reduction simulation. This shows that the model output may improve with some increased complexity, although this would need to be weighed up against the loss in model applicability on a landscape scale.

The main reason for the PO₄-P mass balance failing to show an improvement in the mass balance, despite there being a very clear and significant PO₄-P uptake during the macrophyte growth phase, was a short-term high nutrient load in the inflow water from the river. This inflow occurred in late September. During this month there were high river PO₄-P loads, which caused a large inflow load. The high turbidity of the 0% and 25% scenarios contained the increased load through a high sedimentation rate, as the turbidity levels were above the 70 NTU sedimentation threshold. Due to the turbidity controlled sedimentation threshold, the 50% and 75% turbidity reduction scenarios were unable to buffer this excess load, which is reflected in the increase in phytoplankton growth during the final simulation week, seen in Figure 40. The 50% and 75% turbidity reduction scenarios, having low turbidity and a low nutrient sedimentation rate, have a seemingly greater wetland nutrient load, and hence there is a higher outflow load of nutrient and phytoplankton during this period. This increased nutrient load has an adverse impact on the nutrient mass balance, showing the 50% and 75% turbidity reduction management scenarios to be ineffective in improving wetland nutrient retention. However, the scenarios show that during the period with increased macrophyte growth, see Figure 41, as predominantly seen with the 75% turbidity reduction, the phytoplankton and particularly NO₃-N outflow was reduced (Table 6). Therefore, assessing the results for a season where the model assumes low
sedimentation of nutrients for all scenarios (i.e. all scenarios having the same turbidity sedimentation) there is an obvious visual decrease in wetland nutrient load with each reduced turbidity simulation. Increasing the complexity of the model through introducing sediment resuspension and nutrient release may therefore not be necessary.

The model in this case (Lock 6 wetland) can be used to assess the minimum turbidity improvement required for the wetland to have a positive response to nutrient retention. With this information, wetland managers can more confidently judge the potential success rate of wetland restoration based on their expectation of turbidity improvement. Another management option based on the Lock 6 wetland management scenarios may lead wetland managers to inundate the wetland during the macrophyte growth period only, and introduce wetland dry periods during the cooler winter months where the nutrient removal may not be as successful or when macrophyte health starts to deteriorate. This would then maximise the macrophyte driven nutrient uptake of the wetland. In this case the model would have been used in optimising the choice of wetland dry periods. This is examined in section 6.1.

*Reedy Creek wetland*

The management option of irrigation reduction through constructed wetlands shows an improvement of wetland nutrient and phytoplankton retention. This model simulation suggests a positive result on wetland nutrient and phytoplankton load, and therefore outflow as a consequence of reducing irrigation drainage inflow into the wetland. The outflow reduction was in each instance higher in percentage than the percentage reduction of inflow, suggesting that a small change in irrigation drainage inflow can have a substantial impact on the total exchange of nutrients between the wetland and river. The impact this nutrient reduction has on river nutrient load is discussed in section 6.3.

The model shows that Reedy Creek wetland itself, as a consequence of its high turbidity and lack of macrophyte growth, is presently not capable of improving its nutrient retention. Due to a lack of data, the effective turbidity reduction as a consequence of a reduction in phytoplankton is not taken into account in the model. Decision makers must therefore keep in mind the possibility that phytoplankton reduction may also reduce turbidity and increase Secchi depth. This increase in Secchi
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depth would allow macrophyte growth, which may further reduce wetland nutrient load.

Reedy Creek wetland twin management strategies

Simulating twin management actions provides the opportunity to assess the compounding impact one management strategy may have on the other. With an effective net phytoplankton production, the management strategy of turbidity reduction proved counter productive. Along with the ample nutrient availability in the wetland, the primary cause of net phytoplankton production increase was the added underwater light availability that was enough for phytoplankton growth but still restricted macrophyte growth. This increased phytoplankton growth, became evident during the high nutrient reduction scenario Figure 47C and Figure 46. Further, the simulated loss of sedimentation of PO4-P and NO3-N resulted in the loss of nutrient retention. Therefore, for a net increase in wetland nutrient and phytoplankton retention, the nutrient reduction scenarios through constructed wetlands and without the added management scenarios of turbidity reduction proved to be the more effective management strategies.

Although this conclusion can be drawn at this stage from the twin management strategies scenarios, Beck (1997) discusses the problems faced by modellers when models are calibrated for stressed systems and may therefore have some difficulty in simulating the system when returned to a natural state. WETMOD 2 was calibrated for optimal wetland response for category 4 wetlands, i.e. for a degraded system, largely influenced by irrigation drainage with no significant macrophyte growth. Therefore, allowance must be made to question the accuracy of simulated macrophyte biomass growth particularly as the model is compounding the potential errors of assumptions for two management strategies, as in the case of twin management.

The confidence in the model output must rely on the assessment of expected trends for the wetland as a consequence of twin management. Therefore, before deciding on refraining from twin management of a wetland such as Reedy Creek wetland, the question must be raised as to whether the simulated volume of macrophyte biomass was realistic enough to truthfully represent the impact of macrophyte uptake of nutrients. Although the conclusion drawn at this stage indicates that twin management may be counterproductive, the results elicited help formulate new questions and
therefore focus further potential research. For example, further research could be directed at discovering the true potential response of macrophyte growth trend in such an instance, as well as to discover at what stage of nutrient reduction (through a constructed wetland) would the introduction of wetland dry periods assist in promoting macrophyte growth. As a start for example, monitoring would be required to validate model macrophyte simulations.

5.2 Chapter summary and Implications for the second hypothesis

The simulations of wetland management, based on the two wetlands presented, show that WETMOD 2 can be applied to assess and better understand the impacts of wetland management. The model was effectively applied in the management of wetlands facing different degradation pressures. Both wetlands were degraded as a consequence of permanent inundation, and one was additionally degraded due to irrigation drainage inflow. WETMOD 2 could, as it is a generically applicable model, be applied to other wetlands within these categories. The model developed management scenarios that were successfully used to assess the impact of management, see Table 8. Table 8 shows that “a simplified generic wetland model can be used to answer what if questions”.

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Table 8: Assessment summary of wetlands management scenarios

<table>
<thead>
<tr>
<th>Category</th>
<th>Wetland</th>
<th>Management question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 3 wetland</td>
<td>3 Lock 6</td>
<td>Can the model identify the turbidity reduction that is required for a positive response if a turbid wetland is managed?</td>
<td>YES</td>
</tr>
<tr>
<td>Category 4 wetland</td>
<td>4 Reedy Creek</td>
<td>Can the model simulate the implications of the reduction of irrigation drainage nutrient on a wetland impacted on by irrigation drainage?</td>
<td>YES</td>
</tr>
<tr>
<td>Category 4 wetland</td>
<td>4 Reedy Creek</td>
<td>Can the model indicate the impact of introducing two management strategies to a wetland such as Reedy Creek wetland?</td>
<td>YES (although limited)</td>
</tr>
</tbody>
</table>

The use of deterministic differential models provides a platform with which some of the complexity of wetland management can be organised and examined. Thereby the model user is able to gain a better understanding of the impact of intervention options such as different wetland management strategies or intensities, e.g. minimum turbidity reduction required, and therefore answer “what if” questions. A modeller can experiment with the model to study the impacts of minor alterations within a wetland and therefore gain a larger understanding of the complexity of the ecosystem. By using the model, decision makers can agree on which scenarios are to be run, assess the output, and if necessary trace back the trigger variable to either gain a better understanding or increase consensus. Whether modellers are also able to gain some insight into the potential outcomes of multiple wetland management and therefore the cumulative impact on the river nutrient load is discussed in the next chapter. This would assist managers and decision makers in estimating what intensity of management may be required for a desired regional response.
6 Results of the cumulative assessment of management scenarios, visualisation and discussion

As the model is generic, and therefore shown to be applicable to category wetlands for which “exemplar”-driving variables are available, an assessment of the cumulative impact of multiple managed wetlands was therefore possible. The cumulative impact assessment allows the discovery of the potentially optimal management strategy, not only for one wetland but multiple wetlands, and therefore the optimal strategy for regional scale wetland management.

For a cumulative assessment of the impact wetland management would have within regional scale management, scenarios were developed with WETMOD 2 for those wetlands identified as belonging to category 3 and category 4 wetlands (“exemplar” driving variables from Lock 6 wetland and Reedy Creek wetland respectively). The management of 57 category 3, and 7 category 4 wetlands were simulated (see methodology in section 3.4.2). The application of the model to category wetlands tests the hypothesis of whether “a simplified generic wetland model can be used to assess the cumulative impact of managing multiple same category wetlands”. This would expand the applicability of the model to wetlands where limited data is available and therefore the assessment of potential multiple wetland management on a regional scale.

The category simulation output represents the estimation of the nutrient, plankton and macrophyte trends within a wetland as a result of the differences between the wetlands. These wetland differences are wetland volume, depth and location along the river. The location along the river dictates river flow volume and river nutrient concentration. However, there are important differences between wetlands, which could not be considered in “category wetland” simulations. Future wetland simulation modelling has the potential to upgrade category simulations with improved data for the following, without substantial model alteration;

- Specific exchange volume estimate for each simulated wetland (based on future monitoring, digital elevation models and/or expert input)
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- Substrate composition, i.e. will the wetland sediment compact? (soils surveys may have to determine the sediment compaction potential of individual wetlands)

- Specific irrigation volume, category 4 wetlands only (assumed to be equal to Reedy Creek due to lack of data, results used to show feasibility of simulation only, not result accuracy)

These limitations to scenario modelling were anticipated and, as this project did not include on-site data collection, these limitations were deemed not to be a priority concern. This is discussed further in the conclusions, in section 7.2.

6.1 Cumulative assessment: category 3 wetlands

The cumulative assessment of management of multiple wetlands (a list of all wetlands selected for category 3 management simulations can be seen in Appendix C) shows a trend towards the improvement in NO$_3$-N retention, which can be seen in Figure 51. As seen in Figure 51 the PO$_4$-P retention does not show an improvement. However, this could be due to the spike seen in the final week of simulation (Figure 52), which relates back to the river load at that time where the river load inflow causes a spike in modelling output, see section 3.2.3. The increase in phytoplankton outflow, seen in Figure 51, is due reduced turbidity leading to the increased availability of underwater light. Phytoplankton responds earlier to increased light availability than macrophytes, see Figure 54. Consequently, there is a trend towards an increased phytoplankton growth, particularly in the 50% turbidity reduction scenario, see Figure 51. The 75% turbidity reduction scenario conversely shows a trend toward reducing phytoplankton growth, see Figure 51. This reduction in phytoplankton, when compared to the 50% turbidity reduction scenario, could be associated with increased macrophyte growth seen in the 75% turbidity reduction scenario leading to competition with phytoplankton for underwater light, see Figure 53.

For detailed output for category 3 wetlands cumulative assessment refer to Appendix D Table 20 toTable 22 (PO$_4$-P, NO$_3$-N and phytoplankton biomass respectively). A detailed change in retention for each wetland and each management scenario, as well as the percentage change in the outflow concentration is shown. At the end of each table there is a summary of the cumulative retention, as shown in Figure 51.
Figure 51: Cumulative retention - category 3 wetlands

Results of category 3 wetland management at the 50% (A) and 75% (B) turbidity reduction scenarios, as compared with the average of the status quo for all 57 wetlands are shown in Figure 52, to Figure 56. As the cumulative impact and particularly trends are of concern, not individual wetland responses, the results of individual wetlands are shown in grey only. The average response is shown in green and the median in red. The 50% turbidity reduction scenario was the first to show a response to the management scenario. The 75% turbidity reduction scenario shows the best simulated response to turbidity reduction, with healthy macrophyte growth. Thus only the 50% and 75% turbidity reduction scenarios are shown.

For the 50% turbidity reduction scenario, the wetlands macrophyte growth vary from no growth to healthy summer growth Figure 53A. A 50% reduction of turbidity therefore leads to a response in the form of macrophyte growth. In the 75% turbidity reduction scenario there is also a range in the successful growth of macrophytes of the different wetlands (Figure 53B). For most wetlands the median shows a clear trend towards summer growth (i.e. late summer immediately following inundation) slowing down with temperature and light reduction in winter. In the 75% turbidity reduction scenario some wetlands showed only minor macrophyte growth, such as wetland
numbers S0115 (367), S0229 (978) and S0230 (47) (wetland numbers are as per South Australian Wetlands Atlas (Jensen et al. 1996)). Other wetlands showed an exceptional macrophyte growth such as wetland numbers S0174 (1036), S0203 (471) and S0229 (84) (Figure 53B). These differences in macrophyte growth are related to individual wetland morphology.

The clear trend towards summer growth phase with a winter dieback supports the argument for managed winter dry periods with the aim of re-introducing sediment compaction. Reflooding would lead to macrophyte germination and the summer wet would maximise macrophyte growth and therefore nutrient retention. The phytoplankton growth phase occurs in response to improved underwater light and the lack of competition due to macrophyte dieback in winter. With the winter dry period this would be minimised (Figure 54B). The net impact on a cumulative scale would be nutrient retention by the wetlands. The winter dry/summer wet management strategy is explored more below, with an example of three wetlands that are assumed to be dried following the onset of macrophyte dieback (i.e. with the onset of winter and therefore reduced modelled macrophyte growth).

Going back to the cumulative assessment of the 57 wetlands, some wetlands show a trend towards a better macrophyte growth phase than others, such as wetland number S0219 (996) that has a very short winter macrophyte dieback period. This wetland shows a trend towards a long macrophyte growth period, a minimal phytoplankton growth phase and positive nutrient retention. The main difference between these wetlands is wetland morphology. The trends within wetlands based on wetland depth and volume are discussed below.

The sudden reduction in phytoplankton biomass in the 50% turbidity reduction scenario in mid July (Figure 54), stems from the increase in sedimentation due to turbidity increasing past the sedimentation threshold as discussed previously. The zooplankton biomass trend (Figure 55), follows suit due to its reduced food source. As turbidity (NTU) never exceeds the sediment threshold in the 75% turbidity reduction scenario there is no change in the rate of phytoplankton biomass sedimentation. Consequently, phytoplankton biomass in the 75% turbidity reduction scenario (Figure 54) remains high through the winter period. However, the trend for phytoplankton biomass outflow in the 75% turbidity reduction scenario is less than that of the 50%
turbidity reduction scenario, (Figure 51). The greater macrophyte growth in the 75% turbidity reduction scenario accounts for this variation (as discussed above).

Based mainly on “category wetlands” morphological differences and the different exchange and nutrient loads at the respective river locations, WETMOD 2 was capable of simulating differences of biomass growth and nutrient retention within these wetlands. The implication of multiple wetland management and the potential cumulative impact on river nutrient load, through alteration of nutrient and phytoplankton retention, is discussed below in section 6.3.
Figure 52: PO$_4$-P Concentration Trends
Figure 53: Macrophyte Biomass Growth Trends
Figure 54: Phytoplankton Biomass Growth Trends
Regional Scale Modelling of the lower River Murray wetlands

Figure 55: Zooplankton Biomass Growth Trends

A  Zooplankton Biomass in Category 3 wetlands at 50% Turbidity Reduction Scenario

B  Zooplankton Biomass in Category 3 wetlands at 75% Turbidity Reduction Scenario
Figure 56: NO$_3$-N Concentration Trends
Regional Scale Modelling of the lower River Murray wetlands

Wetland size, volume and location

Category 3 wetlands scenarios include differences in wetland volume, and differences in the monitoring location of river flow data and river nutrient data. The 75% turbidity reduction scenario also includes wetland depth differences due to improved Secchi depth (underwater light penetration was limited by wetland depth). Since in the 75% turbidity reduction scenarios Secchi depth equals the actual wetland depth, these scenarios would be best to compare with each other to understand the impact depth has on wetland response to management.

When macrophyte biomass volume is compared against wetland size and wetland depth (Figure 57), a trend towards greater macrophyte growth with an increasing wetland depth is apparent. However, with a corresponding increase in wetland volume macrophyte biomass reduces. This is however limited by the lack of validation data for macrophyte biomass. These size assessments therefore are subject to this significant model limitation. The assessments are however made to indicate the potential use of the model once adequate validation has been undertaken.

First, there is a trend towards an increase in wetland depth leading to an increase in macrophyte biomass (Figure 58). This goes back to the issue discussed earlier in the model validation, section 4.3, where the underwater light availability, and therefore macrophyte growth, is dependent on the Secchi depth (i.e. logarithmic increase in macrophyte growth with increasing depth). This calculation is not taking into account the maximal wetland depth and the amount of underwater light actually reaching the wetland substrate nor the maximum growth depth of macrophytes (not currently an acute issue).

Second, a wetland with the same depth but smaller surface area and therefore volume seems to have more macrophyte growth. This would relate back to the amount of nutrient entering the wetland, i.e. the model assumes the same fraction of river flow volume is the exchange volume for both the larger and smaller wetland. A small wetland therefore effectively has a greater turnover rate. A more accurate wetland exchange volume for the wetland would improve the results in such an instance, again highlighting the need for improved data on potential exchange volumes. With the current modelling capacity, WETMOD 2 however poses the question whether wetlands with a small volume would be more apt at nutrient uptake (retention) due to
the greater macrophyte growth within these wetlands compared to wetlands with a larger volume?

In an attempt to address this question the results of cumulative wetland assessments were investigated further. Figure 57 shows the relationship between macrophyte biomass, wetland volume and depth. Indicating that greater macrophyte biomass is related more to wetland depth than it is to wetland volume (Figure 57). This is supported by Figure 58, which shows a slight increase in macrophyte biomass with increasing wetland depth. The 57 category 3 wetlands were divided into three wetland depth ranges shallow (<1 m), medium (1 to <2 m) and deep (>2 m). The average depth of the shallow wetlands was 0.9 m. The average depth of the medium wetlands was 1.3 m, and for the deep wetlands 2.1 m. Figure 59 shows the average macrophyte biomass and average wetland volume for the wetland depth ranges. Figure 59 indicates that medium sized wetlands favour optimal macrophyte growth.

Figure 60 shows that for medium depth range wetlands, which have the largest average macrophyte biomass, there is an exponential decline in macrophyte growth with increasing wetland volume. These wetlands have a similar depth and the same turbidity (same “exemplar” data source), therefore they have the same macrophyte growth potential according to the modelled underwater light. Consequently, the major difference between wetlands is volume. The cause of lower macrophyte growth in greater volume wetlands can be correlated back to nutrient availability. That is, the larger wetlands have a greater dilution of the inflow nutrient load within the water body. It must however be remembered that the wetland has not been validated against macrophyte growth. These results are therefore only indicative based on the current model capabilities.
Regional Scale Modelling of the lower River Murray wetlands

Figure 57: Macrophyte Biomass (size of sphere, kg/m³) plotted against Wetland Volume and Wetland Depth

Figure 58: Macrophyte Biomass vs. Wetland Depth
Figure 59: Average Macrophyte Biomass (size of sphere, kg/m³) plotted against Average Wetland Volume and Wetland Depth

Figure 60: Macrophyte Biomass vs. Wetland Volume

\[ y = 2E+08x^{-0.8526} \]
\[ R^2 = 0.9113 \]
As discussed above, for maximum macrophyte biomass growth within wetlands, WETMOD 2 indicates an optimal wetland volume and depth range. Figure 61 to Figure 65 help to demonstrate the relationship between wetlands volume, macrophyte biomass and nutrient dilution.

To establish which wetlands were producing the greatest biomass within the medium wetland depth range (1 to 2 metre), macrophyte biomass was plotted against wetland volume and depth (Figure 61). With the increase in volume macrophyte biomass reduces significantly. If this is compared to Figure 62, where the average concentration of PO$_4$-P within the wetland for the simulation period is plotted instead of macrophyte biomass, a similar pattern is produced. The pattern in Figure 62 indicates a lower average PO$_4$-P load for the wetlands where the macrophyte biomass is low. This suggests that PO$_4$-P may be the limiting nutrient to macrophyte growth. This is supported by Figure 63, which shows the macrophyte biomass vs. average PO$_4$-P load within these wetlands. No such dependency of macrophyte biomass on NO$_3$-N was seen in Figure 64 and Figure 65. Therefore, the optimal wetland volume and depth discovered within WETMOD 2 simulations can within the confines of the present model capability be related back to the PO$_4$-P availability (volume relating to dilution) and underwater light availability controlled by the wetland and Secchi depth.
Regional Scale Modelling of the lower River Murray wetlands

Figure 61: Average Macrophyte Biomass (size of sphere) Plotted against Average Wetland Volume and Wetland Depth range 1 – 2 m

Figure 62: Average PO$_4$-P (size of sphere) Plotted against Average Wetland Volume and Wetland Depth range 1 – 2 m
Regional Scale Modelling of the lower River Murray wetlands

Figure 63: Average PO$_4$-P vs. Macrophyte Biomass at Wetland Depth range 1 – 2 m

![Average PO$_4$-P Concentration vs. Macrophyte Biomass](image)

$$y = -2E-10x^2 + 6E-06x + 0.008$$
$$R^2 = 0.921$$

$$y = 2E-06x + 0.018$$
$$R^2 = 0.6904$$

Figure 64: Average NO$_3$-N (size of sphere) Plotted against Average Wetland Volume and Wetland Depth range 1 – 2 m

![Average NO$_3$-N mg/L vs. Wetland Volume and Wetland Depth](image)
Figure 65: Average NO$_3$-N vs. Macrophyte Biomass at Wetland Depth range 1 – 2 m
As can be seen in Figure 66, zooplankton biomass trend follows macrophyte biomass trend (the data has been ranked by macrophyte biomass (kg/m3)). This would indicate that more so than the food source phytoplankton biomass, the assumed shelter provided by macrophytes is very important for zooplankton (the wetland names corresponding to the numbers used in Figure 66 can be found in Appendix D). Nevertheless, despite a general increase in zooplankton biomass trend following the macrophyte increase, zooplankton exhibits dependence on its food source phytoplankton. This can be observed in wetland S0106 (645) where the phytoplankton is relatively low, which is consequently reflected in the zooplankton.

Figure 66: Comparison of Macrophyte, Phytoplankton and Zooplankton Biomass for each category 3 wetland (Key to wetland numbers adapted from (Jensen et al. 1996), see list in Table 18 in Appendix C)
 Siebentritt (2003) describes a number of different water regimes in the restoration options via flooding and draw down of water for the wetlands of the lower River Murray. Each of these regimes is intended to illicit a diversity of vegetation and habitat types. One of these is the use of the natural flow regime as suggested by Poff et al. (1997), and which has been applied experimentally by the Department of Water, Land and Biodiversity Conservation (DWLBC 2004; Siebentritt et al. 2004). Another recommendation by Siebentritt (2003) is the implementation of restoration water regimes to enhance a mosaic of vegetation structures within the lower River Murray wetlands. Most current wetland management practices attempt to mimic the natural flow regime and enhance macrophyte biomass. The model scenario discussed here however, focuses on the minimisation of phytoplankton growth and suggests a return to a more natural flow regime.

The natural (historical) flow pattern of the River Murray is minimal flow in March, which increases slightly in April and May. In the upper reaches of the River Murray catchment, where the majority of the water is sourced, the flow reduces in early winter as freezing sets in, binding the precipitation in snow and ice. The major annual flow occurs in spring due to snowmelt and continues into mid December due to westerly influenced precipitation. The flow therefore achieves its height in spring and slowly declines until it reaches a minimum in March (Burton 1974; Walker 1979; Walker 1985). Due to the slow transport of water along the river the flow can be delayed for 4 to 6 weeks until it reaches the lower River Murray wetlands (Mackay et al. 1990).

Three wetlands were randomly selected to assess the impact, on wetland nutrient and phytoplankton retention, of restricting the wet period to the macrophyte summer growth period. Assuming that the wetlands are wet for the period of major macrophyte growth only, a change in trend may be observed (Figure 67, phytoplankton on secondary axis). Figure 67A shows a full year wet where the retention is calculated as the average per day for the simulated time period. Figure 67B shows the results of summer wet/winter dry scenario; here the retention is calculated from the average per day for the summer growth period of 88 days. The PO₄-P retention per day does not show a large improvement; however, there is a slight
Regional Scale Modelling of the lower River Murray wetlands

improvement when comparing the status quo and the 75% turbidity reduction scenario (detailed results can be seen in Appendix D Table 23 to Table 25). With summer wet winter dry wetland management, there should be a large reduction in turbidity and therefore increased macrophyte growth for this period. With macrophyte growth for the entire wet period, PO₄-P retention should be mainly through macrophytes rather than phytoplankton. The scenarios in Figure 67 show the NO₃-N retention per day to improve, both when comparing the management scenarios “full year” and “summer wet winter dry”, and as a response to increased turbidity reduction within each of the different management scenarios. The reduction in phytoplankton growth is as a direct consequence of the loss of its growth period, which would normally have occurred as the macrophyte biomass reduced during the winter period. Therefore, the management strategy of summer wet would assist in minimising phytoplankton growth. The nutrient retention during the winter months would otherwise have been utilised for phytoplankton growth that has now been limited. The cumulative trend shows that if the aim of management was to minimise phytoplankton inflow into the river with a maximum potential of nutrient retention through macrophyte growth then, the 75% turbidity reduction scenario with summer wet winter dry management would be the optimum management scenario as it produces less phytoplankton.

This scenario is limited by the monitoring period available. The modelled scenarios are run for the time frame for which there is data available, which is in late summer. The scenarios show that if the wetlands were to be flooded, i.e. the turbidity reduced, at the time of year in which data was available, the macrophytes would be limited to the available timeframe when water temperature is appropriate, and underwater light and nutrients are available. However, the height of the natural flow regime of the lower River Murray when wetlands would naturally have been inundated is considerably earlier, i.e. during spring to early summer (Burton 1974). The results provided here, although shifted in season, do show the impact of managing the flow regime of the wetlands to optimise the use of macrophytes in nutrient removal and reduction in phytoplankton. With full season (one year) data, scenarios could be produced to obtain a more accurate assessment of the impact of mimicking the natural hydrological regime in wetland management. In the mean time the scenarios presented here give an indication of the impact the control of a wetland hydrological regime may have on nutrient retention.
Figure 67: Nutrient uptake for full year wet vs. uptake for summer wet/winter dry
6.2 **Cumulative assessment: category 4 wetlands**

This section presents the results of category 4 wetland scenarios where 7 wetlands were simulated and compared to status quo (a list of wetlands simulated can be seen in Appendix C Table 19). Figure 68 shows the influence of the cumulative loading to category 4 wetlands, where there is a steady increase in the PO$_4$-P and phytoplankton retention. NO$_3$-N retention however is more variable. Due to the high turbidity of the wetlands there is virtually no macrophyte growth (as discussed in section 5.1.1). The phytoplankton shows some growth during the spring and summer months and the zooplankton growth trend follows that of the phytoplankton (Figure 69 to Figure 71). The concentrations PO$_4$-P and NO$_3$-N reduce slightly as evidenced by the slight decrease in the wetland average (Figure 72 and Figure 73).

Of the five wetlands used in model development only Reedy Creek has adequate river data, for its location, that is monitored on the same day as the wetland data, see (Wen 2002a; Wen 2002b). However, although Reedy Creek wetland data is used as an “exemplar” for other wetlands of the same category, the river flow and nutrient load for appropriate wetland locations must also be used (see Box) as in category 3 wetlands described above.

The Reedy Creek monitored river nutrient data was compared to the available river data (from river lock monitoring points) otherwise used in the model. The scenarios that were based on the river data responded with relatively good results. This is despite the model not being calibrated to this river data. Therefore, the use of river data from the respective monitoring locations close to the simulated wetlands was considered to improve the potential spatial accuracy of WETMOD.

There is no significant role played by wetland internal nutrient dynamics. This is due to the lack of macrophyte growth and therefore there being no change in the nutrient uptake. The main impact of category 4 wetlands is therefore produced by the reduction of irrigation drainage concentration. The results in Figure 68 to Figure 73 reflect the change of concentration within the open water of the various wetlands. Detailed results for Figure 68 can be seen in Appendix D (Table 26 to Table 28). The potential cumulative impact the management of the category 4 wetlands have on river nutrient load is discussed in section 6.3.
Figure 68: Cumulative loading to category 4 wetlands
Figure 69: Macrophyte Growth Trends

All fall below the red line showing that the irrigation drainage inflow has no impact on the macrophyte growth trends.
Figure 70: Phytoplankton Growth Trends
Figure 71: Zooplankton Growth Trends
Figure 72: PO$_4$-P Trends
Figure 73: NO$_3$-N Trends
6.3 Implications of cumulative impact of multiple wetland management

For the purposes discussed in the methodology, in this section the assumption is made that the model is quantitatively accurate.

Category 3: Dead end wetlands with carp presence and no irrigation drainage

To assess and discuss the potential cumulative impact that the management of all category 3 wetlands may have upon the river nutrient load the model quantitative output is assumed to be relatively accurate. Therefore, evaluating these results, the cumulative impact shows that there would be a net retention of NO₃-N (Table 9). However, the PO₄-P inflow into the river may increase due to the loss of retention through wetland sedimentation (the model does not fully take into account sediment resuspension) and the phytoplankton load may also increase due to the increased underwater light availability (Table 9).

Table 9: Impact, of category 3 wetland’s management, on river load per annum

<table>
<thead>
<tr>
<th></th>
<th>PO₄-P kg/annum</th>
<th>NO₃-N kg/annum</th>
<th>Phytoplankton m³/annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load in River</td>
<td>245604</td>
<td>364372</td>
<td>3880</td>
</tr>
<tr>
<td>Change from status quo at 75% Turbidity Reduction</td>
<td>-803</td>
<td>6223</td>
<td>-61</td>
</tr>
<tr>
<td>% of River load removed through 75% Turbidity Reduction management</td>
<td>-0.33</td>
<td>1.71</td>
<td>-1.58</td>
</tr>
</tbody>
</table>

The simulations of introducing dry periods as a management strategy for wetlands need to be scrutinised further. WETMOD 2 uses a simplistic sedimentation and re-suspension equation for PO₄-P, NO₃-N and phytoplankton. The wetland internal nutrient concentrations are more dynamic than portrayed in the model. This is one of the most significant limitations (i.e. the abrupt sedimentation threshold) of the model. Although the model can be applied to more extensive wetlands due to its simplistic construction and data prerequisites, it is acknowledged that for management purposes a more accurate estimation of nutrient and phytoplankton retention by the wetlands would be favourable. However, the model does provide a framework for expansion of research to assist in the assessment of the cumulative impact of wetland management on a regional scale.
Presently the model provides the opportunity of simulating the trends within a wetland due to potential management strategies. These wetland simulations would become more accurate with the present model (WETMOD 2) as more data, and particularly comprehensive data, becomes available. As discussed above (chapter 6), model accuracy could be improved if more local knowledge of particular wetlands were applied in cumulative assessments (i.e. better turnover estimate) “exemplar” driving variables could however still be used for category wetlands. Future work on the extension of WETMOD 2 should focus on the inclusion of detailed water and sediment interaction, particularly nutrient uptake, and the potential change that may occur due to sediment compaction.

As discovered in section 6.1 (Figure 59 and Figure 60) there seems to be optimum wetland morphology for macrophyte growth and therefore maximal nutrient and phytoplankton retention. Wetlands were split into the depth categories shallow, medium and deep (Table 10 to Table 12).

The cumulative impact scenarios made by WETMOD 2 for the shallow range of wetlands (58% of wetlands), shows this range to be least effective at nutrient retention (Table 10). In this shallow range of simulations, for the 75% turbidity reduction, there is a net increase of 0.39% in the PO$_4$-P river load and a full 1% of the phytoplankton load. However, there is a decrease of NO$_3$-N of 0.75%. In contrast, the medium and deep wetlands (each 21% of wetlands) show retention for both PO$_4$-P and NO$_3$-N. Of these two depth ranges, deep wetlands have a minimal impact on phytoplankton river load with only a 0.06% increase. From these simulations the conclusion that can be drawn is that the medium and deep wetlands on the whole have a greater impact on nutrient retention than the shallow wetlands. Consequently, if only a small number of wetlands were to be managed the medium and deep wetlands would potentially provide the greatest cost benefit return.

Model application limitations

Prior to WETMOD 2 being used to make management decisions, beyond the theoretical examination presented here, some restrictive issues must be addressed. The reliability of the macrophyte growth representation in very shallow wetlands is questionable. This issue was discussed in section 4.3. As the validation of Lock 6 wetland, which is within the range of shallow wetlands, confirmed the macrophyte
Regional Scale Modelling of the lower River Murray wetlands
growth trend within this range the issue must be raised as to the accuracy of the
macrophyte growth trend of the deep wetland (for which the model was not
specifically calibrated). If the Secchi depth influence on macrophyte growth equation
were to be modified (i.e. to take into account maximum wetland depth) to better
reflect the situation in lower River Murray wetlands this result may change
considerably. Validation with monitored macrophyte data would however still be
required.

Table 10: Impact, of category 3 wetland’s (depth range shallow <1m) management, on river load
per annum

<table>
<thead>
<tr>
<th></th>
<th>PO₄-P kg/annum</th>
<th>NO₃-N kg/annum</th>
<th>Phytoplankton m³/annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load in River</td>
<td>245604</td>
<td>364372</td>
<td>3880</td>
</tr>
<tr>
<td>Change from status quo at 75% Turbidity Reduction</td>
<td>-961</td>
<td>2741</td>
<td>-39</td>
</tr>
<tr>
<td>% of River load removed through 75% Turbidity Reduction management</td>
<td>-0.39</td>
<td>0.75</td>
<td>-1.01</td>
</tr>
</tbody>
</table>

Table 11: Impact, of category 3 wetland’s (depth range medium 1-2m) management, on river load
per annum

<table>
<thead>
<tr>
<th></th>
<th>PO₄-P kg/annum</th>
<th>NO₃-N kg/annum</th>
<th>Phytoplankton m³/annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load in River</td>
<td>245604</td>
<td>364372</td>
<td>3880</td>
</tr>
<tr>
<td>Change from status quo at 75% Turbidity Reduction</td>
<td>91</td>
<td>1981</td>
<td>-20</td>
</tr>
<tr>
<td>% of River load removed through 75% Turbidity Reduction management</td>
<td>0.04</td>
<td>0.54</td>
<td>-0.51</td>
</tr>
</tbody>
</table>

Table 12: Impact, of category 3 wetland’s (depth range deep >2m) management, on river load
per annum

<table>
<thead>
<tr>
<th></th>
<th>PO₄-P kg/annum</th>
<th>NO₃-N kg/annum</th>
<th>Phytoplankton m³/annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load in River</td>
<td>245604</td>
<td>364372</td>
<td>3880</td>
</tr>
<tr>
<td>Change from status quo at 75% Turbidity Reduction</td>
<td>68</td>
<td>1501</td>
<td>-2.43</td>
</tr>
<tr>
<td>% of River load removed through 75% Turbidity Reduction management</td>
<td>0.03</td>
<td>0.41</td>
<td>-0.06</td>
</tr>
</tbody>
</table>
Looking at the impact of the management of Lock 6 wetland only, which is within the
shallow depth range, there is still a positive impact on the reduction of river nutrient
load, Table 13. There is a very small PO₄-P uptake, which suggests that the retention
capacity of the wetland is improved through the turbidity reduction management,
although this is virtually negligible. Comparing Lock 6 wetland results in Table 13
Regional Scale Modelling of the lower River Murray wetlands

with those produced when Lock 6 wetland is considered for summer wet winter dry cycles in Table 14, Lock 6 wetland shows a slightly more promising retention capacity. In this scenario Lock 6 wetland has a slightly greater effective PO₄-P retention and less phytoplankton contribution to the river.

Despite this very small improvement, an assessment of the simulation output of multiple wetland management of category 3 wetlands can be used to gain insight into the cumulative impact that might be obtained on the lower River Murray nutrient and phytoplankton load. Some indication as to the wetlands that may be the most effective at nutrient retention can also be deduced. Where qualitative scenario results can assist in assessing a wetland in the lower River Murray, WETMOD 2 is a functional tool. That is, WETMOD 2 can simulate category 3 wetlands for which limited data is available. The modelling output reliability for these wetlands can be improved with local knowledge of exchange volume, macrophyte growth trend and sediment compaction potential. However, to reliably apply the WETMOD model and decide on potential management scenarios to be applied, the model should still be developed further, as discussed above.

Table 13: Impact of Lock 6 wetland management, on river load per annum

<table>
<thead>
<tr>
<th></th>
<th>PO₄-P kg/annum</th>
<th>NO₃-N kg/annum</th>
<th>Phytoplankton m³/annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load in River</td>
<td>245604</td>
<td>364372</td>
<td>3880</td>
</tr>
<tr>
<td>Change from status quo at 75% Turbidity Reduction</td>
<td>0.44</td>
<td>24</td>
<td>-1.89</td>
</tr>
<tr>
<td>% of River load removed through 75% Turbidity Reduction management</td>
<td>0.00</td>
<td>0.01</td>
<td>-0.05</td>
</tr>
</tbody>
</table>

Table 14: Impact of Lock 6 wetland management, summer wet winter dry, on river load per annum

<table>
<thead>
<tr>
<th></th>
<th>PO₄-P kg/annum</th>
<th>NO₃-N kg/annum</th>
<th>Phytoplankton m³/annum</th>
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<tbody>
<tr>
<td>Load in River</td>
<td>245604</td>
<td>364372</td>
<td>3880</td>
</tr>
<tr>
<td>Change from status quo at 75% Turbidity Reduction</td>
<td>1.79</td>
<td>17</td>
<td>-0.21</td>
</tr>
<tr>
<td>% of River load removed through 75% Turbidity Reduction management</td>
<td>0.00</td>
<td>0.01</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

Category 4: Dead end wetlands with carp presence and irrigation drainage

As in category 3 wetlands, to assess the cumulative impact on river nutrient load, the scenarios for category 4 wetlands are assumed to be quantitatively accurate. In
category 4 wetlands the nutrient and phytoplankton retention calculated includes the irrigation drainage inflow reduction. Therefore, the improvement in category 4 wetland retention and its impact on river load includes the PO₄-P, NO₃-N and phytoplankton assumed to be removed through constructed wetlands that would otherwise have been flowing into the wetland as part of the irrigation drainage.

Table 15 shows the potential nutrient retention capacity of category 4 wetlands and the impact on the river nutrient load. It must be remembered that due to the limited data available on wetlands of the lower River Murray, which are affected by irrigation drainage, the data available from Reedy Creek wetland was applied to wetlands within this category as an “exemplar” data source. Despite these wetlands being within the same category as Reedy Creek wetland, the irrigation drainage inflow would vary more than is accounted for in these scenarios. However, although the irrigation concentration and volumes would differ, some floodplain wetlands of the lower River Murray are directly impacted by irrigation drainage, having very high nutrient loads. Category 4 wetland cumulative assessment is hypothetical scenario testing intended to examine the cumulative impact of management, and to assess the capacity of the model to simulate category 4 wetlands.

Through the introduction of constructed wetlands, to reduce irrigation drainage nutrients entering a wetland, a net retention of nutrients normally flowing into the river is achieved. Table 15 shows the hypothetical cumulative retention if all category 4 wetlands are successfully managed. The model indicate that these 7 wetlands would, in case of 75% irrigation drainage nutrient reduction, contribute a 2.68% reduction of the river phytoplankton load, as well as a small reduction of PO₄-P and NO₃-N river load.

**Table 15: Impact of category 4 wetland’s management, on river load per annum**

<table>
<thead>
<tr>
<th></th>
<th>PO₄-P kg/annum</th>
<th>NO₃-N kg/annum</th>
<th>Phytoplankton m³³/annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load in River</td>
<td>1376872</td>
<td>338228</td>
<td>12231</td>
</tr>
<tr>
<td>Change from status quo at 75%</td>
<td>5850</td>
<td>1205</td>
<td>328</td>
</tr>
<tr>
<td>Irrigation Drainage Nutrient Reduction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of River load removed through 75%</td>
<td>0.42</td>
<td>0.36</td>
<td>2.68</td>
</tr>
<tr>
<td>Irrigation Drainage Nutrient Reduction management</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The wetland retention portrayed in Table 16 is that of Reedy Creek wetland, whose data quality and therefore modelling accuracy, both qualitatively and quantitatively,
was most comprehensive and accurate. Table 16 is therefore bound to be the most accurate reflection qualitatively and quantitatively of the impact of wetland management on wetland nutrient retention capacity.

Table 16: Impact, of Reedy Creek wetland management, on river load per annum

<table>
<thead>
<tr>
<th></th>
<th>PO$_4$P kg/annum</th>
<th>NO$_3$-N kg/annum</th>
<th>Phytoplankton m$^3$/annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load in River</td>
<td>1376872</td>
<td>338228</td>
<td>12231</td>
</tr>
<tr>
<td>Change from status quo at 75%</td>
<td>1052</td>
<td>163</td>
<td>48</td>
</tr>
<tr>
<td>Irrigation Drainage Nutrient Reduction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of River load removed through 75%</td>
<td>0.08</td>
<td>0.05</td>
<td>0.40</td>
</tr>
<tr>
<td>Irrigation Drainage Nutrient Reduction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Through the management of Reedy Creek wetlands, with the assumption of 75% nutrient reduction capacity, the model indicates a small reduction of PO$_4$-P, NO$_3$-N and phytoplankton to the river. Therefore, the model suggests that the management of even one category 4 wetland may slightly reduce river nutrient load.
6.4 Chapter summary and Implications for the third hypothesis

Although there is a limited availability of data for wetlands of the lower River Murray modelling does allow for scenario development of multiple wetlands. The generic nature of WETMOD 2 has therefore allowed its application to multiple wetlands where only rudimentary morphological data is available. The model has thereby been applied on a landscape scale. The modelling limitations have been described and include the important point that the quantitative results can only be qualitatively indicative of potential management outcomes.

Reviewing the data produced during cumulative assessment of multiple wetland management the third hypotheses “A simplified generic wetland model can be used to assess the cumulative impact of managing multiple same category wetlands” can be addressed. The simulations above show that this is possible. The main outcomes from the cumulative simulations are to find the optimum wetland morphology (for the best return on investment), the hydrology season for optimum nutrient uptake, and the impact of effective constructed wetlands in removing irrigation drainage load. However, this ability is presently restricted as per the following;

- The output is qualitative and not quantitative due to the nature of simplified models and the use of “exemplar” data.
- Due to the limitation in the simulation of turbidity reduction, i.e. turbidity controlled sedimentation threshold of nutrients and phytoplankton biomass, the management scenarios estimate comparisons of nutrient removal efficiency may become biased towards a turbid wetland. This limitation is solvable through further model development; therefore the methodology used and described above remains applicable particularly when this limitation has been addressed.

Thus, the output of the cumulative assessments of management of multiple category 3 wetlands is preliminary. However, the potential of using generic models for cumulative assessments is substantiated by the methodology used as shown by its application to category 4 wetlands and the application to the preliminary management scenarios of the category 3 wetlands.
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The nature of differential equations allows the conservative use of available mass. Theoretically therefore the assessment of the mass balance should be possible; for the wetlands where monitoring has taken place some indication of mass balance is available, particularly for Reedy Creek wetland. However, due to the limitation of data availability the current modelling effort should only be viewed as being capable of estimating potential mass balance. That is, the qualitative information obtained through the landscape scale scenarios allow for a simplistic understanding of the cumulative impact of management of multiple same category wetlands on river nutrient load.
7 Summary, Context and Discussion

The use of differential equations allows a deterministic approach where simulations or scenario analysis are possible. The predictive modelling of wetlands contributes to informed decisions on management strategies based on the data available. The uncertainty or lack of knowledge and data does affect the quality of model predictions (Wallach et al. 1998). However, this does not prevent management and decision-making and is a part of ecological simulation modelling (Reckhow 1994; Wallach et al. 1998). As long as the decision makers understand the limitations, they can still use a model to assess scenarios within these model limitations. The model may, in fact, provide decision makers with the only tool to experiment and increase understanding, without which they could be limited in assessing potential management impacts. This enhanced knowledge enables a better prediction of outcomes and therefore aids decision making in regard to management. Further, with enhanced knowledge and transparent assessment, consensus between stakeholders involved in the decision-making is more readily achieved (Thomann 1998).

Management decisions for ecosystems may be made by many stakeholders, not all of whom would fully understand the ecological implications of different intervention options. Furthermore, experts in the field can hold opposing views on subjective topics. Modelling can be seen as a structure to assist in regulating knowledge, data and assumptions used for decision-making. Other experts can participate and comment on the model as it is defined. Most decision support models have inherent uncertainties of an acceptable magnitude (Reckhow 1994). It must however be made clear where there is a lack of knowledge and/or other uncertainties, and how this has been dealt with within the model. This information will reflect on how the model can and should be used, and how much reliance can be placed on the modelling predictions. Which detail is required and the appropriateness of assumptions is dependent on the purpose of the model (Caswell 1988).

For the model developed in this project to be applicable on a regional scale, data obtained from monitored wetlands was assumed to be appropriate for internal wetland behaviour and relationships of similar wetlands. This assumption was used to overcome the lack of knowledge and data for the lower River Murray floodplain wetlands and simulate regional scale scenarios; and thereby obtain a cumulative
impact assessment of the management of multiple wetlands on river nutrient load. Therefore, implicitly the understanding should be that the model output is of trend behaviour and potential impacts on the river, both prior to and post management scenarios.

7.1 Assessment methodology

The application of WETMOD 2 was designed for wetlands where minimal data, such as morphology and spatial location, has been sourced. For these wetlands the driving variables are borrowed from their associated “exemplar” wetland. Quantitative data from parameters measured in wetlands were used in WETMOD 2 to act as “exemplars” to provide qualitative outcomes in other wetland systems based on wetland categories. Due to the assumptions made and described in section 3.1, as well as the intended purpose or aims of the model, WETMOD 2 is maintained in a generic form to be qualitatively applicable to wetlands where only basic morphological data are available. Through this methodology a model was developed that is based not only on scant data but is also applicable to wetlands with no time series data (the modelling predictions of WETMOD 2 were therefore not assessed strictly in a quantitative manner).

It is not possible to statistically assess the model outputs for these wetlands, as no data with which to compare the output exist. There must therefore be general confidence in the simulated time-series seasonal trend and approximate magnitude produced by WETMOD 2, for the wetlands used in validation of the model. Otherwise, no confidence will be placed in the scenarios produced for category wetlands, i.e. those using “exemplar” driving variables. It can be said that the qualitative assessment of such model scenarios may be a more significant assessment of the model performance, than an improvement in statistical accuracy of individual wetlands (i.e. optimisation of quantitative performance of the model). Modelling effort was therefore directed at the development and improvement of spatial contributions to wetland modelling, rather than focusing on the improvement of the individual wetland process modelling. This approach is an extension of the view presented by McIntosh, et al. (2003) that flexible and cost effective models are more beneficial than one off models that perform very well for one ecosystem only.
To represent qualitative model performance the score $D$ was used and served the model development well and is used extensively in the model validation. Other statistical options are discussed in (Mayer et al. 1993), however the statistical accuracy of the model would not solely or adequately improve the confidence of users when WETMOD 2 is used as a landscape decision support tool. When assessing the performance of WETMOD 2, by comparing the modelled output with its monitored counterpart, the model behaves qualitatively correctly and logically for each wetland considered. This is reflected in the similarity of seasonality of the modelled response and monitored concentrations. The seasonal response of the non-monitored wetland parameters macrophyte and zooplankton in model scenarios was logical, supporting model validity.

As discussed in the introduction (section 1.4.2), the qualitative difference in the comparison of different wetlands is a legitimate model assessment methodology. The purpose of the model determines its required precision. In the case of WETMOD 2, the qualitative assessment of model results can in fact be the most appropriate methodology when the model is applied outside its development envelope. Evidence of this is in the discrepancy between visual assessment of validation results and the $D$ for some of the wetlands, see section 4.1. This would in fact particularly be the case where WETMOD 2 is applied to category wetlands where data from “exemplar” wetlands is used. Nevertheless, the statistical evaluation of the modelling accuracy is a significant validation step required to assess the model performance. This can however, only be undertaken for scenarios where the model is simulating actual monitored data using monitored driving variables. Values of $D$ are presented in Table 3 and Table 4 and discussed during the validation of the model.

### 7.2 Current capabilities

The results, described and discussed in chapters 4, 5 and 6, have shown the applicability of the model at the present stage of development, its limitations and identified areas requiring further research and model improvement. A summary of the present capabilities of the model, in providing information which was previously not available, include:
Regional Scale Modelling of the lower River Murray wetlands

- finding the exchange volume of water and therefore nutrient and phytoplankton load between wetlands and the river (for wetlands with nutrient date time series)
- calculating the status quo nutrient retention of wetlands
- developing estimates of the potential impact of management on the nutrient retention of wetlands
- estimating the impact wetlands may have on the river nutrient load due to improved management
- producing an estimate, based on qualitative output, of the cumulative impact of multiple wetlands management on the river nutrient load, and
- developing comparative studies of wetlands based on their morphological differences, using the same driving variable time-series.

Further advantages of the model include:

- presenting a framework from which to expand the model capabilities through an improvement in the workings of the model (some of the model expansion would not require a dramatic increase in model complexity)
- presenting a framework from which to expand the model capabilities as data availability increases
- focusing future monitoring for improved assessment, and enhanced modelling capabilities which may aid management decisions, and
- posing questions where model limitations are encountered due to a lack of data or knowledge

Currently the central problem for modelling wetlands of the lower River Murray is data quality and quantity. Now that the model has been developed, future monitoring can take its data prerequisites into account to alleviate this restriction, thereby the model serves the purpose of focusing future research needs. Model limitations are discussed below.
Regional Scale Modelling of the lower River Murray wetlands

External influences and Landscape Scale

WETMOD 2 is capable of estimating the exchange volume between a wetland and the river where wetland nutrient time series are available. Using the exchange volume the model can further account for external influences acting upon, and therefore improve the modelling of, wetland internal dynamics. Together with the exchange estimate and the internal nutrient dynamics the probable outflow load, of nutrients and phytoplankton biomass, can be estimated. Thereby, the model can be used to assess the impact the wetland has on river nutrient load, and how this can be altered through potential management strategies. A call for such a model for Australian wetlands was made by McComb and Qiu (1997).

Due to the models simple structure and low driving variable demand it is generically applicable to other wetlands within the region, which were not used in model development. Thereby, the model can be used to estimate the status quo or the potential impacts management may have on wetland nutrient and phytoplankton retention and consequent river load, even if minimal data for the wetland is available. WETMOD 2 simulates the qualitative behaviour without the quantitative accuracy. In this case the qualitative behaviour of multiple floodplain wetlands (where morphological data only is available), reflecting model potential as proposed by Rykiel (1996). Specifically, although the data simulated for each category of wetlands may not be quantitatively accurate, the trends are plausible. In a cumulative assessment the simulated impact of multiple wetland management, is indicative of potential results.

As discussed in chapter 6, cumulative assessment assists in focusing management oriented research. The model allows the user to determine the implications of assumptions made, i.e. whether they are valid or otherwise. The role of the modelling tool is therefore (in part) to confront users with the implications of beliefs that they may hold (Bart 1995). Therefore, the potential outcomes of modelling on a regional scale, where minimal data are available, may assist managers in directing future monitoring studies and thereby aid in eventual decision making. For example, modelling outcomes of optimal wetland morphology are related to exchange rate for nutrient retention.
Although the results presented can be used to the degree discussed in chapters 4, 5 and 6, it is stressed that the model is still in early development. Model improvements and validation with specifically monitored data should be performed. Further research is suggested in chapter 8.

The application of the model is at this stage still restricted to wetlands of category 1, 3, 4 and 5, as the data available for wetlands of category 2 were insufficient for proper validation. Management strategies are available only for category 3 and 4 wetlands however; model applicability can be enhanced as data becomes available.

Presently the model can be used to assess, qualitatively, the potential cumulative impact of multiple wetland management. For example, the comparison of two wetlands, for which there is limited data availability, is possible by developing scenarios based on wetland categories and the morphological data available for these wetlands. Future feedback when comparing model predictions with actual outcomes will aid in identifying incorrect hypothesis, model inaccuracies and therefore contribute to future improvement of the model and enhancing its performance and applicability.

**Limitations**

There are four significant limitations to the model at this stage (in order of significance), with the second and third being related.

- The first is the abrupt sedimentation threshold (70 NTU for PO$_4$-P and NO$_3$-N and 95 NTU for phytoplankton), which makes distinguishing change in nutrient retention due to varying management scenarios difficult. More data on sedimentation rate and resuspension would be helpful.

- The second limitation is the inapplicability of the model to very shallow wetlands. Although the wetlands, where data was available, were not shallower than the 0.6 m, some wetlands of the lower River Murray are. An update of the equation that considers macrophyte growth in relation to Secchi and maximum depth of the wetland should improve this model aspect. Currently the data available for wetland depth is only used to calculate wetland volume within model simulation. The addition of wetland depth to
factor in the impact on macrophyte growth would improve the generic modelling applicability and allow the simulation of shallow wetlands.

- The third limitation relates to model output. The shallowness of modelled wetlands (below 1 metre depth) may still be the best wetlands for management, despite the model results. Asaeda et al. (2001) in fact found in their modelling studies that, despite shallow wetlands having a higher concentration of phytoplankton, macrophyte growth did increase due to more favourable light conditions. In shallow wetlands macrophyte growth may be expected throughout the wetland, causing increased sedimentation, increased nutrient uptake and shading out of phytoplankton. The increased macrophyte growth would also provide more shelter for zooplankton, which feed on phytoplankton further reducing their numbers. Therefore, the equation that was discussed in model validation section 4.3, and which shows a logarithmic growth pattern with increasing wetland depth needs to be reviewed.

- As stated in the methodology, zooplankton and macrophyte biomass data were not available for model development, validation and calibration. The model output and conclusions made are therefore limited by this lack of data and do not necessarily accurately reflect what could occur in a real environment.

Despite these limitations to the methods applied, the WETMOD 2 simulation results and assessment of potential cumulative impact of wetland management remain applicable. WETMOD 2 is a work in progress, and this project mainly contributes to the spatial factors of lower River Murray wetland modelling. The present assessment of the model’s capabilities has helped to identify future research requirements such as the model structure (equation improvement/replacement), model expansion (sediment water interaction), and data acquisition (wetland monitoring).

The use of river Chlorophyll-a levels from Murray Bridge as the driving variable for all phytoplankton exchange (as discussed in section 3.2.3) led to Pilby Creek and Lock 6 being the only wetlands that showed virtually no improvement in model performance with regard to phytoplankton simulation (as is shown in section 4.1). With additional monitoring of river Chlorophyll-a levels the accuracy of model phytoplankton simulation should be improved.

Other avenues to improve model performance include:
Regional Scale Modelling of the lower River Murray wetlands

- measurement/establishment of exchange volume estimates for simulated wetland (based on future monitoring and digital elevation models)
- determining the sediment compaction potential of individual wetlands
- measurement of irrigation volume (category 4 wetlands only), and
- determination of evaporation impact on wetland nutrient retention balance calculations.

In its present state the model can be used for some restricted management assessment. This management focus would be on potential:

- nutrient retention of wetlands
- exchange volume and nutrient load
- twin management (limited)
- comparative studies of wetlands based on morphology (limited)
- impacts on river nutrient loads (indication only), and
- cumulative impact of multiple wetlands management.

Revisiting the Project Aims

Now the model capabilities have been assessed it is necessary to revisit the aims of the project to assess whether the model extension has fulfilled the intended purposes. Model extension aimed to:

I. overcome shortcomings in knowledge due to limited data and incomplete system understanding

II. address processes requiring further development, which were identified at the beginning of the study. These included river and wetland water exchange, nutrient exchange, and irrigation drainage data influence, and

III. adapt and test the application of the model on a regional scale; i.e. develop a cumulative assessment of potential management impacts of multiple wetlands on the river nutrient load.

To fulfil the first aim the model first fulfilled the second, which is the extension of the models capabilities. The model is now able to estimate water exchange, therefore
developing data for a previously unknown quantity for those wetlands where data is available. This has led to the ability to estimate the nutrient retention capacity of monitored wetlands and simulate potential change due to management. From this the bi-directional nutrient exchange has been modelled. Based on a similar methodology the irrigation drainage influence has also been accounted for, where relevant.

The third aim was fulfilled with the use of the different “wetland categories”, i.e. using “exemplar” driving variable data. Thereby, qualitative estimates of the cumulative impact of multiple wetlands on the river nutrient load could be developed, as well as an assessment of the impact of management of these wetlands.
8 Conclusion & Future Work

This project set out to develop a model capable of simulating nutrient retention capacity of the lower River Murray wetlands. The model was to be applied on a regional scale encompassing wetlands for which limited data is available. In applying the model, it was to assess the change in nutrient retention capacity of multiple wetlands and the cumulative impact on the river following hypothetical management interventions of these wetlands.

The application of the developed regional model WETMOD 2 is constrained by the availability of comprehensive data of adequate quality and frequency in the lower River Murray. However, the study does serve the purpose; demonstrate the provision of a tool for examining the impact of management interventions on the broader scale. The model also helps to purpose of focus future research, including purpose driven monitoring and model improvement.

Hypotheses

The modelling has fulfilled most of the objectives and aims of the project, with the assessment of model output and its limitations discussed in the respective results and discussion chapters and summarised in section 7.2. These hypotheses were:

I. A simplified generic wetland model can be used to realistically simulate multiple and different wetlands qualitatively.
   - Given adequate driving variables the model can simulate different wetlands realistically, e.g. Lock 6 and Reedy creek using non-calibration data see section 4.4.

II. A simplified generic wetland model can be used to answer “what if” questions, and
   - Management simulations for selected degraded wetlands have been successfully run, see section 5.2.

III. A simplified generic wetland model can be used to assess the cumulative impact of managing multiple same category wetlands.
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- Limited qualitative assessments are possible. For category 3 wetlands this assessment is preliminary due to (solvable) model limitations (see section 6.4). For category 4 wetlands these same limitations restrict the adequate modelling of two concurrent management strategies.

With the scenarios developed of the different wetlands, general understanding of the system can be enhanced and the hypotheses tested with regard to alternate management options and their required response. The differential equation based deterministic model WETMOD 2 does provides a tool for hypothesis testing of management effectiveness for wetland regeneration. WETMOD 2 is a tool that can be used in the facilitation of understanding of the required management effort for successful wetland restoration, i.e. percentage of turbidity reduction required for macrophyte growth response and therefore wetland regeneration.

Understanding of the cumulative response of multiple wetland management is enhanced by the model scenario output. Although the model output is qualitative it does provide some assessment of cumulative impact. Further development of the model would enhance this feature. Some understanding can also be obtained of the general differences between wetlands (smaller versus larger, shallow versus deeper etc.), although minimal data is available. While the model outcomes cannot be viewed as quantitatively accurate (particularly in individual category wetland comparison), the model outcomes do provide a point of reference from which further research can be made. The model outcomes, in such a comparative use, are for general understanding as well as an aid in facilitating consensus on the potential impact of restoration options, assuming there is confidence in the model.

**Future development of WETMOD**

During the development, calibration, validation and application of the model, certain limitations were discovered, as well as potential improvement identified for which there was inadequate time to address. The following recommendations for future model improvements are made (this list is not exhaustive as other improvements could be made). Model improvements need to take into account the lack of data in the region.

- Underwater light and Secchi depth need to be fixed for very shallow wetlands.
This projects purpose was to use the previously developed wetland ecosystem process model WETMOD 1 and extend this beyond theoretical wetland dynamics to include spatially relevant data. The project therefore was not primarily concerned with improving internal modelling dynamics. The prerequisite for this omission being that limitations did not affect model verification, and that consequent management simulation restrictions were identified. Where limitations were identified, future improvements are suggested. This model restriction was therefore an issue that was not only outside of the scope of this project, but also one for which there was not sufficient data to address the problem. For future application of WETMOD 2 this limitation must be taken into account, as very shallow wetlands will, with the present model structure, not be simulated accurately. Therefore, this limitation is of a high priority for future development of WETMOD 2.

- River turbidity & temperature are not used in the model and are only included as potentially relevant data for the future.

Both the river turbidity and temperature will impact on wetland ecosystems and should therefore in an ideal model be included. Depending on the distance of the wetlands from the river the full impact of river turbidity and temperature on wetlands may be variable. Therefore, their inclusion in a model may add to its complexity. As discussed previously the relative simplicity of WETMOD 2 should be maintained. Given the implications added complexity has on the model generic applicability it must therefore contribute substantially to model output. Testing of relative improvement in model performance following increased complexity will need to be a deciding factor as to its merit and ultimate acceptance (i.e. a sensitivity analysis).

- Rather than relying on estimates of expected efficiencies of constructed wetlands a separate module for which artificial wetlands can be individually modelled should be added to WETMOD 2.

Although this would add complexities to the model this module would only need to be operational in circumstances where the availability of data allows. Such a module could be turned on in circumstances such as done for the external nutrient inflow (irrigation drainage) in the Reedy Creek wetland example.

- Include wetland soil substrate and therefore sediment re-suspension (turbidity) potential in status quo (in permanently inundated wetlands) and as an
assessment of the potential success of management through the introduction of dry periods.

- Include sediment nutrient dynamics to more accurately account for sediment nutrient source and sink.

Sedimentation of suspended particulate matter improves water quality by reducing turbidity and suspended solids concentration. Any nutrients and contaminants adhered to particulate matter are also deposited during sedimentation effectively removing them from the water column thereby further improving the water quality (Johnston 1991; Oliver 1993; Walker et al. 1982). Sediment retention and reduction of turbidity within multiple individual wetlands can have an important cumulative impact on water quality at a catchment scale (Johnston 1991; Johnston et al. 1990). Despite some sediment re-suspension, sedimentation is a long term and relatively irreversible sink (Johnston 1991). This could therefore be included in sedimentation expansion of the model to account for the nutrient impact of sedimentation and sediment compaction/binding. However, some sediment nutrient source is still a possibility. Modelling of sediment as a nutrient source is therefore necessary to accurately assess the impact of sediment and water nutrient balance. Again a balance of model complexity and generic applicability will need to be found.

The model is still in its infancy. When more spatial patterns are introduced more complexities will develop within the model, making it more discriminate to individual wetland characteristics. This can to some degree still be done whilst maintaining the simplistic model structure. An example where this was accomplished is the inclusion of spatial dependent wetland characteristics, wetland depth and volume (section 6.1 (Wetland size, volume and location)).

One of the next development stages could be to include soil substrate data. Sediment properties are the deciding factor to changes due to drying and reflooding (McComb et al. 1997), therefore the wetland substrate plays an important role in the effectiveness of the reintroduction of wetland dry periods. The fieldwork would only need to be conducted once, as the results would be conclusive and therefore not constitute an ongoing expense. This would deliver a strong spatial criterion in modelling of scenarios, so much so that a potential wetland may be found to be entirely unsuitable for management through the introduction of dry periods.
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- Improve twin management simulations

Currently the twin management scenarios are effective in formulating further research questions such as “is sedimentation (e.g. using clay to adsorb nutrients followed by sedimentation) the best management strategy in a highly eutrophic system or will constructed wetlands allow sufficient nutrient removal to facilitate wetland rehabilitation?” Developing this capacity within the model may provide some direction for further field based research.

- Adoption of WETMOD 2 into Spatial Modelling Environment (SME) modelling software

The initial attempt at using GIS (geographical information systems), with SME as a platform, as a data source to the model was deemed as inappropriate in the case of the development of a wetlands model for the lower River Murray. The sole reason for this was the lack of GIS data, particularly a DEM (digital elevation model). The model however was designed in a manner of keeping this option open should adequate GIS data become available. The major advantages would be the simultaneous simulation of all wetlands, thereby making cumulative assessments and/or comparisons between wetlands that much easier. The recent baseline surveys of select River Murray wetlands (SKM 2004; SKM 2006) have included relatively accurate DEM developments, the accuracy of the DEM being between 0.25 and 0.5 meters. Modifying WETMOD 2 for these wetlands may be possible in the future although this would restrict the model to the monitored wetlands.

- Development of an evaporation module

Evaporation as a water loss can be added using an evaporation spreadsheet compiled by DWLBC (Simpson 2003), the “Water Loss Calculator”. This was avoided early in model development due to its own inherent inaccuracy that would have complicated model development. The water exchange volume for a wetland was based on the inflow estimation required to reach an optimal nutrient dynamic simulation. The evaporation loss would reduce the simulated outflow from a wetland which was previously assumed to be equal to the inflow. Therefore, a wetland could actually be retaining higher loads of nutrient than so far simulated. Consequently the full development of an evaporation module for WETMOD 2 may improve the assessment of nutrient retention. As “Water Loss Calculator” is currently used by state...
government agencies and wetland managers to calculate wetland evaporative water loss, building this into the model would work in with current practice (despite its inherent inaccuracy). The “Water Loss Calculator” is as generically applicable as WETMOD 2 and would therefore not add to the model complexity.

**Monitoring needs**

Progress in model development to enhance results requires the availability of validation data or improvement of and/or inclusion of new driving variable data (de Wit *et al.* 2001). Although some of these would increase model complexity, the relative improvement in model output may warrant their inclusion. Many would therefore need to be considered. These new data could include:

- all driving variables within a wetland;
  - temperature
  - turbidity
  - Secchi depth
  - PO₄-P
  - NO₃-N
  - phytoplankton
- results of monitoring within wetlands for;
  - dissolved oxygen
  - zooplankton
  - macrophyte biomass
  - substrate (soil composition and compaction potential)
  - ground truthing of through flow
- information from monitoring external nutrient sources concurrent with the wetland monitoring including concentration and volume, such as;
  - irrigation drainage
  - river
  - groundwater
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- external climatic factors besides solar radiation, such as wind direction and speed, shelter by surrounding vegetation (could contribute to resuspension modelling and flow direction of water exchange).

All of these factors could impact on the division of the wetland categories. As an example of a classification procedure Strager et al. (2000) used a landscape based approach to classify wetlands and riparian areas based on habitat requirements of amphibians and reptiles. This classification also included forested and non-forested groupings as this had an impact on the wind reaching the wetlands (Strager et al. 2000). Borrowing this approach, forest cover mapping or obtaining a cover representation from satellite imagery, might be used to differentiate classifications in the Murray wetlands model in future work, particularly if wind and therefore sediment resuspending equations are developed in the model.

The model developed by Muhammetoglu et al. (1997) is too complex to apply to the lower River Murray wetlands given the lack of data, but it shows the work presently underway to develop models of nutrient retention by wetlands. As such WETMOD 2 contributes to this research by providing an example of a simple generic model applicable on a regional scale where very limited data are available. In the modelling of complex environmental ecosystems, particularly where scant data is available, simple models provide a basis with which to advance or focus management and future research. The desire to increase complexity therefore needs to be carefully balanced between improved model performance and applicability of the model on a landscape scale.