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BASELINE MEASUREMENTS ON THE PERFORMANCE OF FOUR CONSTRUCTED WETLANDS IN TROPICAL AUSTRALIA

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Abstract : Constructed wetlands provide several benefits that are not solely limited to stormwater management and are becoming common in stormwater management. In this research, four recently constructed wetlands underwent in situ and laboratory water sampling to determine their efficiency in removing stormwater pollutants over a 5-month period. From the sampling results, it was determined that each of the wetlands was able to reduce the concentration of pollutants in the stormwater. To aid in the assessment of the wetlands against each other, a model was developed to determine the extent of removal of stormwater pollutants over the length of the wetland. The results from this model complimented the data collected from the field. Improvements, such as increased amounts of vegetation were recommended for the wetlands with the aim of increasing the effectiveness. Further investigations into the wetlands will allow for better understanding of the wetland's performance.

Key Words : Constructed wetland, First-order kinetic model, Pollutant removal, Metal removal, Vegetation

INTRODUCTION

Appropriate management of stormwater and stormwater runoff is essential as unmanaged stormwater can lead to intensive and frequent flooding. Constructed wetlands are becoming common in the management of stormwater, as they are able to reduce flooding while providing an aesthetically pleasing structure.[1)] Other advantages of using constructed wetlands are that they attract native wildlife, can provide a suitable environment for fauna native to the area and lead to an improvement in the stormwater quality.[2)] Wetland treatment schemes have been successful in removing enteric bacteria, lowering biochemical oxygen demand, and decreasing nitrate concentrations in the effluent.[3,4)]

As Townsville, a city in the State of Queensland, Australia, is located in a semi-tropical environment, the average annual rainfall is 1143 mm, which highlights the necessity for proper stormwater management to reduce flooding. Citiworks and Environmental Planning Services, business units of Townsville City Council (TCC), planned and constructed four stormwater wetlands in the Townsville area. The purpose of the wetlands is to facilitate stormwater management and improve the quality of the stormwater leaving the Louisa Creek wetlands - Greg Jabs

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Court and Camuglia Street and the inner city constructed lakes - Curralea and Paradise Lake. The location of the wetlands is shown in Figure 1. As the wetlands have only recently been completed, no data is available to indicate the performance of the wetlands. It is intended that this study will be able to (i) determine if there is any reduction in pollutants by monitoring the water quality, (ii) indicate the performance of the wetlands in terms of the reduction of pollutants and water quality indicators (eg pH or dissolved oxygen), during the wet and dry seasons, and (iii) recommend improvements to increase the wetlands performance.

SITE DESCRIPTIONS

The average rainfall was sourced from the Bureau of Meteorology website and the average was collected at the Townsville Airport from 1941-2001. This data is summarized in Table 1. From this table, it is seen that the majority of the annual rainfall occurs from December to March. The time of year that this study occurred was from late February to late August and therefore encompassed the driest part of the year. For the year to date (October), there has only been 450 mm of rainfall, only a proportion of average rainfall of 921 mm for the time of year.

Greg Jabs Court Wetland

The Greg Jabs Court wetland is one of the two Louisa Creek wetlands installed under the Clean Seas Program run by TCC's Environmental Planning Services. Of the 5.6 ha of

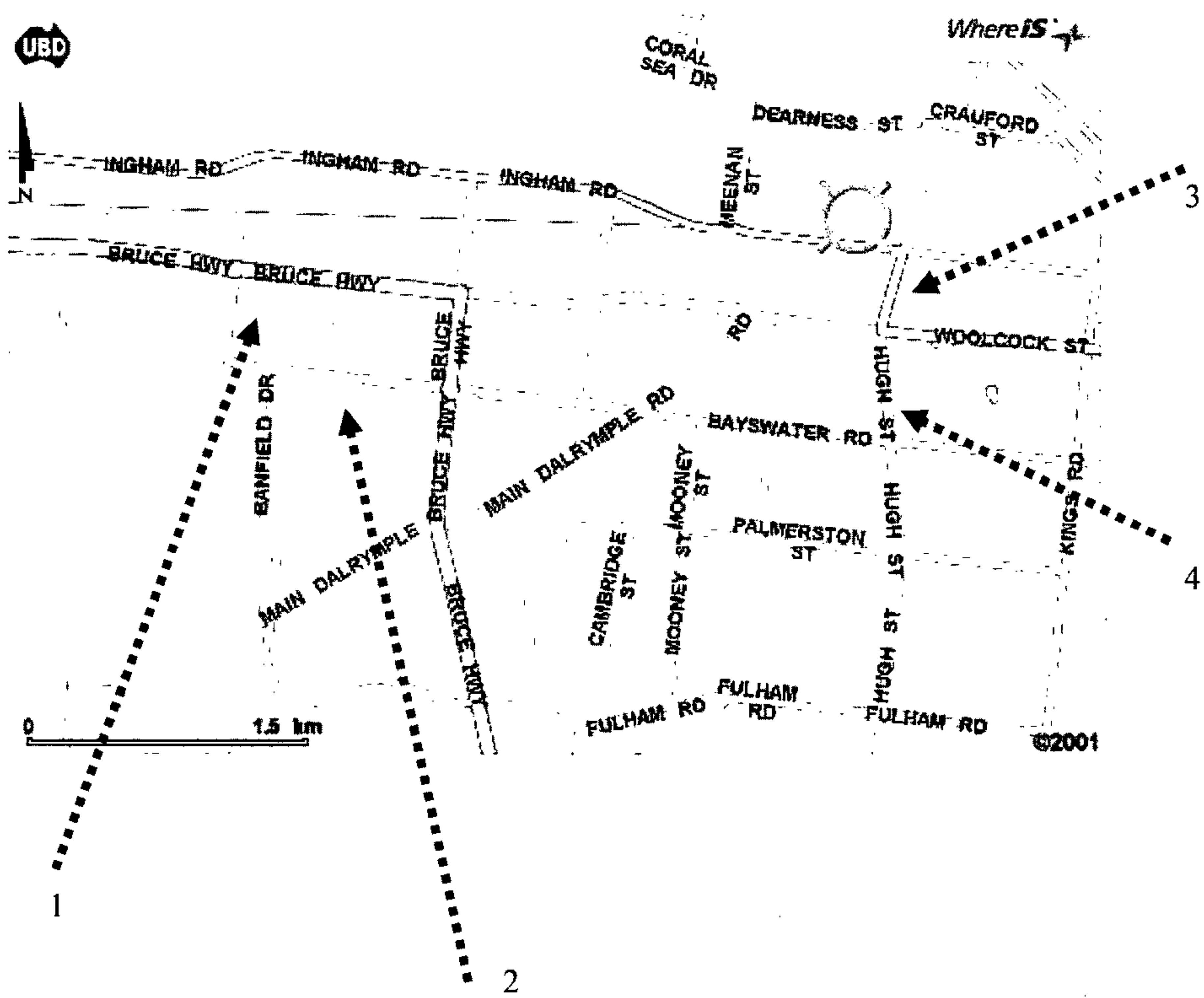


Figure 1. Locations of all Four Constructed Wetlands in Townsville (1-Camuglia Street wetland, 2-Greg Jabs Court Wetland, 3-Paradise Lake Wetland, 4-Curralea Lake Wetland).

Table 1. Average rainfall for the Townsville area

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Rainfall (mm)	270.5	291.8	194	70.5	36.4	20.4	13.6	17	10.5	26	60.9	131.4	1143

catchment, the majority is unvegetated and unsealed land which may lead to an increased amount of transported sediments. The wetland is designed such that the inflowing stormwater enters and passes through a gross pollutant trap (GPT). The stormwater can then flow through two identical vegetated paths and then discharges to Louisa Creek. There is also a high flow bypass, which flows directly into Louisa Creek as shown in Figure 2. The wetland is also designed such that it is dry for the majority of the year. The vegetation has been chosen to regenerate each wet season, when the wetland would be submerged. The vegetation used around the wetland predominantly consists of trees such as *Casuarina cunninghamia, Eucalyptus terticornis and Melaleuca leucandendra.*

Camuglia Street Wetland

The Camuglia Street wetland is the second wetland constructed under the Clean Seas Program. Predominately the land use for the area surrounding the Camuglia Street wetland is light to medium industrial. The wetland allows for the stormwater runoff from the catchment of 145 ha to enter one of two primary interceptors each with its own GPT. From the primary interceptors, the stormwater then merges into one interceptor. The stormwater subsequently flows into the first wetland train and then passes through a second wetland train before discharging into Louisa Creek. Figure 3 shows the layout of the Camuglia Street wetland. The Camuglia Street wetland also has a high flow bypass that allows high flows to pass via an alternate path, which also contains significant amounts vegetation. The vegetation that makes up both of the wetland trains is *Typha domingensis* or the common reed which is also found in the high flow bypass along with *Nymphaea* species.

Curralea Lake Wetland

The Curralea Lake wetland serves a catchment area of 304 ha and has been designed for rain events of 2-year average recurrence

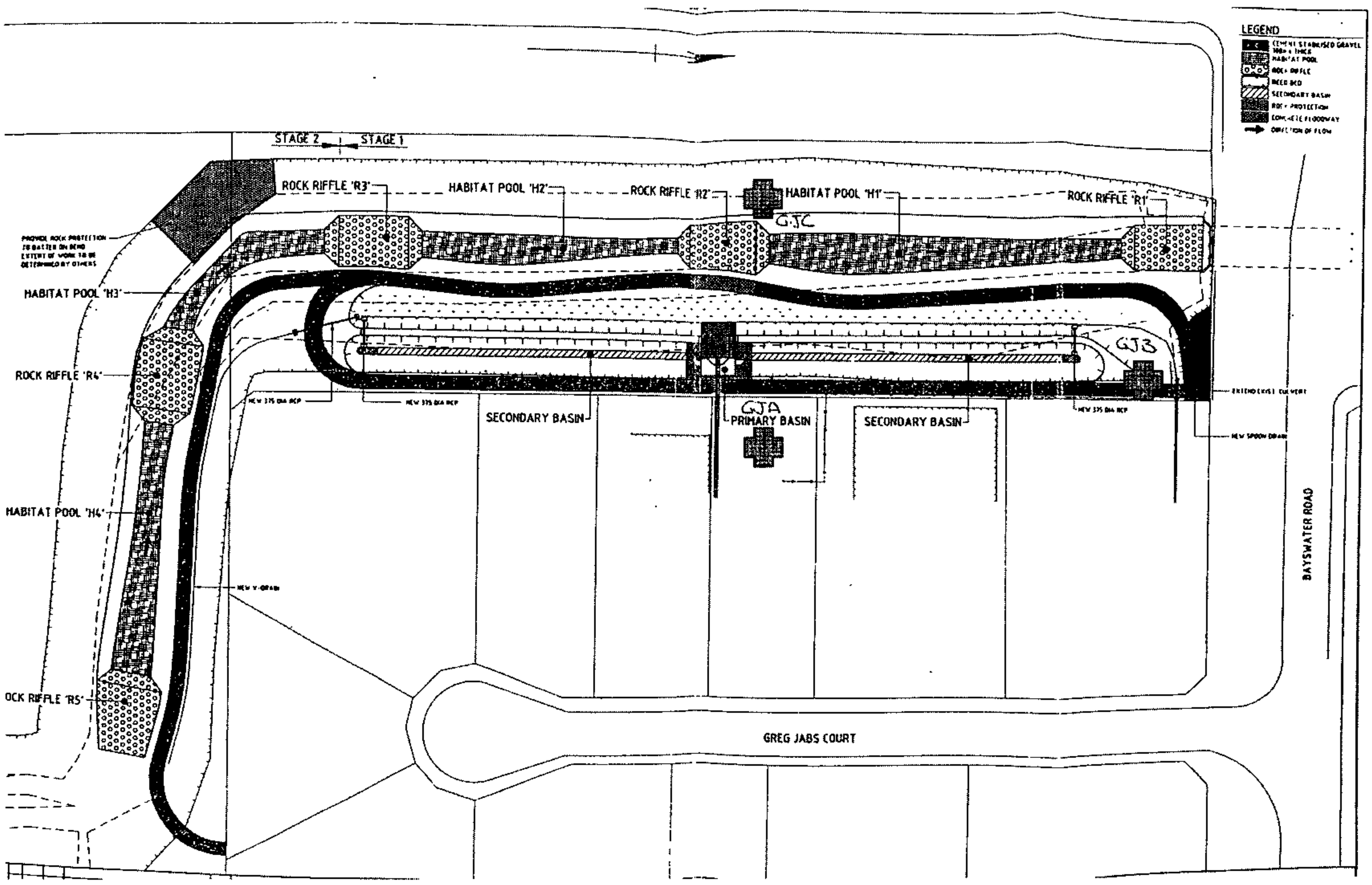


Figure 2. Greg Jabs Court wetland (Sampling locations GJA, GJB and GJC).

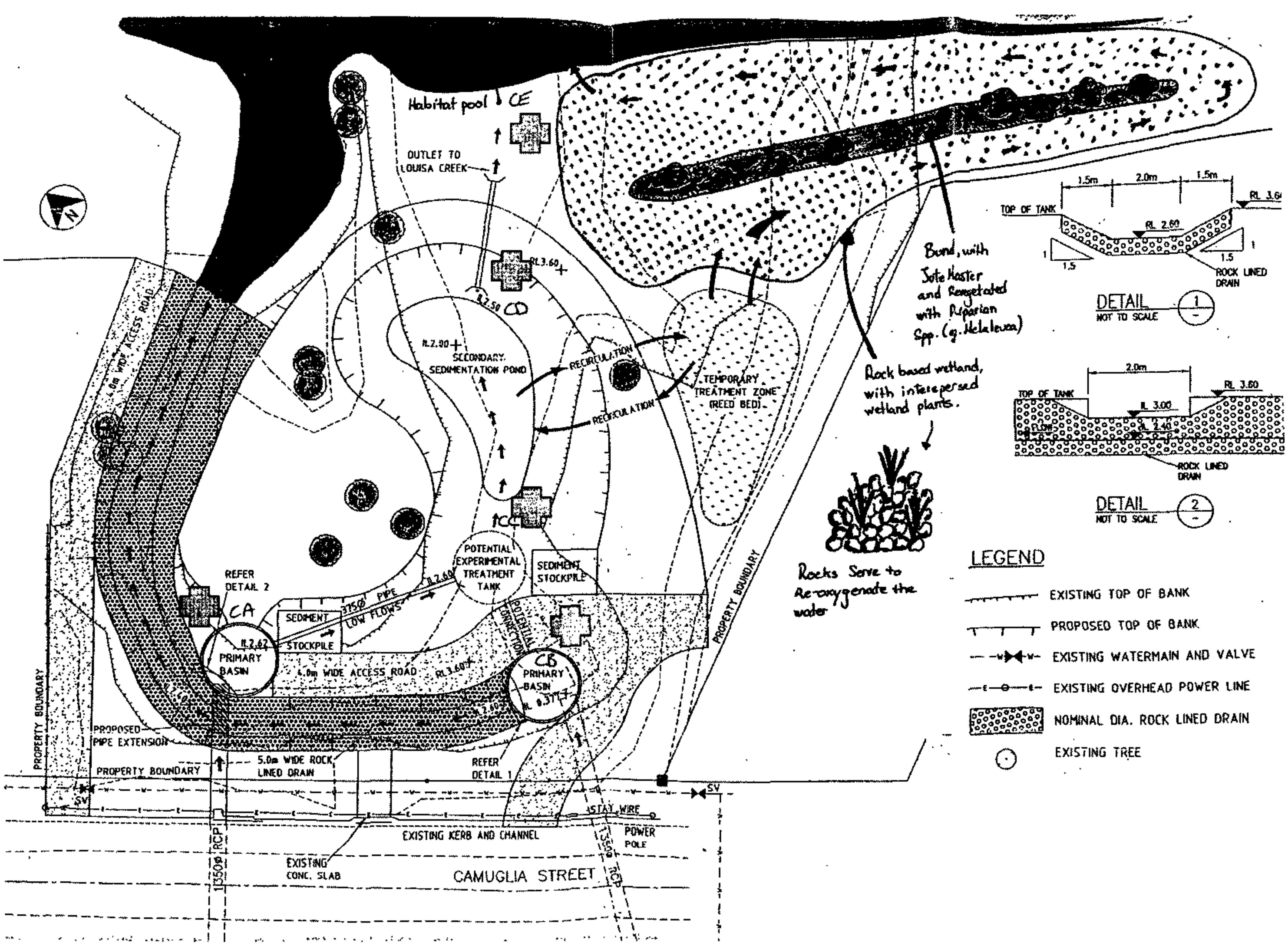


Figure 3. Camuglia Street Wetland (Sampling locations CA, CB, CC, CD and CE).

interval. The purpose of the wetland was to improve the stormwater quality and to increase the amount of dissolved oxygen (DO) entering into Curralea Lake. The stormwater enters the wetland system by passing through a GPT then flows into a sediment pond and along a turf flow path where it enters a purification pond. The final stage of the Curralea Lake wetland is a rock-lined path, which flows into the Lake, which is shown in Figure 4. The rock-lined path allows for additional nutrient removal due to the establishment of biofilms on the surface of the rocks. The vegetation used at the Curralea Lake wetland is not as extensive as the vegetation at the Louisa Creek wetlands. The planting of the vegetation has not been overly successful with only a few plants such as the common reed remaining at the edges of the wetland. To circulate the water in Curralea Lake, a mechanical pump has been installed by Citiworks to transfer water from the Lake to the purification pond at

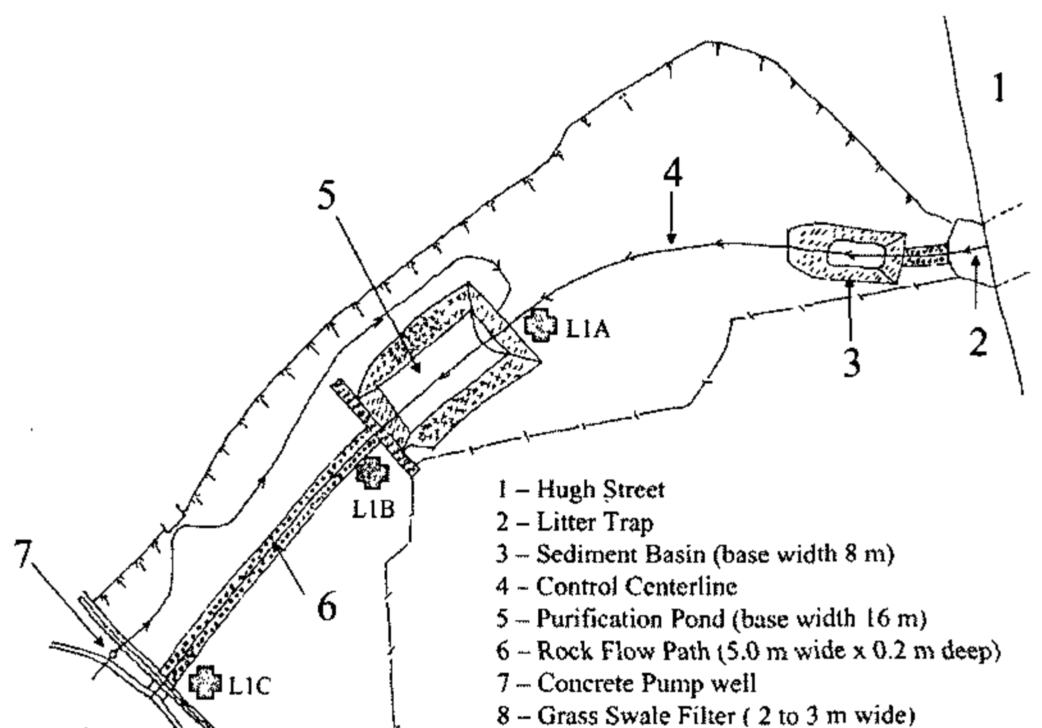


Figure 4. Curralea Lake wetland (Sampling locations L1A, L1B and L1C).

4 m^3/s. The aim of the pump is to enhance the water quality of the lake through increasing the amounts of DO and reduce pollutants. This also allows for the wetland to be completely submerged throughout the year. Due to the installation of the pump, the wetland will experience both fresh and saline water. This is due to the

fact that the pumped water from the Lake is brackish.

Paradise Lake Wetland

The Paradise Lake wetland is designed to receive stormwater runoff from a catchment area of 20 ha and the wetland has been designed for 2-year ARI (average recurrence interval) rain events. The stormwater enters the wetland system by passing through a GPT, then flows into a sediment pond and then along a rock flow path. At the end of the rock flow path, the stormwater enters a purification pond. The final stage of the Paradise Lake wetland (another long rock lined path) carries the stormwater to its outlet at the Lake, which is shown in Figure 5. The vegetation used at the Paradise Lake wetland is not as extensive as that used at the Louisa Creek wetlands. The planting of the vegetation at the purification pond has not been overly successful with only a few plants such as the common reed remaining at the edges of the wetland. To increase the water quality of Paradise Lake, a similar system to that at Curralea Lake has been adopted. A windmill has been constructed to transfer water from Paradise Lake to the entry point of the purification pond. The windmill can constantly pump the water to the wetland at a maximum rate of 1 m^3/s providing there is enough wind to turn the windmill. The Paradise Lake wetland, as with the Curralea Lake wetland, will experience both fresh and saline water for the same reasons previously mentioned.

METHODS

In Situ Monitoring

Weekly in situ monitoring using a multi parameter meter (TPS 90-FLMV Field Lab supplied by ENVIROEQUIP) as well as after each rain event was undertaken at each wetland which gave broad spread of results and provided the baseline conditions of the wetlands. The in situ parameters monitored were: pH, Temperature, Dissolved Oxygen (DO) and Conductivity. At each wetland, in situ samples were taken at several locations. This allowed for the determination of any potential change in the pollutants. The locations and the identification names of each monitoring site at each stormwater wetland are shown in Figures 2, 3, 4 and 5. No water samples, in situ or laboratory, were taken from the Greg Jabs Court wetland, which, unlike the other wetlands, had no permanent flow of water. The in situ monitoring ran for a

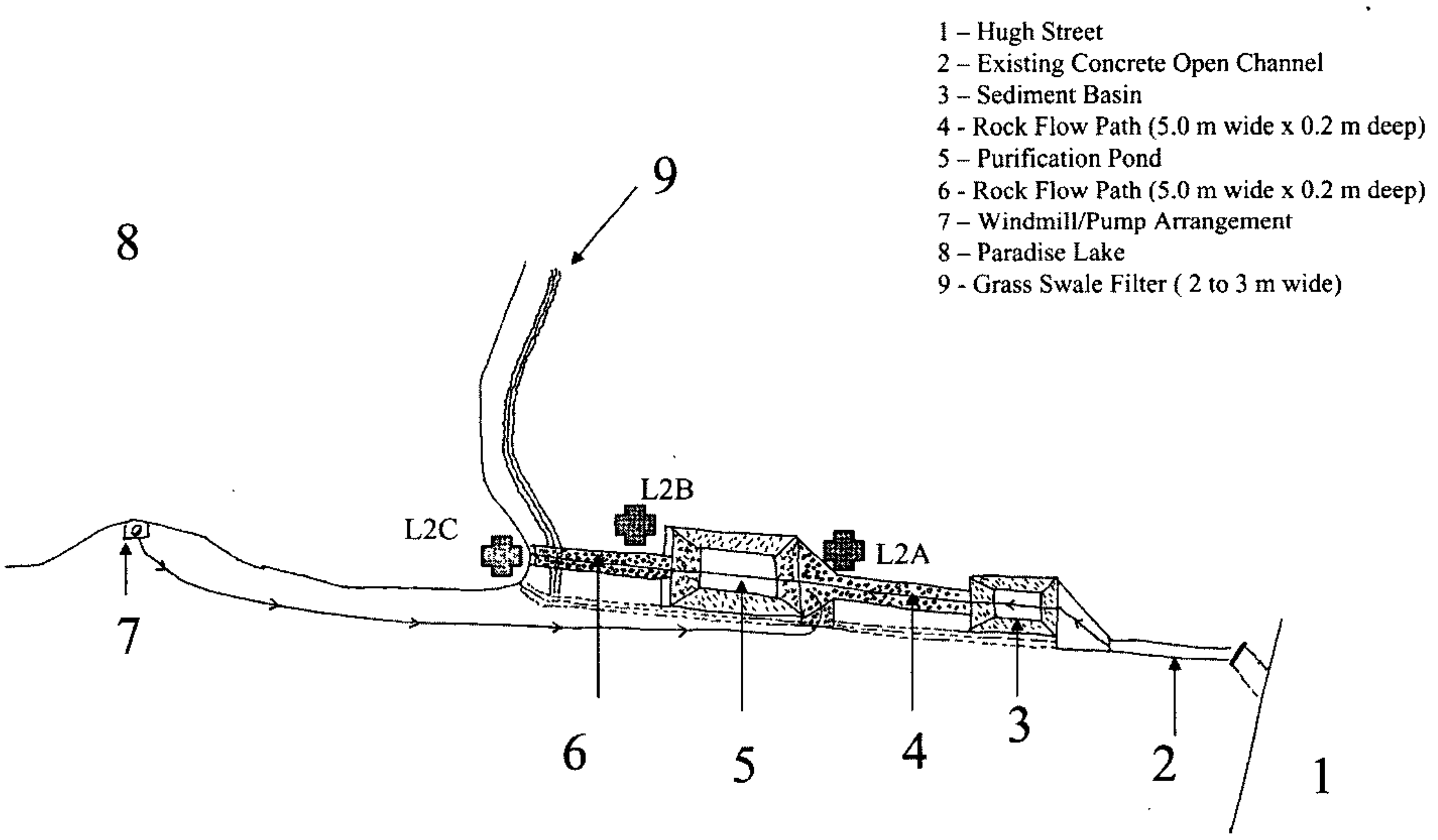


Figure 5. Paradise Lake wetland (Sampling locations L2A, L2B and L2C).

total of 15 monitoring events for the Camuglia Street and Curralea Lake wetlands and 7 monitoring events for Paradise Lake wetland from March to August. The length of the monitoring ensured that an accurate assessment of the performance of the wetlands could be established and the resulting information would be easily comparable due to the similar study duration.

Laboratory Analysis

The parameters analysed in the stormwater were: Total Nitrogen (TN), Total Phosphorus (TP), Suspended Solids (SS), Turbidity, Ammonia, Phosphate, Nitrate, Chlorophyll a, Faecal Coliform, Calcium, Magnesium, Sodium, Potassium, Iron, Manganese, Copper, Zinc, Aluminium and Hydrocarbon. The Douglas Laboratory undertook the laboratory analysis for each water sample. The sampling ran concurrently with the in situ monitoring and was conducted weekly (predominately Tuesday mornings) and after each rain event. The sampling ran for a total duration of 15 sampling events for the Camuglia Street and the Curralea Lake wetlands from March to August and 9 events for the Paradise Lake wetland. After a few monitoring events, it was noted that the concentration of hydrocarbons and aluminium were negligible in every monitoring event and for each sample site. It was therefore decided to cease the testing of these pollutants and to concentrate further on the remaining parameters. To aid in the laboratory sampling in the event of a storm, two permanent water sampling devices (Discrete Stormwater Sampler: SS505 by Global Water Instrumentation Inc.) were installed in the pre-constructed cages at the inlet to the Louisa Creek wetland and the Greg Jabs Court wetland. From these permanent water samplers, an inflow sample was obtained from the Greg Jabs Court wetland during a light shower during the end of April. This inflow data was the only data obtained from this wetland due to the exceptionally dry weather patterns.

Analysis of Vegetation

An analysis of the wetland vegetation was undertaken to determine the nutrient uptake. This sampling was performed at the Camuglia Street wetland, which has the most abundant vegetation. The methodology of the sampling followed a similar pattern to the successful studies performed[5,6] on the treatment of municipal effluent using constructed wetlands. It was found[5] that for the parameters studied, the concentrations found within the vegetation were equal to or less than the concentrations found in natural wetlands. Phosphorus storage[6] ranged from 0.26 g/m^2 to 4.20 g/m^2 and the nitrogen storage ranged from 1.36 g/m^2 to 15.0 g/m^2 within the vegetation. It was expected that the sampling undertaken for this study would establish a similar concentration range for phosphorus and nitrogen in the reeds. It was anticipated that there would be higher concentration of phosphorus and nitrogen in the reeds located near the inflow. Reed samples were taken at 2 m intervals in the middle of the wetland train at the Camuglia Street wetland. The reeds were then transported to the Douglas Laboratory for nutrient uptake analysis.

Flow Rate Monitoring

There were no flow meters at the wetlands and it was therefore necessary to determine the flow rates of the wetlands through other means. It was decided a V-weir would be placed at the outlet of the Camuglia Street wetland, as the width of the outlet is narrow enough to place a weir so that all the flow passes through the weir. The weir was placed into the Camuglia Street wetland six times and the height of the water was measured above the V-notch. The flow rate was determined from this information using tables from the Queensland Water Resources Commission's Water Officer's and Storage Supervisor's Manual.[7]

RESULTS AND DISCUSSION

In Situ Monitoring

From Table 2, it can be seen that there was an increase in DO at two of the wetlands. The

Table 2. Average percentage change of the Dissolved Oxygen levels at the constructed wetlands

Constructed Wetland	Camuglia	Curralea	Paradise
% Change	34.36	32.42	-5.22

Camuglia Street wetland had the greatest increase, when compared to the other wetlands. A possible cause for a reduced amount of DO at the Paradise Lake wetland is that there is limited vegetation established at the wetland. Another reason for a decrease in the level of oxygen in the Paradise Lake wetland is that inflow water is relatively aerated and mixed due to the continuous flow from the windmill. Therefore the inflow water may have a higher dissolved oxygen level than normal.

From the in situ results, it was also found that the conductivity levels at the Curralea Lake and Paradise Lake wetlands were far higher than that found at the Camuglia Street wetland (Table 3). These higher levels are associated with brackish waters. This becomes important when trying to establish vegetation at the wetlands, as chosen vegetation must be able to withstand saline waters.

Laboratory Analysis

The monitoring data indicates that the Curralea Lake wetland and Paradise Lake wetland had an increase in the turbidity and SS levels, which is attributed to the high levels of chlorophyll a. For high chlorophyll a levels, there is usually high corresponding turbidity and suspended solids values. The concentrations of chlorophyll a and hence the amount of algae present at Curralea Lake wetland and Paradise Lake wetland was far higher than that found at the Camuglia Street wetland and this has been shown in Table 4. The Camuglia Street wetland has the highest performance of the four wetlands, as there are only three pollutants that have a minor negative percentage change over the wetland. The wetland with the next highest performance is the Curralea Lake wetland. The reasoning behind the high pollutant removal at the Camuglia Street wetland could be the fact that it is completely vegetated by common reeds, which thrive in nutrient-rich soil that is continually submerged.[6] The Camuglia Street wetland also has a significant amount of sediment on the bottom of the wetland, which will also increase the amount of pollutants removed due to the microbes living within the sediment. A possible reason for the better performance of the Curralea Lake wetland over the Paradise Lake wetland is that the Curralea Lake wetland is more established than the Paradise Lake wetland in terms of the sediment at the bottom of the wetland and a slightly larger amount of vegetation. The Curralea Lake also has an advantage over the Paradise Lake in that there are established biofilm communities on the rock-lined path.

There was one rain event that officially produced 4.4 mm during the course of the study. The results are varied for the single rain event recorded during this study and that there is not much change in the results from the rain event when compared to the average pollutant removal. It has been noted that the wetlands appear to have difficultly in removing some metals,

Table 3. Average conductivity levels at the constructed stormwater wetlands

Wetland	Camuglia Street			Curralea Lake			Paradise Lake		
Site ID	CC	CD	CE	L1A	L2A	L2C	L2A	L2B	L2C
Conductivity (mS/cm)	3.7	2.99	2.02	13.28	11.09	10.84	18.70	15.28	18.80

Table 4. Average chlorophyll a levels

Wetland	Greg Jabs Court		Camuglia Street		Curralea Lake			Paradise Lake		
Site ID	GJA	GJC	CC	CD	L1A	L1B	L1C	L2A	L2B	L2C
Chlorophyll a (μg/L)	36.3	8.3	7.32	6	29.36	20.3	20.65	16.81	7.41	13.89

ammonia and nitrate once rain occurs. To further understand the wetlands during the wet season, more water sampling is required.

Vegetation

There were 10 reed samples submitted to the laboratory for analysis for TN and TP within in the reeds. The results from the laboratory are shown in Figure 6. When comparing the amount of nutrient concentration found in the vegetation at the Camuglia Street wetland, it was found that the concentration of TN and TP were generally within the range.[6] The TN concentration range determined by the reed analysis was 0.21-4.03 mg/g (dry weight) and for TP the range was found to be 0.15-4.73 mg/g (dry weight). It was found that there was a higher concentration of nutrients at the inflow than the outflow, but it was also found that there are peaks in the concentration of nutrients at points within the wetland. These peaks may be indicative of which vegetation is the oldest and therefore has the most nutrients stored within its stem and roots or of the flow patterns within the wetland.

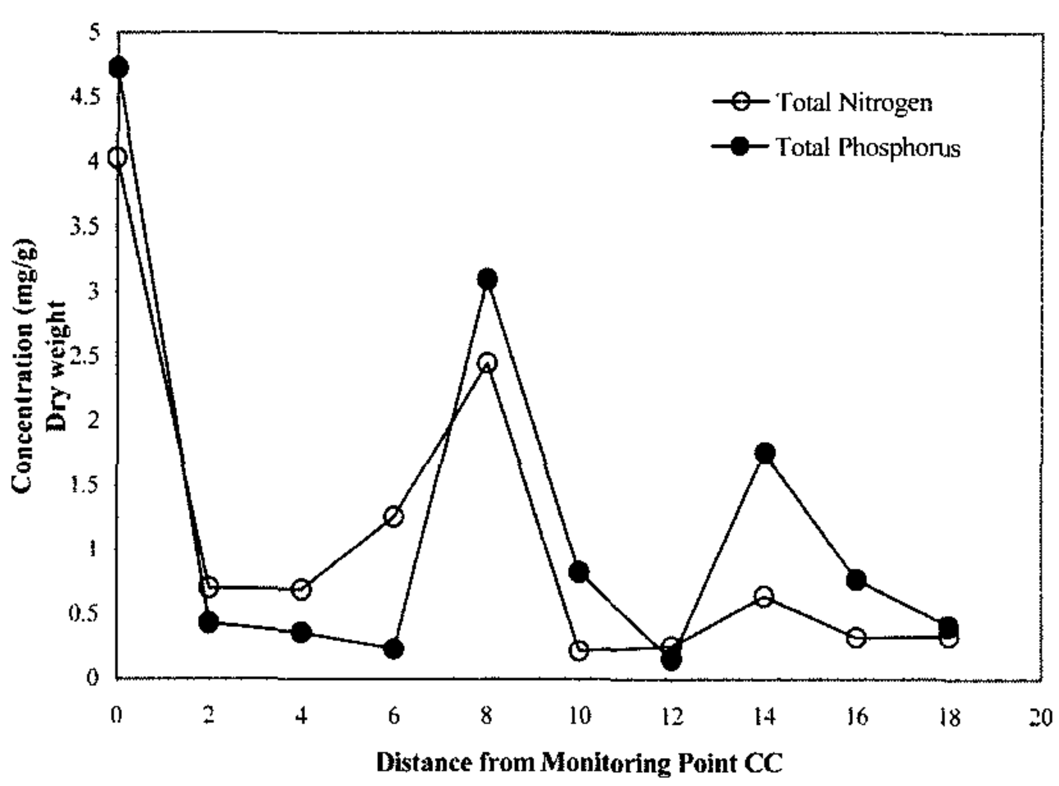


Figure 6. Concentration of Total Nitrogen and Total Phosphorus in Vegetation at Camuglia Street Wetland.

Flow Monitoring

The flow rate for the Camuglia Street wetland was taken as three times the average flow rate determined from the V-notch weir of 150 L/hr because this average was only taken over six samples and there were higher flows visually observed at the Camuglia Street wetland. Through the conservation of mass law, the outflow determined also corresponds to the stormwater inflow rate was also found to be 150 L/hr.

Wetland Model

It was determined that a mathematic model would be useful in further investigating the performance of the wetlands. The model adopted to determine the change in pollutant concentrations for this study was the one established previously.[8] This model uses a first order kinetic model, which measures the change in pollutant concentration as the stormwater passes through the length of the wetland and has been named the "k - C* model". This model is expressed as:

$$q\frac{dC}{dx} = -k(C - C^*)$$

Where q = hydraulic loading rate (m/y), defined as the ratio of the inflow and the surface area of the system

x = fraction of distance from the inlet to the outlet

C = concentration of the water quality parameter

C^* = background concentration of the water quality parameter

k = areal decay rate constant (m/y)

In applying the "k - C* model", the variables must first be determined for each wetland. To determine the hydraulic loading rate (q), the surface area and inflow of each wetland must be determined. The flow rate for the Lakes wetlands was taken 4 L/s at Curralea and 1 L/s at Paradise. The flow rate for the Camuglia Street wetland was taken as three times the average flow rate determined from the V-notch weir of 150 L/hr. The fraction of distance, x was determined by considering 2 m intervals for the length of each wetland. The background concentration of the water quality parameter (C*) was taken to be less than average inflow concentration (0.05 mg/L for both nitrogen and phosphorus) of the pollutant at each wetland. There was no available data to determine the areal decay rate constant (k), so this variable was found through calibration for each parameter at the wetlands. The following finite difference scheme is used to calculate the concentration along the wetland:

$$q\frac{(C_n - C_{n-1})}{(x_n - x_{n-1})} = -k(C_n - C^*)$$

$$C_n = \frac{kC^*(x_n - x_{n-1}) + qC_{n-1}}{k(x_n - x_{n-1}) + q}$$

Since, C* is less than the concentration at the inlet, concentration will decrease along the flow direction. The values for the variables used at each wetland, including the separated sections at the Lakes wetlands but excluding the areal decay rate constants, can be found in Table 5. The background concentration levels are not applicable for the Curralea and Paradise Lake rock lined path because the concentration is dependent on the finishing concentration from the purification pond.

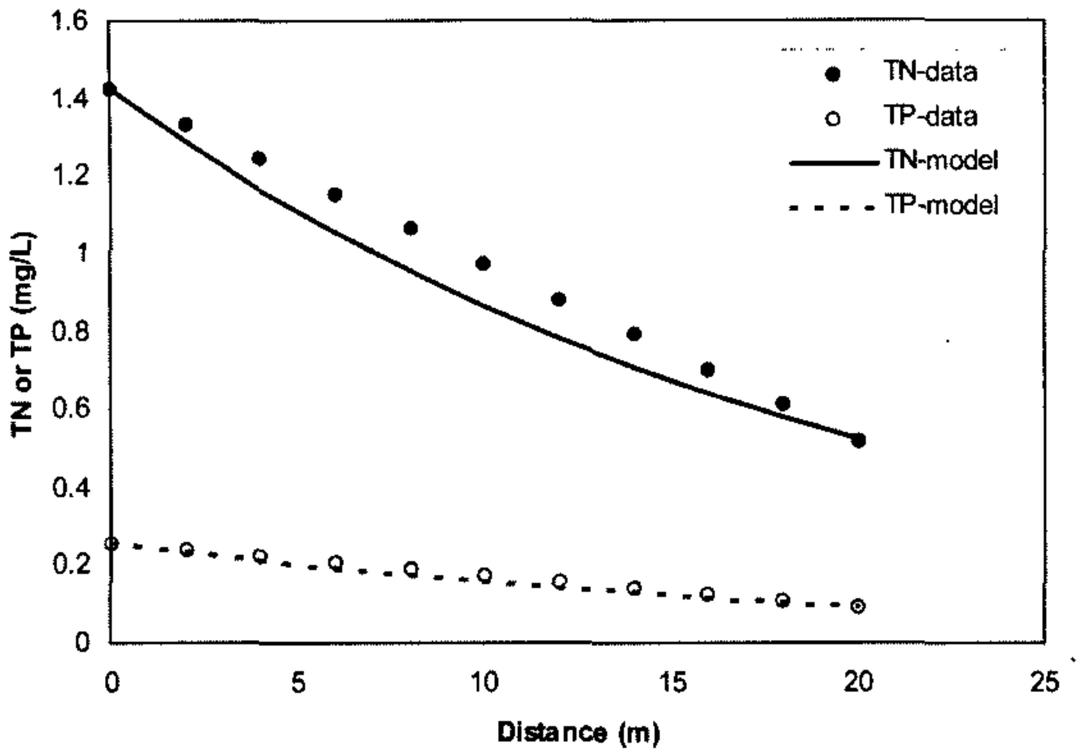
The results from the rain event were also used in the model to see if the model could accurately predict pollutant removal with higher flows. The flow rates used for this simulation were taken from the catchment area and the rainfall.

The results obtained using the "k - C* model" were calculated using Microsoft Excel. From Figures 7 (a), (b) and (c), it can be seen that the "k - C*model" follows the actual data relatively closely. As the results obtained from the model have only used low flow rates, it can be assumed that if a higher flow rate were used, the results from the model would be close to what would actually occur. This simulation was run for the each of the wetlands using two flow rates of 150 000 m^3/y and 200 000 m^3/y and total nitrogen concentrations of 1.75 mg/L and 2.5 mg/L. From these simulations, it was found that the Curralea Lake wetland had the highest removal rate of 6.64% reduction in pollutants, using the "k" values from the actual data. This was followed by the Paradise Lake wetland, then Camuglia Street wetland. From the simulations, it can be seen that the trends the wetlands follow are the same for each simulation.

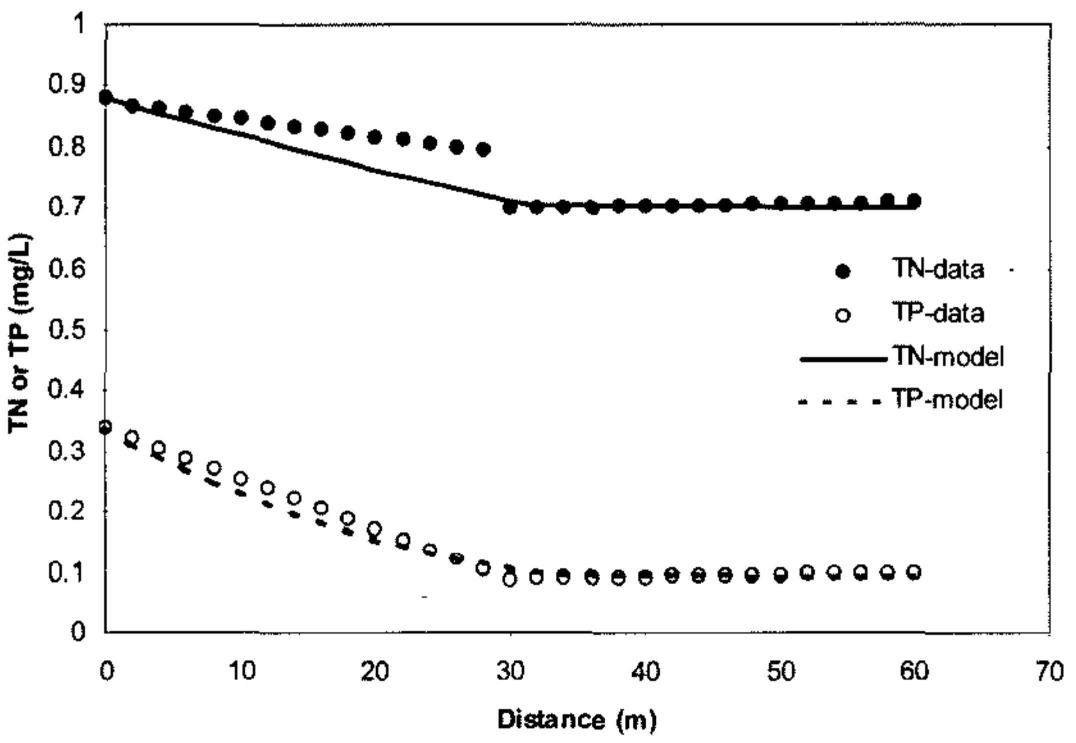
The rain event data has also been put through the "k-C* model" to determine the comparison between the model results and the actual data. The flow rate for the rain event has been determined by using the rainfall in the area, the catchment areas for each wetland, an estimation of the fraction impervious for the catchment (60%) and the fraction of the runoff water from the catchment area that will enter the wetlands (40%). The results can be seen in Figures 8 (a) and (b). It can be seen from these figures that the "k-C* model" predicts that the pollutant concentration will remain relatively constant and does not follow the actual data too closely, with the exception of the Paradise Lake wetland. A problem with these figures is that the actual data is based on one event only and this may

Table 5. Values of the variables used in the "k - C* model"

Variable	Camuglia Street Wetland	Curralea Lake Purification	Curralea Lake Rock Path	Paradise Lake Purification	Paradise Lake Rock Path
S.A (m^2)	314.16	790	320	510	112
Q (m^3/y)	1314	126144	126144	31536	31536
q (m/y)	1.394	2.64	6.57	1.03	4.69
x (m)	0-20 @ 2m intervals	0-38 @ 2m interval	40-120@ 2m intervals	0-30 @ 2m intervals	32-60 @ 2m intervals
TN C* (mg/L)	1.425	1.83	N/A	0.87	N/A
TP C* (mg/L)	0.259	0.26	N/A	0.10	N/A



(a)



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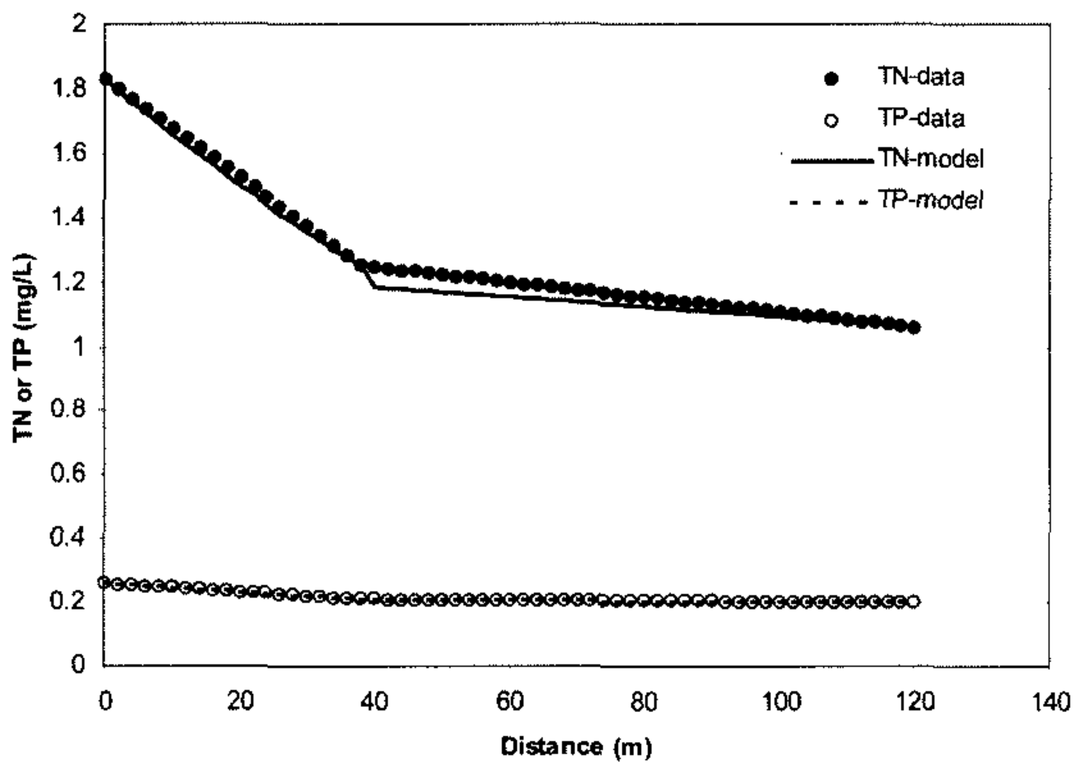
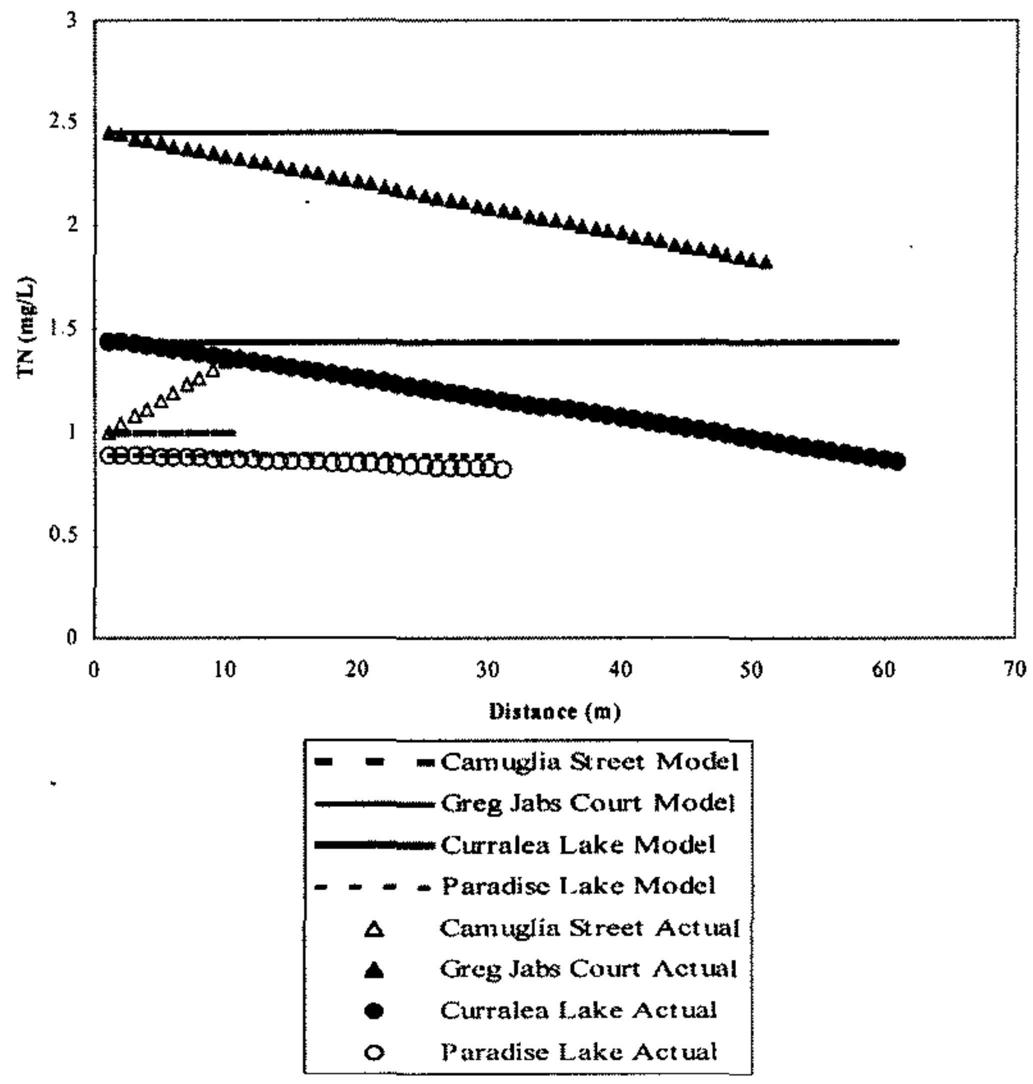
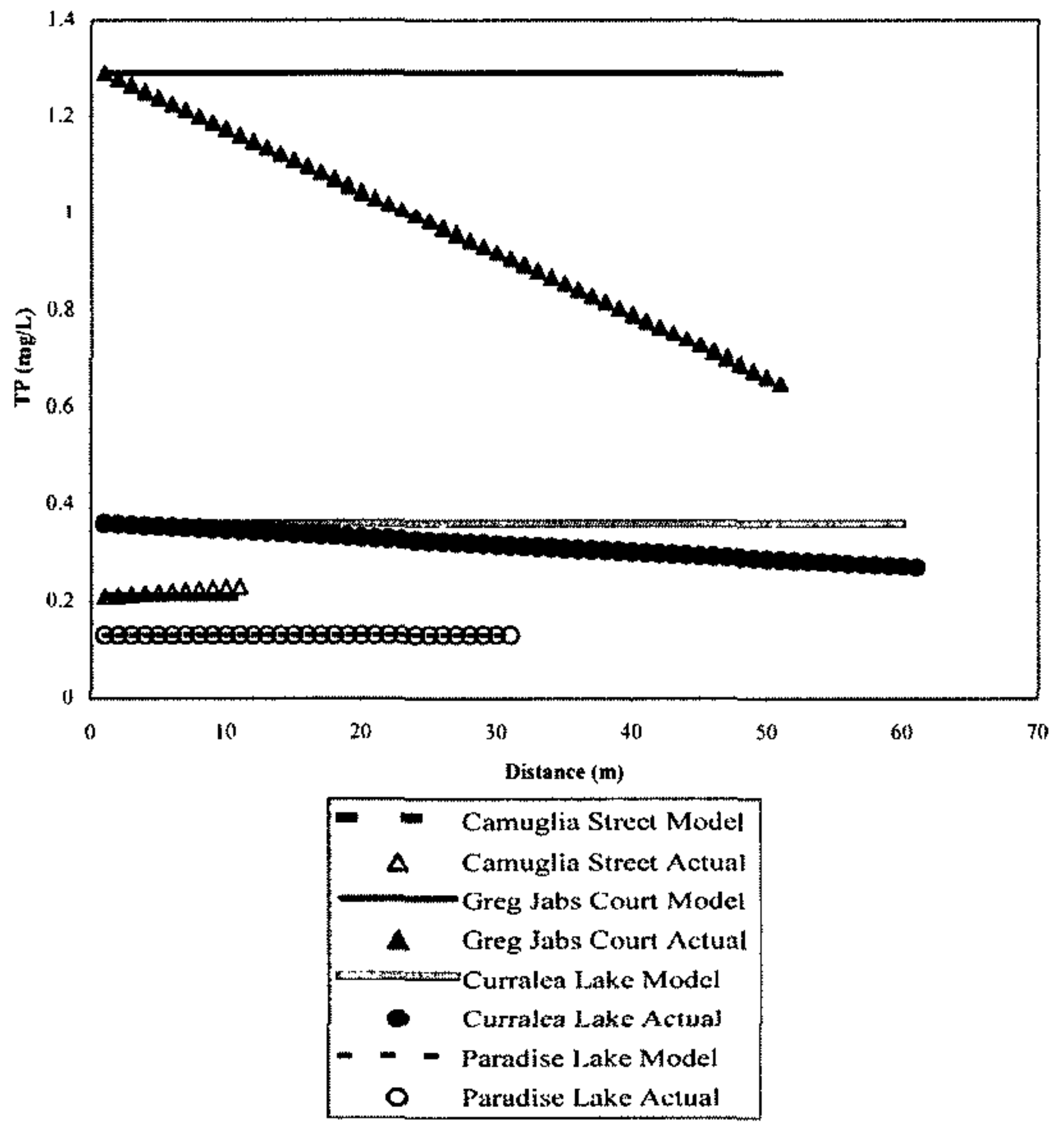


(c)

Figure 7. (a) Comparison of Actual Data and Model Data for TN and TP at Camuglia Street Wetland; (b) Comparison of Actual Data and Model Data for TN and TP at Curralea Lake Wetland; (c) Comparison of Actual and Model Data for TN and TP at Paradise Lake Wetland.



(a)



(b)

Figure 8. (a) Comparison of Rainfall Event Data and Model Predicted Data for Total Nitrogen; (b) Comparison of Rainfall Event Data and Model Predicted Data for Total Phosphorus.

not be a true representation of the pollutant removal.

From the model simulation, it was found that the Curralea Lake wetland had the highest removal of total nitrogen followed by the Paradise Lake wetland and finally the Camuglia Street wetland. From the field results, however, it was determined that the Camuglia Street wetland had a higher total nitrogen removal than the Curralea Lake wetland. This difference may be attributed to the estimation of the areal decay rate constant ("k values") as well as the length of the two Lakes wetlands. To further verify this model and allow for more accurate use, there needs to be additional investigation into the determination of the areal decay rate constant. However, the estimation of the "k values" for this study has been acceptable in proving that the model can describe the change in pollutant concentration over the distance of the wetland.

CONCLUSIONS

From this study, it was determined that using wetlands as a form of stormwater management is quite acceptable, as the results obtained indicate that the wetlands studied were able to reduce the concentration of the majority of the stormwater pollutants. Table 6 summarises the advantages and disadvantages of each wetland, the recommendations made at each wetland and how the wetlands are ranked from the results obtained from the water sampling.

1) From the sampling, it was determined that Camuglia Street wetland had the best pollutant removal.
2) The second best performing wetland was the Curralea Lake wetland.
3) The Paradise Lake wetland had a lesser pollutant removal than the other wetlands which was attributed to the lack of vegetation at the wetland.
4) There was no comprehensive data obtained from the Greg Jabs Court wetland due to the dry conditions of the study duration.

Recommendations were made regarding ways that the wetlands could be further understood in terms of pollutant removal, flow regimes and patterns. This entailed more frequent water sampling, hydraulic residence time testing, determining if the deeper wetlands are stratified and sediment analysis. Overall it was determined that the four constructed stormwater wetlands in the Townsville area are performing in the manner for which they were designed. That is, each of the wetlands is able to improve the quality of the stormwater by reducing the concentration of common urban stormwater pollutants. However, further study needs to be undertaken at the wetlands especially during the wet season, to investigate the wetland's performance during high flows.

ACKNOWLEDGEMENTS

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Table 6. Summary of the wetlands

Wetland	Average Pollutant Removal Rank	Advantages	Disadvantages	Recommendations
Greg Jabs Court	4 (Based on limited results)	Long length Large GPT	No permanent water body	Installation of pump or windmill to pump water from the Creek to the wetland
Camuglia Street	1	Fully vegetated High flow bypass vegetated	Short wetland train Clogged GPT	More frequent gross pollutant removal
Curralea Lake	2	Longest wetland Biofilms on rock path	Minimal vegetation at the wetland	Planting of brackish tolerant vegetation
Paradise Lake	3	Water pumped continually from windmill - no power needed	Minimal vegetation at the wetland	Planting of brackish tolerant vegetation Further investigation of the fault at the purification pond

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