Wetland investigation project for Greenland Landfill in Barbados in collaboration with New Water Incorporated

Presented to

Dr. Inteaz Alli – director of the program
Ms. Susan Mahon – internship coordinator
Dr. Robert Bonnell – internship supervisor
M. Burton Ward – C.E.O. of New Water Inc.
M. Robert Hacking – Vice President of New Water Inc.
Dr. Vijaya Raghavan - Design 3 course supervisor

By

Thomas Fortin-Chevalier
Christian Saad
Pénéloppe Thériault

Barbados Field Study Semester
Bellairs Research Institute
McGill University

Fall 2007

Reference :

Fortin-Chevalier, T., C. Saad, & P. Thériault (2007). Wetland investigation project for Greenland Landfill in Barbados in collaboration with New Water Incorporated. Bellairs Research Institute of McGill University, Barbados.

Executive Summary

The use of the Greenland landfill will produce leachate, which needs to be treated before released into Green pond and eventually the ocean. Effectively, the leachate treatment has to meet high water quality standards set by the Coastal Zone Management Unit of Barbados. New Water Incorporated, a company working throughout the Caribbean and specializing in water treatment with membrane technology, submitted a proposal for a leachate treatment plant to the Sanitary Service Authority. The micro-filtration system used by New Water Inc. has proven to be very efficient in treating wastewater. However, it is expected that when used for landfill leachate treatment, nitrate as well as iron, zinc, manganese, and other heavy metals will not be fully removed. Hence, the effluent needs to be further treated to conform to the environmental standards for safe marine discharge. A surface constructed wetland used as a second treatment system can polish the water and increase its quality so that it meets the required standards.

Multiple benefits are associated with the use of constructed wetlands. First, this eco-technology requires minimal power input, which considerably lowers its operational cost and maintenance, making it more advantageous than traditional water treatment systems. Furthermore, such 'natural' systems increase the biodiversity by providing habitats for a wide range of wildlife species, including migratory birds.

For such reasons, it is believed that a wetland would be an ideal solution for secondary treatment. Hence, this project aims to assess the feasibility of using a wetland system for the Greenland landfill leachate and to produce a preliminary design.

After an extensive literature review and the consideration of many factors influencing constructed wetland efficiency, the team agrees on the feasibility of this project and supports its implementation since it is the best alternative from an environmental perspective.

An area of about 1600 m^2 with a retention time of about 3 days is required to bring the nitrate levels down to 4.5 mg/L during periods of maximum flow. Nonetheless, such an area would ensure a positive water balance even during dry periods with minimal inflow. The wetland would be located east of the landfill site, in the field on the other side of the creek. The design takes into consideration flow variations, initial concentrations of pollutants, evapotranspiration rates, nitrate removal rate, temperature variation, vegetation, and bird habitat.

Acknowledgements

This wetland project would not have been possible without the precious and generous help of many people. We are extremely grateful to everyone who supported us during this program.

First and foremost, thank you to New Water Inc. for giving us the chance to work on this exciting project. A special mention to Robert Hacking who was present, very supportive, and helpful throughout the project. Without him, we would not have accomplished and learned as much. Thanks also to Burton Ward and Olivia Drescher.

We would also like to thank Susan Mahon for the structure and coordination she gave to the internship projects. Thanks also to Dr. Inteaz Alli, who facilitated the integration of the students in their new environment. In addition, we would like to thank all the professors from various universities and departments who gave us time and precious advices. From McGill University, we would like to thank Dr. Bonnell, Dr. Barrington and Dr. Gehr for sharing their knowledge on wetlands, as well as for their advice on the design. From the University of West Indies, we would like to thank Dr. Watson, Dr. Carrington and Dr. Fields for their information on the wildlife and vegetation of Barbados. This information was one of the key elements of the project.

Thanks to Ryan, from the Graeme Hall Nature Sanctuary, who gave the team an extensive tour of the sanctuary, and provided us with useful information. A special thank you also goes to Santiago, for helping with the GIS maps and keeping us grooving during the last busy month.

Finally, we cannot forget to mention the staff from Bellairs who extremely facilitated our stay at the institute. First of all, a special mention to Richard Haynes for its support and warm welcome. Arlene, Gwen and Sharon, who daily provided the team with a clean environment, delicious food, and fun stories. Thanks also to Sandra, Judith, and Bruce.

Bellairs Research Institute of McGill University
Holetown, St. James, Barbados
Tel (246) 422-2087 Fax (246) 422-0692
Email : bellairs@caribsurf.com
http://www.mcgill.ca/bellairs

December 12, 2007

Dear Mr. Hacking,

We would like to let you know how grateful we are for the opportunity to work with you on this exciting project. We greatly appreciated your help and guidance throughout the project. You provided us with constant support and rapid feedback, which kept us motivated. Thank you also for the time you dedicated to discussions, visits of the site, sharing of the project's progress, etc.

The wetland project appealed to us from the beginning. It was an amazing opportunity to apply our knowledge and gain experience in the field of environmental engineering. We learned an enormous amount about the procedure such projects need to go through in order to be approved at the governmental level. Moreover, we now have a better idea of the plant ecology and the birds frequenting Barbados, as well as the social infrastructure regulating decision-making. You also provided us with strong insight on the physical functioning of the Greenland landfill, as well as the membrane filtration system used by New Water Inc. We feel privileged for the knowledge we gained in the last three months. This positive learning experience will definitely be of great help when starting our careers as Bioresource engineers.

We hope to keep in touch with you and New Water Inc., and are looking forward to being updated on the status and development of the leachate treatment plant, as well as the wetland system for the Greenland landfill site. We are also keeping the door open for future collaboration with New Water Inc.

Sincerely,

Mr. Thomas Fortin-Chevalier
BFSS student

Mr. Christian Saad
BFSS student

Ms. Pénéloppe Thériault
BFSS student

Dr. Inteaz Alli
Program Director
Barbados Field Study Semester 2007

Ms. Susan Mahon
Internship Coordinator
Barbados Field Study Semester 2007

Table of Contents

List of Figures

List of Tables

1. Introduction

Landfill engineering has developed over the years, evolving from open dumps to well managed sites with rigorous designs to meet environmental considerations and pollution control. Even with a state-of-the-art landfill structure, leachate production due to the infiltration of water is unavoidable (Parkes, Jolley et al. 2007). Robert Hacking, vice-president of New Water Inc., asserts that leachate from landfills is known to be the dirtiest type of wastewater. This polluting substance contains various contaminants at high concentrations, which migrate horizontally and vertically into the environment (Aluko and Sridhar 2005). Solid waste management sites can lead to a low yield of farm produce, loss of biodiversity, and contamination of water sources (Aluko and Sridhar 2005). High concentrations of heavy metals and nitrogen are to be expected even though leachate composition varies from site to site depending on the nature and the age of the wastes, the landfill management techniques, as well as the weather (Bulc 2006; Parkes, Jolley et al. 2007; R.J.Burnside.International.Limited 2007).

Over the past 20 years, constructed wetlands have been used for treating leachate. They have been used in various places around the world. The scientific literature reports cases from Nigeria, US, Slovenia, Thailand, Uganda, and Australia. The constructed wetlands were used as a primary, secondary or tertiary treatment for landfill leachate, and showed satisfactory results (Aluko and Sridhar 2005; Mwiganga and Kansiime 2005; Bulc 2006; Davison, Pont et al. 2006; Nivala, Hoos et al. 2007; Sawaittayothin and Polprasert 2007).

Currently, a landfill is being constructed in Barbados' Scotland District. This landfill is located in a unique natural setting in terms of its vegetation and soil composition, which consists of a specific arrangement of clay layers. The area is surrounded by various livestock farms and is close to the eastern littoral. Consequently, an extremely high level of leachate treatment is required.

New Water Inc. is one of the companies that submitted a proposal for the construction of a leachate treatment plant for the Greenland landfill project. Even though the effluent quality exiting the membrane filtration plant is close to drinking water standards, there are still concerns about the nitrate and heavy metal levels. A constructed wetland used as a secondary treatment system appears to be a viable option for reducing the remaining contaminants.

New Water Inc. has mandated three McGill Bioresource Engineering students, participating in the Barbados Field Study Semester, to assess the feasibility of implementing a constructed wetland as a secondary treatment system for the Barbados Greenland landfill leachate. Therefore, the team's goal for their internship is to conduct a feasibility analysis, preliminary design and cost approximation of a constructed wetland project for secondary treatment of the Greenland landfill leachate.

The team has a vision of a human-made wetland polishing the effluent from the treatment plant. The water exiting the system would meet the required standards for safe discharge into the environment. The system would also represent a great habitat for the fauna. The final product would be a location where numerous bird species coexist. Furthermore, the site would provide aesthetic beauty that would counter balance both the harsh reality of waste disposal as well as the social and political controversy concerning water and marine contamination from landfills.

In order to complete this project, background knowledge on the site and constructed wetland technologies needs to be acquired, so that the type of wetland that best suits the natural environment of the site and the proper treatment requirements can be determined. A preliminary design can then be completed in order to determine the amount of land required, the volume of soil to be excavated, the type of plants needed, and other physical characteristics. All potential locations for the wetland in the area need to be identified. The preliminary design will also allow for an approximation of the cost for this project. Finally, based on the literature review, a general maintenance and monitoring manual can be completed.

2. Goal & Objectives

The goal of this internship project is to:

Conduct a feasibility analysis, preliminary design and cost approximation of a constructed wetland project for secondary treatment of the Greenland landfill leachate.

Within a period of 3 months the following objectives will be accomplished:

1. Gather all data to have a complete picture and understanding of the current situation and design environment. This includes: watershed characterisation, weather data, determination of land use in the area, landfill size, size of potential leachate treatment plan, flow range, composition and concentration of water contaminants, Barbados' natural wetland state, and birds habitat.

2. Undertake a literature review on constructed wetlands in order to build up the necessary knowledge to carry out the project.

3. Determine the most suitable type of wetland considering all the conditions, constraints, and expectations of various stakeholders.

4. Design a preliminary wetland which includes
    a) Modeling possible scenarios
    b) Determination of expected nitrate removal
    c) Determination of the surface area, volume of water, and perimeter required
    d) Design of physical components such as: inlet, outlets, berms, etc.
    e) Drawing of the cell profile
    f) Positioning the wetland on the maps

5. Perform a cost analysis

6. Satisfy the requirements of the McGill University Bioresource Engineering course BREE 491- Design II

7. Satisfy the requirement of McGill University Urban Planning course URBP 519 – Sustainable Development Plans

3. Approach & Methodology

In order to achieve the objectives listed in the previous section, a GANTT chart was used and a journal was kept for successful planning. This supported our choices on the approach and methodology that should be used throughout the internship.

The overall approach and methodology used is summarised below. Table 3 provides a detailed listing of the tasks and activities completed throughout the project.

- Complete an extensive literature review
- Obtain information on the Greenland landfill and become familiar with the functioning of the leachate treatment plant proposed by New Water Inc.
- Meet with personnel from New Water Inc., more specifically with our mentor, Robert Hawking
- Visit the Greenland landfill site and the surrounding area
- Meet with various professionals to gather information about wildlife and vegetation native to Barbados
- Meet with McGill engineering professors for a discussion of the design portion of the project
- Select the type of wetland
- Select the location for the wetland system
- Draw the surface shape and depth profile of the wetland cell
- Design the physical components: inlet, outlet, berms, emergency spillway, etc.
- Writing of monitoring and maintenance section
- Perform a cost analysis
- Redaction of internship report

The realisation of these activities marked the accomplishment of the internship goal and objectives.

Table 3: GANTT Chart

Tasks \ Weeks	septembre 3, 2007	septembre 10, 2007	septembre 17, 2007	septembre 24, 2007	octobre 1, 2007	octobre 8, 2007	octobre 15, 2007	octobre 22, 2007	octobre 29, 2007	novembre 5, 2007	novembre 12, 2007	novembre 19, 2007	novembre 26, 2007	décembre 3, 2007	décembre 10, 2007	Completed
1- The watershed is characterized																
Read Report made on Greenland Landfill Projec			■													X
Get Burnside Report on Greenland Landfill			■													X
Get geospatial data of the greenland watershed (paper maps)			■													X
Get digital maps of the site and surroundings						■	■									X
Visit GreenLand Landfill proposed site			■													X
Visit Land and Survey Department of Barbados			■													X
Obtain Long Pond Watershed Report from Robin Mahon										■						X
2- Find most suitable wetland for this particular application																
Litterature Review			■	■	■	■	■	■	■							X
Fundamental of wetland functionning			■	■	■	■										X
Case study on use of wetland for landfill leachate			■	■	■	■										X
Get information on various wetland type			■	■	■	■										X
Get EPD water quality requirement - Class I			■													X
Determine feasibility of doing a wetland				■	■	■	■	■	■	■						X
Meeting with:																
Dr. Karl Watson							■	■	■							X
Prof. from UWI - expert on fauna and flora (A.Fields & M.Carrington)									■							X
Ryan from Graeme Hall Nature Sanctuary										■						X
3- A wetland system is designed with considerations to:																
a) respect of the environmental conditions																
Visit Mangrove Pond Landfill				■												X
Visit Greame Hall Wetland										■						X
Operating treatment plants from New Water inc				■	■	■										X
b) ownership of the land																
Map the site with GIS											■	■	■			X
Present a proposed site for Wetland								■	■	■	■	■	■			X
Use GIS to represent the proposed site												■	■			X
c) wetland conditions needed to achieve nitrate removal																
Expected efficiency							■	■	■	■	■					X
Seasonality Analysis							■	■	■	■	■					X
Proposed type of Wetland							■	■	■	■	■					X
Design the wetland system											■	■	■			X
Write maintenance considerations													■	■	■	X
d) ensure that the effluent water meets the CZMU standards																
Visit Government Printery			■													X
Visit Costal Zone Management Unit			■													X
4- Cost benefit analysis													■	■	■	X
Course requirement																
Plan and Time Schedule Document			■													X
Oral presentation for the first presentation			■													X
Mid-Term progress report						■										X
Mid-Term oral presentation						■										X
Meet with Susan						■										X
Progress Report Internship									■							X
Final Report															■	X
Final Presentation															■	

4. Design

4.1. Design Considerations and Current Situation

4.1.1. Influent Qualities & Characteristics

The Greenland landfill is equipped with a leachate retention pond that is designed for a ten-year return period event capable of holding a maximum of 5200m^3 (R.J.Burnside International Limited 2007). The various wastewater sources and daily volume that will be treated in the landfill wastewater treatment plant are described in 4.1.1.1. Note the abattoir wastes and hauled sewage will be carried by trucks to the landfill to be treated with the leachate.

Table 4.1.1.1: Flow rates of the various components of the leachate

	Maximum Day Before Equalization	Maximum Day After Equalization (Treatment Design Flow)
Leachate (m^3/day)	5,200	302
On-site Sewage (m^3/day)	8	8
Abattoir Wastes (m^3/day)	4.5	2.3
Hauled Sewage (m^3/day)	49	36.5
Total (m^3/day)	**5,262**	**349**

(R.J.Burnside International Limited 2007)

Based on the New Water Inc. proposed design, the leachate leaves the retention pond and are sent to an equalization basin in order to provide the plant with a maximum constant flow rate of approximately 350m^3/day. From the Burnside report, the flow range that will be used for the design of the wetland is 30 to 350 m^3/day.

The water quality entering the first treatment plant is presented in table 4.1.1.2.

Table 4.1.1.2: Concentrations of various parameters of leachate

Parameter	Design Concentration for Blended Equalized Influent
Biological Oxygen Demand (BOD_5) (mg/l)	9,000
Total Suspended Solids (TSS) (mg/l)	1,600
Total Kjeldahl Nitrogen (TKN) (mg/l)	610
Total Ammonia-N (mg/l)	550
Fats, Oil & Grease (FOG) (mg/l)	340

(R.J.Burnside International Limited 2007)

The ultra-filtration system proposed by New Water Inc. is expected to treat the wastewater to effluent concentrations as described in table 4.1.1.3.

Table 4.1.1.3: Expected concentrations of the various wetland influent parameters exiting the membrane filtration plant proposed by New Water Inc.

Parameter	Expected
PH	6.0 to 9.0
BOD5 (mg/L)	≤5
TSS (mg/L)	≤5
TP	≤1
TN (mg/L)	≤10+n.b.org.N[1]
NH3-N (mg/L)	≤1
NO3 Max (mg/L)	≤10
Fats, Oils and Grease (FOG) (mg/L)	≤15
Total residue Chlorine	≤0.1
Residual chlorine (mg/L)	≤0.1
Calcium (mg/L)	1000
Sodium (mg/L)	200
Potassium (mg/L)	300
Sulphate (mg/L)	300
Manganese (mg/L)	80
Magnesium (mg/L)	90
Iron (mg/L)	60
Zinc (mg/L)	10

(New Water Inc. 2007)

[1] n.b.org.N: non-biodegradable soluble organic nitrogen

The effluent from this treatment plant goes directly into the constructed wetland for further polishing of the water. This water quality data is selected as the influent quality entering the wetland and will be used for the design as well as for determining the feasibility of this project.

4.1.2. Effluents Standards Requirements

The constructed wetland is designed to polish the treated water according to governmental regulations before discharging it into the surrounding environment. This measure serves to decrease, as much as possible, the negative impacts of the leachate on the marine environment downstream. The end of pipe standards proposed by the Environmental Protection Department (EPD) is defined as Class 1 and is described in table 4.1.2.

Table 4.1.2: Effluents standards proposed by EPD

Parameter	Units	End of Pipe Standard Class 1
pH range	-	6.0 – 9.0
BOD_5	mg/l	30
TSS	mg/l	30
Total Nitrogen	mg/l	5
Total Phosphorous	mg/l	1
Faecal Streptococci	colonies / 100 mls	< 35
Faecal Coliforms	colonies / 100 mls	< 200
Total Residual Chlorine	mg/l	0.1
Fats, Oils & Grease (FOG)	mg/l	15
Floatables	-	Not visible

(R.J.Burnside International Limited 2007)

From the values in Table 4.1.2 and the effluent concentrations expected out of the treatment plant (listed in table 4.1.1.3), it is possible to determine the design performance of the constructed wetland. The constructed wetland is expected to reduce the total nitrogen concentration from 10mg/L to at least 5mg/L in order to comply with the EPD standards. It is important to note that less than 1 mg/L of ammonia is expected in the treated water. Consequently, the bulk of the total nitrogen content consists of nitrates (NO_3^-). Therefore, the constructed wetland is designed to optimize the denitrification mechanism.

4.1.3. Hydraulic Considerations

The leachate production rate from the landfill is influenced by the rainfall events and the cells area. The precipitation that infiltrates the waste is collected through the leachate collection layer, and stored in the leachate retention pond. Precipitation falling outside the cell boundaries or running off the top waste layer will overflow and be drained out through ditches. (R.J.Burnside International Limited 2007).

AS the cell ages, the top layer of waste becomes impermeable. Therefore, the water run off the surface and ends in the side drains. At the beginning of the cell operations, the top waste layer is not well established, therefore precipitation percolates to the leachate collection layer instead of running off the surface. Thus, the highest amount of leachate being collected and treated in a landfill is at the beginning of its operation. (R.J.Burnside International Limited 2007)

The Hydrologic Evaluation of Landfill Performance model (HELP) was used in order to estimate the leachate generation of the Greenland Landfill. The 100 year precipitation record for Barbados or for any other Caribbean nation was not available for this analysis; thus, the precipitation data of Miami was used to estimate the leachate generation. From the latter it can be concluded that the peak leachate generation rate can be as high as 5000m^3/day, but the creation of a retention pond allows for equalization of the flow to a peak design flow rate of approximately 300m^3/day. (R.J.Burnside International Limited 2007)

4.1.4. Actual Bird Habitat Situation in Barbados

Wetlands can serve as watering holes and habitats for migratory and resident birds. In fact, the presence of suitable water bodies on the island encourages migratory birds to land. Furthermore, Barbados lies on the transatlantic migratory flyway for eastern North American bird species. The chances that these birds will land on the island depend on many factors such as weather patterns, air currents, influence of southerly winds on the usual north-east currents, the possibility of tropical systems, and the visibility of water bodies. Over 150 migratory bird species have been recorded in Barbados, thirty-five of which are common shorebirds passing through between July and December. In fact, Graeme Hall Swamp, Chancery Lane Swamp, Long Pond, and Green Pond are important refuge habitats for such birds. (Government of Barbados 2002)

4.2. Selection of the Wetland Type

Constructed wetlands can come in two different forms; surface flow wetland and subsurface flow wetlands. These two types accomplish comparable functions, but perform differently under various conditions. Generally, both types are exposed to similar temperatures and include significant anoxic conditions allowing for denitrification to occur. However, the major difference lies in the availability of carbon. The surface flow wetland has a constant source of carbon from plant detritus, where as the subsurface flow wetland requires an additional supply of carbon due if the BOD levels in the influent are low. Figure 4.2 compares the performance of both types. It shows that for nitrate input concentrations greater than 6mg/L, the removal is more efficient in surface flow wetlands. This is possibly due to the less-developed root system in the subsurface wetlands. (Reed 1995)

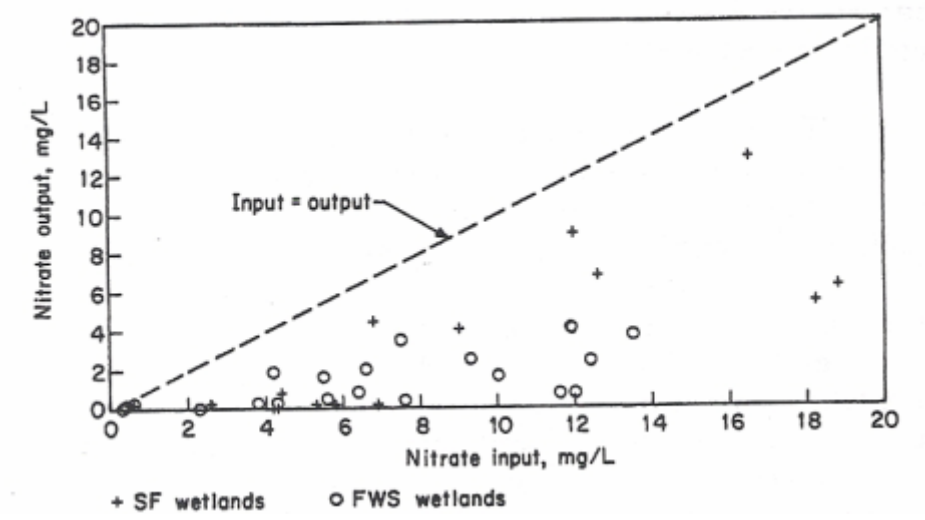


Figure 4.2: Nitrate removal in function of wetland type

On a different note, the surface flow wetland is an environmentally friendly and natural treatment that can create a biodiversity pool. Once the wetland has matured, no nutrients or carbon need to be added to the system and the water quality is safe for waterfowl life. Moreover, the water body serves as resting and feeding grounds for migratory birds in addition to nesting areas for resident birds. Additionally, the surface flow wetland is an aesthetically pleasing alternative that helps to counter-balance the unattractive reality of waste management.

Considering all criteria mentioned above, a surface flow wetland is selected as a natural polishing treatment to reduce the nitrate concentration of the treated leachate.

4.3. Hydrological Modelling

When designing a constructed wetland for nitrate removal, one of the major challenges is to determine the retention time required to achieve the desire level of treatment. In the process of modeling the wetland, two major trends exist: hydrological and microbial modeling. The advantages with microbial models are that they consider the complete nitrogen cycle and the fluctuating removal rate. However, those models are extremely complicated, often site specific and require data which are not easily accessible. The most common approach to design a wetland is to utilize hydrological models, which assume a constant transformation rate. The use of such models has been suggested in many handbooks on wetland construction.

The hydrological model equations and calculations are presented in section 9.2 of the appendix. A summary table of the results can also be found.

Based on the hydrological modeling, the best option would be to accept effluent nitrate concentrations between 4 to 5 mg/L under maximum flow situations. Such level of treatment is in accordance to EPD class 1 requirement. This means that the cell's surface should be approximately 1600m^2. Furthermore, it takes into consideration the relationship between the treatment efficiency, the surface area, the retention time during the low flow period of the year, and the water loss through evapotranspiration. Hence, the selected option provides decent hydraulic retention time throughout the year. In addition, the area that it requires allows for a positive water balance year round.

Scenarios aiming for lower nitrate levels would require greater surface areas. However, there is a limit to the maximal allowable area. This limit is found by comparing the volume of water that evaporates from the wetland with the minimal incoming flow of 30m^3/day. Areas under which the volume lost via evapotranspiration is larger than the minimal inflow are considered too big. Such surface areas would have negative water balances and the wetland could potentially run dry for some periods of the year. Consequently, a wetland can decrease in treatment efficiency when it experiences significant droughts.

Moreover, wetlands with large surface areas are susceptible to other problems. As one can observe in table 9.2.1.2 of appendix 9.2, the retention time for periods associated to low flow rates and treatment levels of 3mg/L is of about one month and a half. This is extremely long since the water would almost be stagnant in the cell and this could affect the microbial communities. Hence, the system could potentially undergo anaerobic conditions, which would lead to odor issues and/or ineffective treatment.

On the other hand, designing for effluent nitrate levels above 5 mg/L under maximum flow conditions represent inappropriate treatment for discharge in the environment.

4.4. Cell Depth & Side Slopes

The cell depth throughout the wetland differs as the water flows from the inlet to the outlets. According to the literature review conducted prior to this design, it is recommended that the bed profile of the wetland have a wave-like pattern (BarrEngineeringCo.; MelbourneWater 2005). The water depth along the wetland fluctuates between 0.3 and 0.6 m. This accounts for different root depths associated with different types of vegetation. Furthermore, a micro-pool of 1.2 m in depth is designed to ensure settling of solids, appropriate retention time given a surface area, reduction of flow velocity, and reduction of short-circuiting.

The bed profile of the wetland is designed to progressively decrease in depth as it approaches the contour of the wetland. Hence, a 3H:1V side-slope ratio is implemented. In addition, two small islands are designed for biodiversity purposes and are given depths of zero meters in order to represent them at ground level.

A free-hand sketch was first used to design the initial shape of the wetland and its features. The sketch consisted of tracing a contour and positioning the small islands. The design was then transferred to an Excel spreadsheet, where each cell would represent $1m^2$ of surface area and would contain an elevation value in meters as represented in figure 9.3 of the appendix. The cells outside of the wetland and the ones associated with the small islands were assigned zero values to represent the ground surface. This concept simulates a digital elevation model that is commonly used in Geographical Information Systems for topographic or hydraulic analysis. The next step was to convert the Excel spreadsheet into comma-separated values in order to read and manipulate it using the MATLAB application. The MATLAB script is available in section 9.3 of the appendix. After several adjustments to the Excel spreadsheet it was possible to design the shape and features of the wetland in accordance with the cell depth and side-slope criteria. The volume, the surface area, and the perimeter of the wetland designed in Excel are then calculated, with the help of matrices in MATLAB, to respective values of $1618m^2$, $1552m^3$ and 170m.

4.5. Volume of Soil & Gravel

The topsoil and gravel layers are designed to respectively account for 0.25 and 0.15meter in depth (DuPoldt 2000; Morris and Laura 2004). The latter is meant to ensure proper nutrient storage and supply to plants and microorganisms, in addition to provide the appropriate habitat for those organisms. The volumes required for soil and medium crushed stones were approximated by multiplying the area (1618m^2) by the depth of each layer. Thus, the volume of soil is 242m^3 and the volume of medium gravel is 405m^3.

4.6. Berm Size

Considering the free board required, the width to facilitate any machinery operations in the wetland and maximal side-slope, the berm going all around the wetland has been sized and should have the following characteristics:

- freeboard of 0.6 m
- inside slope = 3H:1V
- outside slope = 3H:1V
- crest width = 4 m
-

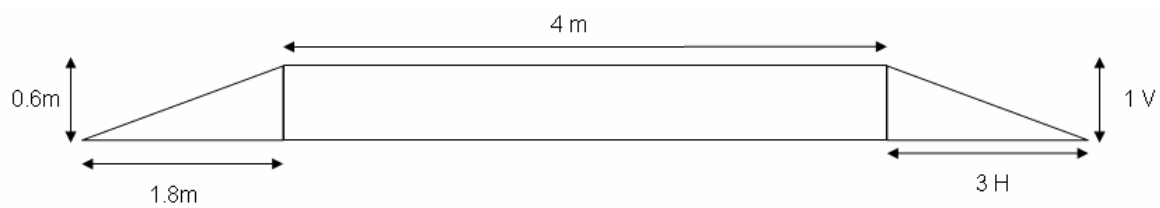


Figure 4.6: Berm dimensions

A freeboard of 0.6m should provide proper buffer in the case of heavy rain and prevent against over flow of the wetland. Also, a crest width of 4m permits machinery to access the inside part of the cell.

Such a berm has a unit volume of about 3.5 m^3/m length. The perimeter of the cell will be approximately 170m, which will give a total berm volume of roughly 924m^3. The earth excavated for the wetland construction will be used to build the berm.

4.7. Inlet & Outlet Structures

The inlet structure will be a 6inch diameter pipe discharging directly from the leachate treatment plant. This inlet pipe should be connected to a diffuser using a "T" junction to allow for an even distribution of the flow throughout the fore bay. The "T" junction should be wrapped in concrete, to avoid disassembly. Moreover, the holes on the diffuser should be placed upward, to reduce as much as possible short-circuiting and flow velocity.

The outlet structure selected consists of pipes disposed in a reverse slope fashion, discharging into a riprap structure leading to the creek. A concrete box could also be built as a transition phase between the pipes and the rip-rap. In this case, it is required to have one-way valves on each pipe, in order to prevent backflow. The present design has two outlet pipes of 8inch diameter each. This allows for a maximum outlet flow of 540m^3/d with maximum velocity of 0.1m/s. Since the daily flow should not exceed 350m^3/d, there will be a big enough safety factor to account for the important rainfall events occurring between the months of July to October.

In order to have some control over the water level in the cell, two systems are possible. The first option is to use flexible plastic for the last section of the pipe outlet. Hence, the end of the pipe could either be lifted or lowered in order to change the water level to the desired depth. Such system could easily be built out of wires and pulleys. Secondly, a 90 degree elbow could be placed at the end of the pipe. In this case, rotating the elbow can modify the water level. The latter alternative is more solid and reliable.

There should be a lockable structure dug in the ground to encompass the outlet pipes along with the system used to control the water level. Such construction protects the infrastructure against vandalism.

It is very important that the effluent of the wetland is discharged into the creek via a riprap conduit. This looks more natural, and is therefore better viewed from the public point of view.

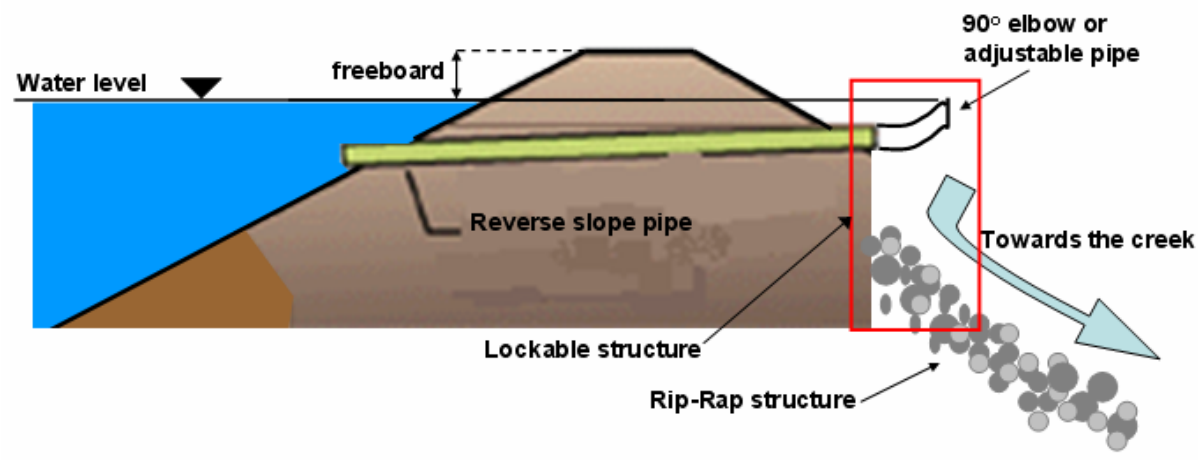


Figure 4.7: Schematic of the reverse slope outlet structure

4.8. Draining System

For maintenance purposes, it is important that the wetland cell is easily drained. Literature suggests a drainage system capable of draining the water body within 24 hours (BarrEngineeringCo.).The idea of having underground drains in the deeper areas of the cell was discussed. However, such structure would represent extra costs and might clog over the years. For this reason, no drainage system was designed. Instead, it is suggested to use submersible pumps to drain the wetland when required. Such pump would provide reliable effectiveness. Also, it may be cheaper to rent a pump for one day then to incorporate drains in the design of the wetland cell that could lead to potential problems associated with drain usage. When using submersible pumps in shallow water, it is a good idea to put the pump in a hole [dug with a shovel] to avoid filling the pump with mud or sediments.

4.9. Emergency System

Many types of emergency systems exist. A pipe emergency spillway could be used to ensure that no water spills over the berm. Assuming that the head difference between the entrance and the exit of the pipe is of 0.3m and that the pipe is 6 m in length, a 8inch diameter pipe could handle overflows up to 485m^3/d.

A crushed stone emergency spillway could also be used. This system consists of a channel made on the side of the berm in which the overflow of water runs. For such infrastructure, it is important to cover the channel with rocks to protect against erosion. It is strongly recommended that the rocks are assembled in what is called a

Gabion Mat. Such structures are about 6inch thick. Also, the use of an impermeable geotextile prevents from infiltration in the berm. The geotextile should be installed between the clay layer and the crushed stones layer.

Like the outlets, the conduit should unload into the riprap structure leading to the creek. However, the price for crushed stones being relatively high, the use of this type of spillway may be more expensive than using a simple pipe emergency spillway.

4.10. Additional Features

Two islands were designed within the wetland cell. Not only such feature increases the beauty of the wetland by making it look more natural, but they also enhance the bird establishment by providing different niches to bird populations. The island could be vegetated with sedges and white mangroves. This flowering tree would be one of the best mangrove species capable to adapt to a fresh water environment. As it is the case in Graeme Hall Nature Sanctuary, mangrove islands provide habitat for different bird species such as the snowy egrets. Mangroves would also provide habitats for land crabs.

4.11. Site Selection

Two potential sites for the establishment of the wetland system were surveyed next to the Greenland landfill. Location number one runs between the leachate treatment plant platform and the creek. Location number two is just on the other side of the creek, on the agricultural field. Refer to figure 4.11 to see these sites. The green polygon represents location #1 and while the red polygon represents location #2.

The analysis made with the Geographical Positioning System (GPS) indicates that location #1 has an area of 2420m^2, while the area of location #2 is 3340m^2. As discussed in section 5.3, the actual surface area required for the cell ranges roughly between 1500m^2 and 2000m^2, depending on the treatment efficiency desired. This implies that the total area occupied by the wetland will be greater if the surface occupied by the berms and the buffer zone surrounding the system are considered.

Therefore, due to its very narrow shape that complicates maintenance and to its limiting surface area, location #1 was discarded. On the other hand, location #2 is still easily accessible from the leachate treatment plant. Moreover, the size of the field does not restrain the design, and would even allow for future projects, like the construction of a boardwalk and/or the creation of a park next to the wetland.

Figure 4.11: Maps showing the potential sites

4.12. Vegetation

4.12.1. Vegetation Selection

When planning the vegetation, the designer should look at the ratio of open water to emergent vegetation. This factor has often been overlooked, resulting in numerous problems such as low oxygen levels, odor problems, and an increased number of mosquito breeding niches (EPA 1999). For this project, the most favorable ratio of emergent vegetation is of about 30 percent. In addition, plant selection depends on the type of water being treated. For wastewater treatment, the establishment of a dense stand of vegetation is more important than the species themselves (DuPoldt 2000). At an early vegetative stage, the best practice is to have higher plant densities since vegetation stands develop sooner. However, higher costs are associated with this initiative.

Several factors need to be considered when selecting the vegetation. A good understanding of the natural system will help establish healthy, self-maintaining, and effective stands. The main factors that have to be considered are the following:

- Well adapted to the surrounding environment in terms of:
    - Soil
    - Climate
    - Vegetation
    - Wildlife
- Water depth
- Light availability
- Ease / risk of invasion

The first of the above criteria could be respected by using native plants species of Barbados. When looking at various handbooks on constructed wetlands, it was noted that *Cyperus* (Sedge), *Juncus* (Rushes), *Phragmite* (Reeds), or *Typha* (Cattails) are the four main families of plants that are recommended. However, the three last families are not present in Barbados according to the *Flora of Barbados* book used for this analysis. (Gooding, Loveless et al. 1965)

Based on the collected information, a summary of the plants commonly used in constructed wetlands was made. This summary is presented in 4.12.1.1. Subsequently, the *Flora of Barbados* helped to narrow down the list of potential plants that grow naturally in Barbados. In addition, plants generally found around fresh water wetlands were included in the list presented in table 4.12.1.2 according to *Plant Communities of Barbados*. (Gooding 1974)

Nonetheless, a flora specialist of Barbados should be consulted in order to ensure that the plants would adapt to the conditions present in the constructed wetland (clay soil, saturated soil, presence of heavy metals, and the ability to establish a dense stand).

Table 4.12.1.1: Vegetation Summary from Literature

Name	Flora of Barbados	Number of the same species
Alternanthera philoxeroides	No	7
Aster squamatus (Spreng)	No	-
Bolboschoenus maritimus (L.)	No	-
Cyperus papyrus		
Commelina communis	Yes	9
Cyperus glomeratus (L.)	No	
Cyperus papyrus	No	
Cyperus spp.		19
Digitaria sanguinalis	Yes	
Erigeron canadensis	Yes	4
Echinochloa crus-galli	No	1
F. miliacea	No	0
Glyceria maxima,	No	0
I. globosa	No	0
Ipomoea aquatica (free-floating)	No	27
Juncus spp	No	
Lemna spp.	Yes	3
M. violaceum .	No	
Mint (Mentha arvensis L.).	No	
Miscanthidium violaceum.	No	
P. mauritianus	No	
Scirpus maritimus	No	
Penniserum purpureum	Yes	
Hydrocotyle umbellata L	No	3
Phalaris arundinacea	No	
Phragmites communis	No	
Pistia stratiotes (free-floating)	No	
Polygonum hydropiper	No	
Potamogeton pectinatus	No	
Primula (Primula veris L.),	No	
Salix nigra Marshall),	No	
Scirpus atrovirens georgianus.	No	
Scirpus spp.	Yes	7
Typha latifolia	No	
Typha latifolia (L.)	No	
Typha latifolia L	No	
Typha spp.	No	
Eichhornia crassipes	Yes	
Z. latifolia	No	

Table 4.12.1.2: List of suggested plants found in Barbados

Scientific Plants name	Zone	Annual/ Perenial	Height (m)	Physionomy	Soil	Anaerobic tolerance	Habitat
Bacopa monnieri	Shallow	Perennial	0,3	Erect			
Caperonia castaneifolia	Shallow	Annual	0,3 - 0,6	Erect			Mud pond margin
Chloris radiata	Shallow	Annual	0,35				Common weed of dry ground
Commelina diffusa	Shallow		0,3		Fine to medium	Medium	Shade tolerant
Cyperus planifolius	Shallow	Perenial	0,3 - 0,6				
Digitaria sdscendens	Shallow		0,3		Fine to coarse	low	Shade Intolerant
Eleocharis interstincta	Shallow	Perenial	0,4 - 1,0	Spreading by rhizome			
Eleocharis macrostachya	Shallow	Perenial	0,25 - 1,0	Spreading by rhizome			
Erigeron canadensis			1,0	Erect			
Panicum geminatum	Shallow	Perenial	0,45				Damp /swamps
Paspalum distichum	Shallow	Perenial	0,4		Coarse to medium	High	Moist / Ponds
Pennisetum setosum	Shallow	Perenial	0,6				Varies to dry to moist
Pontedaria cordata	Shallow		0,3				Full sun to partial shade
Scirpus brizoides	Shallow	Annual	0,6	Tufted			
Scirpus ferrugineux	Shallow	Perenial	0,2 - 0,8	Tufted			
Setaria barbata.	Shallow	Annual	0,45	Tufted			Shade/under trees/moist
Setaria geniculata	Shallow	Perennial	0,3				Dry to Moist /wet ditch
Cyperus odoratus	Deep	Annual	1,0	Erect	Coarse to medium		Sun
Cyperus alternifolius	Deep	Perenial	1,5				moist environment
Pennisetum purpureum	Deep	Perenial	2,0 - 4,0	Tufted/Erect	Fine to coarse	None	
Eleocharis mutata	Deep	Perenial	1,0	Spreading by rhizome			
Eriochloa punctata	Deep	Perenial	1	Culm erect			
Setaria tenax	Deep	Perennial	1 - 1,5	Tufted			
Ludwigia octavalis	Deep		over 1m				Gully / Damps gutter / Pond
Ludwigia erecta	Deep		up to 2 m				Swampy Ground
Nymphaea ampla	Pool			Floating Plants			This is a native water lily

4.12.2. Planting and Vegetation Establishment

The establishment of vegetation in a constructed wetland is a process that requires attention. The water level, type and amount of soil, as well as the planting process itself are parameters that affect colonization of the basin. (EPA 1999; DuPoldt 2000)

Soil texture and chemistry are important players in plant selection. Some plants grow well in sandy coarse soil, while others perform better in clay. Trying to establish plants in a soil type that is inappropriate may be detrimental to the growth of the plants (EPA 1999). In addition, the pH characteristics of the soil may impact the nutrient availability and restrain, or even stop, the growth of certain plants (EPA 1999). In some cases, the concentration of micro- and macro-nutrients is not sufficient and organic fertilizer may be required. As mentioned previously in section 4.5, it is required to have about 20 to 30 cm of loose soil at the top of the gravel layer in order for the plant to properly grow roots (DuPoldt 2000). When selecting the soil, it is important to choose a type that has little or no undesired seeds (EPA 1999; EPA 2000).

The planting process can be conducted using either the seedlings or transplants method. The seedling method demands less labor and is a less expensive option. However, the successful establishment of a desired number of plants is not guaranteed. (EPA 1999) In addition, seedling and young shoots could be eaten by the wildlife (DuPoldt 2000). To avoid the latter, one could prepare seedlings in a nursery so that the plants are transplanted in the wetland only when they have reached an acceptable size. Another option to introduce native plants in a newly constructed wetland is to harvest them from wetlands in the area, and transplant them. However, this should be done only if permitted by law. Moreover, one needs to use common sense regarding the quantity of plants to be removed from the natural wetlands.

During the germination stage of the plants, the wetland should be drained out in order to only have a saturated soil. Consequently, this allows the seeds to germinate and emerge. The water level can be increased once the shoots are 10 to 12 cm long. The plants should never be over flooded. In fact, during the first growing season, too much water is more detrimental than too little.

The design consideration should incorporate the positioning of the vegetation. Planting vegetation strips perpendicular to the flow helps to decrease the risk of short-circuiting. In addition, it is recommended that the outlet of the system is located in a vegetated area, otherwise the desired water standards may be altered due to algae growth in the open water. (EPA 1999)

Lastly, the establishment of fully mature vegetation stands can take up to 2 years (DuPoldt 2000). Therefore it is important that all parties involved in the wetland construction be aware of this since it might take time before the desired effluent quality is obtained.

4.13. Wetland as Bird Habitat

According to Karl Watson, a local naturalist and bird watcher, the most common species of birds recorded and hunted in Barbados are listed in table 4.13. The migratory birds have needs, which are similar to the resident species. These needs include food, water, proper shading, hiding grounds from predators, and nesting spots.

Table 4.13: Common migratory bird species hunted in Barbados

Local Name	**Scientific Name**
Longleg	Tringa flavipes
Chirp	Calidris melanotos
Cue	Calidris himanoptus
Pica	Tringa melanoeuca
Plover	Pluvialis dominica
Duckleg	Limnodromus griseus
Sandy Plover	Arenaria interpres
Curlew	Numesius phaeopus
Cotton Tree Plover	Bartramia longicauda
Snipe	Gallinago gallinago
Sandy Snipe	Calidris alba
Blue Winged Teal	Anas discors
Green Winged Teal	Anas creccas

(Government of Barbados 2002)

Considering the list of birds provided above, the idea of having islands of irregular shape in the middle of the wetland is important in order to provide some hiding ground and potential nesting areas. For example, in the Graeme Hall Swamp, the island with mangrove is highly inhabited by egrets. In addition, islands mimic natural wetlands better, and therefore create a more attractive environment for the birds.

The forebay and the micropool are not absolutely essential, considering that it is expected to have very little sediments in the water. However, keeping them would give the birds, especially ducks, some open water areas. Without these, attracting birds to the wetland would be more difficult.

5. Costing of the Project

The approximation of the total cost was evaluated with the help of Robert Hacking. From the literature review and the preliminary design, a list of the required items along with their respective quantity was made. Total cost per item is then approximated using the fees and rates that apply for Barbados.

Table 5: List of material required for project location #2.

	List of material required for project location #2 *(in Barbados Dollars)*				
	Item Description	**Specifications**	**Quantity**	**Cost / unit**	**Total Cost**
	Excavation		2300 m^3	30 $/$m^3$	69000 $
	Bottom	gravel	801 ton	57 $/ton	45652 $
	Bottom	soil	534 m^3	60 $/$m^3$	32036 $
	Bottom (if needed)	liner / geotextile	2241 m^2	7 $/$m^2$	15687 $
	Ripe Rap	crush stone	60 m^3	65 $/$m^3$	3900 $
		geotextile	120 m^2	7 $/$m^2$	840 $
	Inlet	pipes 6 in dia	13 m	45 $/m	585 $
	Outlets	pipes 4 in mm dia	20 m	45 $/m	900 $
Probably not needed	Drains	drains polyethylene pipe-4in dia.	135 m	5 $/m	675 $
		CPVC			
		Geotextile	135 m	7 $/$m^2$	945 $
		valves (butterflies)	5	150 $/units	750 $
Probably not needed	Access Ramp Micropool 1	concrete	30 m^3		
	Access Ramp Micropool 2	concrete	30 m^3		
	Berms	Soil required	1092 m^3	60	65520 $
	Plants	seedlings/transplants	9870	0,5 $/plant	4935 $
		plants on berms	3912	0,5 $/plant	1956 $
		mulch, weed netting & fertilizer			10 000 $
	Labour	not for excavation			0 $
		pipeline excavation	15 day	50 $/d	750 $
		planting	100 day	50 $/d	5000 $
		nitrate fertilizer			
	Equipment				0 $
	Contingencies				10 000 $
					264 770 $

Assuming contingencies of 10,000Bb$, the realisation of the project would not exceed 265,000Bb$. This is relatively small compared to the overall budget dedicated to the construction of the Greenland landfill.

6. Maintenance & Monitoring

Wetlands require routine maintenance and monitoring if they are to perform well. The maintenance process serves to ensure that the flow reaches every part of the wetland and that no short-circuiting occurs. Also, it serves to maintain a vigorous vegetative cover and prevent undesired invasive species to establish in the wetland.

In addition, the forebay should be dried and cleaned out every two years to protect the vegetated area from excessive sediment build-up. If not done properly, sediments will eventually need to be removed from the shallow areas, which would most likely damage the vegetation and therefore de-regulate the system. It is possible to monitor sediments accumulation in the forebay using a fixed marker to determine the sediments depth (StormwaterManager'sResourceCenter).

It may be desirable to harvest the vegetation in order to maximize the removal of heavy metals and nutrients, which tend to accumulate in the plant tissues. Harvesting the plants is more important for heavy metal removal, since contrary to nutrients which can be degraded by other processes, their only main removal pathway is through plant adsorption and extraction. If not harvested, heavy metals and nutrients return back to the water as the plants decay.

Additional maintenance requirements include a regular monitoring of the wetland system. Effectively, constructed wetlands, like any other natural system, are expected to experience some variations over time. Consequently, by monitoring the changes, any major disturbance can be identified before it becomes a major issue. An example of monitoring checklist is included in Appendix 5 of the Melbourne Water document (2005). The suggested parameters to verify include water quality, sediment accumulation at inflow point, presence of litter and sediment in inlet and outlets, integrity of the overflow structure, evidence of dumping, condition of terrestrial and aquatic vegetation, need for re-planting, settling or erosion of banks, and damage or vandalism.

Monitoring for the establishment of invasive species is also important during the first year of the system’s operation. Inspections should be performed regularly, and invasive species should be manually removed. The use of herbicides is not suggested since it can severely impact the emergent vegetation.

Inspection and monitoring of the system should be conducted at least twice a year during the first three years after construction, and annually from then on. Gathered information from such inspections should be recorded, mapped and assessed.

7. Self-Evaluation

At the beginning of the internship, the team's mentor, Robert Hacking, from New Water Inc. presented the students with a clear and well defined project. Throughout the internship period, Robert Hacking was present and helpful. Moreover, he was always supportive when the group needed maps, contact information, or technical information. Also, the numerous meetings between the team and their mentor helped the two parties remain up to date, which allowed the team to focus on work that was actually needed from New Water Inc. as well as the work required for their internship objectives.

The initial vision remained the same throughout the internship since the project was well defined from the beginning. This was not the case for the project goal, which was redefined throughout the process in order to make it more realistic. Furthermore, the objectives underwent major transformations during the internship period due to a better understanding of the context of the project and its constraints. As the project evolved, the students became more realistic with regards to what they could achieve. Also, as their knowledge on wetlands increased, they realized that some of their initial objectives were not relevant.

Overall, the internship went well and smoothly; the refined goal and objectives were met. In addition, collaborating with New Water Inc. allowed the students to gain much experience in project management, and provided them with good exposure to the business world, which differs greatly from an academic context. Lastly, the work achieved enhanced the students' knowledge on a topic which is extremely relevant to their field of study.

8. Conclusion

The internship offered by New Water Inc. to three students from the Barbados Field Study Semester was successfully completed. The students first assessed the feasibility of using a constructed wetland for the secondary treatment of the Greenland landfill leachate. Secondly, they proposed a preliminary design to achieve polishing of the treated leachate to discharge standards set by the EPD.

The surface constructed wetland presented in this report would provide a natural polishing treatment to the effluent of the leachate treatment plant proposed to SSA by New Water Inc. It is designed to reduce the nitrate concentration by about 50% and to considerably decrease the heavy metal concentration. Therefore, the proposed wetland system would treat the water so that the end-of-pipe standards set by the environmental protection department are met. Moreover, the wetland offers an opportunity to increase biodiversity, where migratory and resident bird species can co-exist. It also provides aesthetic beauty that counter-balances the presence of a landfill in the area.

The goal and objectives of the internship were achieved by first conducting a literature review to gather the knowledge required to assess general wetland performance as well as parameters of importance for wetland design. The design process only started once wetland systems were considered as a good alternative for the Greenland landfill situation. Hence, the appropriate design parameters were determined, and a series of calculations were conducted to establish the requirements in terms of land size, excavation volume, and other physical characteristics. These design parameters were entirely based on a hydraulic model. Furthermore, all potential site locations were explored and a final location was picked. Finally, a rough estimate of the project costing was done and the feasibility of the wetland was determined in monetary terms. In addition, recommendations on the maintenance of the wetland were conveyed from the knowledge gathered.

However, the relatively short time attributed to this project did not allow the team to consider designing under microbiological models. Therefore, further research on the microbiological performance of the wetland is recommended. This project has the potential to generate various graduate research projects.

9. Appendix

9.1. Literature Review

9.1.1. What is a Constructed Wetland

A constructed wetland is a human-made natural system that is mimicking a marsh or a swamp and that is used to treat contaminated water bodies. The main three components are water, substrates and plants. It is designed to utilize mainly microorganisms and plants to remove pollutants such as nitrogen, phosphorous, and heavy metals. The microbe communities and the aquatic invertebrates develop naturally in the system and contribute to treatment process.

Many advantages are associated with treating wastewater from municipal systems, agricultural and industrial effluent or leachate from landfills using a wetland. The main advantage is that it is a low-cost system. It requires minimal energy input and low maintenance since they contain very little mechanical components. Moreover, it has a small ecological footprint as well as a significant aesthetic value. It promotes biodiversity by creating habitats for various species of fauna and flora. It can also be used to absorb and retain high floods, treat water before groundwater recharge, provide, enhance or restore native wildlife habitats.

Associated constraints include the requirement of large area of land. Drought in wetland should be avoided in order to keep the different communities of microorganisms alive and therefore require a constant minimal flow. Furthermore, their performances are fluctuating where as traditional wastewater treatment technologies offer more stable treatment efficiency.

9.1.2. Types of Constructed Wetlands

In the field of wetland design, many type of wetland as been engineered: surface, subsurface and mix. Each of them has their own strengths and weaknesses which makes them more efficient for different types of treatment and conditions. The following section presents each of them.

Subsurface

As the name describes it, a subsurface wetland consists of an underground natural treatment system. It is designed so that water flows within a certain layer of substrate. Its path can either be vertical or horizontal. Furthermore, this type of system is ideal for wastewater with low dissolved solids concentration flowing under relatively uniform flows. Subsurface wetlands are insulated from the ambient air due to plant detritus or mulch layers and the air present in the gravel interface which make them ideal for cold conditions.

This type of wetland experiences smaller rates of atmospheric re-aeration. Anoxic conditions are likely to be found at the bottom of the wetland, while aerobic ones at the top. Therefore, the plant roots and rhizomes have aerobic and anaerobic microsites on their surfaces, which provide the required conditions for nitrification and denitrification. However, microbial processes requiring higher levels of oxygen can be achieved using different methods such as frequent water level fluctuations (tidal-flow), passive air pumps, or direct mechanical aeration through the gravel bed.

In such a system, the hydraulic retention time varies between 3 and 14 days. The basin depth ranges from 0.3 to 0.6 meters. Moreover, the active root zone of aquatic plants appears to be 0.3 meters below the ground surface as recorded in the United-States of America. The average uptake rate of organic loading is 600kg/ha*day. The major sources of carbon for this type of system are dead roots and rhizomes, organic detritus, as well as residual BOD that might still be present in the effluent. (Reed 1995)

Surface

A free water surface wetland consists of a natural treatment system exposed to the atmosphere and the surrounding wildlife, which contains both aerobic and anaerobic conditions within the water body. The upper surface upper surface layer is generally aerobic; algal photosynthesis and atmospheric diffusion are the two main sources of oxygen supplied to the system. However, the anoxic/anaerobic conditions develop as depth increases. It is expected that most of the denitrification processes occur in the deeper part of the water column.

A typical surface flow wetland has a slightly longer hydraulic retention time range that varies between 7 and 17 days. The depth ranges from 0.1 to 0.6 meter.

Furthermore, such systems can receive on average 200 kg/ha*day of organic loading. (Reed 1995)

Similar to the subsurface wetland system, the sources of carbon are organic detritus from plants in the wetland, but an additional source comes from the surrounding buffer elements. Right after a wetland becomes operational, it needs some time to mature in order to get a stable and fully developed treatment potential.

One major benefit of surface wetlands over the subsurface is that it generates habitats for the fauna and flora. The water body is populated with native emergent of submergent plants that are preferably native. Providing a buffering zone around the wetland is a good practice. Such buffering zone includes grassland, shrubs and trees, which serve as resting, feeding and nesting areas for resident and migratory birds.

Comparison

In order to decide on the most appropriate type of constructed wetland, advantages and disadvantages of both types must be taken under consideration. The comparative chart is presented in table 9.1.2.

Table 9.1.2: Advantages and Disadvantages of subsurface and surface flow wetlands

Advantages	Disadvantages
Subsurface Wetland	
Minimization of pest and odors	More expensive to construct per unit area
Greater assimilation potential per unit of land area due to porous medium	More difficult to regulate
Requires less area for same influent quantity	More difficult to maintain
Less public access problems (certain operate in parks)	Repair cost are higher
Detention time Potential shorter	Possible problems consist of clogging and unintended surface flows
Surface Wetland	
Capital and operating cost are low	Requires larger land area
Construction, operation and maintenance are simpler	Less efficient to treat nitrate
Enhancement of biodiversity due to creation habitats	

(Reed 1995)

9.1.3. Nitrogen Cycle

Considering that the major pollutant to be removed for this design project is nitrate, a literature review is done on the nitrogen cycle. This helps to have a better understanding of the mechanisms the drive efficient nitrate removal. The complete picture from the literature review is presented in the following section.

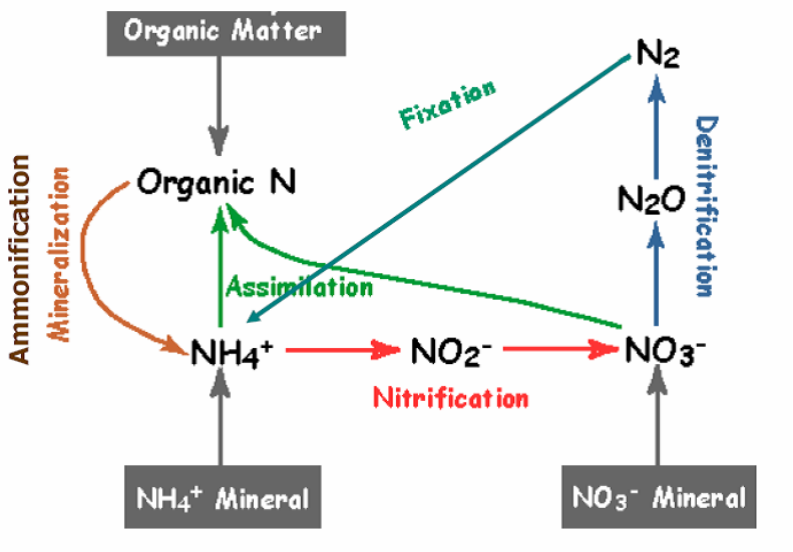


Figure 9.1.3.1: Nitrogen Cycle

The nitrogen cycle has four major sequences; nitrogen fixation, nitrification, denitrification and assimilation. Each of these reactions occurs in different conditions and includes various reactants and products.

Nitrogen fixation converts inorganic nitrogen from the atmosphere into an organic product. For instance, N_2 is biologically reduced by cyanobacteria, such as diazotrophs, to ammonium (NH_3). Another common nitrogen fixation process is lightning. When a lightning strikes, it discharges high energy in the air which triggers the reaction showed in figure 9.1.3.2.

$$N_2 + 3H_2 \rightarrow 2NH_3$$

Figure 9.1.3.2: Nitrogen fixation reaction

The nitrification process consists of the conversion of ammonia/ammonium to nitrate. This transformation process includes two distinct reactions, and therefore involves two distinct types of bacteria. In fact, the first transformation converts

ammonium (NH_3) and ammonia (NH_4) into nitrite (NO_2) due to the nitrosomas bacteria. Subsequently, nitrobacters convert nitrite (NO_2) into nitrate (NO_3). Nitrosomas and nitrobacters are both aerobic bacteria. Consequently, their optimal growth environments are water bodies with high level of dissolved oxygen. Reactions are represented in figure 9.1.3.3.

$$NH_3 + \frac{1}{2} O_2 \rightarrow NO_2^- + H^+ + H_2O$$

$$NO_2^- + \frac{1}{2} O_2 \rightarrow NO_3^-$$

Figure 9.1.3.3: Nitrification reaction

The denitrification process is the final step before the nitrogen is released back as gaseous N_2 into the atmosphere. This reaction occurs principally in anoxic or oxygen-deprived conditions. The process is done with the help of various heterotrophic bacteria such as pseudomonas which use nitrate as the last electron acceptor in their respiration process. It is this metabolic activity that reduces the nitrate back to N_2. figure 9.1.3.4 shows the reaction.

$$NO_3^- + 5H_2 + 2H^+ \rightarrow N_2$$

Figure 9.1.3.4: Denitrification reaction

Another process involved in the nitrogen cycle is the nitrogen assimilation by plants, which can be perceived as a "short–circuit" to the overall process. In fact, plant tissues can store nitrogen. This integration of nitrogen as biomass material removes it from the overall cycle. Therefore, the assimilation occurs when vegetation takes up mineral nitrogen (NH_3, NH_4, NO_2, and NO_3) and converts it to organic nitrogen. This nitrogen is stored in the biomass until the vegetation dies and decays. Only then is the nitrogen released back into the system. Initially, the organic nitrogen is bound to organic molecules, but with time, mineralization occurs. This reaction releases the organic nitrogen in the form of NH_3 and NH_4, which will either be reabsorbed by growing vegetation or converted to atmospheric N_2 through nitrification and denitrification processes.

9.1.4. Nitrogen Removal Mechanisms in Constructed Wetlands

As mentioned in the description of the nitrogen cycle, removal of nitrogen from the effluent involves a nitrification and a denitrification phase. This process implies the conversion of ammonia into nitrate under aerobic conditions, followed by the transformation of nitrate into N_2 under anaerobic conditions. In a surface flow wetland the top layer is usually aerobic due to the dissolution of the oxygen from the air in the water. As the depth increases, the oxygen concentration decreases. This gradually creates anoxic conditions required for the nitrate removal. In fact, the denitrification processes are known to occur deeper in the water column. In addition, denitrification is typically limited by the presence of O2 or by the availability of NO3 or labile organic carbon (Hamersley and Howes 2002). The accepted value for the nitrate removal rate is between 250 to 2000 mg $N/m^2/d$ (Hamersley and Howes 2002; Fleming-Singer and Horne 2006).

Additionally, the plant litter that settles at the bottom of the wetland acts like an impermeable layer and restrains the dissolved oxygen from dispersing to the bottom layer. The plant biomass surrounded by particulate organic matter also provides anoxic conditions that trigger localized denitrification. Anaerobic microsites are created around the biomass; thus, it is ideal environment for the growth of heterotrophic denitrifiers since the carbon supply is present.

Various models can be used to estimate the nitrogen removal performance of a wetland. Two majors trends exist in the modeling of wetland. The hydraulic model is usually used for design purposed while some microbial one are develops by academics. Those are more complete and by far more complex (Wynn and Liehr 2001; Mayo and Mutamba 2005). The hydrological model assumes a nitrate removal rate treatment rate to be a first order (exponential) decay function. The ideal plug-flow reactor model, presented in figure 9.1.4, is a perfect example.

$$\frac{(\mathrm{AvgNO_3}^-)_{\mathrm{in}}}{(\mathrm{AvgNO_3}^-)_{\mathrm{out}}} = \exp^{-k_v t}$$

Figure 9.1.4: Plug-flow model for nitrate removal (Hamersley and Howes 2002)

Another way for nitrogen to be removed is through plant uptake. The plants need

nitrogen for their metabolic activities and for growth as discussed in the previous section. It is estimated that biomass removes approximately 10 to 30% of the nitrogen available in the water depending on the species (Reed 1995). In some cases, the plants are harvested in order to make sure that none of the assimilated nitrates return in the water body once the plants die. In addition, plant harvesting helps remove the heavy metals stored in the plants tissues.

9.1.5. Factors Influencing Wetland Efficiency

A wetland is a complex system in which living organisms and physical factors develop and maintain synergic interactions with each other. The health of this natural system is a major factor affecting the capacity of the wetland to purify and treat water from various contaminants such as high nitrogen or heavy metal concentrations. In fact, the major players that influence the treatment capacity of the wetland are microorganisms, which highly depend on the vegetation and the soil substrate. Hence, it is not evident to completely control such a living system due to the complexity of interaction between its various components.

The design of a constructed wetland requires to first asses each parameter influencing the efficiency in a wetland ecosystem. Once those parameters are well understood, it is possible to use the natural elements of the local environment to generate a more 'controlled' system that can satisfy all of the design criteria. The following section explores factors that are involved in the efficiency of nitrogen removal for a constructed wetland.

9.1.5.1. Hydrology

The hydrological parameters of a wetland are considered as the most important design criteria. Such parameters include the hydroperiod (hydraulic retention time), the hydraulic loading rate, the flow, the concentration of constituents in the effluent and the surface area of the system. Most wetlands are designed based upon hydrological parameters since they are simpler to manipulate and model than biological processes; however, to attain a fully functional and sustainable system, the latter can not be omitted.

The hydrological design must take into account the implication of fluctuating water levels and/or inflow of water. In general, the treatment efficiency of a wetland is optimal in conditions of low flow rate variability (Ishida, Kelly et al. 2006). Similarly, the efficiency of removal processes is affected by fluctuating hydroperiods (Ishida, Kelly et al. 2006). However, such fluctuations do not negatively impact the potential for the system to remove nitrate if optimal hydraulic conditions are reestablished at a later time; the latter was proven in a study conducted by Ishida et al. (2006). In addition, low flows allow solids to settle, while increasing the contact time between the wastewater and the microbes in the wetland.

9.1.5.1.1. Hydraulic Retention Time

The hydraulic retention time (HRT) represents the time required for a particle of effluent to travel through the wetland. This parameter can vary a lot with the type of wetland, the land available, the flow, and the effluent concentration.

Wetlands with large values of HRT were observed to produce more dissolved organic carbon (DOC) than those with smaller HRT due to plant decomposition. Hence, long HRT might be desirable in wetland systems with low influent carbon concentrations. Another by-product of vegetation decay is dissolved organic nitrogen (DON). A fraction of the humic-bound DON can be mineralized by micro-organisms. Mineralized nitrogen can then re-enter the system and act as a nitrogen source. Some studies estimated that 15% of DON is expected to be mineralized, while others stated that it is an insignificant source of nitrogen(Fleming-Singer and Horne 2006).

9.1.5.1.2. Hydraulic Loading

The hydraulic loading rate refers to the volume of wastewater discharged in the wetland per unit surface area. The units are commonly expressed in m^3/m^2*d. Furthermore, the optimal conditions for nutrient and/or heavy metal removal consists of a low hydraulic loading rate combined with a relatively long retention time. In other words, the most efficient treatment of effluent for given values of HRT, effluent flow and effluent concentrations is attainable through greater surface area and smaller hydraulic loading rate.

9.1.5.1.3. Inflow Concentration

The concentration and the nature of the pollutants present in the influent as well as the desired outlet levels greatly influence the type of wetland and the types of vegetation to use. In general, the required HRT increases with an increase in the inflow concentration of the contaminant, a decrease in the acceptable outflow concentrations or under both conditions.

A study conducted by (Hamersley and Howes 2002) found that there is a positive linear relationship between the rate of nitrate removal and the effluent concentration. In fact, a high nitrate concentration in the effluent results trigger an increase of the transformation rate from organic to inorganic nitrogen.

9.1.5.2. Temperature

Temperature is another significant parameter influencing microbial growth in a wetland system. The design of an efficient nitrate removal system must therefore take into consideration the thermal fluctuations occurring throughout the year. A series of calculations can be performed to evaluate the average working temperature of a wetland. The removal rates used in the hydrological model are temperature-dependent. Such calculations are more relevant in temperate climates. However, in warm climates it is assumed that temperature is more or less constant throughout the year and that the treatment efficiency remains stable.

9.1.5.3. Seasonality

For tropical and subtropical climates, seasonality refers to the dry and wet seasons. The wet season usually brings a fair amount of rain, which can significantly increase the rate of inflow and generate floods. On the other hand, the dry season can have extended periods without rain. In fact, negative water balances can occur if the evapotranspiration rates are more important than the sum of the precipitation and the inflow of water in the system. In extreme cases, the water table could decrease to the point where the wetland basin is completely dry. Consequently, the vegetation and the microbial populations will be affected according to the severity of the situation. Hence, it is important to keep in mind these factors when designing a constructed wetland.

The literature is not consistent regarding the influence of fluctuating water levels and hydroperiods on treatment efficiency. Meutia (2001) compares the variations in the efficiency of total nitrogen removal from dry, transitional and wet seasons in a surface wetland. The average values of total nitrogen removal were 42%, 74% and 95% for the dry, the transitional and the wet seasons respectively. On the other hand, a study conducted by Ishida et al. (2006) affirms that flood conditions would decrease the efficiency of nitrate removal.

Seasonal variations represent a moment where the bed of a wetland and the sediments of the bottom layer can be re-oxygenated due to the potential retreat of water during the dry season. Furthermore, the fluctuations in the water level or in the hydroperiod do not impair the wetland capacity to remove nitrate or change the composition and size of the bacterial communities. In fact, once the water table returns to an adequate level, the system has the ability to fully recover (Ishida, Kelly et al. 2006).

9.1.5.4. pH

The pH is another important parameter even though it is rarely a problem when operating a constructed wetland. The relative distribution of ammonia and ammonium varies depending on the pH. In fact, the pH interferes with the normal equilibrium between NH_3 and NH_4. Only ammonium is present under a pH of 7, while higher pH levels favor the formation of ammonia. Furthermore, the wetland treatment process tends to increase its pH level(Reed 1995).

9.1.5.5. Micro-Organisms

The micro-organism populations are the principal living component in a wetland since they regulate the system. They include bacteria, yeasts, fungi, protozoa, and rind algae. Each of those microorganism populations has a specific range of temperatures for which they are more active (Reed 1995). When environmental conditions are less suitable, most microorganisms switch to a dormant mode. Some can remain dormant for many years. In order to have healthy micro-organism communities, sufficient food and adequate media need to be available.

The main bacteria involved in denitrification are the pseudomas; more specifically the Paracoccus denitrificans and the Thiobacillus denitrificans(F-Rodriguez 2006). They are heterotrophic and anoxic, therefore, they need a source of organic carbon to feed on and they a source of nitrate to fulfill their breathing needs. In order to have a constructed wetland system which favors high nitrate removal, the system should have low oxygen concentration and a source of carbon.

9.1.5.6. Dissolved Oxygen

Not all wetlands need artificial oxygen supply. Oxygen requirement depends on the desired reactions within the cells and the BOD load of the wastewater. Hence, oxygen supply may not be desired for cells performing denitrification because oxygen would inhibit the process. Lower oxygen levels are usually found at the bottom of a wetland. The supply of organic matter fuels heterotrophic activity and increase the oxygen consumption, favoring the development of anaerobic conditions while creating a favorable environment for denitrification.

9.1.5.7. C:N Ratio

According to Reed (1995), the carbon to nitrate-nitrogen ratio should be approximately 5:1. This ratio influences the rate of denitrification. In fact, some research shows that denitrification performance can be manipulated by varying either the carbon loading or the hydraulic loading rate (Ingersoll and Baker 1998). The ratio in the wetland is affected by the nature [the relative abundance of lignin, hemi-cellulose and cellulose] of the organic material falling in the water (Fleming-Singer and Horne 2006).

9.1.5.8. Available Carbon

The denitrification rates can vary a lot from site-to-site (i.e. 200 to over 5000mgN m^2/d). Depending on the sampling location within a system, Ishida (2006) observed variations in potential rates of denitrification, bacterial cell densities and benthic community structures. Such observations were made in different systems regardless of their hydraulic parameters and vegetation. Considering that most of the denitrifying bacteria of a wetland are heterotrophic, carbon availability in the water body would explain the spatial variation.

In fact, several studies performed in many ecosystems identified the availability of carbon as the main parameter responsible for limiting the denitrification process. Between 5 and 9 mg of BOD are required to treat 1g of NO_3-N (Bastviken 2003). However, the denitrification process is generally enhanced when the theoretically required level of carbon is exceeded since part of the BOD is lost to the heterotrophs in the aerobic section of the surface wetland.

The emergent vegetation represents a source of carbon by ensuring that organic material is transferred to the water column and sediments. Lin (2007) reports that the soil denitrification capacity is highly correlated with water-soluble organic carbon, rather than with the total organic carbon. Some subsurface wetlands may need an exogenous source of carbon in order to maximize the denitrification process. Easily degradable sources are mulch, grass clipping or harvested wetland plants(Burchell 2007) . Acetate and methanol are also commonly used (Hamersley and Howes 2002).

9.1.5.9. Phosphorous

Phosphorus is an important growth limiting factor. It needs to be considered to ensure optimal microbial population and vegetation growth. Kietlinska (2005) reported that influent with low level of phosphorus may reduce the denitrification rate.
However, the required phosphorous concentration is very small. Thus, it may not be an issue for the situation in the Greenland watershed since concentrations above 1mg/L are sufficient and available.

9.1.5.10. Soil

Soils represent a major area in which denitrification occurs since they are usually oxygen-poor environments. However, not all types of soil are ideal for denitrification. Mineral soils, sometimes used in construction of wetlands, can limit the denitrification process due to their low content of organic matter. When soils are not suitable for denitrification, organic matter can be added to provide additional carbon and nutrients. This should be done early in the development of the wetland to enhance and maximize biomass growth and therefore denitrification. Lin (2007)

observed correlations between the extractable organic carbon, the organic matter, the redox potential of the soil, and the nitrate removal rate. It is also important to note that the soil properties of a wetland change over time due to the accumulation of vegetative debris.

9.1.5.11. Substrate & Litter

The physical and chemical characteristics of the litter and the substrate of a wetland inevitably impacts the denitrification process. In fact, parameters such as the C:N ratio and the lignin content influence the abundance and the activity of denitrifying bacteria. The initial litter composition influences the decomposition rates and therefore the rate at which carbon is made available to the heterotrophic bacteria. Actually, the distribution of denitrifiers is regulated by the availability of organic material. Consequently, the layer of sediments has higher denitrification rates than plants, algae and twigs found at the surface.

9.1.5.12. Vegetation

The vegetation, also referred to as macrophyte, slows down the flow of wastewater. This allows the microorganisms to degrade the waste and toxins. Vegetation also blocks the sunlight and the wind. Several studies show that wetlands with proper selection of vegetation have higher nitrate removal efficiencies.

The vascular plants have a stem that emerges from the water body. They limit the runoff by stabilizing the substrate and decreasing the velocity of flow. This helps the suspended material in the wastewater to settle. Vegetation also takes up part of the available carbon and incorporates it into their tissues and stem. In addition, plants create a niche for the microbial communities. This is particularly the case for mature plants, as they experience higher leakage of nutrients through the shoots. Moreover, when they die, the submerged parts of the plants degrade and provide carbon to the microbes. In fact, the role played by the submerged surfaces of plants in sustaining microbial populations is as important as the role played by the sediments. Therefore, plants are a key element in the denitrification process. Commonly used emergent plant species are bulrushes, cattails, reeds and broad-leaved.

The non-vascular plants are algae mainly present in surface flow wetlands. They contribute in the increase of dissolved oxygen in wastewater bodies.

The percentage of plant coverage affects the amount of dissolved organic nitrogen (DON) produced via plant decomposition. In fact, by harvesting the vegetation, it is possible to remove about 10% of the nitrogen from the system. (Reed 1995) A study done by Fleming-Singer and Horne (2006) showed that a macrophyte coverage smaller than 10% limits the amount of DON in the wetland cells. However, wetlands with 80 to 90% vegetation coverage are easily achievable. Such coverage enhance the denitrification rates by providing a greater source of litter-derived carbon for denitrifying microbes. Table 4.12.1.1 (in section 4.12.1) enumerates various plants and states their removal functions.

In general, temperate climate wetlands are vegetated with Phragmites ssp (Reeds), Scirpus ssp (Bulrush) & Typha ssp (Cattails). However, Typha seems less effective in terms of nitrogen removal. For warmer climate, Cyperus papyrus seems to be gaining popularity. Moreover, an experiment conducted in Costa Rica on six different surface wetlands demonstrated that those free-floating macrophytes are not a viable option.

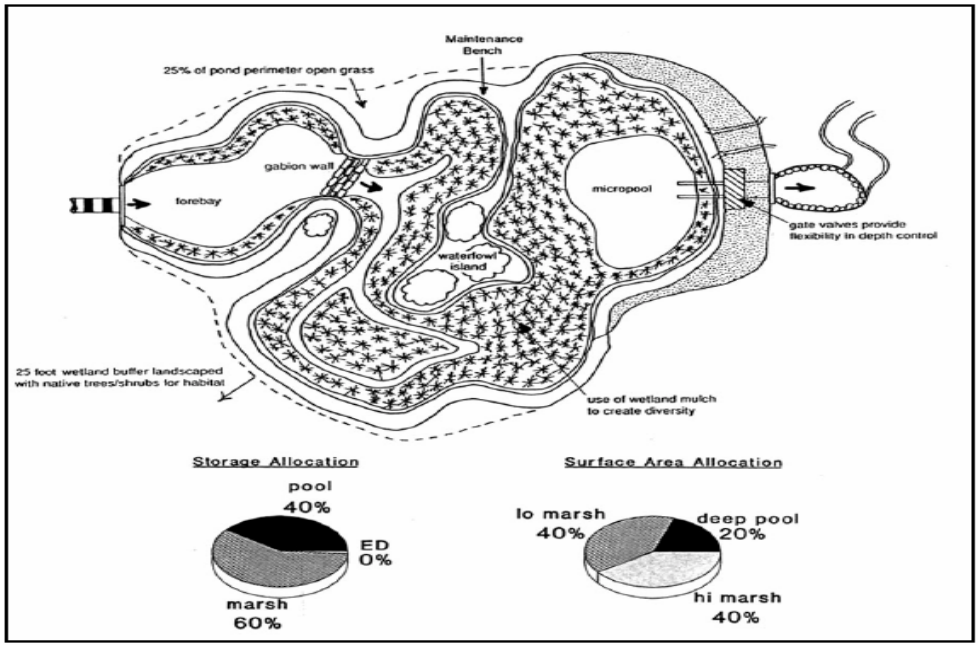
9.1.6. Design Parameters

There are many types of surface wetland systems. Four main categories are used to differentiate them: shallow marsh systems, pond/wetland systems, extended detention wetlands, and pocket wetlands. The two types of interest for the purpose this project are the shallow marsh and the extended detention wetland systems. The pond/wetland system is not relevant since the influent has very little suspended solids.

The shallow marsh wetland is characterized with a moderate pollutant removal capability and a constant water level. It offers a reliable removal of sediments and nutrients. Its land requirement is high, since the shallow marsh area increases proportionally with storage capacity. This type of wetland is recognized to provide good habitat for wildlife. Also, the establishment of native plants is relatively easy.

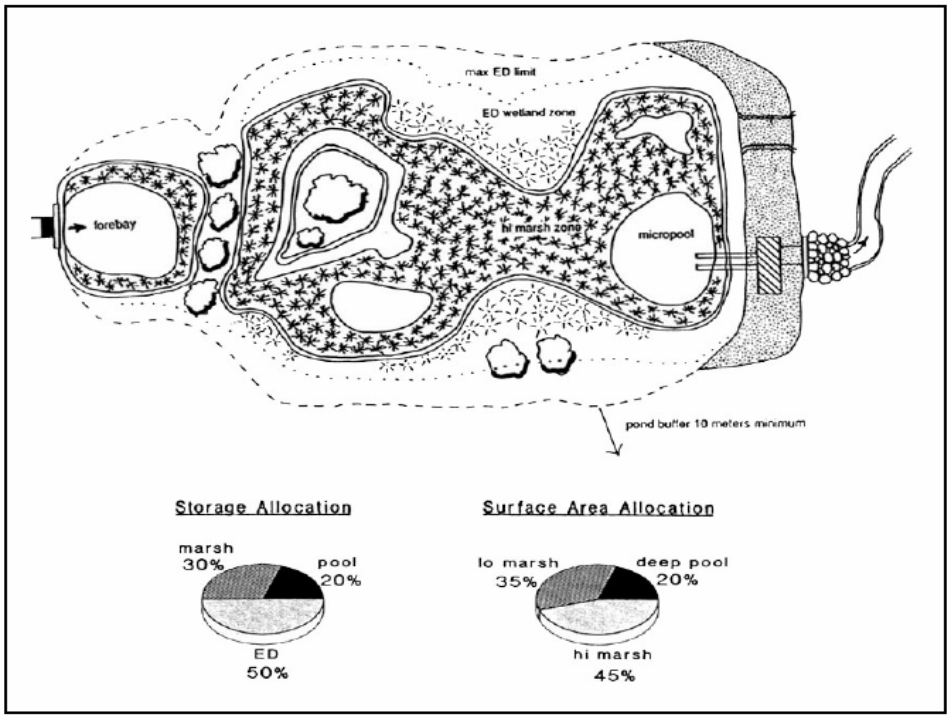
The extended detention wetland is also characterized with a moderate pollutant removal capability and fluctuating water levels. It is however less reliable for the

removal of nutrients. This system consumes less land per volume of water. Due to the fluctuation in the water levels, it might be harder to introduce native plants capable of resisting the different conditions. For the same reason, wildlife habitats are regularly disturbed by the varying water levels.



(BarrEngineeringCo.)

Figure 9.1.7.1: Shallow march system



(BarrEngineeringCo.)

Figure 9.1.7.1: Extended detention wetland system

9.1.7.1. Location

The Wetland should be located at proximity to the surface water discharge and have adequate spacing. The selected site should take advantage of the natural features, such as the soil, the topography of the land or the current vegetation. Surrounding land use and access around the site is also important. Furthermore, the most favorable site should minimize the disturbance of the natural environment. (Reed 1995)

9.1.7.2. Geometry

The length to width ratio varies in the literature between 1:1 and 1.5:1. Long flow paths and irregular shapes are recommended (BarrEngineeringCo.). Moreover, such shapes will create niches for the surrounding wildlife.

The bed of the basin should provide a wide range of depths, broken into zones perpendicular to the flow. Appropriate plant species should be selected for each depth. Islands may also be designed to increase the potential for wildlife habitat on the site.

9.1.7.3. Forebay & Micropool

The shallow marsh and the extended detention wetland systems have characteristics in common. They both include a forebay, which is a depression at the entrance of the flow (Stormwater Manager's Resource Center). This allows the sediments to settle while decreasing the velocity of the influent, and uniformly distributing the flow across the system. The forebay should account for approximately 10% of the wetland water volume. Its depth should vary between 4 and 6 feet. The bottom of the forebay can be hardened in order to make sediment removal easier (Stormwater Manager's Resource Center).

A micropool is located at the end of both wetland types. This feature has approximately the same dimensions as the forebay in terms of fraction of the total volume and depth. Its main purpose is to prevent the outlet from clogging. It also helps to reduce the risk of short circuiting that could be created by the outlet.

9.1.7.4. Outlets, Inlets, Drains

The most desired system operates only with gravity flow. In addition, multiple inlets are recommended to minimize short-circuiting. They should be easily accessible and independently adjustable to ensure a control over the water level in the wetland. Furthermore, PVC pipes have been proven to work effectively; they should be sized to handle maximum flow conditions. In addition, they should be partially submerged in order to avoid high velocity surface flows, which could damage the vegetation and erode the side banks.

Many outlets types can be used to exit the water from a wetland. A reversed slope pipe located in the micropool and at least one foot below the normal pool surface has the advantage of preventing against clogging caused by floating debris. A riser attached to a siphon outlet is also used to provide the varying depth ranges. In any case, a grid should be installed on the pipe entrance or along the riser to prevent impurities from getting inside the outlet drain. Emergency spillways could also be used. However, they do not offer the option of changing the water levels and incorrect water levels can lead to wetland failure. Furthermore, locations of the outlets should be such that they are easily accessible and maintainable.

Pond drains are also an essential feature for wetlands. They are used to empty cells completely by gravity for emergency purposes or for maintenance. Pipes and pond drains should be equipped with adjustable gate valves. It is recommended that these valves are fully manual. Moreover, they should be capable of dewatering the wetland within 24 hours.

If the wetland system is easily accessible to the public, all valves, inlets and outlets should be enclosed in lockable structures to avoid damage or tampering of water level.

9.1.7.5. Dikes & Ramps

Dikes are used to protect cells from runoff infiltration. They should not be steeper than 2H:1V and should be covered with vegetation to limit erosion. The best cover is grass because it prevents shrubs and trees from establishing on the dikes; their roots could create channels and leakages through the berm. Frequent mowing, and the use of fertilizers are two methods used to enhance vegetative growth. Moreover,

an access ramp should be constructed to allow movement of machinery in the wetland zone, mainly in the forebay area for the removal of sediments. Such ramps should be capable of supporting approximately 20 tons.

9.1.7.6. Buffer Zone

A buffer zone of approximately 15 meters should be allocated around the wetland. The latter minimizes the disturbance to wildlife activity in addition to providing a new habitat for the surrounding fauna. In fact, planting of appropriate indigenous trees or shrubs provides additional habitat for bird species. The wetland margins should also be planted densely with robust sedges and rushes. This reduces the risk of invasion by unwanted plant species or nuisance vegetation such as cattails and primrose willow.

9.1.7.7. Liner

Constructed wetlands should be protected against groundwater infiltration or from water leaching from the system. Hence, a liner should be used as an impermeable bed on sand, gravel or karstic terrain. However, a layer of well-packed clay six to twelve inches thick is sufficient to provide an adequate seal against leakage of water out of the wetland and prevent against groundwater intrusion (DuPoldt 2000).

9.1.7.8. Basin Bed

The wetland bed should also be covered with gravel. This enhances the establishment of microbial populations. Gravel can also serve as a landmark point when maintenance is done in the basin. On top of the gravel, a minimum of 15 cm of topsoil with a minimum of 5 percent of organic content is required throughout the wetland cell (MelbourneWater 2005). This is required for the establishment of aquatic macrophytes.

9.1.7.9. Mosquitos

Open and stagnant waters represent the ideal mosquito breeding environment. Moreover, high nutrient water is perfect for larvae development. It is therefore

primordial to ensure that the water body is constantly flowing and that no stagnant area. Shading the water and introducing floating mats of duckweed in the system is an appropriate alternative to keep mosquitoes away from wetlands. Installing bat boxes in the buffer zone also helps to reduce the number of mosquitoes in the wetland area.

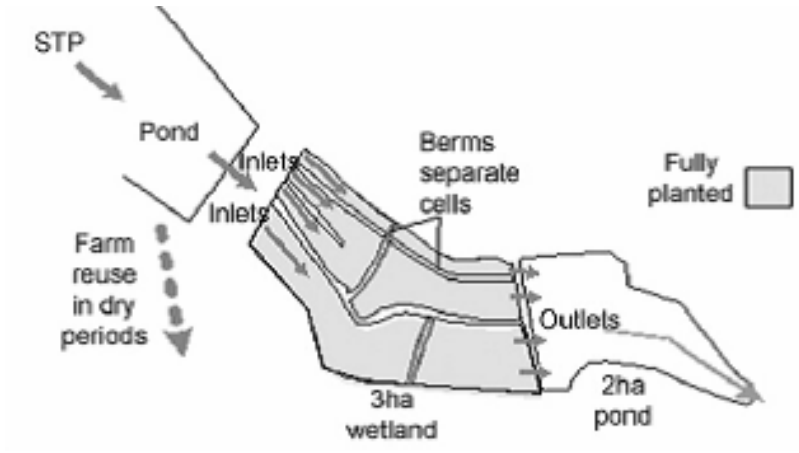
In addition, the berms should also be flattened out after the construction in order not to leave any depression that could turn into small water reservoirs. The latter also represents good breeding grounds for mosquitoes.

9.1.7.10. Vegetation

The chosen vegetation species, both aquatic and terrestrial, should be native to the area. Selecting native plants makes their establishment easier since it mimics the natural conditions in which they normally grow in and it decreases the disturbance to the ecosystem. It has to be planted during the growing season, so that the plants have enough time to store food reserves (EPA 1999). The range of plants selected should also account for the variation in depth throughout the basin (MelbourneWater 2005). Selection of vegetation should also be based on the type of soil and substrate in the basin. Moreover, resistance to dewatering or dry periods is another important consideration (EPA 1999).

9.1.7. Various Case Studies

Constructed wetlands have been used for environmental purposes all over the world for a relatively short period of time. These treatment systems are based on ecological principles in order to reduce human impact on the environment. Considering the complexity of modeling and designing such natural processes, a large proportion of human-made wetland projects have failed to achieve a sustainable and effective treatment process during their initial trial. Actually, this was the case for several human-made wetlands of eastern subtropical Australia, which were dealing in part with nitrogen removal. The main reason behind such failures in early wetland projects was the little collective knowledge of the processes involved within this innovative polishing system.



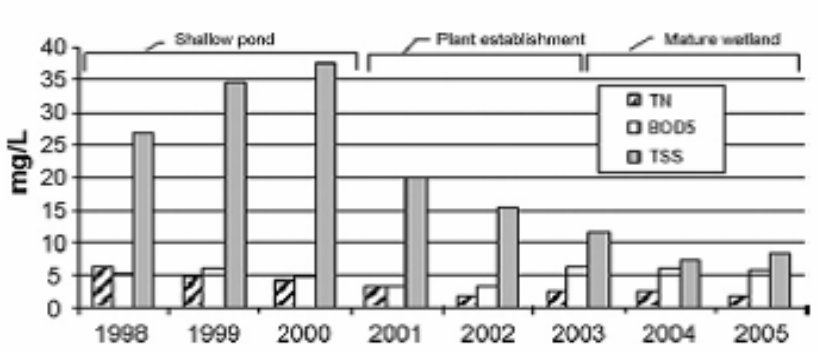
(Davison, Pont et al. 2006)

Figure 9.1.8.1: Casino wetland layout

The Casino surface constructed wetland, shown in figure 9.1, is a good example of learning experience through wetland failure. It was first constructed in 1990 and redesigned to operate at a constant depth of 0.2 m. It requires 3 hectares of land in order to treat approximately 2.5 MegaL/day of effluent water originating from a trickling filter plant and a 4 hectare pond. Several problems aroused from its poor initial design. One of the major issue as the inlet structure consisted of single pipes creating a stream rushing into the wetland. This caused many problems like short-circuiting, death of shoots and root since the small plants could not grow under a high velocity stream. In addition, the bottom sediments were uplift by the high current. The second problem was that the gravel weirs which were meant to regulate the flow between cells were not permeable enough which resulted in an increase of water level to 0.4 to 0.5 m.

Thus, assessment and redesigning of the wetland was required and conducted. The wetland was drained and seedlings were replanted for a period of 2 years using Typha orientallis and Bolboschorenus fluviatilis. The inlets were redesigned, using perforated pipes to avoid concentrated streams from generating scouring flows. Furthermore, the redistribution system between cells was replaced with outlet pipes passing through impermeable gravel berms in order to ensure proper flow spreading. Additionally, varying flow sequences were applied through the 3 possible flow routes, using a valve system. The effluent passed through 2 paths for a period of 3 months pursued by 1 month designated for drying. This methodology ensures system longevity and treatment efficiency. Moreover, maintenance operators were trained to recognise plant health and properly manage flow levels in order to maintain vegetation cover at all times.

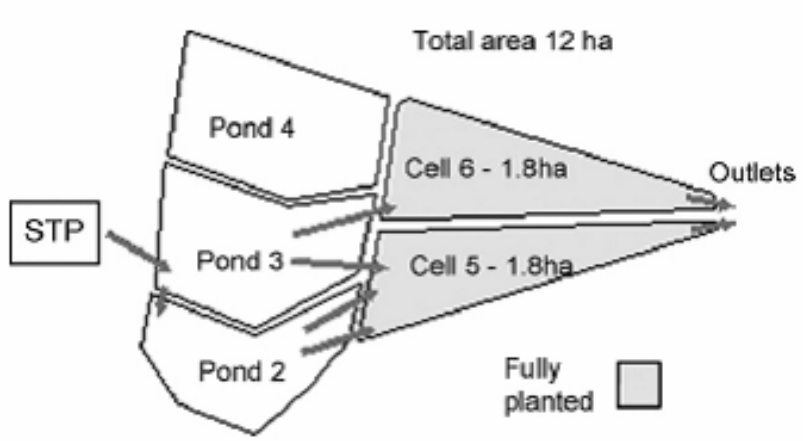
As a consequence of these modifications, the depth of flow remained constant between 0.1 to 0.2 m as initially desired; the retention time was less than a day and by early 2004, full vegetative cover was reached. The results showed improvement in the total nitrogen and total suspended solid removal as figure 9.2 portrays.



(Davison, Pont et al. 2006)

Figure 9.1.8.2: Mean annual outlet concentrations of TSS, TN & BOD_5 at Casino wetland

Similar to the previous case, the South Lismore free water surface wetland was redesigned to optimize its treatment efficiency. This wetland was originally divided into 6 cells, covering a total of 12 hectares of land area and receiving fluctuating flow of 3.5 to 20 megaL/day from a trickling filter system. It was active in 1994 and 1995, but its status was quickly tarnished. Deep depressions in cell floors and high positioning of outlets resulted in poor drainage and accumulation of organic sediments. In addition, the overwhelming number of water birds limited the growth of Macrophytes as they plucked away the seedlings. Moreover, the triangular shaped cells 5 and 6 (as shown in figure 9.3) increased the velocities and depth of flow towards the outlets leading to the degradation of the wetland. With time, the cells turned into a set of ponds.

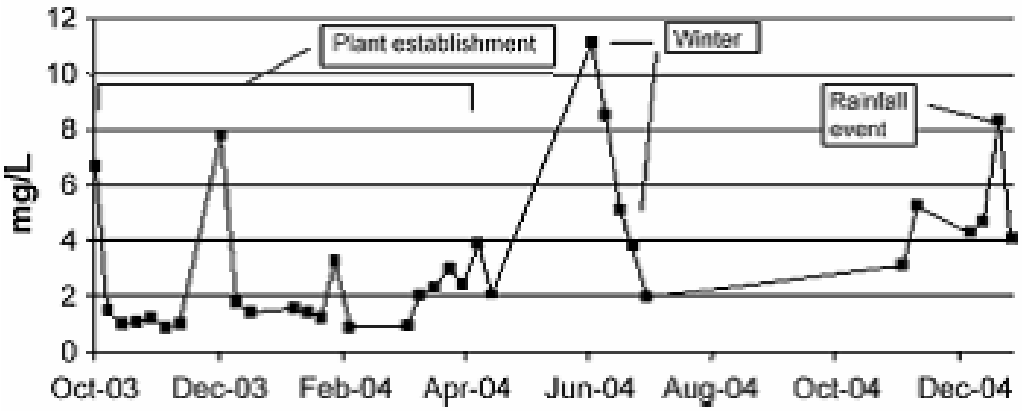


(Davison, Pont et al. 2006)

Figure 9.1.8.3: South Lismore surface constructed wetland layout

Thus, the same team that redesigned the Casino free water surface wetland replanted and observed the South Lismore cells for a period of 2 years. Weed control was applied at specific areas and wire netting cages were set up to prevent waterfowl from disturbing the plant growth. Furthermore, outlets were lowered considerably by 0.9m and modifications to the bed of the wetland were undertaken to deal with undesirable slopes as well as poor drainage. Additionally, dry season drainage was put into practice in order to reduce high concentration of toxic minerals.

Consequently, the total nitrogen concentration of the wetland effluent became low during the maturing phase of the plants. Furthermore, the system should slowly, but progressively increase in efficiency of nitrogen removal as the wetland matures. However, as shown in figure 9.4, the concentration of total nitrogen at the outlet spikes during the wet season and rainfall events. In addition, an overall trend of decreasing total nitrogen concentration in the wetland effluent is not yet visible; however, further measurement of the wetland product should be conducted in order to determine the long-term efficiency and sustainability of this project.



(Davison, Pont et al. 2006)

Figure 9.1.8.4: Total nitrogen outlet concentrations, South Lismore Sewage treatment plant

Long-term monitoring of constructed wetlands has proven effective in determining changes to vegetation cover and wetland efficiency. A study made by (Garde, Nicol et al. 2004) on an urban constructed wetland in Adelaide, capital of South Australia, compared surveys conducted 18 months after project activation with its status 10 years later in order to determine the sustainability of the design. The survey parameters included vegetation, soil electrical conductivity, texture and pH. The study showed that after a decade of operation, the heterogeneity of the vegetation was higher than after 18 months. Although phragmites and salt-tolerant species appear to dominate the shoreline, none of the species invaded or acted as a limiting

factor to the wetland treatment. However, on going monitoring of the vegetation is suggested in order to ensure habitat variety due to the dominating presence of phragmites. Moreover, the electrical conductivity was relatively more uniform and lower 10 years after wetland activation. It is believed that salinity decreased through time due to high flows during storm events, which might have also disturbed the margins of the wetland. Thus, the study showed that continuous monitoring and management is necessary to ensure sustainable and effective treatment using constructed wetlands.

9.2. Calculations

9.2.1. Hydrological Design

A hydraulic model is used to optimize the nitrate removal of the Greenland constructed wetland. The latter allows to size the wetland according to the known nitrate influent concentrations and the desired effluent concentrations. This model assumes uniform flow conditions and negligible contact restrictions between the water and the microsites where treatment occurs. (Reed 1995)

The equations used in this model are:

$$K_T = 0.248 \times (1.048)^{T-20} \qquad \text{Equation 9.1}$$

$$\frac{Ce}{Co} = \exp\left(-K_T \times t\right) \qquad \text{Equation 9.2}$$

$$A_S = \frac{Q \times \ln\left(\frac{Co}{Ce}\right)}{y \times n \times K_T} \qquad \text{Equation 9.3}$$

Where :

C_e	Effluent nitrate concentration (mg/L)
C_o	Influent nitrate concentration (mg/L)
T	Temperature (degrees Celsius)
n	Actual Porosity of the wetland
Y	Depth real / excavated
Q	Average flow through the wetland (m^3/d)
K_T	Temperature-dependent rate constant
A_s	Surface area of wetland (m^2)
T	Hydraulic residence time (d)

The model is done so that the nitrate influent and effluent concentration, the working temperature, the porosity, and the average depth are the fixed parameters. From these fixed criteria, the retention time and the area required to respect the constraints are found.

In this design, the flows are expected to vary between 30 and 350m^3/d. The incoming total nitrogen is expected to be about 10 mg/L. Hence, assuming the worst case scenario, where the total nitrogen is only in the nitrate form, the influent nitrate concentration is estimated at 10 mg/L. The average temperature of the wetland is arbitrarily estimated to be 25°C. The mean porosity is determined according to a weighted average of the porosity for the various layers (gravel, soil and water).

Table 9.2.1.1: Porosity calculation

Porosity gravel (medium) Depth gravel	0,24 0,15 m
Porosity soil () Depth soil	0,3 0,25 m
Porosity vegetated waterway Depth water	0,7 0,53 m
Total depth	1,03
Actual porosity	**0,47**

Based on the soil and gravel porosity values provided in *A Practical Technique for Quantifying Drainage Porosity* (Brady and Kunkel 2003) and in the *Natural Systems for waste management and treatment* book (Reed 1995),the actual porosity of the wetland was estimated to be around 0.47.

Once the model is built, one needs to analyze the outputs to find the ideal conditions for the system. Parameters such as nitrate concentration in the effluent, retention time under maximum and minimum flow conditions, and surface area need to be evaluated. The results are summarized in table 9.2.1.2.

Table 9.2.1.2: Design parameters obtained from hydrological model

At maximum flow **(350m^3/d)**			At low flow **(30m^3/d)**		Volume ET (m^3/d)	Actual Volume (m^3)
Ce (mg/L)	RT(d)	Surface Area (m^2)	R.T.(d)	Ce (mg/L)		
0,5	9,56	6609	111,5	6,00E-15	83,9	3344
1	7,34	5080,1	85,7	2,15E-11	64,5	2571
2	5,13	3550,9	59,9	7,00E-08	45,1	1797
3	3,84	2656	44,8	7,93E-06	33,7	1344
4	2,92	2021	34,1	2,20E-04	25, 7	1023
5	2,2	1529	25,8	3,00E-03	19,4	774
6	1,63	1127	19	2,50E-02	14,3	570
7	1,14	786,9	13,3	1,50E-01	10,0	398
8	0,71	492,3	8,3	7,00E-01	6,3	249
9	0,34	232,5	3,9	2,92E+00	3,0	118

To obtain those results, one first needs to find the K_T value by using equation 9.1. Once the temperature dependant rate constant is found, it is possible to enter it in the equation 9.2 to find the retention time and in equation 9.3 to find the surface area. With the area, it is possible to calculate the volume of water that each scenario represents using the average depth and porosity.

The following section illustrates the series of calculations performed for an effluent concentration of 4 mg/L of nitrate.

Equation 9.1 – Determining the temperature dependent rate constant

$$K_T = 0.248 \times (1.048)^{T-20}$$

$$K_T = 0.248 \times (1.048)^{25-20} = 0.314 \mathrm{d}^{-1}$$

Equation 9.2 – Determining the retention time

$$\frac{C_e}{C_o} = \exp\left(-K_T \times t\right) \quad \Rightarrow \quad t = \ln\left(\frac{C_e}{C_o}\right) \times \frac{1}{-K_t}$$

$$t = \ln\left(\frac{4\ {}^{\mathrm{mg}}\!/_{\mathrm{L}}}{10\ {}^{\mathrm{mg}}\!/_{\mathrm{L}}}\right) \times \frac{1}{-0.314\,\mathrm{d}^{-1}} = 2.92 \text{ days}$$

Equation 9.3 – Determining the required area

$$A_S = \frac{Q \times \ln\left(\frac{Co}{Ce}\right)}{y \times n \times K_T}$$

$$\mathrm{A_S} = \frac{350\ {}^{\mathrm{m}^3}\!/_{\mathrm{d}} \times \ln\left(\frac{4\ {}^{\mathrm{mg}}\!/_{\mathrm{L}}}{10\ {}^{\mathrm{mg}}\!/_{\mathrm{L}}}\right)}{0.53\ \mathrm{m} \times 0{,}47 \times 0.314\mathrm{d}^{-1}} = 2021\mathrm{m}^2$$

Equation 9.4 – Determining the water volume

$$V = d \times n \times A_s$$

$$V = 0.53\ m \times 0.47 \times 2021 m^2 = 1023 m^3$$

This first set of calculations gives the area required under a maximum flow of 350m^3/d. One now needs to evaluate the systems behavior under minimum flow conditions. Hence, with the obtained surface area, the retention time and the treatment efficiency corresponding to flow rates of approximately 30m^3/d are calculated.

Equation 9.5 – Determining the retention time for $30m^3/d$

$$t = \frac{V}{Q}$$

$$t = \frac{1023m^3}{30\ {}^{m^3}\!/_{d}} = 34.1\ d$$

Equation 9.6 – Determining the treatment level using the retention time found with equation 9.5

$$C_e = C_o \times \exp\left(-K_T \times t\right)$$

$$C_e = 10\ {}^{mg}\!/_{L} \times \exp\left(-0.314\ d^{-1} \times 34.1\ d\right) = 2.20\ E-4$$

It can be observed that the smaller the flow, the longer the retention time. Hence, choosing very high treatment efficiencies under high flow situations tends to over-increase the retention time of the water during periods of low flows.

The last criterion to select the proper surface area is to evaluate the quantity of water, which would leave the wetland through evapotranspiration. It is very important to make sure that there will always be a positive water balance in the system.

Based on meteorological data obtained from The Caribbean Institute for Meteorology and Hydrology website, the biggest precipitation event that occurred in Barbados between the year 2001 and 2004 was 12.7mm for one day. This value was selected to estimate the worse case evapotranspiration rate in the system.

Equation 9.7 – Determining the evapotranspiration

$$V_{ET} = A_S \times D_{ET}$$

$$V_{ET} = 2021m^2 \times 12.7\ {}^{mm}\!/_{d} \times \frac{1\ m}{1000\ mm} = 25.6\ m^3$$

9.2.2. Sizing the Berms

<u>Determining length normal to the cell:</u>

First, the length taken by the berm on the ground is found. This is easily done knowing the following variables:

- freeboard of 0.6m

- inside slope = 3H:1V
- outside slope = 3H:1V
- crest width = 4m

Also, to avoid infiltration that could occur through the moved and loosen clay, the water level inside the wetland cell does not go higher than the soil level.

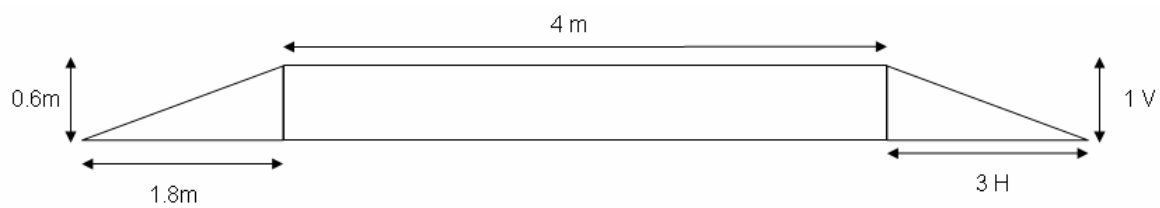


Figure 9.2.2: Berm dimensions

Therefore:

$$\text{Length} = \left(\text{inside slope}\right) + (\text{crest width}) + \left(\text{outside slope}\right)$$

$$= \left(0.6\text{m} \times \frac{3}{1}\text{ slope}\right) + (4\text{m}) + \left(0.6\text{m} \times \frac{3}{1}\text{ slope}\right) = \mathbf{7.6\ m}$$

<u>Determining the total volume of the berm around the cell:</u>

First, one needs to find the volume per unit meter of length.

$$\text{Volume}_{\text{bern}} / \text{meter} = \left(\left(\text{Area}_{\text{Inside Slope}}\right) + \left(\text{Area}_{\text{Crest}}\right) + \left(\text{Area}_{\text{Outside Slope}}\right)\right) \times 1\text{ m length}$$

$$= \left(\left(\frac{1.8\text{m} \times 0.6\text{m}}{2}\right) + (0.6\text{m} \times 4\text{m}) + \left(\frac{1.8\text{m} \times 0.6\text{m}}{2}\right)\right) \times 1\text{ m} = \mathbf{3.48\ \frac{m^3}{m\ length}}$$

Then, the total volume can be calculated:

$$\text{Total Volume} = \left(\text{Volume}_{\text{bern}} / \text{meter length}\right) \times \text{Perimeter}_{\text{bern}}$$

$$= \left(3.48\ \frac{\text{m}^3}{\text{m length}}\right) \times \left(\text{perimeter (m)}\right) = \left(3.48\ \frac{\text{m}^3}{\text{m length}}\right) \times (170\text{ m}) = 591{,}6\text{m}^3 = 592\text{m}^3$$

To this volume, a safety factor of 1.25 is added. In addition a cut / fill ratio of 1.25 is taken into consideration, since the earth excavated for the construction of the wetland will be used to build the berm. Hence, the total soil volume required for the berm becomes:

$$\text{Total Required Volume} = (\text{Total Volume}) \times \text{Safety Factor} \times \text{Cut / Fill ratio}$$
$$= 592\text{m}^3 \times 1.25 \times 1.25 = \mathbf{924\text{m}^3}$$

<u>Determining the berm surface area:</u>

The surface area is useful to better assess the area available to seed dry plants in order to prevent erosion on the berm and to prevent the establishment of potential invasive plants surrounding the wetland.

$$\text{Bern Surface Area} = \text{Outside bern perimeter} \times \text{Cell perimeter}$$

$$= \left(2 \times \sqrt{\text{height}^2 + \left(\text{height} \times \frac{3}{1}\text{ slope}\right)^2} + \text{crest width}\right) \times \text{cell perimeter}$$

$$= \left(2 \times \sqrt{0.6\text{m}^2 + (0.6\text{m} \times 3)^2} + 4\text{m}\right) \times 170\text{ m} = 7.8\text{m} \times 170\text{m} = \mathbf{1325\text{m}^2}$$

9.2.3. Sizing the Outlet Structures

The outlet pipes are made of PVC. A roughness coefficient value of 0.013 is found in appendix B of the *Soil and Water Conservation Engineering* textbook. In this same book, equations 9.8 and 9.9 allow to calculate flows for different type of restrictions: entrance restriction (equation 9.8) or pipe restriction (equation 9.9). Hence, using both equations, it is possible to determine when a pipe will switch from an orifice controlled flow to a pipe controlled flow with respect to the length of the pipe and the head of water parameters.

$$q = \frac{a\sqrt{2gH}}{\sqrt{1 + K_e + K_b + K_C L}} \qquad \text{Equation 9.8}$$

$$q = aC\sqrt{2gH} \qquad \text{Equation 9.9}$$

<u>Where :</u>

Equation 9.8 → Flow restricted by friction loss in pipe
Equation 9.9 → Flow restricted by the entrance

Q	Flow (m^3/s)
A	Pipe cross-sectional area
g	Gravity acceleration (m/s^2)
H	Head
K_e	Entrance loss coefficient
K_b	Loss coefficient for bends in the culvert
K_c	Friction loss coefficient (1/L)
L	Pipe length (m)
C	Entrance edge coefficient

With given values for head and diameter, one can solve for q with equation 9.9. This gives the maximum flow that the inlet will allow in the pipe given the initial conditions. But the flow in the pipe becomes restricted due to friction after a certain length. Hence, deriving equation 9.8 into equation 9.10, one is able to find the specific length at which the flow switches from being restricted by the entrance to being restricted by the pipe.

From 9.8,

$$\frac{a\sqrt{2gH}}{q} = \left(\sqrt{1 + K_e + K_b + K_C L}\right)$$

and, therefore

$$L = \frac{\left(\frac{a\sqrt{2gH}}{q}\right)^2 - 1 - K_e - K_b}{K_c} \qquad \text{Equation 9.10}$$

Hence, the length found using equation 9.10 is the critical length after which the flow becomes controlled by friction in the pipe. For all the potential diameters that could be used for the outlet pipes, the critical length is smaller that the actual length required for the pipes. In other words, the orifice of the pipe allows more water that what the pipe can handle. Hence, all scenarios will undergo flow controlled by friction within the pipe.

Therefore, using equation 9.8, one can find the flow obtained from different scenarios. [fixed variables = head and length & unfixed variable = diameter] An excel table is built in order to decide on the optimal outlet pipe diameter and the number of pipes required.

Table 9.2.3: Sizing of the outlet structure

H=	0,2	M
L=	13	M

D		A		n	Kc	Q		v	
(mm)	**(in.)**	**(m^2)**	**(mm^2)**	**coeff. rough**		**(m^3/s)**	**(m^3/d)**	**m/s**	**ft/s**
13	0,5	0,0001	133	6,881	1927737,48	0,000000	0	0,00	0,00
25	1	0,0005	491	2,877	140916,64	0,000001	0	0,00	0,00
51	2	0,0020	2043	1,112	8136,77	0,000012	1	0,01	0,02
76	3	0,0045	4536	0,653	1648,46	0,000061	5	0,01	0,04
102	4	0,0082	8171	0,441	507,86	0,000199	17	0,02	0,08
127	5	0,0127	12668	0,329	211,02	0,000479	41	0,04	0,12
152	6	0,0181	18146	0,259	102,91	0,000982	85	0,05	0,18
203	8	0,0324	32365	0,176	32,31	0,003121	270	0,10	0,32
254	10	0,0507	50671	0,131	13,28	0,007600	657	0,15	0,49
305	12	0,0731	73062	0,102	6,31	0,015810	1366	0,22	0,71
381	15	0,1140	114009	0,0761	2,61	0,037791	3265	0,33	1,09
457	18	0,1640	164030	0,0598	1,26	0,076118	6577	0,46	1,52

Therefore, using two pipes of 8 in. diameter seems to be a viable option. This would provide a flow capacity of **540 m^3/d**, which is more than what is required for the system. However, this provides with a good safety factor which will account for the potentially higher discharge resulting from heavy rainfall events.

9.2.4. Sizing the Emergency Spillway

The emergency spillway is sized using the same two equations (9.8 and 9.9). Given the head and the pipe length, the maximum flow has been evaluated with both methods for different pipe diameters. Between the two results obtained, the smallest flow value prevails.

Similar to the outlet pipes, a pipe emergency spillway would be made of PVC. Hence, the roughness coefficient and other variables used for the calculations are the same as the ones used to size the outlet structure.

Table 9.2.4: Maximum flow for various standard pipe diameters

Dia. (in.)	Q (m^3/d) Pipe controlled	Q (m^3/d) Entrance controlled
0,5	0	17
1	0	62
2	2	257
3	10	570
4	31	1028
5	75	1593
6	153	2282
8	485	4070
10	1177	6372
12	2433	9187
15	5722	14336

Independent Parameters

H=	0,3	m
L=	6	m
C=	0,6	

Based on the results, one can observe that the restriction imposed on the flow by the pipe leads over the entrance restriction. Considering that the emergency spillway has to allow for flow greater than 350m^3/day, an 8 inch diameter pipe is the best option.

9.3. Excel Spreadsheet

The wetland depths were put on a excel sheet which created the wetland matrix.

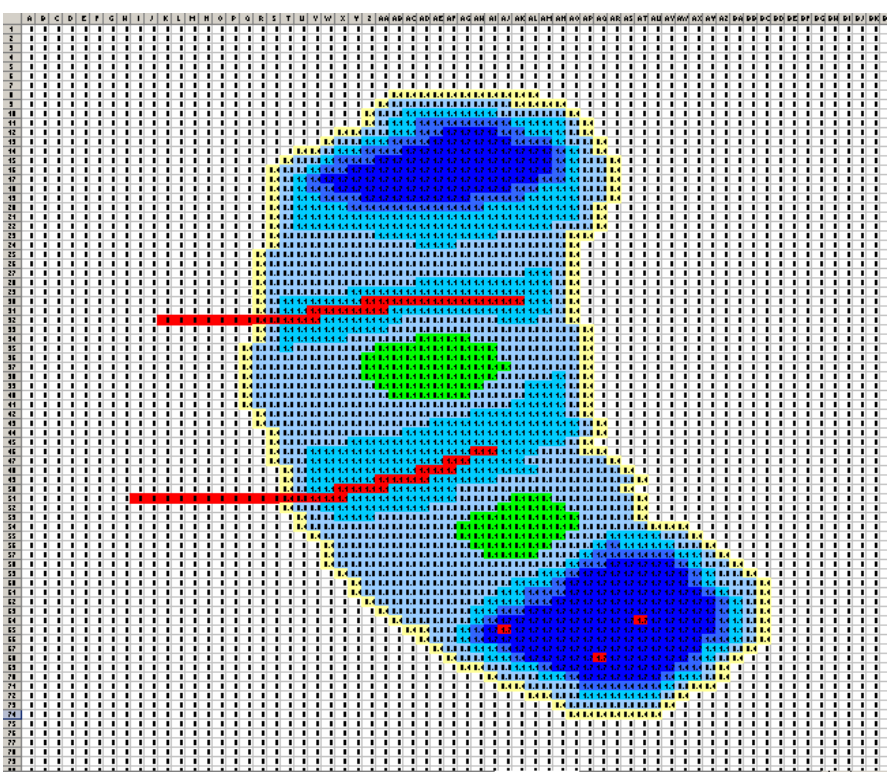


Figure 9.3: Excel representation of the wetland cell

9.4. Matlab Script

Here is the matlab script that was used to calculate the volume, the area and the perimeter of the wetland as well as graphing a 3-D representation of the wetland. From the excel spreadsheet, it was possible to accurately calculate the area, the perimeter and the volume of the wetland, considering its very irregular shape.

```
%Determine Number of  COLUMNS(m) and ROWS(n) in excel sheet
m=100;
n=100;
%open the matrix file
fid1 = fopen('wetland.csv','r');
%assign elevation values to matrix
C = textscan(fid1,'%f','delimiter',';');
%convert cells to matrix (1column, Xrows)
z=-1*cell2mat(C);

%Reshape the matrix to have 100rows & 100columns
ZZ = reshape(z,m,n)';

%Now open matrices to have X and Y values

%open the X matrix file
fid2 = fopen('Xaxis.csv','r');
%assign Xposition values to matrix
A = textscan(fid2,'%f','delimiter',';');
%convert cells to matrix (1column, Xrows)
x=cell2mat(A);

%open the Ymatrix file
fid3 = fopen('Yaxis.csv','r');
%assign elevation values to matrix
B = textscan(fid3,'%f','delimiter',';');
%convert cells to matrix (1column, Xrows)
y=cell2mat(B);

%Build a table with X,Y,Z data
Table=horzcat(x,y,z);


%Assigning min and max values for x and y matrices
xin=min(x); xmax=max(x);
yin=min(y); ymax=max(y);
%Generating x and y grid vectors
xgrid=linspace(xin,xmax,100);
ygrid=linspace(yin,ymax,100);
%Generating square grid matrix using xgrid and ygrid vectors
[X,Y]=meshgrid(xgrid,ygrid);
%Data gridding using a triangle-based cubic interpolation
Z = griddata(x,y,z,X,Y, 'cubic');

%Calculating volume
volume=sum(sum(-z))

% Calculating area by finding the number of none-zero elements in
matrix z
```

```
Area=size(find(z),1)

%Calculating perimeter (contour values of 0.001 were previously
assigned in ‘wetland.csv’)
per=find(z==-0.001);
perimeter = size(per)

%Generating 3D plot
mesh(X,Y,Z);
axis tight; hold on
surf(x,y,z);
%Defining axis labels and title
xlabel('x'); ylabel('y');
title('Ponds: 3-D view');
% setting color shading properties to interpolated
shading('interp');

%Closing all input files
fclose(fid1);
fclose(fid2);
fclose(fid3);
```

9.5. 3-D Representations

9.5.1. Aerial Photos

Figure 9.5.1: Proposed wetland location for the Greenland Landfill

9.5.2. Matlab Modeling

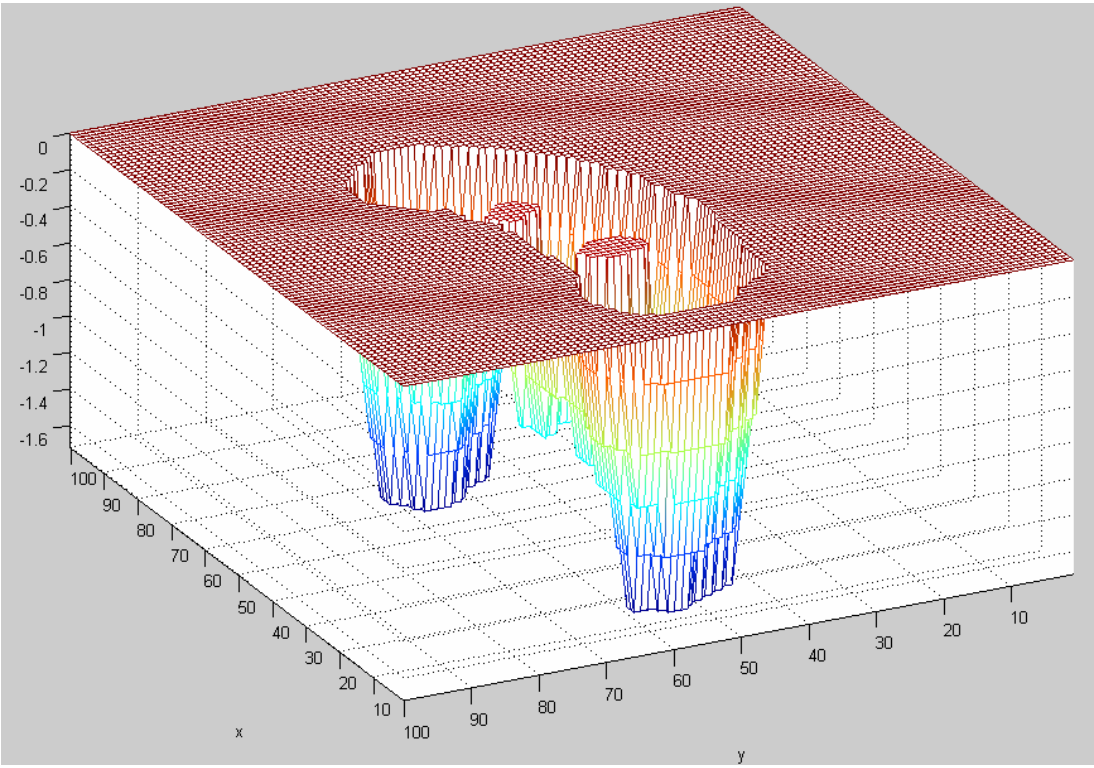


Figure 9.5.2.1: Wetland 3-D representation obtained from the matlab simulation

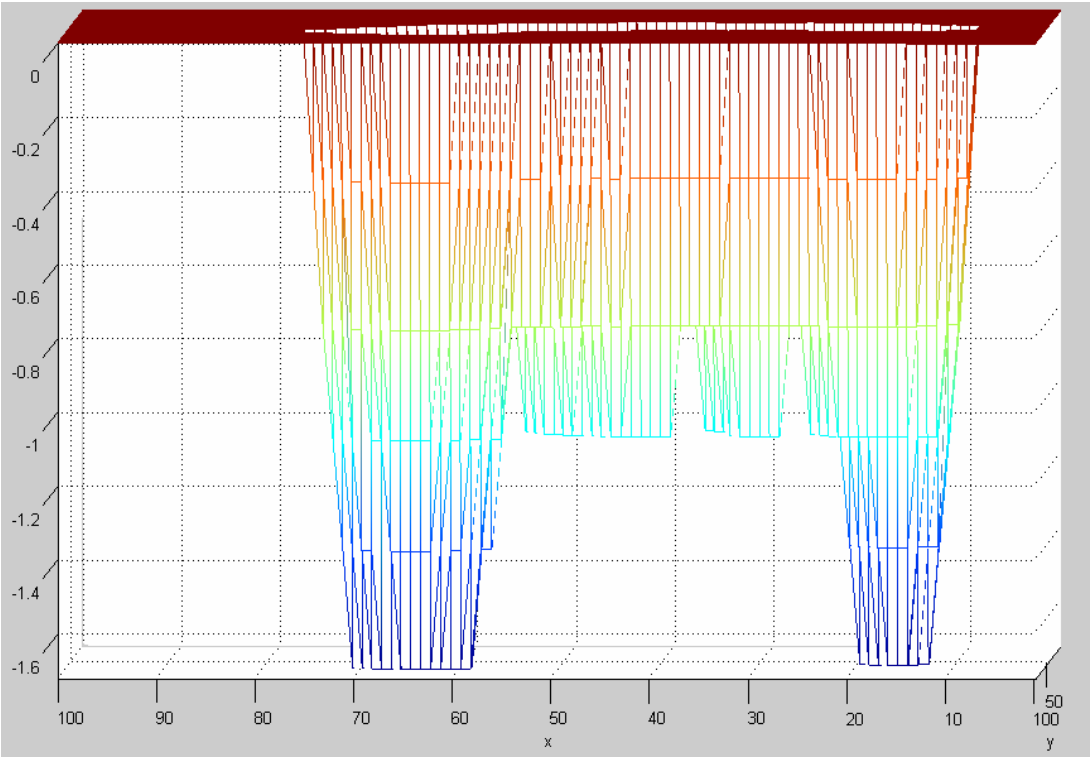


Figure 9.5.2.2: Side view of the wetland obtained from the matlab simulation

9.5.3. ArcGIS Modeling

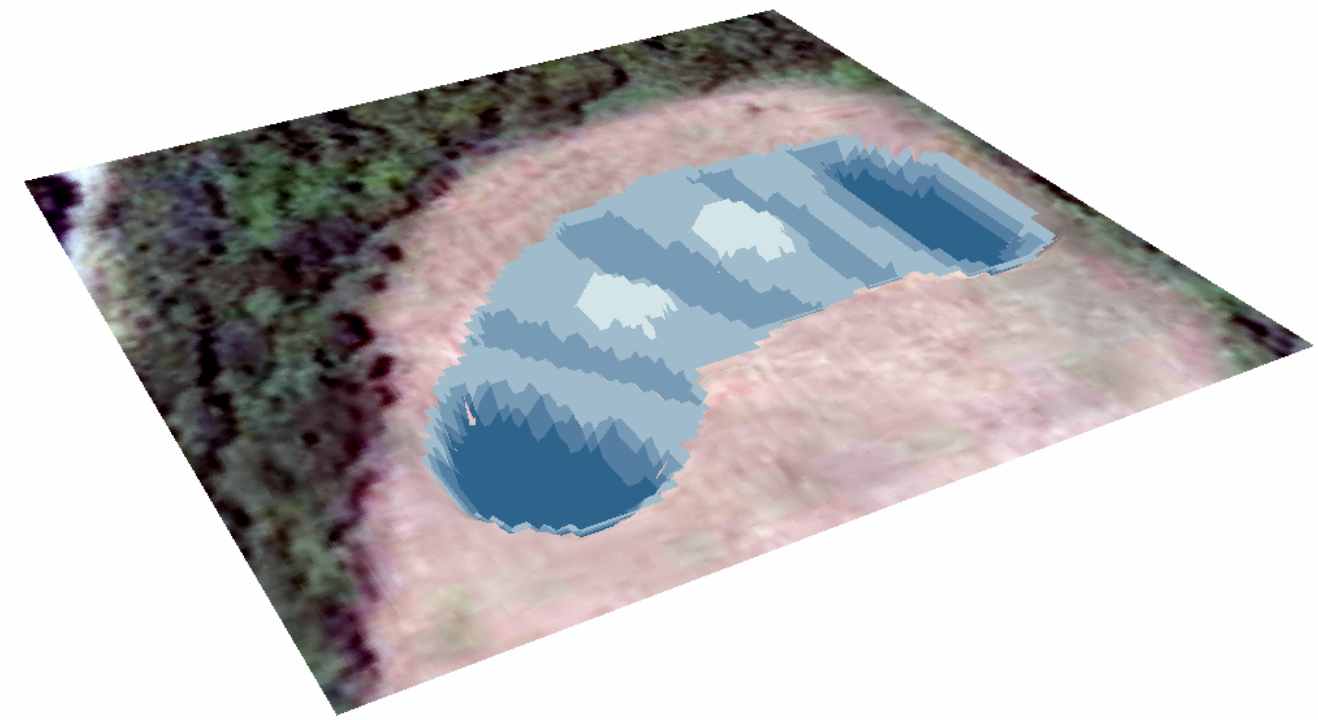


Figure 9.5.3.1: Simulation of wetland cell on location #2 obtained with ArcGIS software

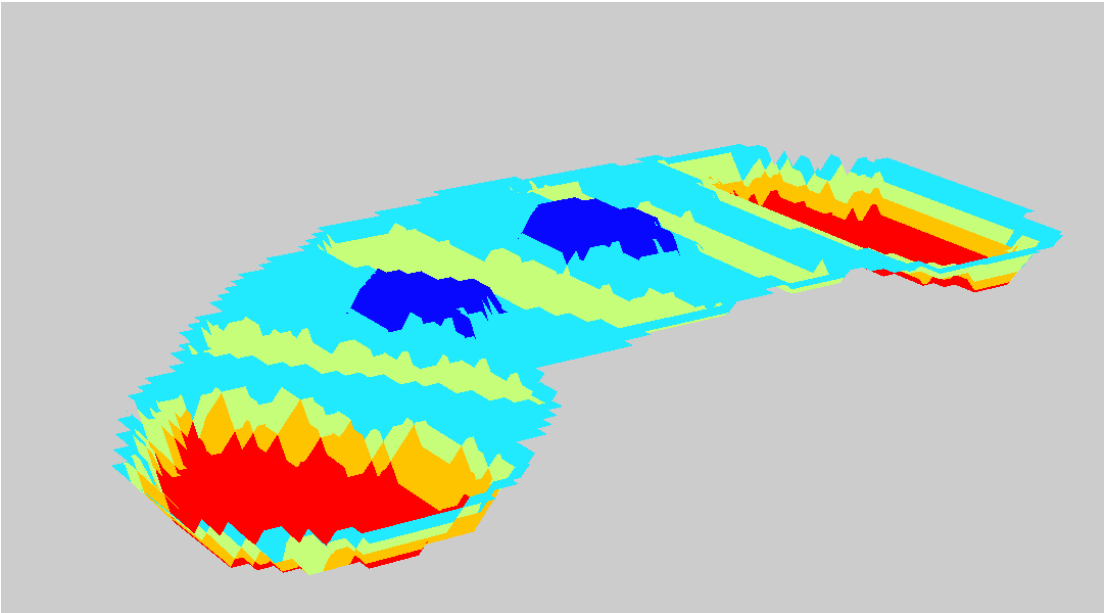


Figure 9.5.3.2: Wetland cell basin obtained with ArcGIS software

9.6. Internship Journal

Week 1

Sept 10th –

- Brainstorm of the main objectives, deliverables, what the team wants to get from the project

Sept 11th –

- Meeting with Olivia to discuss on the project and the possibilities that it would engender

Week 2

Sept 17th –

- Meeting with Burton and Robert. Discuss the project in details. The deliverables are decided

Sept 18th –

- Scientific articles are found. The literature review process has started.

Week 3

Sept 24th –

- Readings

Sept 25th –

- visit Mangrove Pond landfill
- visit Greenland landfill

Sept 26th –

- Readings
- The field trip to Graeme Hall is cancelled because Robert and Burton have an important meeting.

Sept 27th –

- Readings

Sept 28th –

- Readings

Week 4

Robert is out of the island this week

Oct 1st –

- Readings

Oct 2nd –

- Readings
- Meeting and discussion with the group members, gathering of the collected information, identification of the design parameters, planning of the next steps

Week 5

Oct 8th –

- Meeting with Dr. Bonnell → suggestions on how to approach the design part
- Meeting with our supervisor, Ms. Susan Mahon → review of the implementation plan, adjustments for the next weeks, discussion on the Progress Report #1
- Work on the Literature Review

Oct 9th –

- Visit to Coral Reef, Vila on the beach, & Wastewater Treatment Plants
- Meeting with Robert Hackins to discuss were we are at with the work, and what we are expecting to do next. (refer to notes)
- Work on the Literature Review
- Work on Progress Report #1
- Work on PowerPoint Presentation
- Email Prof. Barrington to get details on design parameters
- Email Santiago to get digital map of interest for the project

Oct 12th –

- Progress Report #1 is handed in
- Oral presentation

Week 6

Oct 15th –

- Work on the literature review
- Meeting with Robert
- Visit UWI and meet with Karl Watson :
    - need to consider surface flow wetland and to create a bird habitat if we want the government approval for the project
- Work out an equation

Oct 16th –

- Try to modelize the reactions to start the design

Week 7

Oct 22nd –

- Excel sheet with different RT / Flows / effluent concentrations of NO_3 / temp
- Start to model the profile of the wetland

Oct 23rd –

- matlab program is built to plot the basin in 3-D
- Articles are found that basin profiles that were shown to work effectively
- Calculations of the velocity in the basin

Week 8 – Internship Week 2

Oct 29th –

- Literature review

Oct 30th –

- literature review : design criteria, specific migratory birds habitats

Oct 31th –

- literature review : design criteria, specific migratory birds habitats
- evening: meeting with Robert:
    - need to go on the site and check for actual location
    - need to draw the wetland and incorporate it on a map, so easy for people to understand…
    - possibility to present the project to government members

Nov 1st –

- literature review

Nov 2nd –

- literature review
- meeting with Karl Watson, Angela Fields and M. Carrington
    - think about all wildlife that would use the area
      [Fish: guppies & mollies (avoid tilapia), Plants: allodia (birds and fish eat it, oxygenate the water), think about Mongoose, habitat for land crabs, butterflies, etc.]
    - reference book → 'Plant Community of Barbados' by Mc. Gooding
    - Research on Long pond wildlife (by Robin Mahon - CERMES) → 417.4570 or 417.4317
    - Congo Road, meet with M. Robin Hunt (owner) and Jeffrey Skeete (designer)

Week 9

Nov 5th –

- Visit of Greenland Landfill site and evaluate the best emplacement for the wetland
    - 2 possibilities → a small trench between / along the platform and the creek or on the other side of the creek, where there is much more space
- Collection of plant samples in ponds located south-west of the landfill site. Those ponds were created by the government for fish farm purposes.
- Meeting with Susan: go over the Gannt Chart, discussion on the different requirement for the course and the final report
- Contact Mark Welsh [EPD] for GPS – 436-4820

Nov 6th –

- Work on the literature review, mainly plants
- start to work on the design
- Finish the Progress Report #2
- Visit the Graeme Hall Nature Sanctuary (with Ryan) and get samples of plants that grow naturally in Barbados

Week 10

Nov 13th –

- determine table of content of final report
- briefing on what remains to be done
- preliminary design of wetland cell
- work on potential plant species

Nov 14th –

- calculation of outlet pipe diameter required in function of number of pipes used
- figure out inlet system
- discussion on the drainage system requirements
- find out the size the emergency pipe spillway would need to be (will vary accordingly to the head and length)
- Finish list of potential plant species section

Week 11

Nov 19th –

- look up heavy metals impacts on wetlands parameters / performance
- Work on plant selection document
- calculations of the berms (dimension, volume, etc.)

Nov 20th –

- map the site with GPS (2 potential sites)
- Finish wetland plant selection document
- look up heavy metals impacts on wetlands parameters / performance
- Robert needs a document of 3 pages (description / summary, maps, and cost) to present to Sanitary Service Association by Friday
    - Description / summary page is written
    - the shape of the wetland has being adjusted to the GPS data collected
    - A list of the parameters and their relative cost has been started

Nov 22th (Thursday) –

- meeting with Robert
    - we went over the project description, the maps and the cost
    - Now: we only need to focus on the report and the final presentation

Week 12

Nov 26th & 27th –

- work on final report

Week 13 – Internship Week 3

Dec 3th to dec 7th –

- work on the final report
- work on final presentation

10. References

Aluko, O. O. and M. K. C. Sridhar (2005). "Application of Constructed Wetlands to the Treatment of Leachates from a Municipal Solid Waste Landfill in Ibadan, Nigeria." Journal of Environmental Health **67**(10): 58-62.

BarrEngineeringCo. "Constructed Wetlands : Stormwater Wetlands." Minnesota Urban Small Sites BMP Manual.

Bastviken, S. K. e. a. (2003). "Wetlands and Aquatic Processes : Potential Nitrification and Denitrification on Different Surfaces in a Constructed Treatment Wetland." J. Environ. Qual. **32**: 2414-2420.

Brady, M. M. and L. A. Kunkel (2003). "A Practical Technique for Quantifying Drainage Porosity." PTS Laboratories.

Bulc, T. G. (2006). "Long term performance of a constructed wetland for landfill leachate treatment." Ecological Engineering **26**(4): 365-374.

Burchell, M. R., et al. (2007). "Substrate Organic Matter to Improve Nitrate Removal in Surface-Flow Constructed Wetlands." J. Environ. Qual. **36**: 194-207.

Davison, L., D. Pont, et al. (2006). "Dealing with nitrogen in subtropical Australia: Seven case studies in the diffusion of ecotechnological innovation." Ecological Engineering **28**(3): 213-223.

DuPoldt, C. a. (2000). A Handbook of Constructed Wetlands - Volume 1: General Considerations. Washington, EPA.

EPA (1999). "Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment."

EPA (2000). Guiding Principles for Constructed Treatement Wetlands: Providing for Water Quality and Wildlife Habitat. Washington, DC.

F-Rodriguez, O. (2006). "Overview of microbial metabolism : Nitrification-Denitrification." Bioenvironmental Engineering Course, McGill University.

Fleming-Singer, M. S. and A. J. Horne (2006). "Balancing wildlife needs and nitrate removal in constructed wetlands: The case of the Irvine Ranch Water District's San Joaquin Wildlife Sanctuary." Ecological Engineering **26**(2): 147-166.

Garde, L. M., J. M. Nicol, et al. (2004). "Changes in vegetation patterns on the margins of a constructed wetland after 10 years." Ecological Management & Restoration **5**(2): 111-117.

Gooding, E. G. B. (1974). The Plant Communities of Barbados, Her Majesty's Stationary Office.

Gooding, E. G. B., A. R. Loveless, et al. (1965). Flora of Barbados. London, Her Majesty's Stationary Office.

Government of Barbados (2002) A National Biodiversity Strategy & Action Plan for Barbados. To the convention on biological diversity.

Hamersley, M. R. and B. L. Howes (2002). "Control of denitrification in a septage-treating artificial wetland: the dual role of particulate organic carbon." Water Research **36**(17): 4415-4427.

Ingersoll, T. L. and L. A. Baker (1998). "Nitrate removal in wetland microcosms." Water Research **32**(3): 677-684.

Ishida, C. K., J. J. Kelly, et al. (2006). "Effects of variable hydroperiods and water level fluctuations on denitrification capacity, nitrate removal, and benthic-microbial community structure in constructed wetlands." Ecological Engineering **28**(4): 363-373.

Mayo, A. W. and J. Mutamba (2005). "Modelling nitrogen removal in a coupled HRP and unplanted horizontal flow subsurface gravel bed constructed wetland." Physics and Chemistry of the Earth, Parts A/B/C **30**(11-16): 673-679.

MelbourneWater (2005). "Constructed Wetland Systems : Design Guidelines for Developers." Version 3, November 2005.

Morris, G. L. and C. Laura (2004). "The Caribbean's most beautiful wastewater treatment system: Constructed Wetland at Antigua, W.I."

Mwiganga, M. and F. Kansiime (2005). "The impact of Mpererwe landfill in Kampala-Uganda, on the surrounding environment." Physics and Chemistry of the Earth, Parts A/B/C **30**(11-16): 744-750.

Nivala, J., M. B. Hoos, et al. (2007). "Treatment of landfill leachate using an aerated, horizontal subsurface-flow constructed wetland." Science of The Total Environment **380**(1-3): 19-27.

Parkes, S., D. Jolley, et al. (2007). "Inorganic nitrogen transformations in the treatment of landfill leachate with a high ammonium load: A case study." Environmental Monitoring and Assessment **124**(1): 51-61.

R.J.Burnside.International.Limited (2007). Construction of Leachate and Liquid Wastes Treatment Facility. Sanitation.Service.Authority. **Revision A**.

Reed, S. C., Crites, RW. & Middlebrooks, E.J. (1995). Natural Systems for Waste Management and Treatment, McGraw-Hill Professional.

Sawaittayothin, V. and C. Polprasert (2007). "Nitrogen mass balance and microbial analysis of constructed wetlands treating municipal landfill leachate." Bioresource Technology **98**(3): 565-570.

StormwaterManager'sResourceCenter. "Performance Criteria: Stormwater Ponds." Retrieved Oct. 30th, 2007, from http://www.stormwatercenter.net/Manual_Builder/Performance%20Criteria/Stormwater%20ponds.htm.

The Caribbean Institute for Meteorology and Hydrology website. http://www.cimh.edu.bb/ accessed December 2007.

Wynn, T. M. and S. K. Liehr (2001). "Development of a constructed subsurface-flow wetland simulation model." Ecological Engineering **16**(4): 519-536.