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Towards Green Highways: Alternative Runoff Management in Quebec

Report submitted to:

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Executive Summary

Current highway stormwater runoff management systems are inefficient at retaining hydrocarbons, de-icing salts and heavy metals which can lead to contamination of groundwater and streams. From the previous chapter of this project, it was concluded that the implementation of constructed wetlands along highways in Quebec represents the optimal option for treating runoff contaminants. In addition to the primary objectives of this project, design aspects must fulfill wetland characteristics and performance targets while respecting the norms and legislations dictated by the Québec Ministry of Transportation. Constraints were prioritized such that wetland sizing was based on quantitative hydrological considerations while contaminant removal was optimized via the design of system components. Physical and hydrological variables have been characterized and embedded in a mathematical framework, which was used to predict the volume of runoff corresponding to specific rainfall events and required design features and dimensions. Contaminant loads were estimated from snow samples taken from Highway 20 in Montreal. A literature review on treatment performance assessed the great resilience of wetlands for treatment of contaminated runoff water, with main criteria being a retention time of approximately 15 hours for hydrocarbons, a dilution factor of 5 for salts and a sedimentation time of at least 30 minutes for retention of metals and suspended solids which can be removed by sediment scraping and plant harvesting. Predicted performance for the chosen wetland design configuration estimated that contaminant loads reaching the environment will be below critical levels required for aquatic life and ground water preservation. Finally, a risk of failure analysis, strategies for implementation, monitoring and testing were proposed to assess the functioning of a prototype of this wetland design.

1 Introduction

In order to engage in current sustainable development trends, Transport Quebec (TQ), has committed to improving its management of highway runoff as data suggest that current practices are inefficient in preventing destructive effects of contaminated runoff on the surrounding environment (Serodes & Taillion, 2003). The first phase of this project reviewed a variety of runoff management systems such as media filter drains, wet/dry ponds and constructed wetlands. It was determined that a constructed wetland would be the optimal solution as it has the potential to address the main design criteria by respecting low impact development (LID) principles. Additionally, this proposed solution is low cost, has low maintenance requirements and has high potential efficiency, quantitative capacity, and resilience to

Quebec winter conditions. Once preliminary investigation and planning were conducted, focus was placed upon the design and evaluation of the proposed system regarding its primary objectives of (1) respecting original road network configuration by minimizing alterations to the site, (2) proposing a runoff management that is more efficient than current systems, (3) limiting erosion, (4) providing overflow management capacity, (5) including a sediment management scheme that could be adapted to seasonal aggradation in order to prevent sedimentation of streams, (6) preventing a defined amount of pollutants from reaching the surrounding natural ecosystem, (7) developing a system with continuous flow, (8) maintaining optimal capital investment by selecting cost-effective materials, (9) creating a sustainable design, (10) minimizing implementation and maintenance costs, (11) being aesthetically appealing to encourage social acceptance, (12) presenting a reasonable implementation timeframe where occurrence of activities coincide with usual maintenance activities. In order to fulfill these objectives, our approach focused on three main components: provincial standards, civil engineering considerations, and biological processes. This report intends to provide specifications and analysis of the engineering of a constructed wetland. First, provincial design, construction and maintenance activities will be reviewed. The road cross-section and runoff predictions of a typical study site will be defined, followed by the characterization of the wetland lateral slide slopes, pre-treatment cell and wetland design components. An evaluation of the expected design performance (based on literature values for runoff contaminant wetland treatment) and a risk assessment will be presented. Finally, guidelines concerning the implementation of the project, monitoring and testing of parameters and a cost analysis will be discussed.

2 Provincial Standards and Maintenance Activities

The design and construction of constructed wetlands along Quebec's highways should be done in accordance with basic road conception, construction, and maintenance guidelines set out by TQ, thus ensuring its ease of integration and protection of health and safety of the highway network users. As a result, the construction and viability of the wetland should not, in any case, interfere with or damage the existing structure and should be adapted to the current maintenances activities planned by TQ to reduce implementation cost and ensure basic maintenance requirements are met. Therefore, a review of highway construction guidelines, relevant to the design of constructed wetlands, suggested by TQ and defined in tomes one to seven of the *Collection Normes: Ouvrages Routiers* will be required (Transports Québec, 2007); it should be mentioned that only tomes 1, 2, and 6 proved to be useful, presenting information on the conception, construction, maintenance, and materials required for the design of Quebec's highways.

3 Building our "Typical Study Site"

3.1 Road Cross-section

In order to assess whether the proposed systems have the potential to withstand runoff generated by targeted rainfall events, a typical study site was developed to meet specific criteria. This hypothetical highway would be located in a region near the Island of Montreal and would be affected by important traffic. It would be based on a typical cross-section of a two-lane highway with each lane measuring 3.7 m wide and with shoulders measuring 3 m and 1.3 m respectively. This gives a total width of 11.7 m for the impervious surface. In addition, the assumption has been made that drainage systems would collect runoff from vegetated (grass) slopes on both sides. The width of these surfaces is estimated to be 12 m on both sides. When the drainage ditch width is taken into consideration, the total width of the cross-section will be 45 m. The infiltration rates will vary depending on the type of runoff control measures that will be used along the highway. These characteristics were combined to give the typical cross-section displayed in Figure 12-5. For calculations and comparison purposes, highway segments of 500 m will be considered to measure the "typical" volume of runoff generated for that section.

In this cross-section, runoff from the impervious surface is divided between the outer and the inner sides of the highway lane. This means that the runoff generated on the inner sides of both lanes is drained into a common area between the lanes where it will flow toward the nearest subsurface outlet or percolate through the soil. This gives a total drainage surface for the inner side of 13,500 m^2 and a surface of 9,000 m^2 for the outer side. This cross-section is used when there is enough space between the two highways, so water can flow away from the highway without any risk of damaging road infrastructures. This is the typical cross-section used in the urban region surrounding the Island of Montreal.

3.2 Predicting Runoff

3.2.1 Total runoff depth

To calculate our typical runoff volume the *Curve Numbers Method*, developed by the NRCS, must be used. This technique allows for calculation of runoff values according the following equation:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{1.0}$$

In this equation, "Q" is the runoff depth (inches), "P" is the amount of rainfall (mm), "I_a" is a parameter that describe the amount of rainfall that is absorbed or infiltrates and does not become runoff (mm) and "S" is a storage parameter (mm) calculated according to:

$$S = \frac{25400}{CN} - 254 \tag{1.1}$$

In order to calculate "S", the Curve Number (CN) (a parameter associated with different soil infiltration capacities) must be obtained, according to the type of land cover and antecedent moisture conditions. These values are given in hydrology textbooks; these values can then be combined to obtain an average CN for the drainage area according to:

$$CN_{average} = \sum \left(\frac{A_{zone\ n}}{A_{total}}\right) CN_{zone\ n} \tag{1.2}$$

The "I_a" parameter can be approximated by $0.2S$ (Ward & Trimble, 2004) which tranforms equation 1.0 into:

$$Q = \frac{(P - 0.2S)^2}{(P - 0.8S)} \tag{1.3}$$

The value for "P" will be given by obtaining the amount of rainfall generated by a 1:10 year, 24 h long storm from IDF curves designed for the region of Montreal (MDDEP, 2003). Curves made from data collected at the Montreal-Trudeau International Airport weather station were used as a reference for the hypothetical site.

3.2.2 Peak runoff rate

After calculating the total runoff depth according to equation 1.3, the Graphical Peak Discharge Method can be used to determine the peak runoff flow rate that can be generated. This method was also developed by the NRCS, and is calculated according to:

$$q = q_u AQF \quad (2.0)$$

In this equation, "q" is the maximal flow rate (m^3 s^{-1}), "A" is the surface area drained (km^2), "Q" is the depth of runoff (mm) and "F" is a correction factor that reflects the presence of wetlands or ponds along the path taken by the water. The last factor, "q_u", is the unit peak discharge (m^3 s^{-1} km^{-2} mm^{-1}) calculated according to:

$$q_u = C_f 10^k \quad (2.1)$$

In the previous equation, "C_f" is a correction factor for the conversion between imperial and international units, "k" is an exponent calculated according to:

$$k = C_0 + C_1 \log_{10} t_c + C_2 (\log_{10} t_c)^2 \quad (2.2)$$

In order to calculate "k" according to equation 2.2, the different values for "C_n" parameters are obtained from hydrology textbooks (Methods & Durrans, 2003). The time of concentration (h) for runoff formation (t_c) is approximated according to:

$$t_c = \frac{t_L}{0.6} \quad (2.3)$$

Here, "t_L" corresponds to the lag time required for water from the highest point of the drainage basin to reach the lowest point. Its value is calculated according to:

$$t_L = \frac{L^{0.8}(S+1)^{0.7}}{1900 Y^{0.5}} \quad (2.4)$$

In this equation, "L" corresponds to the flow length of the drainage basin (ft), and "Y" represents the average slope along the flow path. "S" was already defined according to equation 1.1.

3.2.3 Results and interpretations

Using the equations provided above, the following values of predicted runoff were obtained (for complete calculations, see appendix 4):

Table 3-1: Runoff Related Values

Parameters (1:10 yr, 24 h storm)	**Value**
Designated Rainfall Intensity	3.5 mm hr^{-1}
Total Precipitation	84 mm
Estimated Runoff (inner side)	39.86 mm
Time of concentration (inner side)	~ 9 min
Peak Runoff Discharge (inner side)	0.1196 m^3 s^{-1} per section of 100 m
Total Runoff Volume (inner side)	717.5 m^3
Estimated Runoff (outer side)	38.50 mm
Time of concentration (outer side)	~ 10 min
Peak Runoff Discharge (outer side)	0.0825 m^3 s^{-1} per section of 100 m
Total Runoff Volume (outer side)	519.7 m^3

The estimated peak discharge corresponds to the amount of water that the studied systems will have to withstand since these rates correspond to the requirements established by TQ (MDDEP, 2003). Because the predicted rainfall intensity is equal to predicted rates of snowmelt (3.5 mm h^{-1} in average), these design parameters should permit the proposed system to withstand runoff volumes generated during spring snow melt conditions.

4 Wetland Design Components & Characteristics

According to information available from the literature, the wetland should be broad, flat, have shallow water and high resistivity in order to enhance treatment performance. These characteristics allow for slow water velocity and high residence time in order to favor settlement of particles (which is important given that most contaminants tend to bind to sediments). Moreover, the inlet and outlet shape should diffuse surface water at a slow rate to minimize erosion, turbulence and suspension of sediment matter (US Army Corps of Engineers, 2000).

4.1 Lateral side slopes

The two lateral delimitations of the lateral wetland systems consist of a stormwater inlet slope and an internal water flow-containing slope. The central wetland consists therefore of two inlet slopes. When designing wetlands for general applications, the maximum recommended inlet slope on the system is 1:5 (Ontario Ministry of Environment, 2003). However, according to TQ drainage structure construction standards for highways, the slope on which stormwater from the highway tributary area flows towards one drainage system must be 1:6 (Transports Québec, 2007). Selecting an inlet slope of 1:6 concurs with the recommendation for general wetland application and with TQ's regulations. The bottom of the inlet slope will be covered with geotextile to prevent erosion.

On the other side of the lateral wetland, the primary function of the border slope will be to contain water within the system, meaning no water volume that will enter the system from this source are accounted for in the wetland flow calculations. Under these circumstances, TQ recommends a grade of 1:2 for such slope functioning (Kadlec & Wallace, 2009). Impermeable geotextile will be installed on 50 cm of this lateral slope starting from the bottom of the 40 cm of substrate and up to 10 cm above its surface, which correspond to the maximum attainable water height within the wetland.

4.2 Pre-treatment cell

A pretreatment cell is a necessary wetland characteristic that diminishes the risks associated with day-to-day operations, thereby increasing longevity of the wetland (Ontario Ministry of Environment, 2003). The designed wetland therefore includes a forebay and pervious berm that will act together as a pretreatment cell.

4.2.1 Berm

The main functions of a wetland exterior berm are (1) to regulate the flow velocity entering the system, (2) to retain water in the forebay to allow for sedimentation of suspended solids and (3) to prevent coarser materials from entering the wetland. To regulate the flow passing from the forebay to the wetland, the berm material must provide an adequate hydraulic conductivity in accordance with rainfall occurrence and frequency for which the system was designed. Stacked crushed rocks are a common and recommended pervious material used for berm construction in the context of a wetland due to the possibility for rock size selection; different rock dimensions allow for different sized air spaces, which provide a wide range of water conductivity through the pores. Therefore, for a storm event with a frequency of 1:10 years of 24 h duration, rock dimension required must allow a flow diffusion of 39.6 mm in 24 h. In the event of an important storm episode (with a frequency of less than 1:10 years, of 24 h duration) or possible partial clogging of the permeable berm, the excess water will flow freely over the berm and be directly conveyed into the wetland. While it is desirable to avoid overflow situations, due to the importance of the pretreatment step, regular drainage operations of stormwater will be uninterrupted under these infrequent circumstances. Geotechnical considerations and slope-stability analysis dictate minimum berm slope in constructed wetlands should range between 2:1 and 3:1 (Kadlec & Wallace, 2009). Because of space limitations, a slope of 2:1 should be selected. The berm height should be equal to the maximum desired water level in the wetland and should be approximately 10 cm above the substrate. However, for this wetland application, the berm is expected to filter water containing various forms of coarse debris running off from the road. For this reason, clogging is more likely to occur and the berm should be modified to include a safety factor of 1.5. Thus, even if the hydraulic conductivity of the berm is reduced, water will still be able to pass through part of the berm as opposed to bypassing this pretreatment step completely as a result of overflow situations. For a trapezoid height of 15 cm with a small base of 10 cm, the berm bottom width should be 70 cm. The length of the berm will correspond to each wetland highway section of 500 m. A metallic mesh will cover the berm and function as a riprap on the inlet side slope, providing protection against burrowing animals (which could severely damage the structure) and material stability; the berm should be situated on an impervious geotextile to prevent rock movement onto the substrate (Kadlec & Wallace, 2009).

4.2.2 Forebay

The forebay lateral side facing the wetland will consist of an underground extension of the wetland substrate. It was assumed that when the wetland is at its full capacity, this side of the forebay would not allow water from the forebay to diffuse into the wetland as a result of water saturation. On the other hand, during drier times of the year, water contained in the forebay will be free to diffuse into the wetland substrate. Captured water in the forebay will only be diffused laterally as a concrete liner in the forebay followed by a geotextile liner will restrict vertical percolation. Furthermore, the pretreatment trench will provide additional storage for flow events that occur less frequently than 1:10 years of 24 h duration and during major spring snowmelt events.

The forebay length to width ratio must be at least 1:2 (Ontario Ministry of Environment, 2003) as each wetland section is 500 m long; length to width ratio must absolutely be respected. To avoid re-suspension of particles, the forebay should be deeper than the wetland water line, which is 10 cm for the lateral side and 20 cm for the central side. Moreover, the forebay should be designed with a surface area equivalent to 20% of the wetland area (Agency of Natural Resources, 2002) (Kadlec & Wallace, 2009). Considering the wetland has an average cross-section area of 0.2 m^2 (0.1 m x 2 m), the forebay cross-section area should be approximately 0.04 m^2 for the lateral wetland and 0.08 m^2 for the central wetland. However, a safety factor of 2 was included in forebay calculations leading to a proposed cross-sectional area of approximately 0.08 m^2 for the lateral side and 0.16 m^2 for the central side. This safety factor accounts for the potentially high rate of sediment accumulation caused by winter sand application and significant quantities of other particles running off from the road, which will reduce the forebay volume over time. Moreover, additional space in the forebay is useful for storage of contaminated snow. Initially, a clay liner was considered for the forebay bottom due to its capacity to adsorb de-icing salts. However, the forebay is designed to promote sediment buildup and requires cleaning during maintenance operations. Clay liner is a soft material and it would be difficult to avoid scraping it during the frequent maintenance operations. Consequently, it could be torn which would allow water percolation, groundwater contamination and could incur additional repair and replacement expenses. For this reason, the Vermont Agency of Natural Resources (2002) highly recommends that the bottom of the forebay be hardened to facilitate the removal of accumulated sediments. The forebay bottom grade should be stabilized with a hardener of a certain thickness that will be selected as a function of geotechnical and maintenance operation device considerations.

The Ministry of Transportation stipulates that a drainage installation must be implemented at a distance greater than 2 m from the road (Transports Québec, 2007). Because the wetland design makes use of existing drainage systems, this distance should be respected. Moreover, the typical road section used in this design provides a 10.66 m length between the road and the forebay inlets.

4.3 Wetland

4.3.1 Liner

Soil liners are used in the wetland as a barrier to stop the migration of pollutants into groundwater. The liner required for this design should be impervious so that water can be retained and treated in the wetland. As was discussed, geotextile will cover both side slopes of the wetland and a hardener material will cover the forebay bottom to facilitate maintenance operations. In order to optimize plant growth, a substrate depth of 40 cm above the liner in the lateral wetlands and 35 cm in the central wetlands will be required. Since contaminated water is less directly in contact with the material under the substrate, salt retention will be inefficient. Hence, an impervious geotextile liner is a better alternative for water retention in the wetland, and is a more economical option. The wetland requires a period of two to three years for plant establishment (Sérodes, Taillon, & Beaumont, 2003), during which bed flooding should be avoided; therefore, a pervious geotextile would be the best option, as it would permit the water to infiltrate the soil during this period. With time, clogging would render the geotextile impermeable.

4.3.2 Substrate, Plants and Ecosystems

To ensure successful establishment of *Typha latifolia*, a substrate depth greater than 30 cm above the geotextile will be required. As such, the lateral wetland will have a substrate depth of 40 cm and the central wetland will have a substrate depth of 35 cm in order to respect the minimum height of the drainage system, in relation to the road, set out by ministry regulation standards. In order to respect an LID approach, this project aims to reuse onsite soil; existing soil will be used to form the wetland bed main substrate. However, the project manager could choose to import topsoil if the soil characteristics are found to be unsuitable for plant growth or to control invasive species. The best soils include sandy loam, silt loam and sandy silt loam; decent soils include sandy clay loams, clay loams and silty clay loams; least desirable soils include sandy clay and silty clays. Soils of the last two categories (decent and least desirable) may be improved by the addition soil amendments or by mixing with other soil types (US Army Corps of Engineers, 2000). *T. latifolia* and *T. angustifolia* thrive in soils with high organic content and can tolerate soils with lower organic content and moderate salinity. These plant species produce enormous amounts of litter, and thus increases soil quality as they grow. The density of *T. latifolia* alone after establishment is on average 70 plants m^{-2} (Kadlec & Wallace, 2009). The wetland ecosystem is expected to reach steady-state within three years. Indigenous wildlife and plants will naturally colonize the wetland and require minimal maintenance. As discussed in the performance section, mixing 1 kg m^{-2} of clay into the subsurface substrate of the wetland and into the side slopes would slightly improve sodium (Na), potassium (K) and chlorine (Cl) retention by ionic exchange (Morteau, Triffault-Bouchet, Galvez, Martel, & Leroueil, 2009).

4.3.3 Outlet

A system of rectangular weirs (stop logs) will be installed at the end of each 500 m section to provide flow control in the wetland. This division system was chosen for its flexibility; it allows for adjustment of permanent water levels contained in the wetland under emergency or maintenance circumstances. Hydraulic analyses and calculations have dictated a maximum stop log height of 10 cm for the lateral system and 20 cm for the central system. The minimum longitudinal slope of the system, which conveys water to the final outlet, is 0.5 %. The treated water leaving the system will be collected in a site-specific natural body of water; professional engineers must perform a hydrogeomorphological analysis to ensure available body mass will support water flowing out of the wetland system. Our present design assumes that each outlet is responsible for two wetland sections connected in series.

4.3.4 Water Flow

4.3.4.1 Water Balance

Once the amount of runoff generated in a targeted event has been established, it is possible to predict how water will flow across the wetland. This is done by first observing the water balance across the various wetland units as described in equation 3.1 and Figure 5-1.

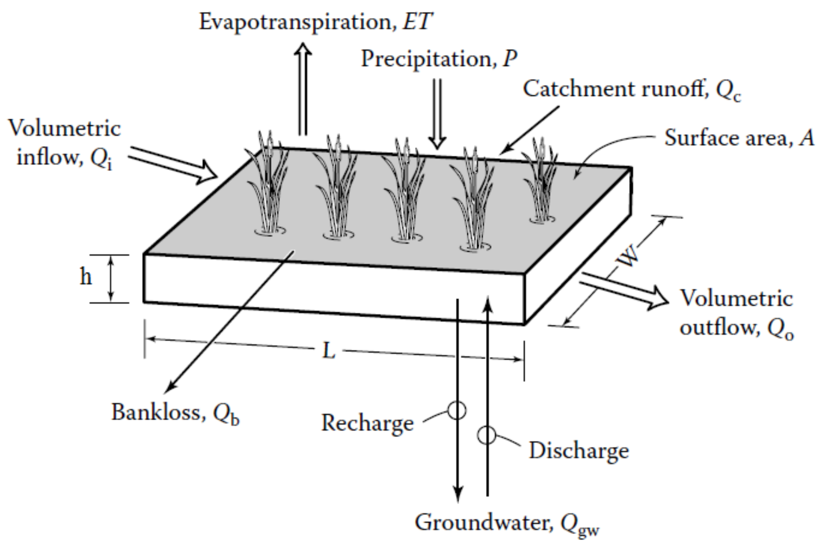

Figure 5-1: Typical Water Balance in a Wetland

$$Q_i - Q_o + Q_c - Q_b - Q_{gw} + P(A) - ET(A) = \frac{dV}{dt} \qquad (3.0)$$

In this equation, "Q_i" is the input wastewater flow rate (m^3 day^{-1}), "Q_o" is the output wastewater flow rate, "Q_c" is the rate of runoff directly entering the wetland, "Q_b" is the bank loss rate, "Q_{gw}" is the infiltration rate, "P" is the precipitation rate (m day^{-1}), "ET" is the evapotranspiration rate (m day^{-1}), "A" is the top surface area of the wetland (m^2), "V" is the water storage capacity of the wetland (m^3) and "t" is time (in days). Because the proposed design uses impermeable liners to seal the wetland, it has been decided that the loss rates (Q_b and Q_{gw}) can be neglected thereby increasing the magnitude of the outflow. Such an assumption permits estimation of flow conditions when the soil is saturated.

Once the output wastewater flow rate has been established according to the water balance equation, it is possible to calculate the potential flow depth in each wetland unit. This is done by using the "weir controlled" flow equation provided in the literature (Kadlec & Wallace, 2009).

$$Q_o = \frac{2}{3}\, C_d\, L \sqrt{2g}\, \sqrt[2]{H^3} \qquad (3.1)$$

In this equation, “g” is the gravitational acceleration, “L” is the length of the weir (m), “H” is the water height above the weir, “H” is the height of the weir and “C_d” is a parameter, specific to a rectangular weir, that can be calculated according to:

$$C_d = 0.611 + 0.075H/H_w \quad (3.2)$$

Then, using a numerical solver, it is possible to calculate the water height, “H”, required to create a pre-established wastewater outflow. This value will vary depending on the height of the weir and the amount of runoff generated on the catchment. Because water flows are relatively low, it can be assumed the that average depth is relatively constant along the length of the wetland (Kadlec & Wallace, 2009). This depth can be calculated according to:

$$\hbar = H + H_w \quad (3.3)$$

The calculated value of the water depth can then be used to measure the average water velocity across the series of wetlands using this equation, which was specially developed for densely vegetated constructed wetlands (Kadlec & Wallace, 2009):

$$u = (1.0 \times 10^7 m^{-1} day^{-1})\hbar^2 S \quad (3.4)$$

In this equation, “u” the mean superficial velocity (m s^{-1}), “h” is the water depth along the wetland (m) and “S” is the average slope of the wetland bed (%). This velocity can then be used to estimate the water residence time in the wetland.

4.3.4.2 Results and Interpretations

Table 4-1: Outer Side Wetlands Flow Characteristics

Parameters (outer side)	Value
first wetland unit outflow (Q_o)	501.73 m^3 day^{-1}
first wetland unit depth (h)	11.36 cm
first wetland unit superficial flow velocity (u)	0.007468 m s^{-1}
first wetland residence time (t)	18.6 hours
second wetland unit inflow (Q_i)	501.73 m^3 day^{-1}
second wetland unit outflow (Q_o)	1003.46 m^3 day^{-1}
second wetland unit depth (h)	12.14 cm
second wetland unit superficial flow velocity (u)	0.008529 m s^{-1}
second wetland residence time (t)	16.3 hours

Table 4-2: Inner side Wetlands Flow Characteristics

Parameters (inner side)	Value
first wetland unit outflow (Q_o)	599.49 m^3 day^{-1}
first wetland unit depth (h)	21.54 cm
first wetland unit superficial flow velocity (u)	0.02685 m s^{-1}
first wetland residence time (t)	5.2 hours
second wetland unit inflow (Q_i)	599.49 m^3 day^{-1}
second wetland unit outflow (Q_o)	1199.0 m^3 day^{-1}
second wetland unit depth (h)	22.43 cm
second wetland unit superficial flow velocity (u)	0.002985 m s^{-1}
second wetland residence time (t)	4.8 hours

The results demonstrate that important differences exist between the wetlands on both sides of the highway lanes. Because the central wetlands must convey water from both lanes, it has been established that their water storage capacity must be doubled in comparison with the lateral wetlands (i.e. 200 m^3 versus 100 m^3) to ensure that the runoff will not be flushed into the outlet too quickly. To increase the storage volume, 20 cm high control weirs will be used instead of 10 cm weirs. Because of sizing considerations and regulatory constraints, the storage volume could not be increased any further, limiting the flow control capacity of the wetland. The increased water depth and outflow will cause an increase in flow velocity thereby greatly reducing the water retention time in comparison with the lateral wetlands.

The approximate flow characteristics of the wetlands on the lateral side of the highway show that the conditions will be optimal for the treatment of the various contaminants. The low flow velocity and the shallow water depth correspond to the required standard literature values. While the lateral side wetlands are adequate, the runoff volume contained in the central wetland might present a challenge. The increased water flow and flow velocity across the wetland greatly reduces the travel time of water compromising the performance of the wetland. This aspect will be discussed in more details in the performance section of this document.

Although the initial steps for these calculations were performed by hand, the various equations have been compiled in an Excel spreadsheet that allows for rapid parameter adjustments. This spreadsheet can be used to quickly calculate the different flow parameters under various scenarios. This allows for validation of the proposed systems on different sites where the feasibility of its implementation can be easily assessed.

5 Expected Design Performance

5.1 Quantification of Highway Runoff Contaminants

Characterization of contaminants in inlet water from snowmelt was required for the analysis of treatment performances for the spring season. On March 10, 2012, snow samples were collected at a distance of 1 m from Highway 20 in Sainte-Anne-de-Bellevue, near Montreal. Samples were analyzed by spectrometry to allow for determination of contaminant concentrations (which were mostly metals). Results are shown in table from appendix. Other inlet concentrations were taken from Morteau, et al. (2008) and Sérode, et al. (2003) in which values were obtained from measurements taken in drainage ditches along Highway 40 near Quebec City and in the vicinity of Montreal, respectively. Runoff concentrations were compared with water quality criteria for aquatic life and consumption/groundwater criteria from Environment Canada and the United States Environmental Protection Agency (US EPA). Focus was placed upon contaminants above or close to acceptable limits. This information is available in Table 5-2.

5.2 Performances

Some of the processes involved in the water treatment performed by wetlands are microbially mediated processes, sedimentation, volatilization, sorption, photodegradation, plant uptake, vertical diffusion in soil and sediments, transpiration flux, vertical root profiles, seasonal cycles and accretion (Kadlec & Wallace, 2009). This section serves to examine potential removal of contaminants from a diffusive source of highway runoff water by a series of linear wetlands. We acknowledge our incomplete scientific understanding of all processes; therefore, empirical values found from two relevant studies were borrowed in order to estimate the expected treatment performances of the system and then compared with results from the literature. The processes of focus are sorption, sedimentation and plant uptake (phytoextraction). The term "general process" in this section refers to any or all of the processes participating in runoff treatment in wetlands. The design of this project involves both a pretreatment ditch and a vegetation strip that optimizes contaminant retention in the spring, summer and fall seasons.

5.2.1 General Process

Sérode, et al. (2003) performed a three-year experimental study that served to compare five types of constructed wetlands for implementation along highways in the province of Quebec. From this list, two were selected based on their treatment characteristics; the first was an "FG" wetland consisting of a 1.5 m transverse strip of roadside vegetation adjacent to a sedimentation ditch, the second was a "GC" wetland consisting of a 3 m longitudinal strip of vegetation. Experimental results lead to the conclusion that water quality was significantly improved as a result of wetland treatment. The experiment did not study the effect of length or width of the wetland on performances; the dimensions were chosen according to space availability. To assess wetland performance, reference values were selected from measurements taken prior to the construction of the wetlands. The samples were measured annually (from 1999 to 2002) in the fall and spring during rainfall events using consistent sampling methods. Table 12-1: Expected Design Treatment Performances (Sérode & al. 2003) displays the values measured in the GC and FG wetlands, and the percentage of pollutant reductions in 2001 and 2002. The measured efficiencies of contaminant removal in those wetlands were combined to obtain an estimate of minimal values for year-round performance for the design proposed in this report. Specific components were modified or added to increase performance, which include a pretreatment sedimentation ditch, a berm to diffuse flow energy and filter debris, clay matter mixed into the substrate surface layer and *T. latifolia* plants for phytoextraction.

5.2.2 Adsorption

In the experiment conducted by Morteau, et al. (2008) clay was investigated for its capacity to adsorb contaminants. In the laboratory, 10 g of clay was added to 100 ml of water containing 787 mg L^{-1} Na and 1213 mg L^{-1} Cl. In this design, the average runoff concentrations for Na and Cl were found to be 350 mg L^{-1} and 1044 mg L^{-1}, respectively. In the best case, removal concentrations for Na and Cl were 13.3 mg L^{-1} and 34.6 mg L^{-1}, respectively. To obtain similar adsorption results as in the laboratory experiment for the proposed wetland design, the mass of clay mixed into the bottom substrate of the wetland can be calculated according to:

$$\frac{10g\ clay}{100ml\ water} * \frac{10L\ water}{m^2 wetland\ area} = 1kg/m^2$$

However, the elements could desorb from the clay matter under low pH conditions or in the presence of competing elements with higher ionic strengths such as Calcium (Ca) and Magnesium (Mg) (Ray & White, 1976).

5.2.3 Sedimentation

In Sérode, et al. (2003), the FG wetland (consisting of a narrow vegetation strip with a sedimentation ditch) achieved greater retention of contaminants in the spring season than in the fall season for 62 % of the measured parameters. In the spring, plants are dead and treatment is achieved by sedimentation and slow degradation by microorganisms. The sedimentation ditch increases the hydraulic retention time, which permits most pollutants to bind to sediments and settle to the bottom of the wetland. This process played an important role in the treatment of runoff water; an efficient sedimentation process occurs in a pretreatment ditch within approximately 30 minutes for a rainfall return period of 1:5 year (Sérodes, Taillon, & Beaumont, 2003) as demonstrated in Table 12-3: Percent Reduction of Contaminant Loads From Sedimentation Process (Sérodes & al., 2003). For this reason, the experiment showed that most contaminant concentrations increased in the sediment matter after the wetland was implemented.

5.2.4 Phytoextraction & Biodegradation

In Sérodes, et al. (2003), a GC wetland (consisting of only a vegetation strip) was more efficient in the fall season for 82 % of measured parameters. During the growing season, plants and decomposers are active and play an important role in the removal of pollutants. Summer experiments showed microorganisms have the ability to degrade hydrocarbons at a minimal mineralization rate of 6.4 g C hr^{-1} (Nix, Steckoest, & Hamilton, 1994). According to a study conducted by Zingelwa & Woolridge (2009), *T. latifolia* stems were found to accumulate significant amounts of metal contaminants, which can be removed by harvesting at the end of the growing season. Table 6 5 APENDIX shows the amount of various contaminants accumulated in *Typha* from several studies. Table 5-1 is an estimate of expected contaminant concentrations that could be up taken by *T. latifolia* over a rainfall event assuming a constant water depth of 10 cm in the wetland, an average plant density of 70 stems m^{-2} (Kadlec & Wallace, 2009), a dry mass for the shoot, rhizome and root component of 6.7 g, 9.9 g and 9.4 g, respectively for individual plants (Zingelwa & Woolridge, 2009), and 72 rainfall events per growing season (Environment Canada, 2010). The contaminants contained in the stems should be removed from the system by harvesting the plants before they die in the fall season. Excluding Na and Cl concentrations, the potential for phytoextraction was calculated to be greater than the contaminant loads over a growing season. This is in agreement with the results obtained by Sérodes, Taillon, & Beaumont (2003) displayed in Table 12-4.

Table 5-1: Expected Contaminants Accumulated in Typha Latifolia for an Average Rainfall Event

Investigated parameter	concentration mg L^{-1}	harvestable plant uptake in mg L^{-1}
Cl	1043.55	6.8
Cu	0.004	0.8
Mg	1.423	2.7
Mn	0.138	6.2
Na	350.27	3.8
Ni	0.0033 –0.990	3.0
Zn	0.0025-0.929	0.3

5.2.5 Hydrocarbons

An experiment conducted by (Nix, Steckoest, & Hamilton, 1994) found empirical values for the degradation of diesel in a wetland by general process to be 1,605 g C h^{-1}, which corresponds to a hydraulic retention time of 15 h for the degradation of 95 % of hydrocarbon species present at an initial concentration of 100 mg L^{-1}. The measured inlet concentration from Sérodes, et al. was approximately 100 mg L^{-1}; the necessary retention time to reduce this value to 5 mg L^{-1} (which represents the threshold value required by aquatic life) should be shorter than 16 h, without taking into account dilution. The design was sized such that water has a minimal retention time of 16 h in the wetland (from inlet to outlet). Microbial mineralization could be inhibited if concentrations of hydrocarbons are too high; retention time and dilution in the wetland minimizes this risk.

5.2.6 Metals

During the growing season, significant concentrations (≥ 90%) of metals are expected to be phytoextracted. In the dead season, sedimentation processes should reduce metal loads by 60 to 80 % (Sérodes, Taillon, & Beaumont, 2003). Metal contaminants should be extracted from the environment by harvesting of plants and removal of sediments. Therefore at the wetland outlet, metals are all expected to be present at concentrations lower than the water quality criteria for aquatic life, consumption and groundwater found in Table 5-2.

5.2.7 Sodium, Calcium, Chlorine, Acetate and Magnesium

The elements found at highest concentrations are salt constituents applied as de-icing agents on roads. They are very soluble in water and consequently hard to retain (Sérodes, Taillon, & Beaumont, 2003). The aquatic ecosystems were found to withstand relatively high concentrations of these salts; however the salt concentrations were lower than those measured in average highway runoff water from. All plants require these salts as micronutrients. *T. latifolia* plants are expected to accumulate insignificant amounts (≤ 0.1 %) over an entire growing season. Clay material is expected to retain approximately 2 % of the Na species and 3 % of the Cl species. Because these strategies only retain a small percentage of these species, the primary strategy to be adopted for treatment of salts in this design is dilution. The wetland acts as a buffer that reduces flows and allows for dilution, which dampens the concentration surge of contaminants to the environment. The “first half-inch rule” is a general rule commonly used in the United States; it states that 90 % of pollutants accumulated on an impervious surface are washed off by the first half inch of runoff during a rainstorm event (WSDOT, 2008). In the context of this design, initially 44 m^3 of polluted water will be retained in the wetland while its final volume will be of 200 m^3 (the volume at which outflow begins), representing a 1:5 dilution. The inlet salt concentrations are expected to decrease to an acceptable level by the time they reach the outlet following dilution.

5.2.8 Total Phosphorus, Nitrogen and Suspended Solids

P and N were found at concentrations 10 to 60 % lower than water quality limits. These are expected to be transformed by microorganisms in addition to being absorbed by plants as macronutrients, and therefore will be beneficial to the wetland by improving vegetation growth and density. The pretreatment sediment ditch unit alone is expected to at least reduce suspended solids to a concentration that meet groundwater requirements. For instance, the suspended solid concentration from the snow water samples was 142 $\mu g\ L^{-1}$ and is expected to be reduced to less than 71 $\mu g\ L^{-1}$ which is very close to the 67 $\mu g\ L^{-1}$ criteria for groundwater (MDDEP, 1998).

6 Risk Assessment

Throughout the wetland design process, potential problems have been identified, along with their adverse effects and extent to which they could lead to the wetland component failure. The system components have been designed to take these risks into consideration thereby minimizing the failure risk without compromising the function of other parameters. The previous table summarizes the risk assessment of the wetland design at steady state (after three years of establishment).

Table 5-1: Estimated Treatment Performances of a Constructed Wetland for Highway Runoff

Para-meter	Concentrations measured from highway runoff water µg L^{-1}			Treatment process				Water quality criteria (MDDEP, 1998)		Toxic limit (EPA , 2011)	
	Design project snow sample	Sérodes et al. (2003)	Morteau et al. (2008)	Phytoextraction[1]	Sedimentation[2]	clay adsorption[3]	General process [4]	limit groundwater µg L^{-1}	limit consumption µg L^{-1}	acute µg L^{-1}	chronic µg L^{-1}
Al	44.09							750		750	87
As	0.29			X				340	25	150	69
Ca	53970		157630	X							
Cd	0.052			X				2.1	5		
Cl			1043550	X		X	X	860 000	250 000	860 000	230 000
Cr	1.43	0.5-10			X			16			
Cu	3.95			X			X	7.3		4.8	3.1
Fe	13.20				X		X				1000
K	1100			X							
Mg	1423			X				50			
Mn	138.31			X	X		X		50		
Na			350 270	X		X			200 000		
Ni	1.99	3.3-990		X				260	20	470	52
Pb	0.24	9-1780		X	X		X	34			0.1
S			76670					200	50	2	2
TN	3	2.05-2.27		X			X	20			5
TP	0.32	0.113-0.998		X		X	X		10		
TSS	142.00				X		X		3		
Zn	8.06	2.5-929		X	X			67		120	120

[1]: From laboratory experiments conducted by Morteau et al. (2009); Zingelwa et Wooldridge (2009); Dushenkov et al.,(1995); Aulio 1986; Ye et al. (1997b); Taylor and Crowder (1983)
[1,2,4]:From field test studies on constructed wetlands by Sérodes et al. (2003) and laboratory experiment from SETRA, 1997 in Sérodes et al., (2003)
[3]: From laboratory experiment by Morteau et al. (2008)

Table 6-2: Risk Assessment of the Wetland Design

Potential problem	Failure risk	Risk management/Risk reduction
Berm clogging (by coarse and abundant debris from highways)	Water overflowing – No pretreatment filtration	Berm sizing safety factor: 1.5
Erosion of ground under rock berm	Berm failure	Impervious geotextile under the rock berm
Burrowing animals	Berm damaging and potential failure	Protective metallic mesh wrap around the berm
High rate of sediment accumulation in the forebay (highway debris and sand)	Space reduction in the forebay – Sedimentation process reduction	Forebay sizing safety factor: 2
Geotextile damage during maintenance operation in the forebay	Contaminated highway stormwater reaching groundwater	Hardened liner (e.g. concrete, asphalt, etc.)
Substrate dryness (impervious liner blocks plant access to groundwater)	Jeopardize vegetation in the wetland	Stop logs retain 10 cm of water in the wetland – *Typha* tolerates dry conditions up to 8 weeks
Maintenance or emergency operation inside the wetland	Access and operation complexity because of permanent water retention	Stop logs can be removed and water can be evacuated directly to the outlet
Important rainfall event	Highway structure damage - Flooding	Impervious geotextile prevents infiltration that could destabilized highway structure – Terrace system allow continuous downward flow toward the outlet
High concentration of salt in stormwater entering the system	Jeopardize vegetation in the wetland	*Typha* are salt tolerant
High energy flow entering the system during an important rainfall event	Turbidity and irregular flow distribution	Berm dissipates energy of water in the inlet - regulates flow entering the wetland
Important flow discharge in spring containing high concentrations of de-icing salts	Sedimentation process, phytoextraction and clay adsorption reduction in the wetland – reduced de-icing salt capture	Impervious geotextile limits high concentrations of salts from reaching ground water – dilution process in the wetland – Forebay sizing safety factor: 2
Water entering the system close to the outlet will not have enough retention time.	Contaminated highway stormwater reaching groundwater	Forebay ensure a pretreatment – Stop logs can retain 10 cm of water in the wetland before discharging in the outlet – Dilution, one of the main treatment process, is still being efficient even at the end of the wetland
Because water does not infiltrate in the ground, the outlet will receive a greater amount of water that it was designed for the existing drainage system	Outlet flooding	The outlet was designed to receive great amount of melted water at spring as the soil is still frozen for infiltration process

7 Prototype Model

Constructed wetlands give variable performance results because of stochastic environmental and climatic conditions. It is a highly complex system as previously mentioned, and present performance models are only tentative descriptions of real circumstances. Since constructed wetlands with this exact design have never been implemented in Quebec, reference values can only be obtained from similar designs and are still scarce. Kadlec & Wallace (2003) recommended avoiding spending money and time on prediction models (software) for which some parameters are tedious and difficult to quantify. As a result, a simplified approach was used to predetermine values of the parameters based on similar experiments from the literature. Due to climatic and time constraints, the construction of a prototype wetland was impossible. However, this report includes recommended guidelines that could be used to calibrate the model by monitoring and testing. A prototype wetland should be constructed on a typical road section and performances should be evaluated to produce empirical standards for the design of all other road sections. Prototype wetlands should be constructed three years prior to the start of implementation of the main project. In Quebec, administrative regions have similar environmental and climatic conditions so, one prototype per region within the project boundaries is suggested.

7.1 Monitoring and Testing

The purpose of monitoring and testing is to asses if the goals were realistic and to identify what possibilities exist to optimize wetland features on both the long and short terms. There will certainly be a need to fine-tune the system and this can be achieved by modifying the management scheme to emphasize the parameters that exert the most influence on improving and sustaining hydrological characteristics and water quality. Evaluation of functionality can be performed using several methods and tools depending on the scope and purpose of testing. The extent, precision and frequency of evaluation will depend on budgetary considerations. To facilitate decision making by project managers, the table below displays a list of the parameters that should be evaluated and also suggested methods and tools that could be used. The table includes performance criteria for each parameter based on its potential influence on the success or failure of the project (US Army Corps of Engineers, 2000).

Table 7-1: List of Monitoring and Testing Operations

Project objectives	Parameter	Evaluation	Method/tools	Criteria (%)	Reference
Drain All Water from Road Infrastructure	Hydrology soil	Subsurface water depth and drainage capacity	Measure soil infiltration rate, soil saturation and depth of water table near road infrastructure	5	Kadlec & Wallace (2003)
16 h ≥ Retention time ≥ 24 h	Hydrology	Time for water to travel from wetland inlet to outlet	Add a tracer at inlet, measure time to reach outlet	5	Kadlec & Wallace (2003)
Storage Capacity ≤ 200 m^3	Hydrology	Proportion of water from rainfall/snowmelt event contained after time of retention	Water budget	5	US Army Corps of Engineers, (2000)
Low Maintenance After 3 Years Establishment	Vegetation	-Ecosystem at steady-state? -Capacity to regenerate itself -Nutrient retention -Wildlife establishment	Assess plants by : -Canopy coverage method -Species diversity - Health characteristics -Record observed wildlife	5	US Army Corps of Engineers, (2000) Kadlec & Wallace (2003)
	Hydrology Sediment Loads	-Maintenance requirements -Rate of sediment accumulation -Control over the stop log outlets	-Record maintenance operations -Calculate rate of sediment deposition -Calculate seasonal water flux and depth		
≈ Year-Round Hydrologic Functionality	Hydrology	Water budget	Measure flow rates	5	Kadlec & Wallace (2003)
Flow Energy = Laminar	Hydrology	Water velocity movement of particles	Measure flow rate and distribution	5	Kadlec & Wallace (2003)
Treatment ≥ Expected Design Performances	Water Quality Vegetation Sediment	Evolution of contaminants from: - Water concentrations -Sediment content -Vegetation content	Monitoring of: - Inlet & outlet water samples -Sediment cores -Plant samples	15	Sérodes & al. (2003)
	Hydrology	Dilution capacity	Add tracer at inlet, measure concentration flux at outlet		Kadlec & Wallace (2003)
Sediment Retention ≥ 90% Loads	Sediment Loads	-Quantity and rate of sedimentation accumulated in pre-treatment ditch, wetland and outlet	-Sediment budget - Measure depth & distribution of soil, litter and sediments -Place array of sediment traps	15	US Army Corps of Engineers, (2000)
Adapts to ≥50% of Length	Design plan	Post-implementation review	Aerial photography	10	
Low Costs	Design budget	Post-implementation review	Financial assessment	10	
Respects LID	Design plan	Post-implementation review	Environmental impact assessment	5	
Life Span ≥ Road Infrastructure	Soil, Water quality, Plant Maintenance	Rate of deterioration of wetland components	Water quality analysis to predict long term functionality and performances.	5	Kadlec & Wallace (2003)

8 Design Implementation

The guidelines for implementation of the proposed wetland were based on standards and recommendations from The Wetland Engineering Handbook from the US Army Corps of Engineers (2000).

8.1.1 Site selection

The wetland should be an integral part of the ecosystem. The topography, soil and hydrology of the site must be modified to meet design objectives. Site investigation and evaluation is crucial in order to determine the feasibility of the project. The project objectives and design were meant to be simple and flexible to allow compatibility with many different types of landscapes and ecosystems; however there will be circumstances where sites will be constrained by regulations, space or property ownership, and will be incompatible with the project and should therefore be excluded. Sites requiring complicated engineering and disruption of natural landscapes should also be excluded. Constructed wetlands that mimic natural systems are low cost and require minimal maintenance (US Army Corps of Engineers, 2000).

8.1.1.1 Site Investigation

The amount of information on topography, hydrology, vegetation, climate and watershed at specific sites will impact the decision making process. Soil investigation must be performed by professionals and the depth of analysis will depend on available time, budget and risk considerations. Assessment of existing conditions is required to provide a baseline for comparison before and after site modifications, and to calculate required wetland size, elevation depth and soil bearing capacity. Recommended methods and procedures for this project are described in this section.

8.1.1.2 Onsite reconnaissance

The highway should be investigated in its full length to identify locations that may pose logistical constraints. Areas with obvious limitations should be screened. Aerial and ground photography could be used to assess land characteristics.

8.1.1.3 Literature search

A compilation of preexisting information should be performed and should include all aerial and/or satellite photography, records and geological data sources. Since the project will be implemented on highway infrastructures, geotechnical subsurface information of the site for structures and earthworks already exist in government registries.

8.1.1.4 Site Sampling

Sampling is required to fill information gaps remaining after the literature search has been conducted. Sampling should be done for the cross-section of the two lateral sides and the central area of the highway. Detailed information of the following components will be needed:

Vegetation: Identify all important plant species and their distance from the road, population density and elevation in reference to the road infrastructure. Vegetation types can serve as indicators for estimation of soil types and hydropatterns.

Soil: Determine soil profile(s) and water table location(s). Test near-surface soil for organic content, nutrient content, pH, salinity, texture, structure density, moisture content, compaction and presence of pan layer(s). Test subsoil for texture, consistency limits, permeability and *in situ* strength. This type of site assessment does not need to be deeper than 1.5 m to 2 m.

Topography: Survey the site to generate topographic maps with precise elevation contour lines, slope aspects and slope angles.

Hydrology: Survey and test for water table depth, local topography, erosion and water quality (turbidity, hardness, P, N and heavy metal concentrations), surface flows, precipitation, evapotranspiration, and groundwater discharge and recharge.

8.1.1.5 Map Study

Computerized tools such as geographic information systems (GIS) will allow for efficient, low cost baseline investigation of site characteristics. When available, databases will provide access to information on geomorphologic, hydrologic, topographic, land ownership, soil and vegetation types and other surveyed characteristics of land. Superimposed data layers can be used as a screening process to illustrate areas that respect design constraints and limitations. In addition, the map should include all water bodies, depth of water table and zones of wetland vegetation cover. These attributes are needed for analysis of water dynamics and for identification of the nearest areas for potential plant supply.

8.1.1.6 Data analysis

An investigation of soil mechanics will serve to calculate the bearing capacity of the soil. It is important to determine if the soil can support machinery and to assess the maximum depth of excavation that can be used without imposing the risk of damage to adjacent road infrastructure.

A complete water balance should be carried out at each site to determine expected inflow rates and seasonal water table depth variations. Quantifying all sources and sinks of water flowing through an area can be a difficult task. However, identification of the main hydraulic components and estimate values can be used in combination with land characteristics for modeling purposes in order to estimate required size for the constructed wetland area and components. Under or overestimates of wetland surface area could lead to recurrent droughts or floods, both of which would reduce the efficiency of the system in periods when it is most needed (i.e. during a significant snowmelt event or a storm event following a long period of drought).

The acquired data should undergo statistical analysis to account for variability. Graphs for each attribute data set produced should include mean, median, standard deviation and other statistically relevant measures of dispersion. Results will be useful for monitoring, testing and calibrating the hydrology and treatment performances before and after wetland construction.

8.1.1.7 Construction

This project aims to reuse onsite soil as its main substrate in accordance with the LID approach. Soil preparation is perhaps the most important factor affecting the performance of the wetland. It is recommended that the soil profiles of a nearby natural wetland be studied by digging to provide reference information regarding substrate layout. The procedure should absolutely respect site investigation lines and design criteria.

8.1.1.8 Preparation of the site

Prior to construction, influent water should be temporarily diverted in order to avoid damage to the structure, sediment wash and drowning of shoots. Mats should be laid down at low grades along site contours. A hollow should be dug to contain earth mounds.

At all times, on-site erosion control will be required to protect undisturbed areas and streams from sediments. Some simple and low cost measures can effectively prevent erosion problems. Bare soil should be covered with a degradable retaining material such as hay, mulches, binders and vegetation netting until complete vegetation cover is achieved. The slope from the road to the screening ditch and the dike should be grooved longitudinally 7 cm to 15 cm deep, seeded and covered by mulches and netting. After planting, the wetland surface can be covered with hay mulch, wood chips or bark. In the case of a planting delay, a cover should be embedded in the soil at a depth of 1.5 cm to prevent erosion caused by runoff and wind.

The construction will begin by delimitating the wetland contours by standard surveying according to the design plan for the specific road section site. Clearing and grubbing will consist of removal all above- and below-ground matter (trees, roots, stumps, rocks, rubble and other obstacles). The organic topsoil layer will be stripped and stockpiled in a shallow for later reuse, and covered with a liner to prevent erosion. Excavation should be 15 cm to 30 cm below the final grade and will depend on site elevation with respect to the road and water table. No rocks or other objects should be left on the grade surface; these items could potentially damage the liner. A semicompaction of the grade will be carried out in order to reduce settling stress. Water content and density will depend on the soil type and will vary from site to site. It should be assured that the grade is smooth and level to 0.5 % slope using measuring devices such as lasers. The liner will be placed at the bottom according to final cell grading. This step will usually be done by a subcontractor and tests will need to be performed to ensure the liner is leak resistant. The forebay, berm and stop log should be constructed according to characteristics and dimensions from section 5 of this report.

Clay will be spread over and mixed into the surface substrate layer at a density of 1 kg m^{-2}. Suitable soil conditions for plant propagation and establishment will require the soil to be light and aerated. Some techniques to minimize damage will include (1) using reduced size machinery with small tires, (2) assuring machinery always passes on the same track, (3) using a chisel plow after all the soil has been spread, and (4) avoiding or minimizing traffic and soil handling. Upon completion of this phase, the final surface can be planted.

8.1.1.9 Ecosystem establishment

When constructing a wetland designed for runoff treatment, it is desirable to control the types of plants present and accelerate establishment time. As such, a contractor should be hired to perform plant propagation and monitor establishment. Plants should be seeded unless a natural marsh is situated within 500 m to 700 m the project, in which case the site will likely be naturally colonized by the same species via wind, runoff and wildlife seed dispersion. *Typha* may spread at a rate of 10 m $year^{-1}$ to 20 m $year^{-1}$. Establishment of the wetland will require approximately two full growing seasons or until plant density reaches 100 stems m^{-2} to 800 stems m^{-2}, including all species. The most important aspect for successful plant establishment is soil condition. The substrate should remain moisture-saturated at all times. All possible precautions should be taken avoid flooding; excess water causes oxygen depletion and may drown shoots. This is usually the main predictive factor of establishment failure. The system may take up to three growing seasons to reach a steady-state. This is the time required for development of a suitable litter layer, microbial colony and effective sorption and CO_2 exchange processes. (Kadlec et al., 2004).

8.1.2 Maintenance

When the wetland is has reached a steady-state, standard maintenance operations for road sides (listed in the appendices) will be performed, with the exception of ditch excavation. A fixed vertical sediment depth marker should be installed to indicate sediment deposition ensuring removal operations are performed at the right time (Agency of Natural Resources, 2002). Maintenance of the forebay will not disturb the wetland due to the exterior berm segregation (Ontario Ministry of Environment, 2003). A concrete liner can be installed to provide a reference point for maintenance operations. Plant harvesting can be performed once a year to remove nutrients; however it is optional, keeping plants will not compromise the wetland functions. With time, natural vegetation will inevitably establish; it is unnecessary to attempt to control vegetation species even in the event of *Typha* being outgrown by other plant species (US Army Corps of Engineers, 2000).

9 Cost analysis

Cost analysis must be performed on a site-specific basis and will vary as a function of local availability of materials, cost of labor, transportation and site requirements. Data on general capital and operating costs of wetland implementation can be found, however it is important to consider that not all these costs can be applied to all treatment systems. Therefore, the cost analysis for this design only represents an estimate and should be reviewed by a local engineering firm at each site. The following detailed cost analysis is based on the construction requirements of a lateral 500 m wetland. Most of the costs were taken from Kadlec et al. (2006) which implies that the prices are presented in US dollars for the year 2006 which were subsequently be converted into equivalent Canadian dollars for the year 2012.

9.1 Capital costs

9.1.1 Direct costs

Basic direct cost components of wetland treatment systems include: land, site investigation and system design, earthwork, liners, media, plants, water control structures and piping, site preparation, fencing, access roads and facilities for human use.

Land: Since the wetland is intended to make use of existing on-site drainage systems, no land purchase is taken into account in the capital cost calculation.

Site evaluation: Site evaluation should include a topography survey since grading of each wetland section and trenching of the forebay will require some earth balance calculations. The costs for such surveys, according to Kadlec et al. (2006), range between \$ 50 ha^{-1} and \$ 500 ha^{-1}. Moreover, a geotechnical investigation will determine if soil on the site is adequate for wetland operation, slope and berm stability; usually a few thousand dollars are budgeted for these activities. Hydrological investigation will also be required even if the wetland has a liner because the rise of a shallow water table could potentially lift and damage the geotextile. A regional study of the body of water to be used for wetland outlfow will also be performed as a part of this investigation. The anticipated cost of these activities is \$ 750 ha^{-1}.

Earthwork: Excavation will be necessary as sites provide only 1 m for the existing lateral drainage system. Therefore, a height of 5 cm of earth will need to be removed in the centre, and forebay cross-section widths of 0.8 m^2 will need to be excavated. Grading work should also be carried out to level each wetland section. In Kadlec et al. (2006), the US EPA estimated earthwork to cost \$ 10.80 m^{-3}.

Phragmites is an undesirable invasive vegetation species that is currently found in areas adjacent to Quebec highways. Since the design proposed planting of *Typha* species, *Phragmites* will need to be removed as a part of the earthwork process. Other unwanted plants and trees present on the site will also need to be removed. In Kadlec et al. (2006) approximately \$ 9,800 ha^{-1} were allocated for clearing and grubbing purposes.

Liner: The total installation cost of the liner includes material, field seaming, seam testing, material inspection, and leakage testing. Moreover, if sharp or angular rocks are present on the site, a layer of granular material, such as sand, should be used to cover the ground surface before the liner is laid down. This would increase the total cost as sand bedding ranges from \$ 1.38 m^{-2} to \$ 3.08 m^{-2}. In the wetland design the main liner and substrate to be used are geotextile and clay applied at 1 kg m^{-2}, respectively. Geotextile liner will cost approximately \$ 8.66 m^{-2}; local clay with a density of 10 kg m^{-2} will cost approximately \$ 7.96 m^{-2}.

Media/Aggregates: No media or mulches are required in this wetland design since *Typha* is a very adaptable plant that grows well on ground sites bordering highways in most areas of Quebec. Coarse stone will be necessary for the berm construction; a median cost of \$ 47.9 m^{-3} was estimated by Kadlec et al. (2006).

Plants: Plant costs are associated with the establishmentmethod agreed upon by the engineers and contractors. Seeding seems to be the most suitable method for this design because *Typha* produce large seed heads containing a large number of seeds, which can easily be picked in fall. This method is slightly more expensive than natural recruitment but is also more reliable. Thus, 2 to 4 kg of *Typha* seeds ha^{-1} will be required, which will cost approximately \$ 381 ha^{-1}.

Structures: The existing drainage system already includes piping and other hydraulic control structures required for the outlet. Therefore, no costs have been allocated for structures in this design.

Site work: Access road or path to the site, fencing, surface restoration after construction and other construction elements must be considered in the direct capital cost. Site work costs generally represent 8 % of the total project cost.

Table 9-1: Estimated Wetland Direct Costs

Component		Unit	Quantity	Unit Cost (\$)	Total (\$)
Land		ha	-	-	-
Site evaluation	Topography	ha	0.1	300	30
	Geotechnical	Lump sum	-	200	200
	Hydrological	ha	0.1	750	75
Earthwork	Ground	m^3	100	10.80	1,080
	Plants	ha	0.1	9,800	980
Liner	Clay	kg	100	0.8	80
	Geotextile	m^2	100	8.66	866
Berm (500m)		m^3	30	10.39	311.7
Plants (seeds)		ha	0.1	381	38.1
Planting (Hydroseeding)		ha	0.1	145	14.5
Stoplogs		-	-	-	110
Site Work (8 % of total)		-	-	-	327.05
Total Direct costs					4,088.12

The total direct cost of this design is very low because land acquisition, structure construction and conveyance costs have been eliminated; concurrently earthwork costs have been reduced by making use of the existing drainage system. In Kadlec et al. (2006), most existing wetlands of equivalent dimensions have a direct cost that is 10 % higher than what is presented in this report.

9.1.2 Indirect costs

Indirect costs are also considered in capital cost estimation; examples of these costs include permits, engineering, financing, mobilization and construction management. Detailed estimates are usually made after final sizing and sitting.

Engineering and permitting: These costs are highly dependent on the size, complexity and novelty of the project; this generally represents 10 % to 15 % of the total construction costs.

Nonconstruction Contractor costs: All contractor expenses including contract cost are included in this parameter, which generally represents 4 % of the total construction cost.

Construction Observation and Start-Up services: All services provided during the construction including construction observation, inspection, testing, start-up assistance and operator training, will represent approximately 10 % of the total construction costs.

Contingency : Any human errors, underestimation of material and labor cost, vandalism, equipment breaking, accident, unfavorable weather, etc. are accounted for in contingency costs and represent approximately 20 % of the total construction cost.

Table 9-2: Estimated Wetland Indirect Costs

Component	Unit	Total ($)
Engineering	15 %	613.2
Construction observation	5 %	204.4
Start-Up services	5 %	204.4
Nonconstruction costs	4 %	163.5
Contigency	20 %	817.6
Total indirect costs	-	2,003.1

Estimated total capital cost for a 500 m lateral wetland = $ 4,088.12 + $ 2,003.1 **= $ 6,091.22**

Therefore, for every 1 km of lateral wetland system (2 x 500 m wetlands in series) the capital cost is estimated to be U.S. $ 12,182 in 2006. In 2012 Canadian dollars, the price would be approximately $ 14,034.20. Capital cost for a central wetland system would cost a few extra thousand dollars considering the fact that it will require more excavation due to presence of the second forebay and a greater quantity of rocks will be required for construction of the additional berm.

9.2 O & M costs

Operation and maintenance for a mature wetland are very similar to the current costs incurred by drainage systems along highways in Quebec. However, in establishment year, more operations will be required therefore additional costs should be allocated for O & M.

10 Conclusion

Finding an alternative solution for highway runoff management in Quebec was a great challenge considering the numerous constraints involved, notably from civil engineering, biological, and provincial regulation perspectives. However, as demonstrated previously, we have presented what we consider to be the best solution to the problem. The constructed wetland design is very innovative as opposed to previous designs; it was adapted to the hydraulic patterns and specific pollutants affecting Quebec's highways. Moreover, this solution is approximately half the price of similar wetland installations and takes advantage of maintenance activities that are already planned by TQ allowing for reduced operations and maintenance costs. Also, we estimate that the designed wetland has a greater performance than existing systems, thereby addressing one of our critical objectives. *Typha* were selected in order to sequester heavy metals; clay was introduced to adsorb de-icing salts; a forebay structure promotes preliminary sedimentation of suspended particles; the berm serves to filter coarser debris; but most importantly, as wetlands retain large volumes of water, it allows salts to be diluted, and therefore reduces their harmful effects on the environment. Given that the wetland is adapted to be compatible with existing road structures, it does not affect the current infrastructures in any way.

Here we are dealing with an organic system, therefore no further conclusions can be established until prototyping, testing, and monitoring activities have been carried out. As this implementation phase will require a considerable amount of time (at least three years) before providing substantial results, it was determined to be beyond the scope of this project. However, our research and contacts with different universities and with TQ have provided us with a lot of optimism for the future implementation of such a system and the will to further develop this design.

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12 Appendices

12.1 Appendix 1: Technical Drawings

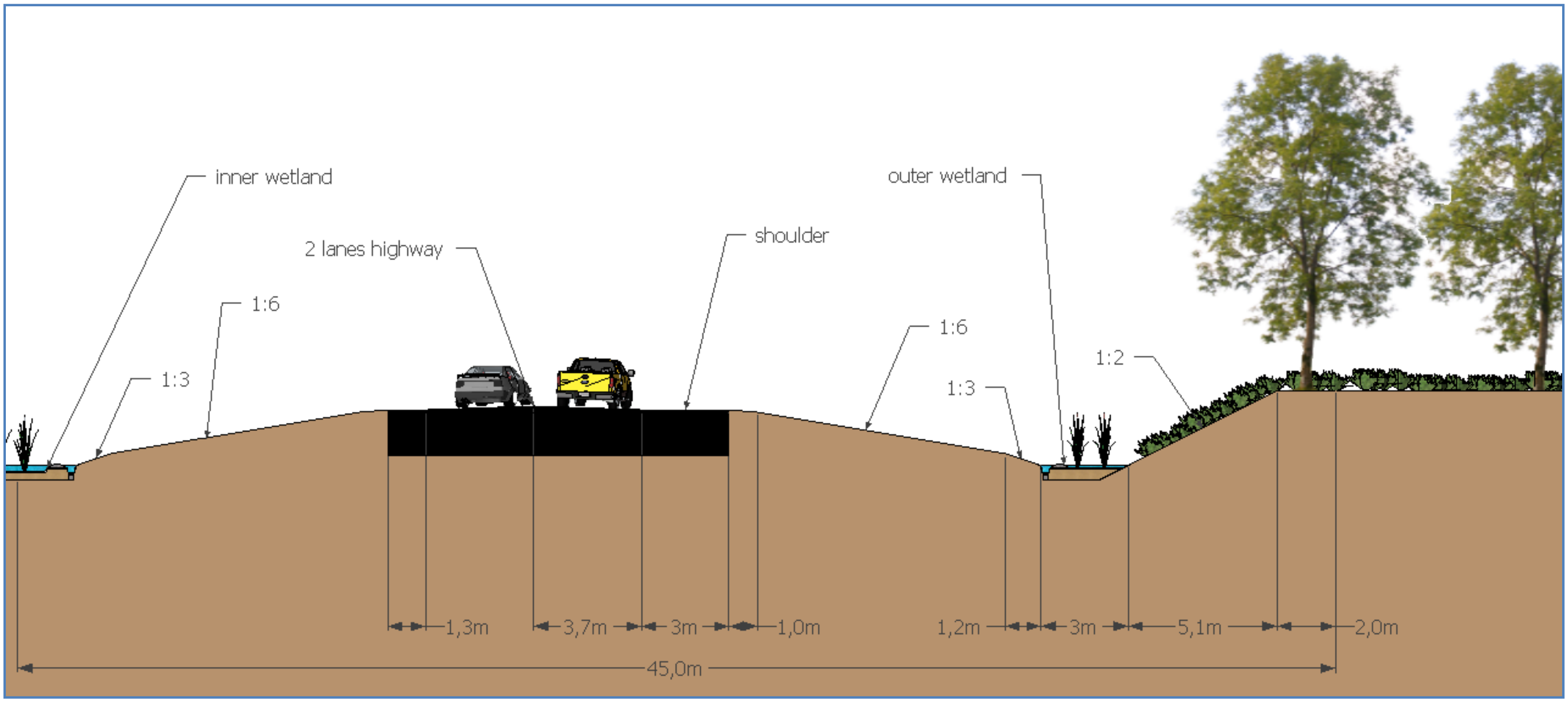

Figure 12-1: Proposed Design Cross-Section

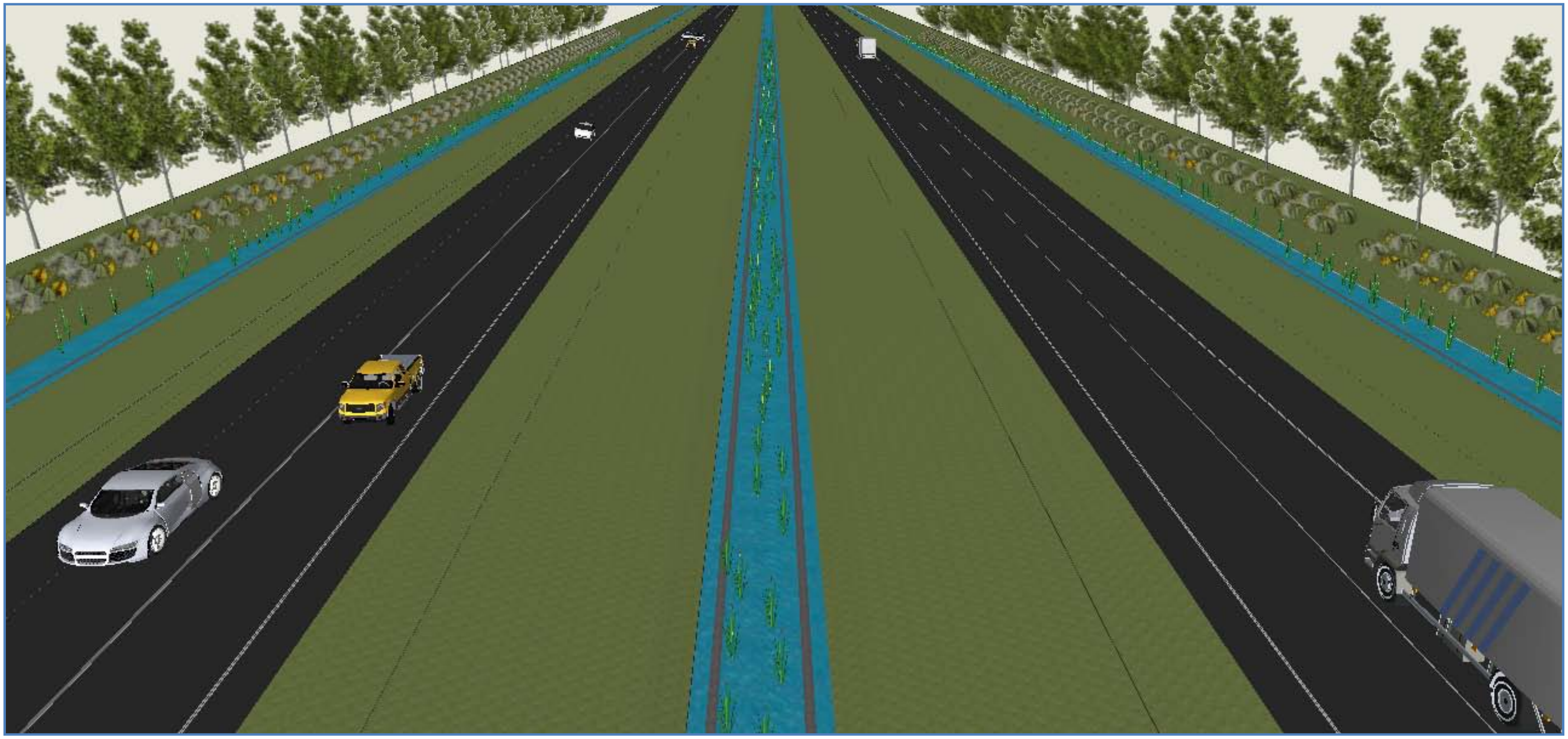

Figure 13-2: Proposed Design 3D View

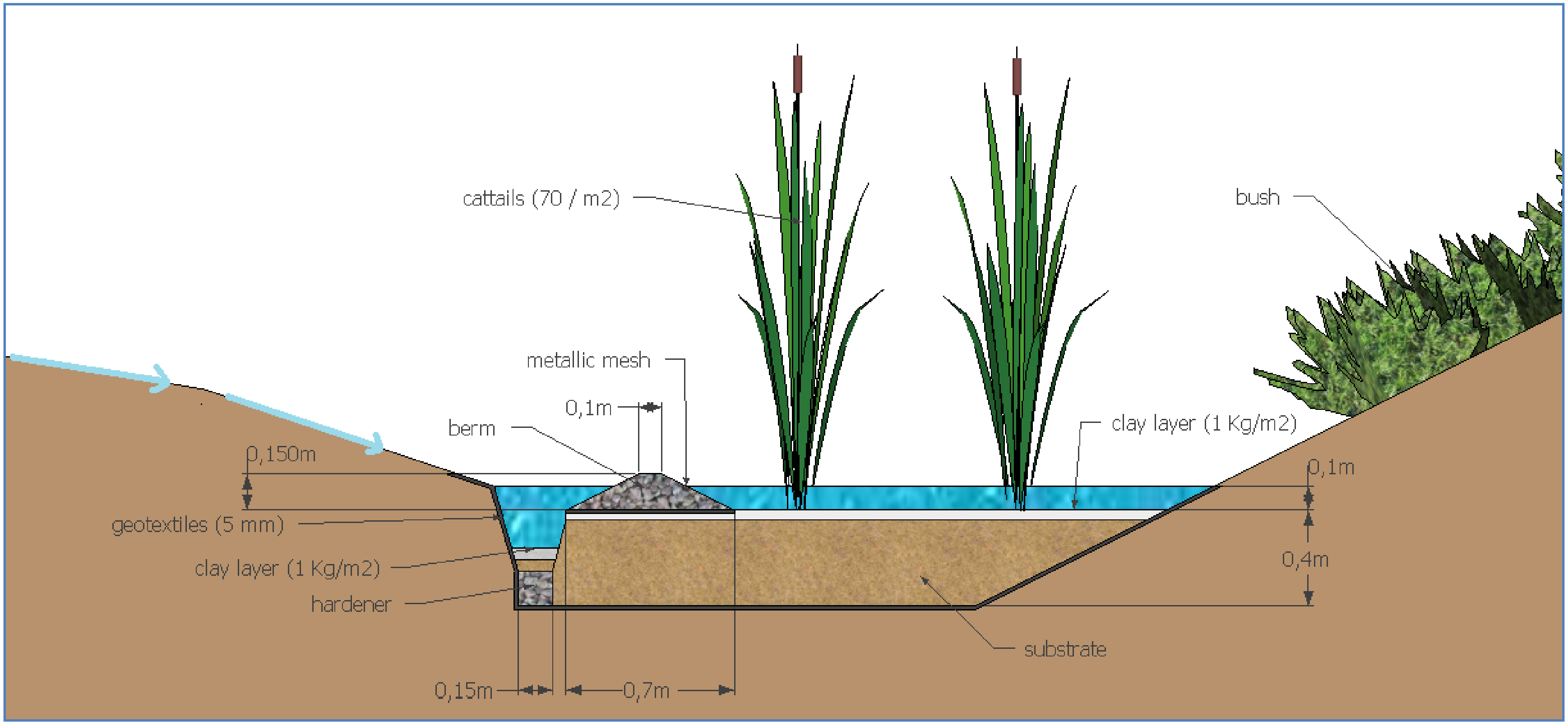

Figure 13-3: Outer Side Wetland

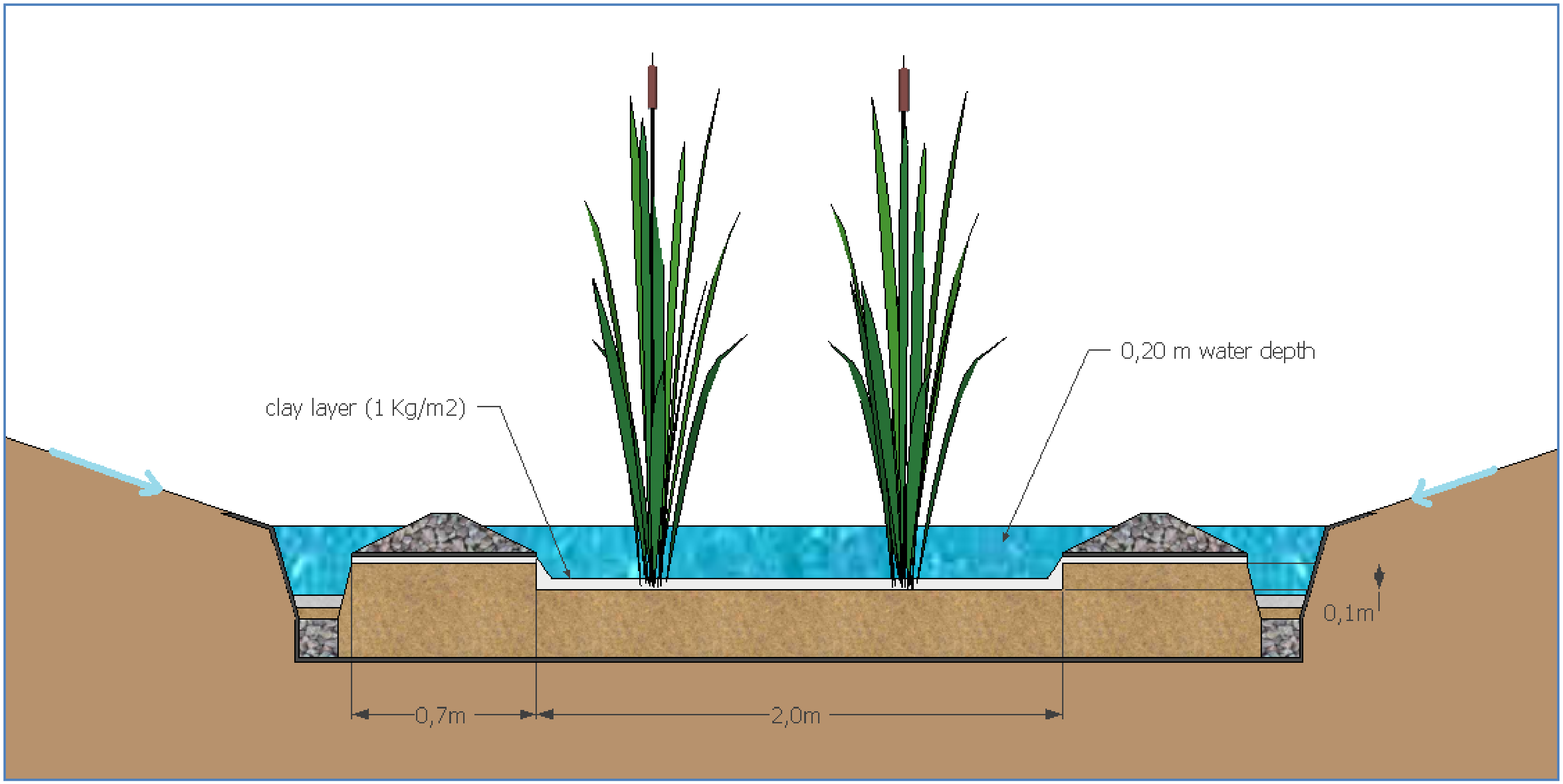

Figure 13-4: Inner Side Wetland

12.2 Appendix 2 : Provincial Standards Overview

12.2.1 Collection Normes: Ouvrages Routiers - Tome 1 : Conception

12.2.1.1 Environmental Framework: Wetland and Water Flow

Transports Quebec recognizes the great ecological role that wetland plays along Quebec's roads. Indeed, in the tome 1 of its *Collection Normes: Ouvrages Routiers,* it is reported that wetlands contributes to the greatening of water quality as it allow surrounding vegetation to fix nutrients or suspended solids to which may be associated toxic product by a settling process. Moreover, the ministry recognize the large water retention capacity of this type of environment as it acts as a regulator of stream flow, retaining water in times of cue and releasing it during low flow periods (Tome 1, chapter 2, page 33) (Transports Québec, 2007).

Transport Quebec suggests that, when approaching streams, runoff waters should be redirected to vegetation zones or sedimentation ponds at a distance of 20 m from the body of water. It is also recommended that if no sufficient space is available, the ditches should be reinforced by sodding or seeding along a distance of at least 15 m.

12.2.1.2 Road Cross section Area Standards

The following figure is an overview of a typical rural highway cross section in Quebec, as suggested by Transports Quebec. All measurements shown are in millimetres. It would be important to note here that the transverse slopes normally vary between 2-3%. For the practical reasons, a slope of 2% will be considered in this project. Moreover, as can be noticed, a width of 1000 mm is normally planned for the ditch, which shall be taken into account in the dimensioning of the constructed wetland.

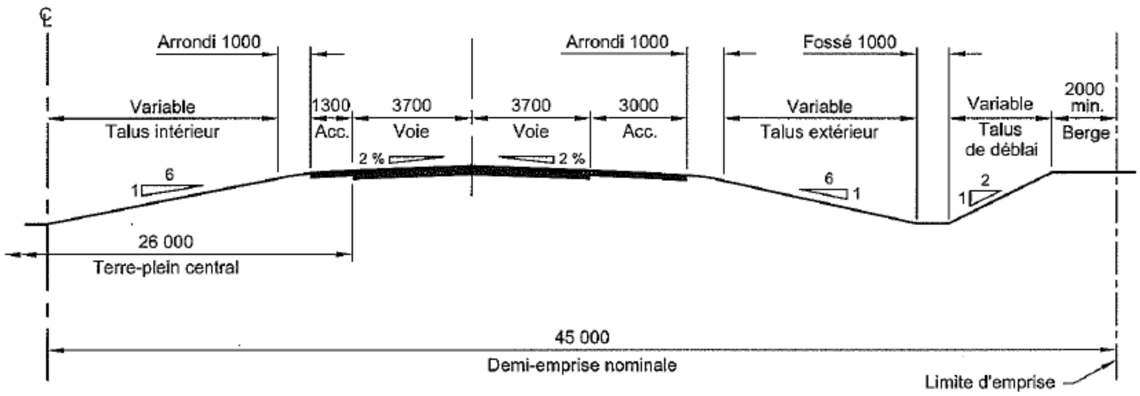

Figure 12-5: Cross-section of a 4 Lines Highway in Rural Area

12.2.2 Collection Normes: Ouvrages Routiers - Tome 2: Construction

12.2.2.1 Earthwork and transition (P)

The variety of soils in Quebec makes it difficult to design highways, as not all types of soils behave in the same fashion when challenged with freezing conditions or when imposed important loadings. In order to prevent the consequences that could be generated by the effect of freeze, Transport Quebec suggests that road designers provide a transition to prevent steep uprisings of the roads. One of the main factors that play into the determination of this transition is the freezing index which is calculated by adding all daily average temperature below zero during the year (units being °C • days). According to Transport Quebec, Montreal is in a 1000°C • days, which correspond to a transition depth of 2 m (Transports Québec, 2007) (Tome 2, chapter 1, page 6). As the constructed wetland will lie beneath this transition line, it can be assumed that the system will freeze during winters and could be vulnerable to shearing action. However, as no considerable loading is assumed to be on the system, this variable is can be neglected.

12.2.2.2 Drainage

The quality of the drainage system affects directly the behaviour and longevity of the infrastructures. Prior designing a drainage system, it is first fundamental to possess great knowledge of the hydrology and hydraulic of the designated area. Transport Quebec recommends that enclosed drainage systems should be designed for a return period of 25 years. However, TQ recognizes that other periods could be used depending on the intensity of the impact the occurrence of such an event may have on the existing structure or users. Slopes of the drainage pipe should be design is such way that the minimum velocity of water is 0.75 m/s and that the maximum velocity is 3.4 m/s. For a freezing index of 1000°C•days in

Montreal, the estimated frost is 1.85 m. It is to note here that in the design of constructed wetlands along highways, no alteration or modification on the existing enclosed drainage structure is planned. However, runoff that will fall in the wetland located in the inner slopes of the highway will be evacuated by the enclosed drainage system to a vegetation zone outside of the road zone. Therefore, a return period of 25 years shall be considered for the inner section of the design.

Transports Quebec recommends that open-air drainage systems, such as ditches, should be design to prevent runoffs from surrounding environment to reach the roads and insure visibility at all times. For practical reason, surrounding runoffs will be calculated only considering the surface area at the right of the ditch in the above drawing. Other runoffs will be assumed to be taken care of by external structure. Moreover, for the external wetlands, a return period of 10 years for the occurrence of a rainfall event of 24h will be considered as the impact on the structure of such a event would be lower for a open-air drainage structure than for an enclosed one. Finally, TQ suggests that the ditches slope along highways should be between 0.5% and 3% to optimize the hydraulic capacity of the system. For design purposes, a value of 1% shall be used (Transports Québec, 2007).

12.2.3 Collection Normes: Ouvrages Routiers - Tome 6: Maintenance

12.2.3.1 Cleaning and Excavation of Lateral ditches

This maintenance activity has purpose to re-establish the initial profile of side ditches or dig new ones in order to allow water evacuation and ensure a constant drainage of the highway foundations. Normally, those activities are conducted when it can be observed that water flow is obstructed, when sediments accumulation is greater than 150 mm, or when ditches depth is insufficient (inferior to 150 mm below infrastructure level). This activity is normally conducted at the end of spring. However, Transport Quebec recommends that excavation should never be done at a depth greater than 600 mm from the infrastructure line. In addition, TQ insist on the fact that surrounding vegetation shall be kept during this task in order to maximize slopes stability.

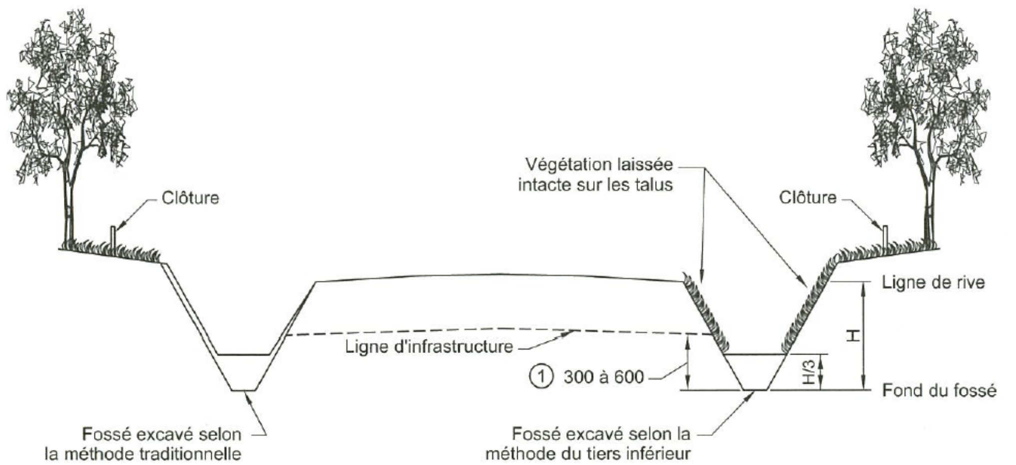

Figure 12-6: Cross-section of the Ditches and Ambient Vegetation

As can be observed on Figure 12-6, the excavation activity shall leave all vegetation at the superior 2/3 of the total ditch depth intact. Moreover, the depth of the ditch from the infrastructure line should be between 300-600 mm according to TQ. For practical reasons and to minimize the risk of damage on the existing infrastructure by the wetland, a value of 600 mm was chosen for the design.

12.2.3.2 Maintenance of the Protection against Erosion of Ditches

In some cases, Transports Quebec suggests the use of dry stones or concrete to protect the infrastructure and the ditches against erosion. Intervention is planed if it is observed that the reinforcement structure is instable and does not serve its function anymore. Punctual activities will be initiated in relevant circumstances in order to correct this problem. It can be reasonably assumed that the frequency of this type of activity will be considerably reduced as wetland will increase the ground stability and therefore reduce erosion risks as well as maintenance costs. Nevertheless, this cost reduction would be neutralized by the increasing risk of closed pipe clogging by vegetal debris that might be generated by the wetland activity. Transport Quebec plans to clean enclosed drainage system when either sediment accumulation reaches 25% of the pipe diameter or that there is any obstruction.

12.2.3.3 Green Space Maintenance

This section has for purpose to reduce risk of erosion or proliferation of ragweed by maintaining grassed surfaces initial characteristics. Moreover, it aims to eliminate any objects that could harm grass clipping or mowing material. Inspections are normally conducted the day prior to the maintenance event. It is assumed that as the constructed wetland will have no direct impacts on the grass layer as it will be built at the bottom of the slope, not reaching the grass zone and separated by the forebay. However, the design will need to be done with respect to the minimum grass width requirements along Quebec highways. TQ recommends that grass clipping along highways should reach a width between 1.8 m to 3 m, starting from shoulder. This width must be increased in curves to increase visibility. Grass clipping must be done at a height of 100 mm. To insure safety and visibility as well as to limit pollen and ragweed proliferation, mowing activities will be required to limit growth of the wetland vegetation. Transport Quebec recommends grass clipping maintenance at least twice a year (3 to 6 times per season in urban areas) when vegetation reaches a height of 45 cm (height limit of 75 mm), when visibility is reduced, or when aesthetics is altered. Mowing activities are prescribed normally when plants diameter reaches 25 mm or when vegetation height reduces visibility. TQ recommends that the mowing height shall be limited to 100 mm until the ditch bank. Moreover, it is recommended that in zones where phragmites are in high density, special attention should be put to ensure that vegetation width is limited to 6 m in the central median and 5 m on the bank of the lateral ditches. TQ plans mowing activities along highways in the zones described in the following figure. It is to note that in Figure 12-7, zone 1 and 2 are areas where it is recommended to keep woody plants such as trees and shrubs to prevent soil erosion. Therefore, TQ proscribes mowing activity in zone 1 and 2. Finally, TQ also encourages the conservation of existing vegetation.

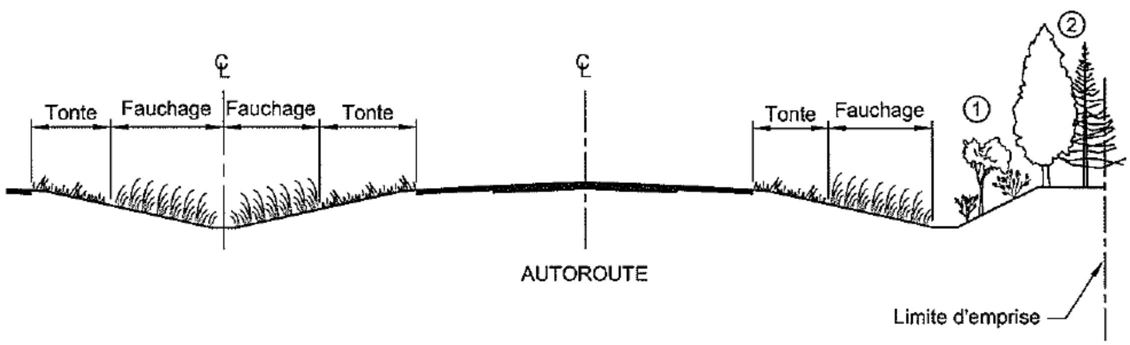

Figure 12-7: Clipping and Mowing Zones Along Quebec Highways

12.2.3.4 Winter Viability: Snow Removal and De-icing

In order to ensure users safety, Transport Quebec recommends the use of salts (sodium chloride or calcium chloride) and abrasives to de-ice highways surfaces during the winter. TQ recommends that as soon as snow precipitation begins, progressive de-icing activities shall start and last until a few hours after the end of the precipitation. On highways, snow removal activities must start once precipitations have reached a height of 2 cm. Detailed sequencing of winter maintenance activities recommended by TQ is illustrated in Figure 12-8.

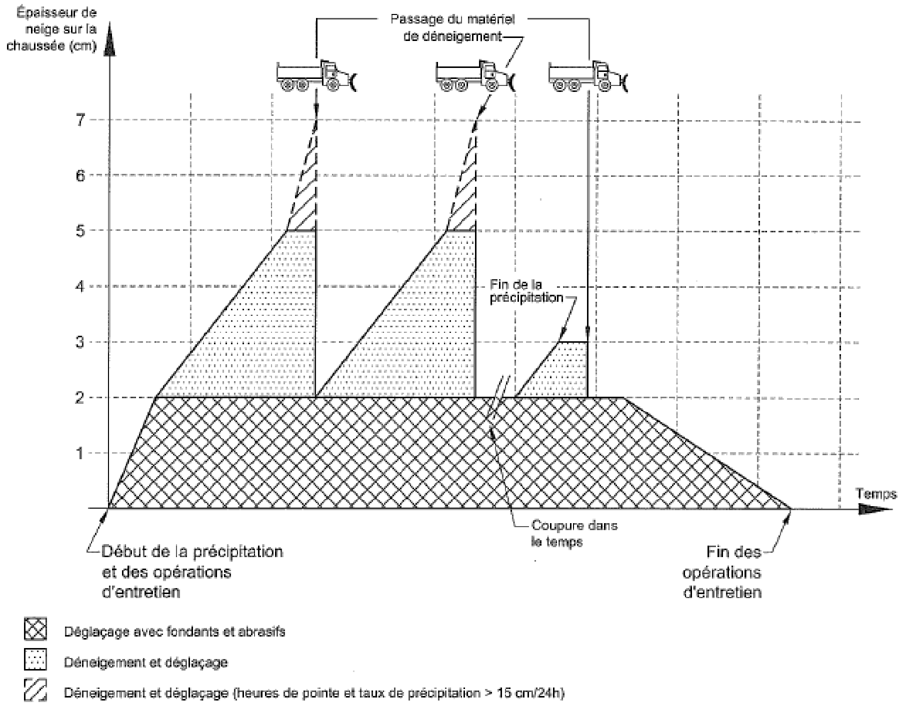

Figure 12-8: Activity Sequence as a Function of Snow Precipitation

Salts and abrasives shall be distributed on highways surfaces with a spreader provided with an electronic controller calibrated to a spreading rate of 0-700 Kg/km for abrasives and 0-350 Kg/km for salts.

12.3 Appendix 3: Reference Tables

Table 12-1: Expected Design Treatment Performances (Sérode & al. 2003)

Parameter concentration in water (mg/l)	% reduction dead period	% reduction growing season	System efficiency trend with time	literature values for max and min % reductions
TN	0	7	↑	40-75
TP	50	107	≈	48-90
TSS	6	6	↑	64-95
EC µS/cm	4	17	≈	-
Cl	7	27	↑	-
Cr	0	0	↑	43-99
Cu	17	41	≈	31-90
Fe	0	14	↑	-
Mn	40	96	↑	-
Pb	40	40	≈	48-95
Zn	0	0	↑	31-90
C10-C50	0	0	≈	50-80

Table 12-2: Comparison of Sediment Contaminants Before and After Wetland Implementation (Sérodes & al. 2003)

Parameter	Concentration in sediment Before (mg/kg)	Residual Concentrations trend	Criteria from Environmental Agencies (mg/kg)		
			NEL [a]	MEL [b]	TEL [c]
As	3.7	↓	3	7	17
Cd	0.3	≈	0.2	0.9	3
Cr	98	↑	55	55	100
Cu	56	≈	28	28	86
Sn	10	↑	na	na	na
Fe	34 000	↑	na	na	na
Mn	410	↑	na	na	na
Ni	63	↓	35	35	61
Pb	48	≈	23	42	170
Zn	150	↑	100	150	540

↑: increased concentration; ↓: decrease; ≈: similar result; a: no effect level: basic content, without chronic or acute; b: minimal effect Level: content where effects are observed but is tolerated by most organisms; c: toxic effect level: content that creates adverse effects for most organisms.

Table 12-3: Percent Reduction of Contaminant Loads From Sedimentation Process (Sérodes & al., 2003)

Parameter in sediments	Suspended solids (SS)	Chemical oxygen demand (COD)	BOD5	Total nitrogen (TN)	Hydrocarbons (HC)	Metals
% reduction loads	50-90	40-80	40-80	30-60	25-80	60-80

Table 12-4: Total Element Accumulated in Typha Latifolia

Element	Stems mg/plant	Rhizome mg/plant	Root mg/plant	Reference
Cl	70	70	70	(Morteau & al., 2009)
K	11	3.7	2.1	(Zingelwa & Woolridge, 2009)
Ca	172	104	56	
Mg	28	25	41	
Na	39	19	20	
Pb	n/a	n/a	16.3	(Dushenkov & al., 1995)
Zn	3.32		117.8	(Aulio, 1984)
Cu	8.51		22.2	(Ye & al., 1997)
Cd	0.00		7.1	(Taylor & Crowder, 1983)
Ni	31.29		9.6	
Mn	63.72		0.0	
As	1.15		2.2	

12.4 Appendix 4: Detailed Calculations

12.4.1 Runoff Calculations (Outer side)

12.4.1.1 Obtaining curve number value

The cross section was divided in different zones: impervious surfaces and vegetated slopes. Assuming that the surrounding soils have moderate infiltration rates (hydraulic soil group B) CN values of 100 for impervious surfaces and 74 for grassed slopes are obtained. These values were obtained from Ward & Trimble (2004). The area-based weighted average curve number is calculated using equation 1.2:

$$CN_{average} = \sum \left(\frac{A_{zone\ n}}{A_{total}}\right) CN_{zone\ n}$$

$$= \frac{6.7\ m * 500\ m}{(6.7\ m + 20.3\ m) * 100\ m} * 100 + \frac{20.3\ m * 500\ m}{(6.7\ m + 20.3\ m) * 100\ m} * 74$$

$$= 80.45$$

12.4.1.2 Calculate runoff depth

Using newly calculated curve number, the parameter "S" is calculated using equation 1.1:

$$S = \frac{25400\ mm}{CN} - 254\ mm$$

$$= \frac{25400\ mm}{80.45} - 254\ mm$$

$$= 61.72\ mm$$

Using IDF curves prepared for the region of Montreal for a 1:10 yr, 24 hr storm event, an amount of precipitation "P" equal to 84 mm is obtained. The total runoff depth is calculated using equation 1.3:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

$$= \frac{\left(84\ mm - 0.2(61.72\ mm)\right)^2}{\left(84\ mm + 0.8(61.72\ mm)\right)}$$

$$= 38.50\ mm$$

12.4.1.3 Calculating Peak Runoff Rate

Combining equations 2.3 and 2.4 using a value for "S" of 2.43 inches, an average slope ("Y") of 11.34% and a drainage length ("L") of 63.63 feet to calculate time of concentration:

$$t_c = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}}\left(\frac{1}{0.6}\right)$$
$$= \frac{63.63^{0.8}(2.43+1)^{0.7}}{1900(0.1134)^{0.5}}\left(\frac{1}{0.6}\right)$$
$$= 0.1733 \text{ hours } (10.4 \text{ min})$$

Then, calculating the peak unit discharge using equation 2.1 and 2.2 by using coefficient values given in Methods & Durrans (2003):

$$k = C_0 + C_1 \log_{10} t_c + C_2 (\log_{10} t_c)^2$$
$$= 2.23537 - 0.50387 \log_{10} 0.1733 - 0.08929(\log_{10} 0.1733)^2$$
$$= 2.5672$$

$$q_u = C_f 10^k$$
$$= (4.3 \times 10^{-4})10^{2.5672}$$
$$= 0.1587 \ {}^{m^3}\!/_{s}/km^2/mm$$

Then, using equation 2.0,with a drainage area of 2170 m^2 and a value of 1 for a correction factor “F” (assuming no ponding will affect runoff flow between road surface and our drainage system) we obtain:

$$q = q_u AQF$$
$$= \left(0.1466 \, {}^{m^3}\!/_{s}/km^2/mm\right)\left(2170 \, m^2 \times \frac{km^2}{(1000 \, m)^2}\right)(24.71 \, mm)(1)$$
$$= 0.0157 \ {}^{m^3}\!/_{s}$$

It is also possible to calculate the total volume of runoff generated during the event using this equation:

$$V_{runoff} = QA$$
$$= 38.50 \times 10^{-3} \, m \, (27 \, m)(500 \, m)$$
$$= 519.7 \, m^3$$

It must be noted that this peak runoff value and corresponding volume are associated to a 500 meters road section and will be used as base values to design the different parameters and elements associated with the constructed wetland.

12.4.2 Water flow within outer side wetlands

12.4.2.1 Calculating the wastewater outflow (Q_0)

Since it has already been established that water seepage can be neglected in the wetland (saturated soil conditions are assumed), equation 3.0 can be modified by removing the infiltration parameters. In terms of water storage, it is assumed that the wetland will be empty at the beginning of the rainfall event. Water outflow will not start before the water level reaches the height of the control weir (10 cm for outer wetland and 20 cm for inner wetland). This gives a storage capacity of 100 and 200 m^3 respectively that must be filled within 24 hours. Using an average evapotransipiration rate of 2 mm /day and a storage volume of 100 m^3, equation 3.0 gives (for the first wetland unit):

$$Q_i - Q_o + Q_c + P(A) - ET(A) = \frac{dV}{dt}$$

$$0 - Q_o + 519.73\,\frac{m^3}{day} + 84 \times 10^{-3}\frac{m}{day}(1000\,m^2) - 2 \times 10^{-3}\frac{m}{day}(1000\,m^2) = 100\,\frac{m^3}{day}$$

Calculating Q_o by solving the previous equation:

$$Q_0 = 501.73\,m^3/day$$

$$\sim 0.00587\frac{m^3}{s}$$

Knowing the required outflow, it is possible to estimate the flow depth using equations 3.1, 3.2, and 3.3. It has been established that the optimal water depth in the wetland should be around 10 cm. To maintain this depth, 10 cm high and 2 m long rectangular weirs (stop logs) will be installed at the outlet of each wetland unit (one weir every 500 meters). These weirs are also useful to maintain a relatively constant laminar flow across the wetland, as they act as flow control structures. By using a weir height of 0.1 m and combining equation 3.1 and 3.2, we obtain:

$$Q_o = \frac{2}{3}\left(0.611 + \frac{0.075H}{H_w}\right)L\,\sqrt{2g}\,\sqrt[2]{H^3}$$

$$0.00587\frac{m^3}{s} = \frac{2}{3}\left(0.611 + \frac{0.075H}{0.1\,m}\right)2\,m\,\sqrt{2\left(9.8\frac{m}{s^2}\right)}\,\sqrt[2]{H^3}$$

Solving for H, the obtained value is 1.36 cm, which gives an average total water depth of 11.36 cm. Then, using equation 3.4, it is possible to estimate the mean flow velocity across the wetland:

$$u = (1.0 \times 10^7 m^{-1} day^{-1})h^2 S$$

$$= (1.0 \times 10^7 m^{-1} day^{-1})(0.1136\,m)^2(0.005)$$

$$= 0.007468\,m/s$$

Using this flow velocity, it is possible to estimate the water travel time along the wetland. This is done by dividing the length of the wetland by the mean flow velocity. This gives a travel time for the first wetland unit of:

$$t = \frac{L}{u}$$
$$= \frac{500\ m}{0.007468\ \frac{m}{s}}$$
$$= 18.6\ hours$$