A case study of constructed wetlands application to restore habitats and treat wastewater

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Abstract

Constructed wetlands (CWs) have been seen as a practical and cost-effective solution to solve both wastewater issues and habitat loss issues. The use of constructed wetlands in Canada is, however, less common than in other countries. The main objective of this project is to investigate the current development of constructed wetlands and the current application of Constructed Wetlands in Canada. The elements of CWs, different types of CWs, as well as the advantages and limitations of CWs were reviewed in this report. In order to assess the current application of CWs in the west coastal area of Canada, a case study in the Greater Vancouver region was selected. It is expected that CWs provide multiple benefits to both wildlife and local communities. Further studies are required to understand the viability and long term performance of CWs in Canada.

Key words

Constructed wetlands, wastewater treatment, wildlife habitat, Greater Vancouver Region, Cultural benefits

List of Abbreviations

BC	British Columbia
CW	Constructed wetlands
DOC	Dissolved Oxygen Content
SF	Surface Flow
FS	Free-Surface
FWS	Free Water Surface
HSSF	Horizontal subsurface flow
VF	Vertical Flow
P	Phosphorous
OM	Organic Matter
SS	Suspended Solids
BOD	Biochemical Oxygen Demand
N	Nitrogen

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1. Introduction

The urban population of the world has grown rapidly from 746 million in 1950 to 3.9 billion in 2014. It is reported that the urban share of the world population will grow to 66% by 2050, with a population of about 6.4 billion. This dramatic increase of urban population is creating a two-part problem with water supply. The first problem is an increase in water demand. The second is an increase in the amount of wastewater created, which creates an extreme challenge to urban watersheds, especially in water pollution issues. Municipal wastewater enters watersheds in the form of surface runoff. Such wastewater may consist of different kinds of pollutants including organic pollutants (PAHs, PCBs, and dioxins) and heavy metals (like cadmium, chromium, copper, mercury, nickel, lead and zinc).

The rapid development of urban areas has also caused the loss and degradation of wetlands. Impacts caused by land use changes have increased sediment loads from urban areas as well as the changes to hydrological and geomorphological processes. Wetland loss and degradation have been associated with the direct loss of wildlife habitat and species diversity. Habitat restoration within urban areas is to be given importance as it is considered the alternation of an ecosystem back.

Constructed wetlands have been seen as a practical and cost-effective solution to solve both wastewater issues and habitat loss issues. A constructed wetland (CW) is an artificial wetland to treat municipal or industrial wastewater, greywater or stormwater runoff. Unlike traditional wastewater facilities, constructed wetlands are less expensive to build and operate and no energy is required. At the same time, constructed wetlands can mimic the natural wetlands to provide multiple services to wildlife.

The main objective of this project is to investigate the current development of CWs, including the elements in CWs systems, different types of CWs, their advantages and limitations. To assess the current application of CWs in west coastal area of Canada, a case study in the Greater Vancouver region was selected.

2. Literature Review

A wetland is a transitional land area that is permanently or seasonally saturated with water ("Wetlands | Earth Science", 2018). In general, wetlands can be divided into two categories: natural and constructed wetlands. Many natural wetlands in northern latitudes occur in a topographic depression and are created by glacial erosion and deposition. Other wetlands can occur in areas of steep land slopes, where groundwater discharges directly to the land surface from the underlying soil or emerges from other upland areas and creates discharge wetlands. In Canada, wetlands are distributed across all regions and occupy around 14% of the country. The wetlands in the province of British Columbia comprise approximately 5.28 million hectares or about 5% of the total land base ("Wetlands in B.C. - Province of British Columbia", 2018). Decades of research has recognized wetland systems as highly productive and unique eco-tones, playing essential roles in maintaining wildlife diversity and other ecosystem services. The ability of wetlands to improve water quality has been recognized since as early as the 1970s (Knight et al., 1999).

Natural wetlands have disappeared significantly in recent years as they have been converted to accommodate agriculture, harbor development, and urban areas. It is reported that wetlands continue to disappear at a rate of one-half hectare per minute. As the land use pressures of urban, agriculture and industry continue to favor the destruction of the remaining natural wetlands in Canada, implementation of alternative protection methods and research initiatives become crucial to ensure public health and the sustainability of our living environment. Constructed wetlands are emerging as an effective, low-cost alternative to solve the problem of degradation and destruction of the natural wetlands. In addition to the traditional values of natural wetlands like wildlife habitat, constructed wetlands have been recognized as a method to effectively manage stormwater pollution.

2.1 Elements of a constructed wetland

A constructed wetland consists of a basin or channel that contains water, a substrate, and most commonly, plants. These elements can be controlled in the design process of a constructed wetlands. Other components like microorganisms and wildlife habitat develop naturally and usually, are not manipulated by the designer.

Hydrology

Hydrology is the primary and the most important factor in a constructed wetland as it central to all the functions of a wetland and it affects the success or failure of a constructed wetland. A wetland can be built almost anywhere on land, as long as the soil can be sealed into a channel or basin to retain surface water. But the hydrology of a constructed wetland differs from other surface or near-surface water bodies in several important aspects:

- even a small change in hydrology can have significant effects on functioning wetlands and its effectiveness of waste treatment
- a wetland system has a strong interaction with the atmosphere through rainfall and evaporation since its characteristics of a large surface area and shallow water depth
- The hydrology process of a wetland strongly affects by the vegetation density. The denser vegetation, the less water will be blocked from sun and wind exposure. Otherwise, the more water will be evaporated into the atmosphere.

It is extremely important to define the hydraulic profile when designing a constructed wetland. A good hydraulic design profile requires a careful consideration of factors, including; expected range of daily average and peak flow rates, the hydraulic conductivity, the water balance, and its resilience to storm event (Ketcheson *et al.*, 2017*)*.

The expected range of daily average and peak flow rates determine the size and depth of the wetland. Hydraulic conductivity is an important factor to determine the hydraulic behavior of a constructed wetlands including the hydraulic retention time of water. The aim of performing a water balance is to evaluate the importance of evapotranspiration in loss of water from the wetlands. More importantly, a water balance evaluation is the key to ensure a wetland function in a desired manner. The resilience of a wetland to respond to storm event determines the size and depth of a constructed wetland.

Substrates, Sediments and Litter

Substrates used in constructed wetlands are extremely important as they affect to all the abiotic and biotic components within the system (Kadlec and Knight, 1996). Substrates used in constructed wetlands include soil, sand, rock, gravel and even organic material such as compost. Substrates can not only support the growth of plants and microbes but also remove pollutants directly during the sedimentation, filtration and adsorption processes. The physical and chemical characteristic of substrates influences the internal chemical and biological processes in constructed wetlands. At the same time, the physic-chemical conditions within the wetlands strongly affect the performance of subtracts in removing contaminants (Novak et al., 2004). Soil that has phosphorous (P) adsorption capacity is most commonly used in the design of CWs as it serves as a potential P sink.

Sediment and litter usually accumulate at the bottom of wetlands as the water velocities in wetlands are much lower than other water bodies such as rivers. Sediments and litter are the energy source that drives important biochemical process in the system. Sediment and litter consist of a high amount of organic matter, which supports plant growth, as well as provide sites for material exchange and microbial attachment.

The selection of substrates is a key step of the design of a constructed wetland. Before the wetland elements are excavated, the original soil usually is removed and stockpiled from the construction site.

Vegetation

Both vascular and non-vascular plants are important for a constructed wetland. Non-vascular plants like algae can increase the dissolved oxygen content (DOC) of the water through the photosynthesis process. Vascular plants can contribute to water treatment in different ways:

- they can stabilize substrates,
- they can reduce the direct evaporation of surface water,
- they reduce the current velocities of the water,
- they create better conditions for sedimentation of suspended solids,
- they reduce the risk of erosion and re-suspension,
- in some cases, they help to prevent clogging of the substrates medium,
- they can take up nutrients and store nutrients to prevent eutrophication at the bottom of the wetland
- they can uptake heavy metals from inflow wastewater and purify water for further use, and
- their stems and roots provide sites for microbial attachment (Bahlo and Wach, 1990).

Selecting appropriate species of plants for constructed wetlands is critical to achieving CW treatment objectives and to optimizing treatment performance. In many regions of Canada, such as the Okanagan, ("Guidebook for Constructed Wetlands in the Okanagan | Okanagan Basin Water Board", 2018), only native non-invasive species are used in CW treatment. The key attributes involved in plant selection are the tolerance of plants to variations in water level, water quality, pH and the area below the surface water for biofilm attachment ("Guidebook for Constructed Wetlands in the Okanagan | Okanagan Basin Water Board", 2018). The ability of plants to take up contaminants is an important attribute, however not as important as the ability of plants to filter wastewater, transfer oxygen to sediments. Additional values of plants conclude such as biodiversity enhancement and creation of suitable biological habitats.

Microorganisms

The functions of wetlands are largely regulated by the microorganisms (Wetzel 1993). Microorganisms in wetlands include bacteria, fungi, protozoa, and algae. Microbial activities play the main role in the transformation and mineralization of nutrients and organic pollutants. This process transforms organic and inorganic substances into innocuous or insoluble substances. Microbial activities remove heavy metals from industrial wastewater and mine drainage. Microbial activities in CWs may be aerobic or anaerobic, which affects the biochemical processes within the systems.

However, the level of some toxic substances like pesticides and heavy metals has a severe effect the microbial community. Thus, considerations must be taken to prevent such chemicals from being introduced at toxic levels.

Animals

Like natural wetlands, constructed wetlands, such as surface flow constructed wetlands, provide habitat for a rich diversity of wildlife. Invertebrates like insects and worms are also involved in the biological process within the wetland systems. They consume organic matter and fragment detritus. Insects like mosquitos also consume significant amount of material from the system. In addition to invertebrates, constructed wetlands also attract a variety of animals such as salmons, amphibians, turtles, and birds (Davis, 1995).

2.2 Types of Constructed Wetlands

Constructed Wetlands (CWs) have been utilized for the following three major areas:

- **Habitat creation:** Because of the degradation and loss of natural wetlands, CWs have been seen as a cost-effective way to restore wildlife habitat. The main goal is to mimic natural wetlands and provide the same ecological services for wildlife species.
- **Flood control:** Some CWs are also built to receive the runoff during storm events. The main goal is to increase the stormwater storage capacity and infiltration volume, while

reducing the amount of water reaching the urban sewer system or flooding residential and commercial areas.

- **Wastewater treatment:** CWs are also built to receive and purify wastewater of various types, including domestic wastewater, agricultural wastewater, coal drainage and stormwater runoff.

CWs can be divided into two major categories: Surface Flow (SF) Constructed Wetlands and Subsurface Flow (SSF) Constructed Wetlands, depending on the hydrological characteristics of the system. SSF CWs can be further divided into two different systems, which are Horizontal subsurface flow (HSSF) and Vertical flow (VF) constructed wetlands, based on whether the main flow is horizontal or vertical (Figure 1).

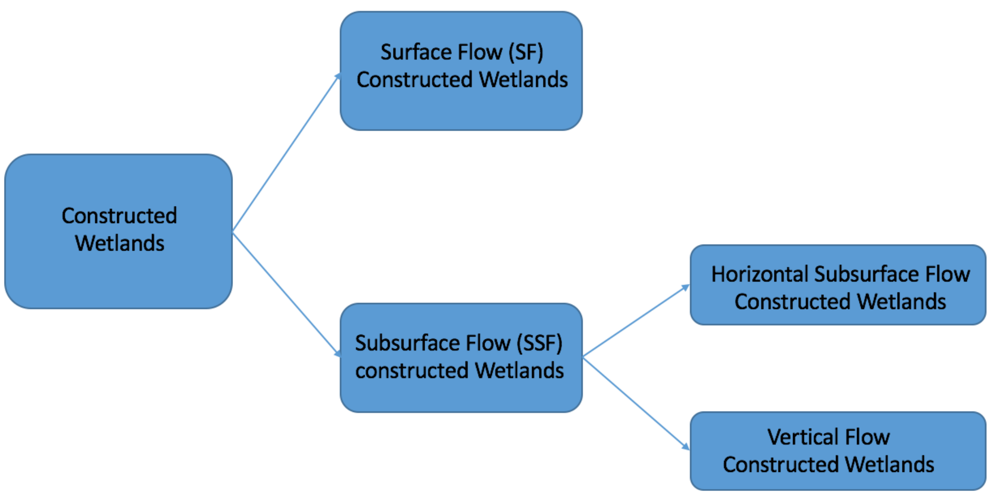

Figure 1. Classifications of constructed wetlands

Surface flow constructed wetlands

Surface flow (SF) constructed wetlands are similar to natural swamps or marshes, which are sometimes called free-surface (FS) constructed wetlands or free water surface (FWS) constructed wetlands. In SF CWs, water flows above ground and plants are rooted in the sediment layer and float in the water. An example of a SF CW is shown in Figure 2. A typical SF CW usually has a shallow sealed basin, containing 20-30 cm of rooting soil, or other suitable medium to support the roots of vegetation, with a shallow water depth of 20-40 cm (Vymazal, 2010). Both emergent, submerged and floating plants can be used in SF CWs.

In SF CWs, the near-surface layer is aerobic, and can directly exchange dissolved gas with the surrounding atmosphere. But the deeper water layers are usually anaerobic. The aim of building an SF constructed wetland is to replicate the ecosystem services provided by natural wetlands, such as marsh or swamps. SF CWs has been proven to be an effective method to remove suspended solids (SS) and biochemical oxygen demand (BOD). In addition, SF CWs have been shown to be effective in the removal of nitrogen (N), pathogens, and other pollutants like heavy metals (Karathanasis *et al.*,2003; Ghermandi *et al.*, 2007; Park *et al.*, 2008). But the removal of phosphorus (P) is limited in SF CWs (Kadlec, 2005). As the water flows through the wetland, the organisms and plants utilize the nutrients, particles settle and the pathogens are destroyed by the natural die-off process (Weber and Legge, 2008).

Usually, SF CWs demand larger surface areas compared to the other two types of CWs for the same wastewater flow and characteristics, especially if nitrogen or phosphorus removal is required. Mosquitoes and similar insect vectors are a problem within SF CWs due to their open water surface. But compared to other two systems, SF CWs tend to better resemble natural wetlands, and thus, have more wildlife habitat benefits.

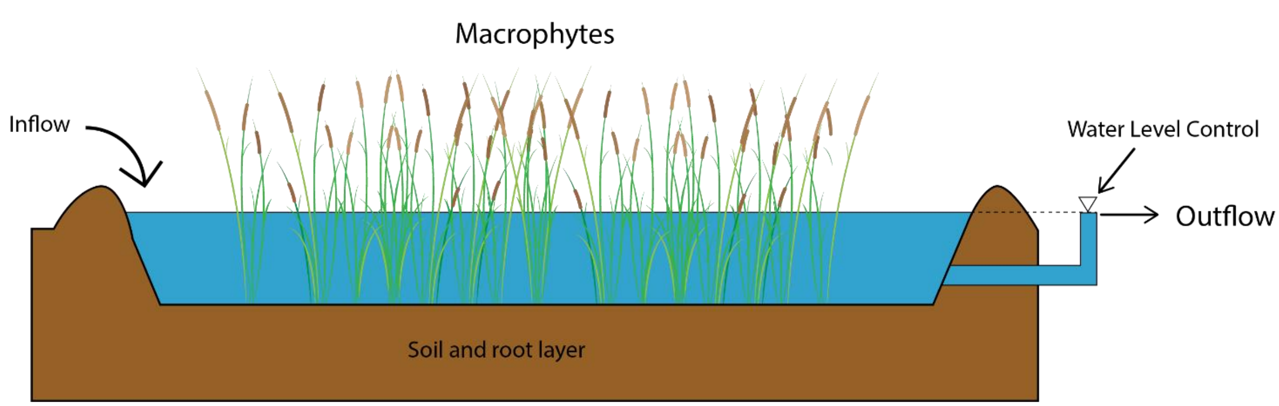

Figure 2. Surface flow constructed wetlands

Horizontal subsurface flow constructed wetlands

Horizontal subsurface flow (HSSF) constructed wetlands are similar in construction to SF CWs, but are typically constructed as a bed, or a channel, containing appropriate growth media and with no water surface exposed to the atmosphere. An example of a HSSF CW is shown in Figure 3. Wastewater flows horizontally through the channel or basin, and the underlying media of coarse rock, gravel, sand and other soils, removes remaining particles from inflow wastewater. The water level in a HSSF CW is 5-15 cm below the top surface of lowest medium. Only emergent vegetation is used in HSSF CWs. In general, the most commonly used emergent vegetation in HSSF CWs are cattail, bulrush and reeds. Unlike SF CWs, the vegetation in HSSF CWs are not the main factor in nutrient removal and do not need to be harvested.

HSSF CWs have been shown to be an effective method in municipal wastewater treatment. Plant roots and porous media provide sites for biofilm attachment which enhance the removal of organic mater (OM) and SS. But the removal of N and P is relatively low. On the other hand, if N and P removal is a project goal, consideration should be given to SF CWs. But compared to FW CWs, the main advantages of HSSF CWs are the elimination of mosquitoes and odors, and the prevention of the risk of children or pets to come in contact with the partially treated wastewater (Kadlec and Wallace, 2009).

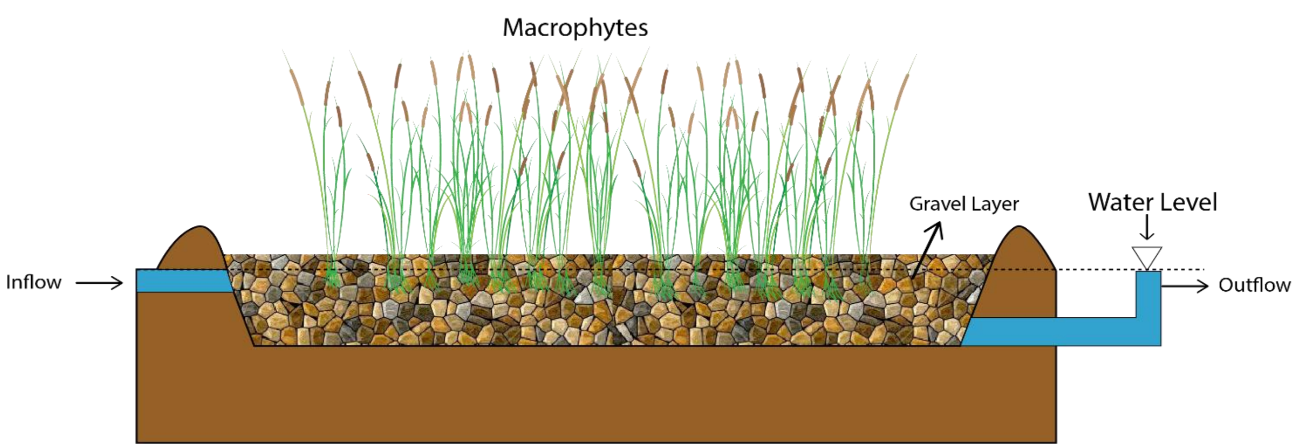

Figure 3. Subsurface flow constructed wetlands

Vertical flow constructed wetlands

Vertical flow (VF) constructed wetlands are designed for the purpose of reducing the size required to build a constructed wetland. VF CWs can be built as a shallow excavation or as an above ground structure. The size and design of the VF CW is dependent on the hydraulic and organic loads. In VF CWs, wastewater spreads over the entire CW surface and moves downward vertically by gravity through the porous media (Stefanakis *et al.*, 2014). An example of a VF CW is shown in Figure 4. Because of its mode of operation, oxygen transfers increase within VF CW systems, which then enhances aerobic conditions for the process of nitrification and decomposition of organic bottom matter (OM) (Cooper et al., 1996; Vymazal, et al., 2006; Kadlec and Wallace, 2009). The depth of VF CWs varies from 0.45 to 1.20 m, and the bottom of the bed usually has a small slope (about 1-2%), which aims to collect the treated water and drains it out of the system. Reeds are commonly planted at the top of VF wetlands.

Compared to SF CWs and HSSF CWs, VF CWs are not widely used because of the higher operation and maintenance requirements. It is costly to pump the wastewater intermittently on the wetland surface.

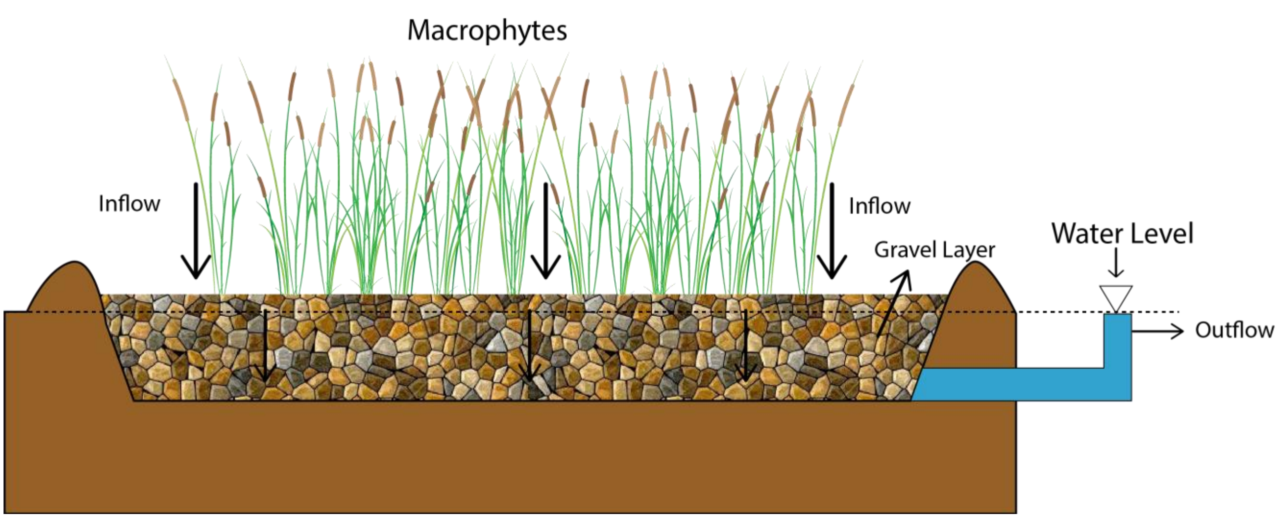

Figure 4. Vertical flow constructed wetlands

2.3 Advantages of constructed wetlands

Compared to traditional engineered treatment plants, constructed wetlands are cost-effective, technically feasible and a are a low-maintenance alternative to treating wastewater for several reasons:

- CWs use natural solar and biophysical energy sources,
- CWs are less expensive to build than treatment plants,
- CWs has more value-added benefits including aesthetic enhancement, habitat restoration and provision of recreational opportunities,
- Unlike the continuous and on-site labor operation and maintenance of treatment plants, CWs require only periodic maintenance,
- the expenses of operation and maintenance of CWs are much lower than treatment plants, and
- CWs are seen as an environmentally-sensitive approach and favored by the general public

2.4 Limitations of constructed wetlands

Treatment efficiency

The chemical and biological process in CW systems depends on environmental factors, including temperature, oxygen, and pH. The metabolic activities that contribute to pollutants removal decrease when the temperature is low. For example, in many cases, temperature is only one of the factor affecting the overall treatment efficiency. However, in some cases, the cold climate is one of the main challenges for CWs' operation and management. Decreased metabolic activities, plant dormancy and the freezing of the water column can all occur in CWs due to cold temperature (Werker et al., 2002). Thus, it is essential to consider all factors when designing CWs for cold climates. Those factors may include the type of CWs, the water depth of CWs, and the vegetation species.

Aerobic respiration and the anaerobic processes are strongly affected by the oxygen concentration within the water column. The change of oxygen concentrations can cause further change in water quality. Many metabolic activities are also pH- dependent, which are less effective if the pH is too high or too low.

Hydrological Limitations

The capacity of CWs to treat wastewater is also limited, including both the quantity of the treated water and the total quantity of pollutants. Hydraulic overloading occurs when the actual water flow exceeds the designed capacity. Consequently, the time of water retention decreases and alters the pollutant removal rate. In addition to hydraulic overload, and pollutants overloading can occur in CWs, when the pollutants input should not exceed the removal rate within the CWs.

Compared to conventional engineered treatment plants, the performance of CWs may be less consistent. This is because CWs are strongly influenced by the surrounding environment. Seasonally changing environmental conditions such as rainfall and drought affect the overall their performance, as it can significantly affect the water flow. Rainfall can cause two different opposing effects. The first effect is it increases the dilution of waters, which can reduce the material concentrations in the systems. The second effect is rainfall increases the water velocity and decreases the water retention time within the wetlands.

3. Case study: a constructed wetland in Greater Vancouver, CA

Wildlife habitats have been the focus of restoration initiatives within urban environments. Unlike developing cities like Surrey and Coquitlam, the land use development and decisions in Vancouver were made before related environmental regulations were published. Consequently, wetlands and riparian areas disappeared from the landscape and very few streams and wetlands left. For a number of years, Port Metro Vancouver has been working with the Vancouver Board of Parks and Recreations to enhance biodiversity and restore habitats for wildlife. The long term target by 2020 is to restore 25 ha of natural areas. Since 2010, approximately 13 ha of forests have been restored in parks in Vancouver such as Stanley, Musqueam, Jericho Parks. Many projects have been implemented, some of them still ongoing. Constructed wetlands have been used as an essential part in many projects.

Within the Greater Vancouver regions, an example of the use of constructed wetlands to restore wildlife habitat is the New Brighton Park Shoreline Habitat Restoration Project.

3.1 CASE STUDY: New Brighton Park Salt Marsh

Site Description

The New Brighton Park is located in the Hasting-Sunrise district of Vancouver, British Columbia, Canada. It is a waterfront park with an area about 10 hectares (ha) facing the North Shore Mountains and access to Burrard Inlet. This area was where the first outlets was established in the city of Vancouver. It is surrounded by railway tracks, the Cascadia Grain Elevators, and Iron Worker's Memorial Bridge. However, the repaid development of industry altered the land use significantly, which resulted in the loss of valuable fish and wildlife habitat. This area was a very important habitat for juvenile salmonids. Prior to the construction of wetlands, the northeast part of the New Brighton Park was filled in to make industrial land in the 1960s.

Figure 5. An snapshot of the study area prior to the construction

In order to restore habitat for Burrard Inlet's fish and wildlife, the Vancouver Fraser Port Authority and the Vancouver Board of Parks and Recreation have been working together to conduct the New Brighton Park Shoreline Habitat Restoration Project. This project contains four major components; the creation of a tidal wetland area with a salt marsh component, the creation of subtidal rocky reefs, the enhancement of riparian areas, and the creation of stream habitat. The creation of a salt marsh is one of the most important parts of the project. The New Brighton Salt Marsh is located at the northeast part of the New Brighton Park (Figure 6).

Figure 6. An snapshot of New Brighton Park Shoreline Habitat Restoration Project

The salt marsh was built in 2017 on the study site. The salt marsh with Island Concept was used in the project, which refers to a salt marsh with two channel openings to Burrard Inlet and create a tidal "island". The presence of the tidal island is able to improve the hydraulic flushing, improve water quality and enhance protected habitat features for wildlife. Two channel openings can reduce the speed of outgoing tide, reduce erosion risk of channels, and enhance the access to the salt marsh for aquatic animals such as juvenile salmonids. By July 2017, the final construction activities were conducted on the study site, which include the planting of about 25,000 salt marsh plugs, more than 200 native trees, and 4000 coastal shrubs like salmonberry, sitka willow and ocean spray (Tranmer, 2018).

The salt marsh in New Brighton Park can be classified as surface flow constructed wetlands, as its inflow enters from the Renfrew Creek and outflows goes to the Burrard Inlet. Compared to a typical surface flow constructed wetlands, the salt marsh in New Brighton Park is much like a natural wetland. The design of tidal islands maximized the desired function of constructed wetlands to provide habitat for aquatic organisms.

Profile of Benefits

The creations of a tidal wetland area with a salt marsh component at the New Brighton Park provide multiple benefits, including ecological benefits as desired, cultural values, recreational benefits and potential educational benefits.

- **Ecological benefits**

  Salt marshes are one of the most productive habitats on earth, which can provide an important source of nutrients and organic matters to support a food web used by aquatic wildlife. Salt marshes are also important nursery area for fish, crustacea and insects. Marsh habitats can provide a refuge for juvenile salmon from predators due to its shallow water and dense plants (Boesch and Turner, 1984).

  It is reported that chum and Chinook salmon fry were seen using the salt marsh in the New Brighton Park after one year of construction. It means the salt marsh has been used as a stopover for fish on their way through Burrard Inlet.

- **Cultural Values**

  The protection of Indigenous Values is one of the most important initiative to accomplish this project. Musqueam, Squamish and Tseil-Waututh First Nations were actively involved in the decision making process. The study area, where Renfrew Creek met the salt marsh, was known to First Nation people as “Kha-nah-moot” or “Haah-ugh-nah-moot,” referring to a traditional story of a couple being “born out of the waters of the stream” (Primeau, 2018). Native plants and salmon have an important role in First Nation culture. Many years ago, Indigenous plants in New Brighton Park area were gathered by the ancestors of First Nation for multiple uses, including nutrimental, medicinal, and ceremonial uses (Primeau, 2018). Salmon berries and their fresh shoots were an important food source to ancestral First Nation. Sitka Willow was used to for making nets and cordage. Ocean Spray that native grow at New Brighton Park was used for making tools such as digging sticks, hunting gear, mat needles and fishing equipment such as spears and harpoon shafts. Wildlife such as Chinook salmon, great blue heron and ducks also play important role in First Nation culture. In Indigenous culture, chum salmon are said to be the best for drying as they have the right amount of fat to keep for the year. Great blue herons are known as expert fishes, and adorned on ancient Aboriginal fishing gear. Ducks are also important for sustaining first nation's language and culture.

- **Recreation benefits**

  As a part of the Shoreline Habitat Restoration Project, the salt marsh also provides new opportunities for Vancouver residents and tourists to experience nature within New Brighton Park. As an essential wildlife habitat, salt marshes are good places for bird watchers and a good overlooking areas for Burrard Inlet (Tranmer, 2018).

- **Educational benefits**

  As a part of the Shoreline Habitat Restoration Project, salt marshes also have potential educational benefits, such as the historical, cultural and ecological values of Burrard Inlet, and the indigenous history and culture.

- **Potential wastewater treatment benefits**

  Even though the value of salt marshes in filtering wastewater was not mentioned as the desired functions in the project report, it is undeniable their potential role in removing organic matters and heavy metals from the inflow water. The Shoreline Habitat Restoration Project upheld the idea of re-creating an ecological corridor through the park through connecting the Renfrew Creek to the salt marsh (Primeau, 2018).

  Renfrew Creek currently receives a small amount of rainfall water and will eventually receive water from a larger catchment area. It means more domestic wastewater will enter the Renfrew Creek and eventually enter the salt marsh. The ability of the salt marsh to treat wastewater, remove organic matters and heavy metals can still maintain the biodiversity in that area.

4. Conclusion and Recommendations

As stated in this report, constructed wetlands are a potential cost-effective alternative to restore wildlife habitats and treat wastewater. In the Greater Vancouver Region, constructed wetlands have been used as an essential part of ecological restoration projects. In the New Brighton Park Shoreline Habitat Restoration Project, construction wetlands are not only an option to restore the historical wildlife habitat, but also get all stakeholders working together to achieve objectives.

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