INTEGRATING WETLANDS INTO WATERSHED MANAGEMENT: EFFECTIVENESS OF CONSTRUCTED WETLANDS TO REDUCE IMPACTS FROM URBAN STORMWATER

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Water detention and water storage during storm events, and water release during dry periods, are some of the main functions wetlands can provide in order to help reduce peak flow and increase low flow runoff into streams. However, wetlands can also be effective in retaining and remediating contaminants. Results of the case study on a constructed wetland that mitigates urban storm-water are discussed. The effectiveness of metal reduction in water is highly variable and not all metals are detained and reduced at the same rate. Concentrations of certain metals in the sediments were not sufficiently reduced, which remains a challenge that can likely be resolved by improving the wetland design. A sediment detention pond could be constructed before the runoff enters the wetland and the sediments accumulated in this pond would then have to be removed and treated on a regular basis. As urban development continues to encroach on hills and sloping terrain, the use of wetlands to regulate water flow and retain contaminants will became more viable.

1. Introduction

Traditional urban development creates large areas of impervious surfaces which means a large proportion of the rainfall can no longer infiltrate and thus extensive storm-water conveyance systems are required [1]. This has a

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profound impact on stream hydrology and water quality [9]. Similarly, many forestry, agricultural and recreational activities compact the soil surface which in turn results in reduced infiltration rates, loss of water storage capacity and higher surface runoff that often results in increased erosion. The cumulative response of creating impervious surfaces and compacting soils results in a stream-flow regime that is more flashy, the risk of flooding in lowland areas is increased, and pollutants that accumulate on impervious surfaces enter streams more rapidly and effectively.

Traditional engineering approaches are usually relied upon to counteract the problems of higher and flashier runoff by diverting storm-water directly into streams and then modifying stream channels to remove floodwater more rapidly. The new paradigm for water management is to infiltrate and store as much rainwater as possible at the site level, while taking precautions not to overload the soils with water that creates instability. This includes the establishment of a permanent vegetative cover that is capable of intercepting and retaining water [25] and then releasing it more slowly into streams or undergoing evapotranspiration. The portion of the rainwater that is recycled via plants and soils and evapotranspired back into the atmosphere is usually referred to as green water [23] while the runoff water that enters streams, lakes and groundwater is usually referred to as blue water. We have lots of experience in managing blue water but have largely ignored managing the green water cycle. There is much to be gained in improving the management of green water and wetlands can play a key role in this process.

There is a long history of draining wetlands because landuse activities in and around wetlands are usually limited due to poor shear strength and aeration of the soils, which is not conducive for growing crops and trees. However, wetlands have many functions that are of great advantage to watershed management. Wetlands moderate stream-flow and can retain large quantities of storm-water. They tend to have high capacities for contaminant removal and carbon accumulation. Also, habitat for a wide range of organisms and unique vegetation communities is provided in the wetland environment, which contributes significantly to biodiversity. There is renewed pressure to protect wetlands in headwaters and widespread efforts are being made to restore formerly drained wetlands or to create new constructed wetlands because of the realization that wetlands provide many benefits. Draining wetlands is relatively easy but constructing wetlands that perform most of the desirable functions is much more challenging.

The aims of this paper are to review the key functions wetlands provide for watershed management, identify the positive and negative factors that influence the effectiveness of wetlands in moderating water quantity and quality, and to document, on the basis of a case study, how constructed wetlands can be used effectively for storm-water management on sloping terrain.

2. Key functions of wetlands in watershed management

Wetlands are considered both "the kidneys of the landscape", because of the functions they can perform in the hydrological and chemical cycles, and as "biological supermarkets" because of the extensive food webs and rich biodiversity they support.

Wetland conservation and rehabilitation is considered a cost-effective way to retain large quantities of rainfall within the watershed and to moderate stream-flow during storm events. Incorporating wetlands into watershed management plans is rapidly emerging as an innovative way of providing multiple functions which include flood control, stream-flow moderation, groundwater recharge, sediment detention, pollutant retention and phyto-remediation. However, a careful analysis of type of wetlands and site-specific conditions is necessary when quantifying wetland functions, and when proposing wetland creation or rehabilitation for particular environmental services.

Not all wetlands perform all of the hydrological functions to the same extent. Indeed, some wetlands perform hydrological functions which may be contrary to human needs, such as riparian wetlands which may act as runoff generating areas, thus increasing flood risk downstream [2], [7].

Headwater bogs are wetland systems that are sustained almost entirely by inputs from rainfall. A unique plant community consisting of a relatively small number of plant species survive in these low nutrient input systems. The productivity is low, the site conditions very acidic and the key functions of bogs in the watershed context are to retain large quantities of rainwater and to store carbon.

In contrast, fens, marshes and various types of swamps are wetlands that also retain large quantities of water but are flow through systems. This means that nutrient input is enriched because a portion of the water input has traveled over or through the soil system where it picks up nutrients. This leads towards a plant community that is more diverse and usually dominated by sedges, reeds, and shrubs [26]. Fens, marshes and swamps may therefore provide functions related to retention of nutrients, thus improving water quality downstream.

3. Wetlands and Water Balances

Moderating the impact of extreme rainfall events and providing base-flow during dry periods is one of the key functions of wetlands. This is a well documented function of wetlands and many constructed wetlands are now being incorporated in water sensitive planning and site designs [14], [3].

Both at the catchment and global scale, wetland drainage has meant a deterioration of the green water cycle. As wetlands are drained, less water is held in the catchment to be evaporated and transpired by wetland plants, and a larger portion of precipitation becomes blue water faster. This reduces the water storage capacity of soils (the land component of the hydrological cycle) and augments peak flows.

The reduction of water stored in catchments both in soils and wetlands (green water) constitutes a reduction of the biggest portion of the hydrological cycle that can be influenced by humans. The total amount of water that is held in soils is almost 40 times the amount of water that is available in rivers [4]. It becomes obvious, therefore, that wetland conservation has a vital role to play in alleviating the global 'water crisis', because wetlands are the places where that accessible and manageable water exists.

The amount of water that can be stored in wetlands is dependant on the site conditions (slope, size, geology and geomorphology) and organic matter content. Organic matter has very high water retention capacity and water storage is usually measured in terms of open water versus water contained in the saturated organic layer in the wetland [22]. The two most difficult components to determine in a wetland are groundwater losses and evapotranspiration. The former can be estimated from water table changes during dry periods by subtracting evapotranspiration rates [24]. Determining evapotranspiration is still a major challenge [25] and there is considerable debate whether evaporation from open water is greater than evapotranspired water from vegetated cover in the wetland. What is clear is that this is dependent on the type of plants, the community structure, and the plant biomass density. Measured evapotranspiration rates from a number of studies in wetlands range from 0.2 –19.9 mm/day depending on season, location and plant communities. Also, C3 plants are more water consumptive and less efficient water users than C4 plants but this is temperature dependent. Highly fluctuating water tables are also a factor that influences plant species distribution [21]. However, wetlands have much better water retention capacity than constructed ponds, and normal soil conditions.

As is the case in comparing watersheds, it is difficult to generalize what the key factors are that control the hydrological behaviour of wetlands. The site-specific nature of wetland processes, make quantification of the benefits of wetlands in regulating the hydrological cycle at any scale, a difficult task.

More conclusive results exist about the capacity of wetlands to reduce pollution impacts on receiving waters. This topic is of additional interest to storm-water managers because pollution from urban areas can be highly toxic and dynamic [19].

4. Effectiveness of wetlands for storm-water quality improvement

The use of constructed wetlands as wastewater treatment systems has become widely accepted in many parts of the world [5], [8], [27]. A combination of physical, chemical and biological processes contribute to the pollutant retention capacity of wetlands. In the past, wetlands have been used as treatment systems to deal with point sources of pollution but more recently they are proving to be effective in dealing with non-point sources of pollution from urban runoff.

Fine sediment retention is one of the most effective ways of retaining metals before they enter streams. Clay rich sediments have large negative charges and can therefore scavenge metals in storm-water runoff. The effectiveness of metal absorption to sediment is dependent on particle size, surface area, type of clay minerals, and prevailing water quality conditions. Organic matter also has highly negative charges depending on the state of decomposition and is also capable of adsorbing metals. The hydraulic residence time, and the extent of the plant cover largely control the efficiency of sediment detention [16]. Numerous studies have shown that metal retention in wetlands is highly variable but generally falls into the 25-50%

removal rates for metals such as Cr, Ni, Cu, Pb, and Zn [5], [20]. In contrast Fe and Mn are generally released from sediments in wetlands and the outflow water usually has significantly higher concentrations than the inflowing water [5], [6], [12]. However, this has not been observed in all studies and suggestions have been made that this might be dependent on Mn nodule formations and changes in pH, alkalinity and temperature. Fortunately these two metals are not considered to be the most toxic metals to aquatic organisms and plants.

Metals can be taken up by plants through bioaccumulation processes [28]. At low levels they can act as essential trace metals, but at high concentrations can become toxic. Plant tolerance to heavy metals varies widely. Some have blocking mechanisms while others sequester metals in compartments within the plant. Carbon content, pH, cation exchange capacity, and mineral constituents influence the rate and type of metals taken up by plants. Unfortunately few wetland plants are hyper-accumulators, although cattail and common reeds, which become dominant under nutrient enriched conditions, can tolerate heavy metals [17].

Some plants can take up metals through a process called phyto-remediation, but this process is relatively slow and requires that the plant biomass be removed from the wetland from time to time.

The uptake of excess nutrients by plants is another service provided by wetlands. This can have some very positive effects since it will reduce the eutrophication risk downstream. Storm-water runoff can contain significant levels of ammonia, nitrate and phosphate from garden activities, use of detergents and industrial processes. Nutrients are also retained in sediments and in the water column where they can be taken up by plants. Usually the nutrient uptake efficiency in wetland for TN, TP and ammonia and nitrate is in the order of 10-20%. Increased wetland size and water residence time can improve nutrient reduction significantly. Sedges, common reeds, cattail, and bulrush are some of the most effective wetland species to take up excess nutrients. Cattail is particularly useful as it is highly tolerant to fluctuating water tables within the wetland.

Pathogen removal in wetlands has been reported to range between 30% and 90% but is obviously less efficient during high flow events [5]. Other factors that have been suggested to influence removal efficiencies include types of plants, temperature, and suspended soils [15].

Retention of organic contaminants has also been reported. Some polycyclic aromatic hydrocarbons (PAHs) can accumulate in membranes of organisms and can affect negatively affect plants, as well as break down by light into photoproducts that can be more toxic. However, they do have a great affinity to be tied up in clay minerals. There is relatively little quantitative data available on the removal rates of PAHs and chemical breakdown, except that considerable amounts are tied up in clays. Also, microbial degradation is known to play a large role in the transformations of PAHs in aquatic ecosystems, which likely affects the removal efficiency in wetlands [11].

5. Long-term challenges in using wetlands for storm-water management

Input of excess nutrients will influence species composition, community structure and productivity. Most plant species adapted to low nutrient conditions do not respond well to high nutrient input and invasive species such as cattail and common reed, which are better adapted to these new conditions, will replace them over time.

Plants need metals in trace amounts but at high concentrations they can bioaccumulate and become toxic to plants. Plant tolerance to heavy metals varies widely. Carbon content, pH, cation exchange capacity, and mineral constituents influence the rate and type of metals taken up by plants. Since most of the wetland plants are not hyper-accumulators, the process of phyto-remediation is not a very effective long-term option particularly since it means that plants need to be harvested from the wetland from time to time and the amount of metals accumulated is relatively low.

One of the main challenges is how to deal with the first flush from urban storm-water runoff. When storms are preceded by a long dry period, the contaminants in the early part of the runoff are usually much more concentrated [18]. This can be dealt with by creating a separate detention pond that accommodates the first flush and the remaining storm-water is then directed into the wetland. This reduces the problem of continuously shocking the aquatic biota and plants in the wetland.

Sediment management remains a long-term challenge when using wetlands as storm-water treatment systems [13]. Sooner or later the accumulated sediments need to be removed and treated chemically. This is a relatively expensive proposition because many sediments originating from urban activities qualify as toxic contaminants and once removed from the wetlands they need to go through a special treatment process. Depending on the wetland type this only needs to be done on a decadal scale. Constructed wetlands are relatively easy to build and since they retain and remove a wide range of contaminants it is obvious that this approach is far more cost effective than trying to treat urban runoff water and sediments on a continuing basis downstream.

6. An example of a constructed wetland that mitigates urban storm-water: Oakalla Biofiltration System, Burnaby, B.C, Canada

6.1 SITE DESCRIPTION

The Oakalla Biofiltration System was constructed in 1990 to detain storm-water runoff from sloping terrain before it enters Deer Lake and to provide an aesthetic amenity to the surrounding park. A 0.3 km^2 primarily residential subdivision drains storm-water into the system. The system is composed of two ponds and one large marsh, creating a constructed wetland environment within the park. The surface area of the wetland system is 966 m^2 and has an approximate volume of 1615 m^3. Approximately 70% of the system is covered with cattails and grasses.

6.2. METHODS

A monitoring program was established in the wetland between July 2003 and June 2004 in order to investigate the quality of the storm water entering the system and the effectiveness of trace metal removal. Water sampling was done every three weeks at the inlet and outlet of each pond. Sediment samples from the top layer were taken manually at the inlet and outlet every three to six weeks. The U.S. EPA method for the determination of metals in environmental samples [10] was used to analyse the metals in the 63 μm sediment fraction. The technique of Diffusive Gradient in Thin Films (DGT) was employed to determine the accumulation of bio-available metals over time. The DGT units consist of a binding agent that accumulates solutes quantitatively after their passage through a well-defined diffusion layer. The DGT units were deployed for periods of three to four weeks at the inlet and outlet. After retrieval, the DGT units were analysed according to existing directions. Analysis for metal concentrations in the water, sediments and DGT units was performed on the Varian Simultaneous ICP-AES.

The results of the monitoring program were used to calculate the percent difference of measured parameters between the inlet and outlet using the following equation:

Percent Difference = ((Inlet Concentration – Outlet Concentration)/Inlet Concentration)*100

6.3. RESULTS AND DISCUSSION

The Oakalla Biofiltration System is effective in reducing all metals from inlet to outlet in both the wet and dry seasons. Results show median percent differences of 13% to 81% for dissolved metals in water, 20% to 81% for bio-available metals as measured by the DGT units, and 18% to 79% for total metals in sediments. These results reflect the variability of the system in its capacity to retain trace metals, which are affected by the season, inlet concentration and rates of runoff at time of sampling. The reductions in iron and manganese concentrations were high in the water, DGT and sediment, particularly in the wet season. The bio-available fraction was consistently reduced through the system for all detected metals, suggesting that the wetland has been effective in improving water quality for downstream aquatic habitat.

The consistent removal of contaminants is likely due to the metal binding capacity of the organic soils as well as the extensive vegetation. The cattails and grasses provide metal uptake, produce dissolved oxygen at the water sediment interface and reduce flows through the pond, which promotes settling of fine particles.

In contrast to the metal reduction in the water column, the overall reduction of metal concentrations in the sediments was not significant, despite some high percent differences between the inlet and outlet. The outlet concentrations of copper and zinc pose a concern, as 100% of samples exceed the Interim Sediment Quality Guideline of the Canadian Environmental Quality Guidelines for Freshwater Aquatic Life (Cu: 35.7 mg/l; Zn: 123 mg/l) and 33 % of samples exceed the Probable Effects Level for zinc (315 mg/l). This suggests that despite successful contaminant reduction in dissolved and bioavailable metals, the wetland did not achieve all treatment goals. This implies that additional research is needed, with a focus on sediment retention and dynamics in the early portions of the system.

7. Conclusions

Wetlands provide many positive functions that need to be given more consideration as we intensify land use. Water detention and water storage during storm events, and water release during dry periods, are some of the main functions wetlands can provide in order to help reduce peak flow and increase low flow runoff into streams. However, wetlands can also be effective in retaining and remediating contaminants. In the present example it was shown that dissolved and bio-available metals in the water column were significantly reduced as the water moves through a constructed wetland. The effectiveness of metal reduction in water is highly variable and not all metals are detained and reduced at the same rate. Concentrations of certain metals in the sediments were not sufficiently reduced, which remains a challenge that can likely be resolved by improving the wetland design. A sediment detention pond could be constructed before the runoff enters the wetland and the sediments accumulated in this pond would then have to be removed and treated on a regular basis. As urban development continues to encroach on hills and sloping terrain, the use of wetlands to regulate water flow and retain contaminants will became more viable. What is needed is more research on how to make wetlands most effective in retaining and remediating contaminants that would otherwise enter streams and adversely affect aquatic biota.

8. References

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