Geoscience Canada

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Volume 22, Number 3, September 1995

URI: https://id.erudit.org/iderudit/geocan22_3ser03

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Berezowsky, M. (1995). Constructed Wetlands for Remediation of Urban Waste Waters. *Geoscience Canada*, *22*(3), 129–141.

Article abstract

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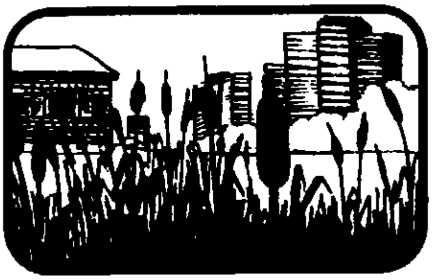

Constructed Wetlands for Remediation of Urban Waste Waters

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SUMMARY
This paper provides a brief review of the characteristics of artificially constructed wetlands and their use in remediating water quality, principally in connection with municipal waste waters, urban storm-water runoff, and acid mine drainage. In the past 15 years, a heightened interest in the application of both natural and constructed wetland treatment for water quality improvement has resulted in the construction of more than 1500 wetland systems worldwide. This rapid growth appears to be part of a global movement that supports more resource conservation and greater reliance on natural ecological processes in preference to the energy- and chemical-intensive systems currently in use.

RÉSUMÉ
Le présent article présente un tableau d'ensemble des principales caractéristiques des zones humides artificielles et de leur utilisation comme outil de restauration de la qualité des eaux, principalement les eaux usées des municipalités, les eaux de ruissellement et les eaux d'exhaure de mines. Au cours des quinze dernières années seulement, on s'est davantage intéressé à l'utilisation des zones humides naturelles et artificielles pour la purification des eaux usées, et plus de 1500 sites de traitement ont ainsi été créés. Cette croissance rapide semble être le fait d'un mouvement global favorisant la conservation des ressources et une plus grande utilisation des systèmes écologiques plutôt que des systèmes de purification en usage basés sur une utilisation intensive de produits chimiques et d'énergie.

INTRODUCTION

Although not applicable to every situation, wetland treatment systems have been accepted as alternatives to many traditional and conventional engineering methods across a wide range of municipal, industrial and agricultural uses. In some cases, wetland systems do not replace, but merely complement or enhance, the performance of the mechanical and/or chemical systems already in place (Haven and Lothop, 1992; Anderson, 1993; Todd and Todd, 1994). The life support functions and values of natural wetlands have long been recognized. Their high primary biological productivity creates the potential to accumulate, transform and cycle organic material and nutrients, as well as providing a major sink for metals (Newman, 1993; Bastian and Hammer, 1993; Knight *et al.*, 1993). It is precisely for these material-processing capabilities that wetlands are exploited for a wide range of applications, namely in the treatment of municipal and domestic waste water, acid mine drainage, industrial waste water/effluent, agricultural waste water/effluent, urban storm-water runoff, compost leachate, sludge, pulp mill effluent, and landfill leachate. Although the first two applications — the treatment of municipal or domestic waste water and acid mine drainage — are by far the most abundant, there is a strong interest in incorporating wetlands as a key component in the management of urban storm-water runoff (Kadlec and Knight, 1995).

Historical Development

The earliest research specifically investigating the waste-water potential of wetlands was by Seidel at the Max Planck Institute in Germany in 1952. She began by examining the possible removal of phenols from waste water by *Scirpus lacustria*. Four years later, she used the same plant in experiments in dairy waste water and continued with her research with wetland plants and waste water until the mid-1970s (Bastian and Hammer, 1993). One of her students, Kickuth, studied the effectiveness of a natural reed marsh in treating municipal waste-water effluent. Upon the successful demonstration of the technical merits of this natural filtration system, more than 200 municipal and industrial waste treatment systems across Europe began using emergent macrophyte-based wetland systems, either as components of their conventional systems or as stand-alone systems. In the United Kingdom, the first emergent macrophyte treatment system, often referred to in the British literature as a rooted bed system, was set up in 1985, and by the summer of 1988, 81 beds had been constructed at 27 separate sites. More than 130 of these systems were constructed in Denmark between 1983 and 1988, while similar wetland systems are also operational in Belgium, Netherlands, Hungary and Sweden.

Developments in the United States and Canada

Throughout the 1970s, studies were carried out by numerous universities and government agencies. Research by the United States Environmental Protection Agency (U.S. EPA), the United States Army Corp of Engineers, and the United States Department of Agriculture investigated wetlands as alternatives to chemical treatment systems. University research was focussed on two areas: municipal waste-water treatment and acid mine drainage (Wildeman, 1993), with the principal researchers being Kalbec and Kalbec at the University of Michigan, and Odum and Ewel at the University of Florida (Taylor, 1992). The first attempts at constructing wetlands for waste-water treatment were carried out at the Brookhaven National Laboratory in New York, followed by pilot scale studies at Santee and Arcata in California in the early 1980s. The earliest small-scale waste-water systems were constructed at Listowel, Ontario, Iselin, Pennsylvania, and Arcata, California, all of which became operational in the mid-1980s.

The application of wetlands for acid mine drainage (AMD) developed very quickly following studies of wetlands in the mid-1970s. Ironically, these studies were initiated to examine the degradation AMD had on wetlands in the Ohio and West Virginia coalfields, and not for evaluating wetlands as alternatives to the application of lime. The earliest pilot experiments appeared in 1978, with fully operational systems in place by 1982 (Taylor, 1992). By 1991, more than 200 wetland systems were treating municipal, industrial and agricultural waste waters and effluent in North America. In addition to Europe, systems are now waters and effluent in North America. In addition to Europe, systems are now operating in Australia, China, Egypt, Columbia, Brazil, India and South Africa (Cooper and Findlay, 1990). International conferences and symposia featuring wetlands have been held every few years since 1972. The proceedings of the last four major meetings resulted in the publication of more than 250 papers in four monographs (Hammer, 1989; Cooper and Findlay, 1990; Moshira, 1992; Mitsch, 1994). An excellent overview on the potential use of constructed wetlands for storm-water management in southern Ontario is presented by M.E. Taylor and Associates (1992). Numerous technical articles have appeared in a variety of journals, most notably *Water Environment Technology*.

NATURAL WETLANDS

Definition and Attributes

Wetlands is a generic term that spans the spectrum from mangrove and cypress swamps, through fresh-water and salt-water marshes, to bogs and fens (Hammer, 1991). Despite this variety, all wetlands share three common attributes. First, wetlands have soils, or substrates, that are saturated for long periods, or for much of the growing season. For that reason, they contain vegetation types with specialized structures that transport oxygen to their roots for respiration; this enables these plants to grow in an otherwise hostile environment. Roots of most terrestrial plants obtain oxygen for respiration from gases within soil pore spaces and if those spaces are filled with water lacking oxygen, the plant dies. Hydrophytic, or wetland plants have developed specialized physical structures called aerenchyma, best described as bundles of drinking straws, to transport atmospheric gases, including oxygen, through leaves and stems down to the roots to provide oxygen for respiration. Aerenchyma also transport respiratory by-products and other gases generated in the substrate back up the roots, stem and leaves for release to the atmosphere, thereby reducing potentially toxic accumulations in the region of the growing roots.

Second, inundation and aerobic conditions also cause specific changes in chemical substances found in most soils. Anoxic substrates with reducing environments cause many elements and compounds to occur in reduced states, creating characteristic colours, textures and compositions typical of hydric soils. Owing to the prevalence of iron in many of these soils, and its colour in reduced states, wetland soils often have a grey or greyish colour and a fine texture.

Third, wetlands are among the most productive ecosystems in the world. This is largely the result of abundant sources of water and nutrients, and the development of plants that have adapted to take full advantage of these optimum conditions. Table 1 shows ranges of primary productivity of selected species and systems under both tropical and temperate conditions. Agricultural productivity in both climatic zones is provided for comparison (Smith, 1992; Newman, 1993). The high primary productivity in wetlands results in a high microbial activity, which, in turn, leads to a high capacity to decompose organic matter and other substances.

Wetland Functions and Values

Wetlands have both functions and values, terms which, although often used interchangeably, are not synonymous. Function describes what a wetland does irrespective of any beneficial worth assigned by humans. It can be an objective process such as water purification, or an objective product such as mosquitoes produced per square metre per day. A value is a subjective interpretation of the relative worth of some wetland process or product such as wild rice, or of a recreational use, say duck hunting. Values can be negative, such as the cost of eradicating the mosquitoes, or positive, such as the flood storage capacity upstream from an urban area.

The functional values of wetlands most often cited are: 1) life support, which includes all types of microbial, invertebrate and vertebrate animals, and microscopic and macroscopic plants; 2) hydrologic modification, which includes flood storage and, conversely baseflow augmentation, ground-water recharge and discharge, altered precipitation and evaporation, and other physical influences on waters; 3) water quality changes, which include addition and/or removal of biological, chemical and sedimentary substances, changes in dissolved oxygen, pH and Eh, and other biological or chemical influences on waters; 4) erosion protection, which includes bank and shoreline stabilization, dissipation of wave energy, alterations in flow patterns, and current velocity; 5) open space and aesthetics, which include outdoor recreation, environmental education, research, scientific influences, and heritage preservation; and 6) geochemical storage, which includes carbon, sul-

Table 1 Net primary productivity of selected plants and ecosystems.

VEGETATION TYPE	ANNUAL ORGANIC PRODUCTIVITY *(tonnes dry weight/ha/year)*
Free-floating macrophytes *Eichhornia crassipes* - water hyacinth	106-162 tropical
Emergent-rooted macrophytes *Typhi* sp. - cattails *Phragmite* sp. - reeds	18-97 temperate to tropical
Fully submergent macrophytes	12-20 tropical 6-8 temperate
Reed swamps	64-87 tropical 32-59 temperate
Phytoplankton	1-4 tropical 7-18 temperate
Agriculture	24-36 tropical 19-26 temperate

tremely multi-functional and, as will be shown below, wetlands constructed for one particular function or value will also provide other functions, and/or create other values (Hammer, 1991).

Wetland Hydrology

Hydrological factors, in particular water depth, modify or determine the structure and functioning of wetlands by controlling the composition of the plant community and, in turn, the animal community. Adaptations to inundation vary considerably, with fewer and fewer species able to survive under longer, deeper flooding. In general, those sites with short-term and/or shallow flooding will support a higher biodiversity of both plants and animals. Under prolonged inundation, many nutrients are immobilized under reducing conditions in the substrate, and are unavailable to plants. Periodic drying and oxidation returns these substances to the nutrient cycles, resulting in an explosive growth response. Changes in oxygen availability and concentration caused by inundation strongly influence decomposition rates (Hammer, 1991).

Wetland Soils

Wetland soils are the main medium for many chemical transformations, and serve as the principle reservoir for minerals and nutrients needed by other plants and a variety of other organisms. As previously mentioned, the principle differences with an upland soil are an abundance of water replacing air that typically fills soil pores or voids, and the isolation of the soil system from atmospheric oxygen. As a result, only a very thin (~m) boundary layer at the soil surface has adequate oxygen to maintain aerobic/oxidizing conditions, and almost everything below is anaerobic/reducing. Shortly after a soil is flooded, any oxygen present is consumed by microbial organisms and chemical oxidation. Diffusion of oxygen through water is many orders of magnitude slower than through well-drained soils, and so the lower layers quickly become, and remain, anaerobic. Many of the interrelated physical and chemical changes that occur are because of limited oxygen, rather than the direct effect of excess water.

Wetland soils are generally considered as hydric soils because they are saturated long enough to develop anaerobic conditions during the growing season to support hydrophytic vegetation. Hydric soils are subdivided into mineral soils with 12-20% organic matter, and organic soils with more than 12-20% organic matter. In well-developed wetlands the upper layers are often organic soils. Organic soils have a high percentage of pore spaces (80%), and, consequently, higher water-holding capacities than mineral soils. Organic soils also have a greater cation exchange capacity, and the major cations are different than in mineral soils. Metal cations (Ca^{++}, Mg^{++}, Na^{+}) dominate in mineral soils, while H^{+} dominates in organic soils. Saturation and loss of oxygen generally cause wetland soils to have negative redox potentials; however, with fluctuations in water levels, the Eh can range from –300 to +300 mV. The pH of wetland soils varies from strongly acidic (3) to strongly alkaline (11), although most wetlands are neutral. Typical wetland soils have a pH of 7 and an Eh of –200 mv, in which case common substances occur in reduced form, nitrogen as N_2O, N_2, or NH_4^+, iron as Fe^{2+}, manganese as Mn^{2+}, carbon as CH_4, and sulphur as S^-. Decomposition rates under anaerobic conditions are 10% of aerobic decomposition rates and frequently much lower than carbon fixation or biomass production rates. It is these fluctuating conditions, characteristic of what is termed a pulsating ecosystem, that provide the conditions for a wide range of complex reactions, which in turn permit the wetland to be a sink for such a large variety of substances.

Table 2 Wetland types of southern and central Ontario (after Taylor, 1992).

TYPE	WATER TABLE LEVEL	SURFACE WATER CHARACTERISTICS	SOIL	VEGETATION
Bog	High	Slow moving Acidic, pH <4.6 Mineral poor (low Ca, Mg)	Peaty Upper layer deficient in minerals Root zone low mineral levels	Sphagnum mosses Heath shrubs Low stunted trees
Fen	High	Very slow moving Alkaline High levels of Ca++,Mg++	Peaty Moderate mineral levels	Graminoid (grassy) fens Shrub fens Treed fens
Swamp	Seasonally variable From complete submergence to below root zone, allowing surface layers to be aerated	Standing or gently moving Neutral to slightly acidic Moderate loadings of minerals	Peaty or mineral High nutrient level Good vegetation growth	Woody with deciduous or coniferous trees
Marsh	Daily or seasonally variable From high complete submergence to below root zone	Moving waters Neutral Well oxygenated	High organic content	Floating aquatics and emergents such as reeds, sedges or rushes (cattails)

Wetland Vegetation

Throughout the literature, many terms are commonly applied to wetland plants. Some of these are phytoplankton, non-vascular aquatic plant, vascular aquatic plant, hydrophyte, aquatic microphyte, vascular hydrophyte, and, simply, aquatic plant. Plankton implies small and current borne, *i.e.*, suspended or floating, and with no rooted attachment. Non-vascular refers to small, simple plants that lack internal transport mechanisms. Macrophyte simply means larger than microscopic.

Common to all wetland plants is their ability to grow in an environment that is periodically but continuously inundated for more than five days during the growing season. Typically, this includes upland plants capable of surviving five days of flooding or saturated soils, as well as deep-water, rooted vascular plants in depths of 7-8 m in very clear waters. However, the vast majority of wetland plants are limited to water depths of less than 2 m.

Wetland plants are divided into free-floating and rooted forms, with the rooted group subdivided into submergent, emergent and floating-leaved types. Woody species can range from low-growing shrubs to towering cypress. As will be seen later, constructed wetlands are classified according to which wetland plant type is used, and descriptions of these plant types are found elsewhere in this paper. The five general wetland types common to southern and central Ontario, together with their pertinent features, are summarized in Table 2.

Problems in using natural wetlands for waste-water treatment. As identified above, natural wetlands are characterized by extreme variability in functional components, making it virtually impossible to predict responses to waste-water application and to translate results from one geographical location to another. Although significant improvement in the quality of the waste water is generally observed as a result of flow through natural wetlands, the extent of their treatment capacity is largely unknown. In addition, their performance may change over time as a consequence of changes in species composition and accumulation of pollutants. Therefore, the treatment capacity of natural wetlands is unpredictable, and the design criteria for constructed wetlands cannot be extracted from results obtained in natural wetlands. There are still too few data from natural systems to allow performance predictions of the treatment capabilities of natural systems and the receiving ecosystems. Moreover, intentional or unintentional use of natural systems for remediating waste waters could lead to serious damage to the ecosystems, from which recovery could take hundreds or even thousands of years (Johns, 1995). Most workers and researchers recommend that natural systems be preserved for their other multifunctional values, and not deliberately used as waste-water treatment systems (Hammer, 1991; Brix, 1993).

CONSTRUCTED WETLANDS

Advantages of Constructed over Natural Wetlands in Treatment of Waste Waters

Pollutant removal in all natural systems involves a combination of physical, chemical and biological processes. Sedimentation, precipitation, adsorption to soil particles, assimilation by the plant tissue, volatilization and microbial transformations are continuously taking place according to the schedule and needs of the ecosystem. These processes often occur at rates and on schedules that are unsuitable for treating large amounts of waste water. Constructed wetlands can be built with a much greater degree of control of substrate, vegetation types, and flow characteristics to enhance these natural processes. Other advantages are site selection, flexibility in sizing, and significantly, control over the hydraulic pathways and retention times (Brix, 1993).

Types of Constructed Wetlands and Pollution Removal Mechanisms

The dominant use of macrophyte- (wetland plant-based) treatment systems is in the treatment of municipal and residential waste water, where four main types of systems are used. These systems are classified according to the life form of the dominating macrophyte. Systems for other purposes are often no more than modified versions of these four systems: 1) free floating, 2) rooted emergent, 3) submergent, and 4) multistage systems consisting of a combination of 1) to 3) with the addition of other kinds of technology systems such as oxidation ponds and sand filtration systems.

Table 3 Removal mechanisms in macrophyte-based waste-water systems (from Brix, 1993). BOD = Biochemical oxygen demand.

CONSTITUENT	REMOVAL MECHANISM
Suspended solids	Sedimentation, filtration
BOD	Microbial degradation - aerobic and anaerobic Sedimentation - accumulation of organic matter/ sludge on the sediment surface
Nitrogen	Ammonification followed by microbial nitrification and denitrification Plant uptake Ammonia volatilization
Phosphorus	Soil sorption - adsorption/precipitation reactions with Al, Fe, Ca and clay minerals in the soil Plant uptake
Pathogens	Sedimentation, filtration Natural die-off Ultra violet radiation Excretion of antibiotics from roots of macrophytes
Trace Metals	Adsorption and complexation with organic matter Plant uptake Microbial transformations

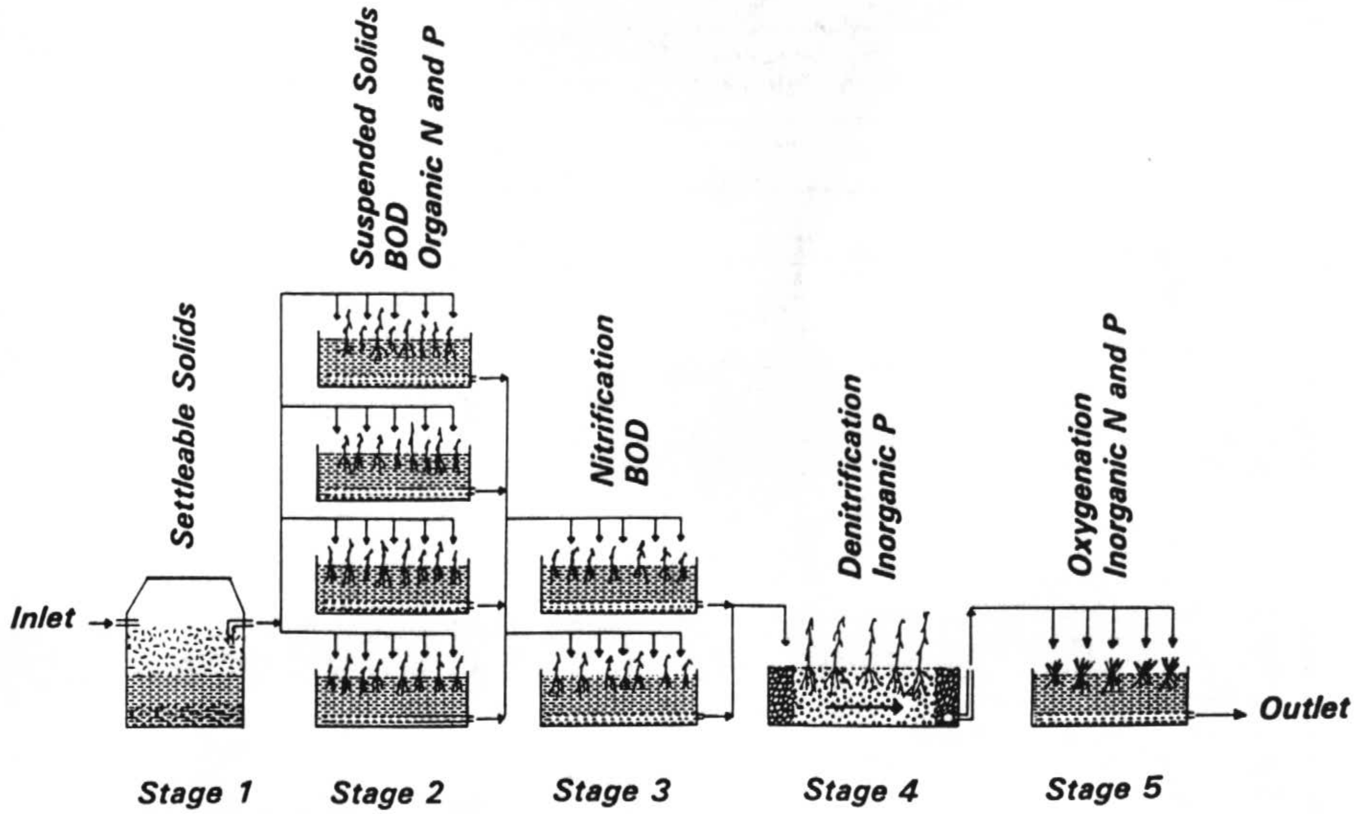


Figure 1 *Multi-stage constructed wetland showing where removal of waste-water components occurs within the system (after Taylor, 1992).*

Removal Mechanisms in Macrophyte-based Waste-water Treatment Systems

Regardless which type of system is employed, all have common removal mechanisms (Table 3). Figure 1 is a schematic showing a multi-stage macrophyte system, illustrating where the removal of the various waste-water constituents listed in Table 3 takes place. Typical systems can involve single cells, cells in series, in parallel, or both.

Free-floating Macrophyte Systems

Free-floating macrophytes are highly diverse in form and habit, ranging from large plants with aerial and/or floating leaves and well-developed submerged roots, such as the water hyacinth, *Eichhornia crassipes*, to minute surface-floating plants with few or no roots, such as various duckweeds, *Lemna*, *Spirodella*, *Wolffia*. Figure 2 is a schematic of a cell with free-floating macrophytes.

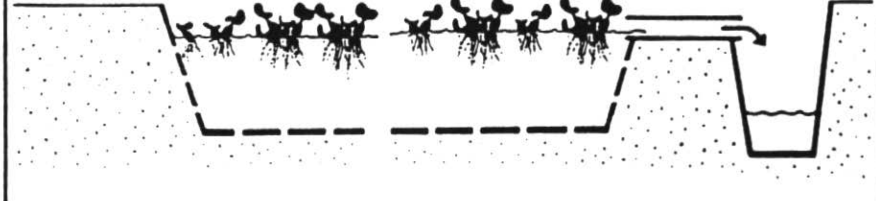


Figure 2 *Typical free-floating macrophyte treatment system. Depth of system is usually less than 1.5 m (after Taylor, 1992).*

Water-hyacinth-based systems. The water hyacinth is one of the most prolific and productive plants in the world. Its rate of growth in the tropics and subtropics is so rapid that it is often regarded as a severe weed, blocking irrigation canals, clogging rivers and lakes, and generally making drainage difficult. In constructed wetlands, it is an ideal species for nutrient removal. When used in the tertiary stage of waste-water treatment (the nutrient removal stage) the water hyacinth removes nitrogen and phosphorus by uptake directly into the biomass. The biomass is harvested frequently to maintain maximum plant productivity and to remove the nitrogen and phosphorus. Some nitrogen may also be removed as a result of microbial denitrification.

Combined secondary and tertiary waste-water systems involve the removal of both BOD and nutrients. In these systems, the degradation of organic matter and the microbial transformations of nitrogen proceed simultaneously, so that the plant is only harvested for maintenance purposes. This system must also include free water surfaces to allow oxygen to be transferred into the water from the atmosphere by diffusion, and to provide areas where algal oxygen production can occur. Retention time is on the order of 5-15 days.

Most of the suspended solids are removed by sedimentation and subsequent degradation. Electrical charges associated with hyacinth roots are reported to react with opposite charges on the suspended solids, causing them to adhere to roots. They are slowly digested and assimilated by the plant and microorganisms. The extensive root system provides a huge surface area for attaching microorganisms, which, in turn, increases the potential for the decomposition of organic matter.

Water hyacinth systems are severely affected by frost. The growth rate is greatly reduced at air temperatures of less than 10°C, thus open-air applications are only possible in tropical and subtropical climates. In temperate climates, they can be used year-round in greenhouses, but only outdoors in the summer. For winter operations, pennywort, *Hydrocotyle umbellata*, a hardier plant with similarly high growth and uptake rates, can be substituted for water hyacinth (Brix, 1993).

Duckweed-based systems. Duckweeds have a much wider geographical range than water hyacinths and are able to grow at temperatures as low as 1° to 3°C. However, they lack an extensive root system, and, therefore, provide a smaller area for attached microbial growth. The main use of duckweeds is for recovering nutrients from secondary waste water.

A dense cover of duckweed inhibits sunlight penetration for oxygen production through phytoplankton photosynthesis, and also prevents the diffusion of oxygen into the water. As a result, the water quickly becomes anaerobic, thereby favouring denitrification. Duckweeds are easily harvested, and the nutritive value of the biomass contains twice as much protein, fat, nitrogen and phosphorus as an equivalent mass of water hyacinth. Retention times vary with the waste-water quality, the effluent quality desired, and climate, but are about 30 days in the summer, and several months in the winter. Winds can easily sweep the duckweeds into piles, so that barriers on the water surface are normally required.

Emergent Aquatic Macrophyte-based Systems

Rooted emergent aquatic macrophytes dominate most natural wetlands. They grow in water up to 1.5 m deep, producing aerial stems and leaves along with

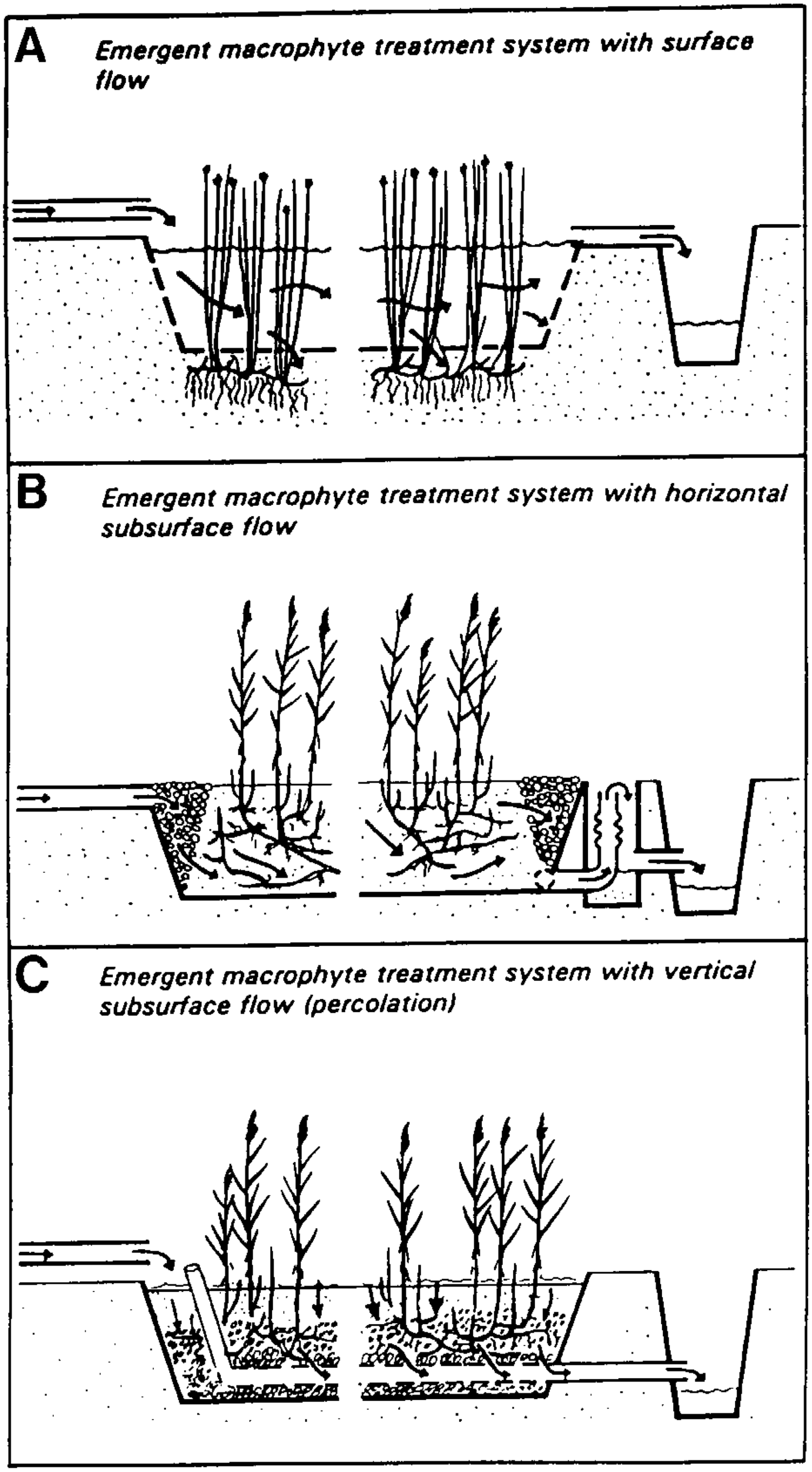


Figure 3 *Different flow systems associated with emergent macrophyte wetlands (after Taylor, 1992).*

extensive root and rhizome systems. Typical species are 1) common reed (*Phragmites australis*), 2) cattail (*Typha latifolia*), and 3) bulrush (*Scirpus lacustris*). Three common system designs are shown in Figures 3A to 3C. All three are suitable for use in southern and central Ontario.

Emergent macrophyte-based systems with surface flow (Cattail-Bulrush). This system typically consists of ditches, 3-5 m wide and more than 100 m long, planted with bulrushes. The submerged portions of the stems and litter serve as the substrate for attached microbial growth. As will be described in more detail in the next section, most of the transformations take place in the soil and rhizosphere. The plant stems capture some of the suspended sediment, and aid in sedimentation by retarding the flow. A considerable amount of waste water can also drain out through the unsealed bottom (Fig. 3A). These systems have been used in Holland for almost 30 years.

Emergent microphyte-based systems with horizontal subsurface flow (Common Reed). This is the original system developed in Germany, and there are now several hundred of these systems in operation in Germany, Denmark and the United Kingdom. Typically, it consists of a bed of soil or gravel, planted with common reed, and underlain by an impermeable membrane to prevent seepage. As the waste water passes through the rhizosphere of the reeds, organic matter is decomposed microbiologically, nitrogen may be denitrified, and phosphorus and heavy metals fixed in the soil. In this system, the main function of the reeds is to supply oxgyen through aerenchyma to the heterotrophic micro-organisms in the rhizosphere (Fig. 3B). Uptake of nutrients in the plant tissue is negligible.

An evaluation of these systems shows that suspended sediments and BOD are generally removed effectively, with the effluent attaining advanced secondary treatment quality. Removal efficiencies for nitrogen and phosphorus are variable. Too-rapid runoff, thus preventing the waste water from coming in contact with the rhizosphere, is a common problem in all soil-based facilities, and the oxygen transport capacity of the reeds is often insufficient to ensure aerobic decomposition in the rhizosphere and for nitrification.

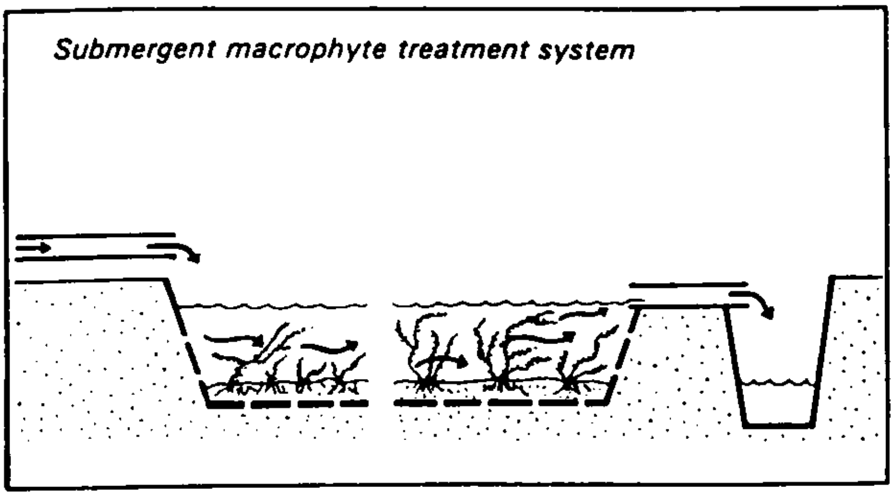


Figure 4 *Typical submergent macrophyte treatment system (after Taylor, 1992).*

Table 4 Performance data for constructed wetlands (from Knight *et al.*, 1993). BOD = biochemical oxygen demand; TSS = total suspended solids; NH_3-N = nitrate; TN = total nitrogen; TP = total phosphorus.

Waste-water source: 89 municipal, 22 industrial, 5 storm water, 11 unclassified
Treatment systems used: 69% free water type, 31% vegetation submergent type
Wetland area: 0.02 ha to 1093 ha
Vegetation types used: cattail, bulrush, pickerel weed, duck potato, duckweed, sedges, grasses (in decreasing abundance)

POLLUTANT ($mg \cdot L^{-1}$)	INFLOW ($mg \cdot L^{-1}$)	OUTFLOW ($mg \cdot L^{-1}$)	REMOVAL EFFICIENCY		PERMITTED LEVEL ($mg \cdot L^{-1}$)
BOD	38.8	10.5	73%	59-90%	5-30
TSS	49.1	15.4	69%	49-94%	10-30
NH_3-N	7.5	4.2	44%	—	1-8 (mun) 50 (ind)
TN	14.0	5.0	64%	30-98%	—
TP	4.2	1.9	55%	20-90%	—
	AVERAGE	AVERAGE	AVERAGE	RANGE	

(The above data are based on n = from 28 to 58)

Emergent macrophyte-based systems with vertical subsurface flow. This system consists of several beds laid out in parallel. Percolating flow and intermittent loading increases soil oxygenation several-fold compared to horizontal subsurface flow systems. During the loading stage, air is forced out of the soil, while during the drying stage, atmospheric air is drawn into the soil pore spaces, replenishing the soil with oxygen (Fig. 3C). These alternating oxidation and reducing conditions in the substrate stimulate sequential nitrification-denitrification and promote phosphorus adsorptions. Treatment performance of these systems is apparently very good with respect to suspended solids, BOD, ammonia and phosphorus (Brix, 1993).

Submergent Macrophyte-based Systems

Plants characteristic of these systems have their photosynthetic tissue entirely submerged, and assimilate nutrients from polluted waters (Fig. 4). As their growth is limited to well-oxygenated waters, they cannot be used for waste water with a high content of readily biodegradable organic matter, because the microbial decomposition of the organic matter will create anoxic conditions. These systems are mainly used for polishing secondary treated waste waters, and their prime area of application is as a final step in multistage systems. Some of the plant species under consideration are egeria, elodea, hornwort and hydrilla.

Multistage Macrophyte-based System

The numerous individual systems previously described may be combined with one another or with conventional treatment technologies. Two such systems are currently operational:

The marsh-pond-meadow system. This consists of 1) a bar screen and an aeration cell using a floating surface aerator, 2) a lateral-flow marsh planted with cattails in a sand medium, 3) a pond with aquatic macrophytes and herbivorous fish, 4) a meadow planted with red canary grass, and 5) a chlorination chamber. The removal efficiency is reported to be 77% for ammonia nitrogen and 82% for total phosphorus.

The Max-Planck-Institute Process. This design is used in France and was a model for a system implemented in Oaklands Park, United Kingdom. The system consists of four or five stages in cascade, each with several basins laid out in parallel and planted with emergent macrophytes in gravel. The flow pattern in the first two stages is vertical, while the final ones have horizontal flow. In the French system, removal of suspended solids and BOD is good, but with poor results for nitrogen and phosphorus, perhaps because of high loading rates. The United Kingdom system produces a nitrified effluent and 98% reduction of BOD and suspended solids (Brix, 1993).

EVALUATING WETLAND PERFORMANCE

The data presented in the previous sections should leave little doubt as to the potential of constructed wetlands in addressing at least some of the water problems prevalent in urban areas. However, as with any emerging technology, after the initial optimism comes the need to demonstrate an acceptable level of performance.

Knight *et al.* (1993) have catalogued information on wetland sites throughout North America and have released preliminary numbers (Table 4). Knight *et al.* (1993) list 127 systems at 96 sites; about 90% of the systems have operated less than three years. As a consequence, many data are preliminary and based on less than one year of operation. Only six systems at four sites have been operational for at least five years. Most systems are small, on pilot scale, often seasonal, treating less than 1000 $m^3 \cdot d^{-1}$. Only five systems averaged more than 10,000 $m^3 \cdot d^{-1}$. Some are treating primary effluent, some secondary, while many are polishers, or act as tertiary treatment systems. Some focus on one particular pollutant, while others are attempting to address the full complement. In general, a comparison between systems is difficult, if not impossible. A more realistic evaluation of performance can be determined by examining those systems with 5-15 years of operation statistics (Table 5).

Although none of these systems is capable of removing all of the pollutants at acceptable removal rates, what they do remove, they do extremely well, and so it is obvious why these systems are still operating after all these years. In addition to the group identified in Table 5, two systems not on the list of Knight *et al.* (1993) serve as excellent examples of the utility of constructed wetlands in remediating waste waters.

American Crystal Sugar Company, Hillsboro Wetlands, North Dakota

This sugar beet operation releases 300-600 million L of water into the Red River during the 210-day processing period (Haven and Lothop, 1992). Over

Table 5 Performance data for constructed wetlands in use for at least five years (from Knight *et al.*, 1993).

SYSTEM	FLOW (cu.m·d^{-1})	YEARS OF OPERATION	REMOVAL RATES (%) BOD	TSS	NH_3-N	TN	TP
Reedy Creek	12,058	11	64	73	76	82	13
Bellaire	572	11	—	—	88	—	89
Houghton Lake	3374	15	—	—	93	97	—
Kinross	1350	15	64	94	98	—	—
Drummond	265	6	—	—	14	85	—

the past 15 years, as all sugar refiners have done, the company has invested in many types of waste-water treatment systems that have high energy requirements and require skilled operators. A biological treatment process was being used, but the design capacity was often exceeded, resulting in a poor quality effluent. The end result was that years of discharging the nutrient-rich effluent into the stabilization pond, which, unfortunately, also served as the water supply reservoir, resulted in serious degradation of water quality. In 1989, the company began constructing a 64-ha wetland which, in addition to the seven cells, ponds and lagoons used for treatment, included nine nesting islands and 10 ha of grasslands for waterfowl habitat. In 1990, 30,000 cattails were planted in the first two cells and these quickly spread to other areas. In 1991, flow to the wetlands averaged 21.9 L·s^{-1}, with an average BOD of 100 mg·L^{-1}. Overall BOD removal efficiency was 85%, peaking at 93%, and well below the 25 mg·L^{-1} discharge limit. The 1992 flow was considerably increased through four cells, and the remaining three cells were completed later that year.

Total project cost for the wetlands was US $1.6 million, or about 20% of the cost of the biological treatment system. The wetlands have also become a popular haven for migrating waterfowl.

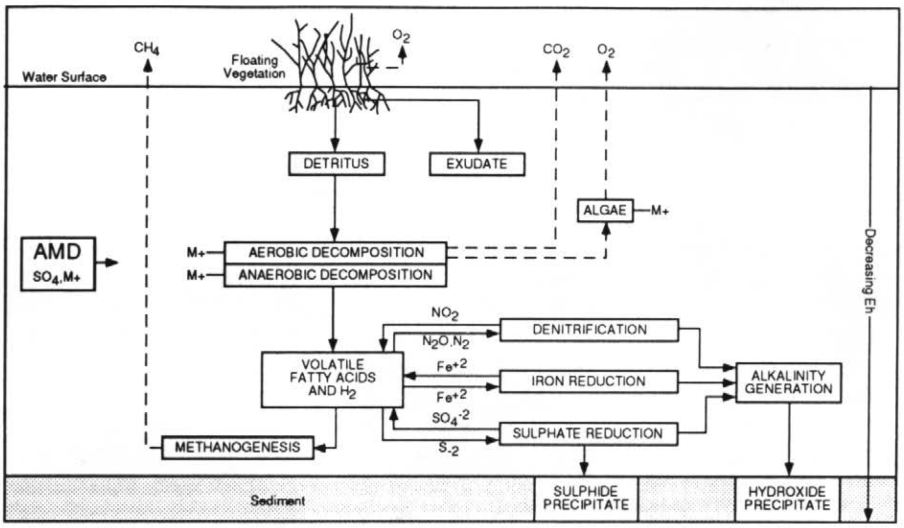
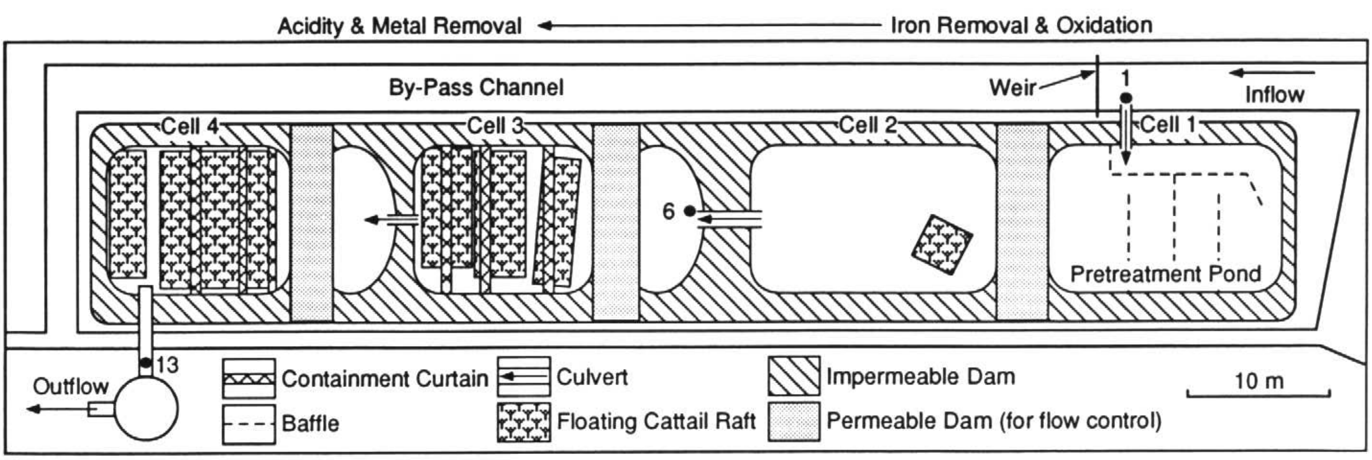


Figure 5 *Macrophyte-based wetland system for remediation of acid mine drainage (AMD) showing principal biogeochemical processes.*

City of Orlando (Easterly Wetlands Reclamation Project), Florida

In the early 1980s, one of Orlando's waste-water facilities was operating near capacity with no opportunity to increase its existing waste load allocation, and the city sought alternative means of tertiary treatment and effluent disposal (Anderson, 1993). In 1984, a 12-ha water hyacinth treatment system was devised as an interim solution. This system was so successful at removing nitrogen and phosphorus, that the interim solution was treating 16 million litres per day. A 506-ha wetland, capable of treating 80 million litres per day of effluent, was then constructed, and full-scale operations began in 1987. Effluent is detained in the wetland for 30 days,



	July Flow 1.125 L/min			August Flow 0.24 L/min			October Flow 0.1 L/min		
	Stn 1	Stn 6	Stn 13	Stn 1	Stn 6	Stn 13	Stn 1	Stn 6	Stn 13
Temp (°C)	17.2	15.5	21.5	15	20.9	19.3	8.4	8.2	8.1
pH	5.65	3.05	5.52	5.76	2.96	3.34	5.70	2.94	6.14
Eh (mV)	284	687	305	260	688	653	289	680	234
Acidity (g/day)	1215	599	315.9	131	100	27.7	84.9	35.9	23.4
Al (g/day)	<1.6	29.2	<1.6	0.01	7.02	0.24	0.32	2.76	0.14
Cu (g/day)	<1.6	7.06	<1.6	0.01	1.9	0.05	0.03	0.4	0.001
Fe (g/day)	505	27.4	59	81.2	3.12	1.71	32	2.52	3.18
Ni (g/day)	60.4	70.6	14	8.71	13.2	1.75	3.66	4.2	0.46
S (g/day)	1408	948	855	292	237	190	122	86.7	60.1

Figure 6 *Structure of a wetland used to remediate acid mine drainage at Sudbury, Ontario, with performance data.*

and discharged into the environmentally sensitive St. John's River. The performance of the wetland is outstanding; treated effluent consistently has <1.0 $mg \cdot L^{-1}$ nitrogen and <0.1 $mg \cdot L^{-1}$ phosphorus. The wetland's success is also evident by the abundance of wildlife in the area, now designated as the Orlando Wilderness Park, which is somewhat remarkable, since five years previously the area was a cattle pasture.

DISCUSSION

These two case studies illustrate the current capabilities and strengths of constructed wetlands. They demonstrate that outstanding results can be achieved from full-scale systems that are low tech compared with conventional chemical-biological-physical treatment systems. Furthermore, constructed wetlands require considerably lower capital and operating costs. Additional benefits to the environment are obvious.

In both cases, wetlands were used for very well-defined problems, with the focus on only one or two contaminants. This is probably an accurate reflection of the current level of understanding of, and capabilities with, wetland technology. It can be concluded that, when operating under appropriate conditions, constructed wetlands are generally able to achieve high removal efficiencies for BOD, TSS and bacteria from municipal and some forms of industrial waste water (Bastian and Hammer, 1993). Success in ammonia conversion/removal by nutrification and denitrification can be highly variable, dependent on system design, retention times, oxygen supply, and other factors. Phosphorus removal rates tend to vary between projects, and may be effective only for limited periods unless large areas or special media are involved.

The application of constructed wetlands to more complex problems, such as urban storm-water runoff, is still very much problematic, and where they have been used, the focus appears to have been on one particular pollutant. At Lacamas Shores, Washington, for example, 95% of the phosphorus entering a recreational lake that had become eutrophic was from urban runoff. Although the problem with the phosphorus, initially the main concern, was resolved, nitrate concentrations continued to straddle the compliance level (Bautista and Geiger, 1993).

CURRENT AND PROPOSED APPLICATIONS IN ONTARIO

There has been considerable interest and research focussed on constructed wetlands, not only as an alternative for treating municipal waste water, but for addressing other urban environmental problems. Constructed wetlands have been proposed for storm-water management and wildlife habitat enhancement in recently developed regeneration plans for degraded urban watersheds (Taylor, 1992; Marshall Macklin Monaghan, 1992; Dillon, 1993; Crombie, 1994). Research is ongoing for the treatment of a variety of waste waters, including those originating from mining wastes which continue to accumulate within urban centres such as Sudbury.

Municipal and Industrial Waste Water

Several experimental wetlands have been in operation since the mid- and late 1980s; however, scale-up has not yet occurred at any major urban sites. Municipal and industrial waste water is being treated and evaluated in five constructed wetlands in Listowel. Cells at Cobalt, Cochrane and, more recently, in Port Perry, are restricted to municipal waste water. In addition, small wastewater operations have been constructed at locations such as campgrounds, where demand is seasonal, and where the costs of installing a standard treatment system are prohibitive (Taylor, 1992). Monitoring and process modifications are ongoing in an attempt to improve cold weather performance to allow for scale-up.

Mine Waste Water/ Acid Mine Drainage

Millions of tonnes of acid-generating

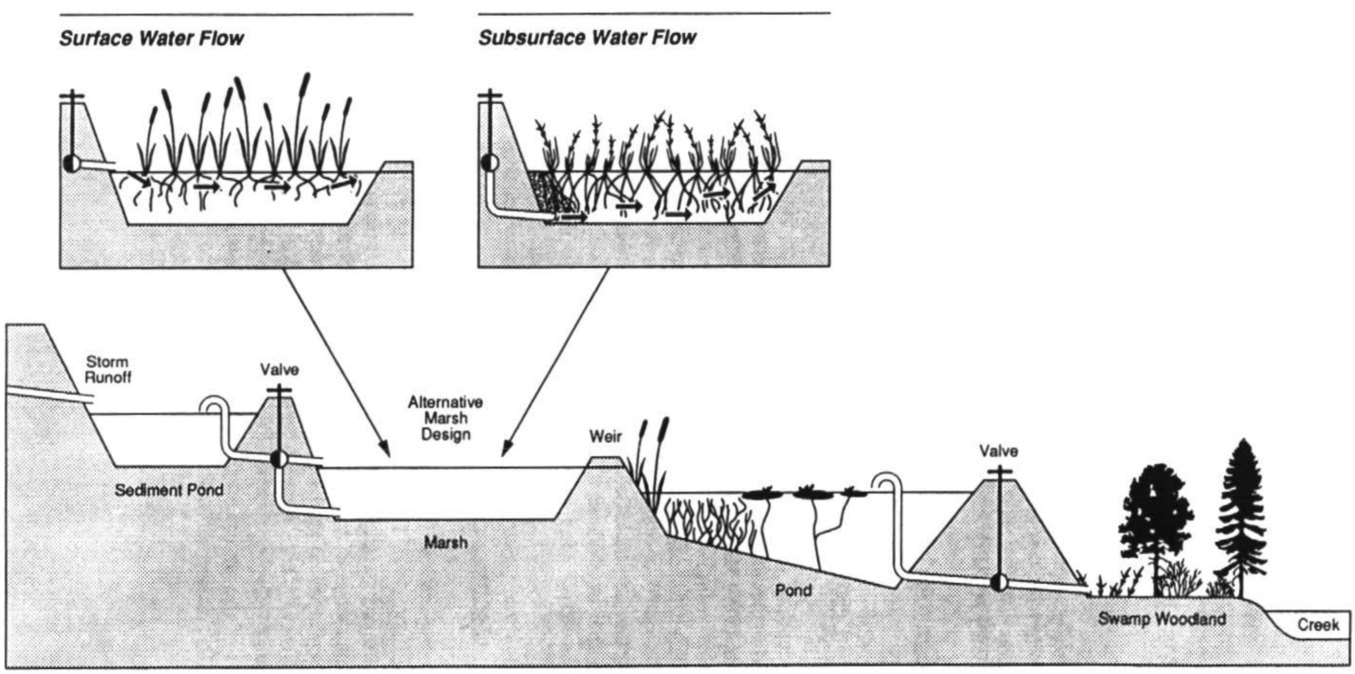


Figure 7 *Schematic of constructed wetland used for remediation of urban storm-water runoff.*

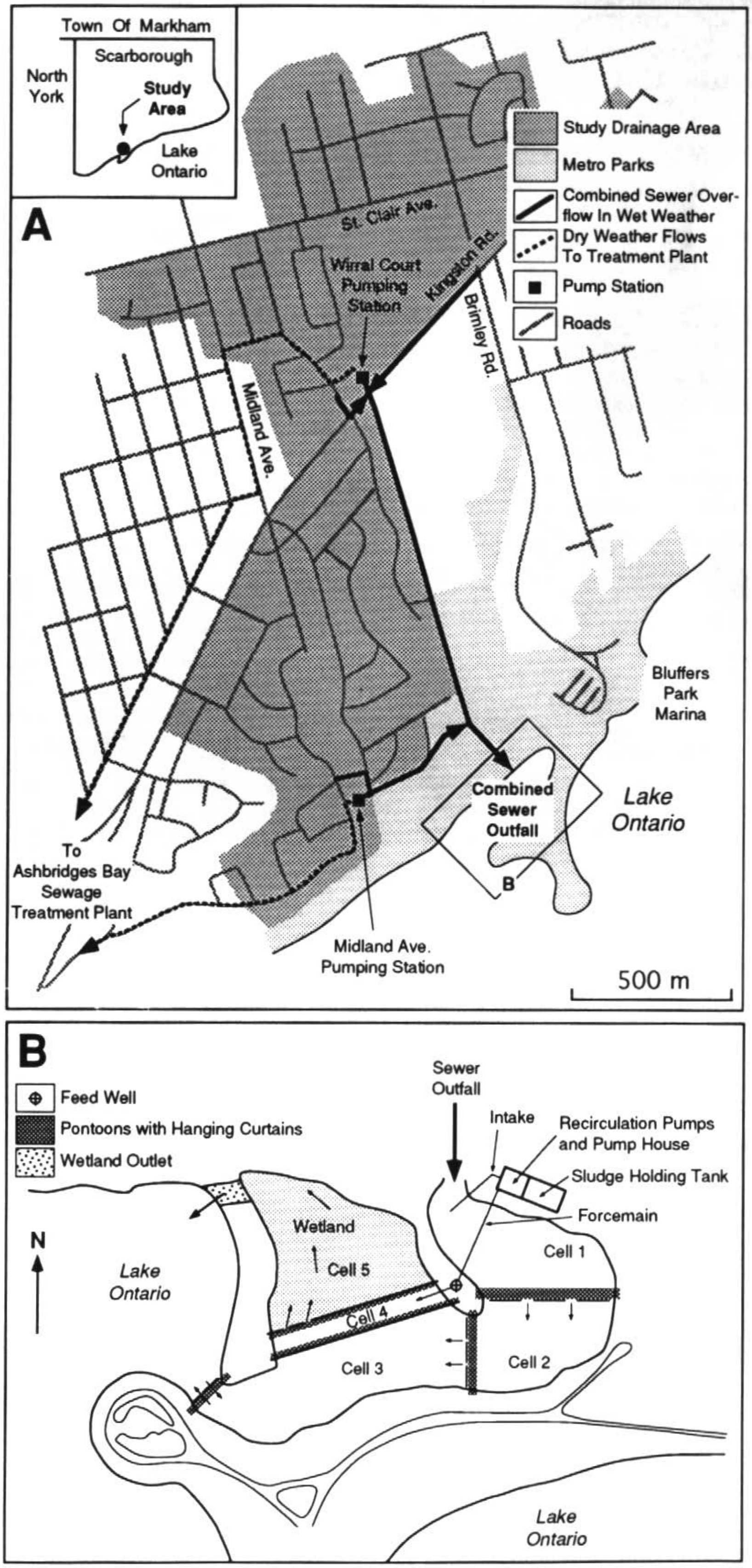


Figure 8 *Design of Dunkers Flow Balancing System at Scarborough, Ontario, designed to remediate overflows from a combined sewer in the adjacent urban area to Lake Ontario (after Aquafor Beech, 1994). See text for details and Nairn and Cowie, in press for location.*

waste rock and tailings are generated annually at numerous mine sites throughout Ontario, and these are added to the hundreds of millions of tonnes already present from more than 100 years of mining in the province. As a result, passive biological treatment systems have received much attention as an alternative to conventional chemical treatment of heavy metals and acidity that originate from the mining waste, and which contaminate both surface waters and ground water (Kalin *et al.*, 1995).

A review of the performance data of emergent macrophyte systems operating at sites of former coal mines in the United States Appalachians indicates that the effectiveness of the biological systems has been highly variable, and generally only works well where the pH of the water is initially high, >4.5 (Kalin *et al.*, 1995). In addition, the precipitation of metal hydroxide alters the hydraulic conditions and leads to system failure. Ontario's base metal mines are high in sulphides and, therefore, the resulting waste water is lower in pH than can be effectively treated with aerobic wetlands. As a result, several alternative systems including compost wetlands, microbial reactor systems, and constructed wetland/sediment systems have been developed and are being tested (Kalin *et al.*, 1995).

A test cell of a constructed wetland/sediment system, referred to as ARUM (Acid Reduction Using Microbiology) has been treating acid mine waste waters from Copper Cliff tailings at Sudbury. In a departure from the processes described earlier in this paper, the constructed wetlands are floating cattail islands. The cattails provide a continuous supply of organic carbon (litter) for decomposition by anaerobic bacteria. In addition, the release of organic acids to the water column complexes metals and converts them to particulates that settle to the sediment. With a retention time of 131 days, a removal of 80-87% of the Ni, 77-98% of the Cu, and 10-20% of the S loadings, as well as 47-73% of the acidity, was achieved during the first year of operation at a flow rate of 1 to 2 $L \cdot m^{-1}$ (Figs. 5 and 6; Kalin *et al.*, 1995).

Storm-water Management

An extensive review and evaluation of constructed wetlands for storm-water management was recently completed by Taylor (1992). In contrast to the treatment of municipal or mining waste water, whose flow rates and compositions tend to be predictable and relatively constant, storm-water flows and compositions vary considerably, depending on the land uses in the catchment basin and the frequency and intensity of rain/snow events. In addition, constructed wetlands may not be effective in treating certain storm-water contaminants, such as road salt and some organic compounds. Pretreatment of sediment using sedimentation/siltation ponds may be necessary to prevent the sediment from choking the wetland soils and rendering them ineffective.

Considering the diverse nature of the contaminants found in urban storm water, the most effective solution appears to be a multi-stage system, such as the marsh-pond-meadow or Max-Planck-Institute process mentioned in an earlier section. A schematic of a multi-stage system with pretreatment sediment pond is illustrated in Figure 7 and the two pilot wetland storm-water projects currently under study/construction in the Toronto area (Emery Creek and Windego Creek-Grenadier Pond) are planned as multistage systems with pretreatment (Marshall Macklin Monaghan, 1992; Dillon, 1993).

Combined Sewer Overflows

In many urban areas, surface water is affected by overflows from combined sewers, which carry both storm runoff and domestic sewage. Being of limited capacity, they overflow during storms and discharge into adjacent watercourses (see Eyles, in press). Figure 8 shows a heavily urbanized portion of the city of Scarborough, Ontario, where dry weather flows are directed *via* pumping stations to the main sewage treatment plant. During significant rainfall events, flows in excess of the capacity of the pumping station are directed to an outfall in Lake Ontario. Flows from roof downspouts directly connected to the combined sewer are the primary cause of the combined sewer overflows which occur, on average, about 30 times a year. Some 60,000 kg of sediment, contaminated with metals and polycyclic aromatic hydrocarbons, are deposited in the lake; concentrations for many water quality parameters exceed Provincial Water Quality Objectives by more than one order of magnitude. Various alternatives for reducing pollutant loadings were evaluated by the city, and Figure 8 shows the design of a system, currently under construction, incorporating a constructed wetland and designed to reduce pollutant loadings to the lake through sedimentation of solids and pollutants with a series of cells (Dunkers Flow Balancing System). Initially, combined sewer overflows will discharge into cell 1, followed by cell 2 and cell 3 if the runoff event is significant. Runoff volumes exceeding the capacity of the first three cells (about 40,000 m^3) will discharge into the lake. After flows subside and settling of suspended particles has occurred (12 hours), water will be pumped from cells 2 and 3 into 1 and thence to cells 4 and 5 *via* a forcemain (Fig. 8). Cell 5 consists of a constructed submergent-emergent wetland that will enhance pollutant removal by the uptake of nutrients. Treated water is then discharged to Lake Ontario. Sludge accumulating within the cells will be periodically removed and dumped on industrial lands. The capital cost of the system is $2.3 million, and annual operating costs are expected to be about $100,000 (Aquafor Beech Ltd., 1994). Mandatory disconnection of roof downspouts and the provision for infiltration of storm runoff will significantly reduce combined sewer overflow volumes.

Wildlife Habitat Enhancement

The construction of wetland areas appears to be a major component of many urban watershed restoration projects. The development of these wetlands should be viewed largely as restoration of natural-wetland areas that originally existed in these watersheds prior to urbanization. Restored natural-wetland areas should not be expected to take on the role of storm-water management. Where this has been allowed to occur, natural wetlands become choked with sediment and heavy metals, resulting in a severe drop in biodiversity. Thus, although increased biodiversity can be expected as an indirect or secondary benefit from wetlands constructed for treating waste water, secondary benefits such as improved storm-water quality from the restoration of natural wetlands are neither desirable nor should they be expected.

Landfill Leachate

In comparison to municipal waste water, landfill leachate is often a higher strength waste water with high levels of not only nutrients and BOD, but also heavy metals and an assortment of organic compounds (see Henry and Heinke, 1989; Howard and Livingstone, in press; Birks and Eyles, in press). As a result, only a few constructed wetland systems are able to treat landfill leachate. The largest of these, in Escambia County, Florida, dilutes the incoming high-strength landfill leachate with rain water before passing it through a multistage system that includes constructed wetlands (Dohms, 1993). The landfill leachate forms a very small percentage of the overall volume. In Ontario, pilot scale tests of treating landfill leachate using constructed wetlands are being conducted at a few localities, principally at Storrington, near Kingston (D. Smith, pers. comm., 1995).

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Accepted, as revised, January 1996.