

CONSTRUCTED WETLANDS
FOR
STORMWATER MANAGEMENT:

A REVIEW

APRIL 1992



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A REVIEW

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and

The Metropolitan Toronto and Region
Conservation Authority

Report Prepared By:

Mark E. Taylor & Associates

APRIL 1992



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A REVIEW

For

The Metropolitan Toronto and Region
Conservation Authority

&

The Ontario Ministry of the Environment

By

Mark E. Taylor & Associates
160 Woodycrest Avenue
Toronto, Ontario, M4J 3B9



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DISCLAIMER

The information contained herein is provided to assist designers in evaluating the use of constructed wetlands for stormwater treatment. This information does not necessarily reflect the position and/or policies of the Metropolitan Toronto and Region Conservation Authority or the Ontario Ministry of the Environment. The use of constructed wetlands for stormwater treatment will be evaluated on a case-by-case basis.

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CONSTRUCTED WETLANDS FOR STORMWATER MANAGEMENT: A REVIEW

Executive Summary

Stormwater management is concerned with controlling water flow rates in streams and rivers and the construction of wetlands for stormwater management provides a feasible solution to improve water quality in urban and rural environments. The success of a constructed wetland is measured in terms of the realization of the goals set out for it.

Constructed wetlands have been built to improve water quality, but they also modify flow rates by storing water temporarily, attenuating flow and reducing downstream scouring and erosion. Many constructed wetlands have been built to provide a low cost alternative to sewage treatment facilities. Constructed wetlands are usually either surface flow marshes where the wastewater flows over the top of the marsh and pollutants are removed by emergent plants, or subsurface flow marshes where wastewater flows through substrates of high hydraulic conductivity upon which aquatic emergents are growing and the pollutants are removed by root systems, associated microflora and the substrate..

The Ontario Ministry of the Environment has been actively involved in the development and monitoring of constructed wetlands at Listowel, Cochrane and Port Perry. However, the wastewater output of these communities is predictable and relatively constant, two characteristics not typical of stormwaters. Estimates of stormwater flow must be based on catchment areas, surface permeability, expected frequency of rain events and annual rainfall.

There is great variability in the efficiency of wetlands at removing contaminants. The removal of excess nutrients is generally good (> 70%). Phosphorus removal may decline after several years as the wetland becomes saturated and nitrogen is lost through denitrification under anoxic conditions. Removal rates for bacteria are good to excellent and many viruses are immobilized and destroyed in wetlands. Heavy metals generally accumulate either in sediments or are associated with organic detritus and may or may not be recycled into the ecosystem. Many pesticides, organic compounds, oils and greases are broken down by microbes and plants.

Marshes and swamps are the commonest remaining wetland types in southern Ontario. They are characterized by fluctuating water levels and are therefore suitable types of wetland to consider for stormwater management. Shallow open water ponds are also useful in that sedimentation occurs, but the purifying effect of open water is in part a reflection of the amount of edge where phreatic vegetation has an important effect on nutrient status and evapotranspiration values. Small wetlands have relatively more edge and serve to slow water flow more than do larger bodies of wetlands with less edge. Vegetation in a wetland impedes surficial water flow and attenuates peak flows. Significant amounts of water may be lost from a wetland by evaporation or evapotranspiration. Therefore a series of small constructed

wetland areas has a greater effect on water flow and evapotranspiration than a single large one.

Stormwater is runoff water which comes from roads, parking lots, roofs and other impermeable surfaces in urban areas. It is usually directed via culverts and storm drains to the nearest ditch, stream, river or lake. Wastewater on the other hand is that water collected from sanitary sewers which is usually treated at a sewage treatment plant. Constructed wetlands for stormwater management are in essence a relatively new concept for use within densely populated areas of the province. Because their efficiency at removing pollutants and the fate of these pollutants is not well documented it is important that pilot projects be monitored carefully. Generally the "first flush" of stormwater carries the highest pollution loadings. Some studies have shown that the first inch of rainfall carries 90% of the pollution load. Urban stormwater is characterized by high pollutant concentrations which are comparable to secondarily treated wastewater.

A constructed wetland should contain a number of cells, either of similar construction and function or of different structure and purpose. The area and shape is largely dictated by existing topography, geology and land availability, but it is recommended that they be as large as possible. Constructed wetlands in Tennessee are between 7.8 m² to 82.2 m² per average flowing litre per minute. If very poor water quality is expected, the constructed wetlands should be increased in size. A constructed wetland should be able to hold water for a ≤ 20 mm storm event and should retain water for 24-48 hours. Some constructed wetlands have been sized according to the annual phosphorus loadings. Spillways should be over-designed by a factor of three. The maintenance of constructed wetlands is considerably easier when water levels can be controlled.

Although many constructed wetlands have operated using essentially monocultures of cattails or reeds, it seems advisable to have several species of plants functioning in each part of a constructed wetland to prevent potential breakdowns of the system due to unusual conditions or pests. Cattails are particularly invasive and some researchers recommend not using them. Because aquatic, semi-aquatic and phreatic plants are dependent upon the water level in which they thrive best, species diversity can be maintained by having distinct topographic gradients within a constructed wetland. This allows different areas to be exposed to different moisture gradients or water depths. In this way a simple difference in depth will permit a variety of species to survive.

Prior to constructing wetlands for stormwater management, the local hydrology must be understood in terms of catchment area and runoff volumes, local recharge or discharge areas, soil types and the climatic effect on water flow. If an area is a recharge area, then water in a wetland contributes to the recharge and polluted or nutrient rich waters may disappear into the ground water. If the area is a discharge area, then polluted waters may be diluted with ground water. The hydrologic characteristics of an urban area are different from those of natural or agricultural areas and these characteristics must be taken into consideration in the design stage. Some criteria for wetland creation are:-

- 1) The watershed area for the constructed wetland must not be too great and should be built within the standard design tables.
- 2) It must have at least 20 acres of drainage area for each acre impounded to ensure adequate water during dry periods.
- 3) It must contain a minimum of one acre of water surface with the maximum limited by watershed and drainage-impoundment ratio.
- 4) The soil must be tight enough to hold water.
- 5) It must form a natural basin which would permit the impoundment of water to a level not exceeding 18 to 24 inches over three-quarters of the surface area.

Constructed wetlands are best planted in early summer using local plant material where possible. A variety of species should be planted and if the weather is good, the wetland may be functioning in six to ten weeks.

In some areas it is advisable to pretreat stormwater before it enters a constructed wetland. Many authors recommend the use of a siltation pond to catch sediments before stormwaters reach a constructed wetland. While several projects have incorporated chlorination technologies for constructed wetland outflow, this does not generally appear to be necessary.

Results to date indicate that constructed wetland designs for wastewater discharge should be conservative. There is still too little data from natural or constructed systems over the long term to allow confident predictions. The performance or effectiveness of constructed wetlands in improving water quality or modifying flow rates can only be evaluated with appropriate monitoring.

The majority of heavy metals are adsorbed on to sediments and become buried with time, the sediments acting as a sink for these contaminants. Particle size of sediments is an important factor in heavy metal deposition, with fine particles such as clays and silts and organic matter adsorbing heavy metals to their surfaces to a much greater extent than sands. It is important that a pretreatment pond be provided for collection of sediment and for the protection of the constructed wetland from accidental spills. The quantity of sediments trapped is related to the characteristics of the watershed.

Because some pollutants may be concentrated in food chains it is necessary to monitor the biotic components of constructed wetlands. Heavy metals ingested by shorebirds and aquatic invertebrates may not accumulate to high concentrations because they are excreted while some organic chemicals such as DDT, mirex and PCBs are concentrated. Efficiencies of bacterial and viral removal are high in some studies, in the order of 99%. Normally bacteria do not last more than two or three days in wetlands while viruses last longer. Some organic compounds may volatilize from a wetland or be metabolized by microbes and plants.

Monitoring for anthropogenic substances is essential. Care is required in interpreting some of the values such as BOD or total phosphorus because organic material may be produced by the wetland and not be of anthropogenic origin. Some pollutants, notably heavy metals and organochlorine compounds, occur in much higher concentrations in aquatic organisms than in sediments or the water column by a factor of 10^3 - 10^6 because of bioaccumulation. Monitoring the biotic components of constructed wetlands is as essential as measuring the sediments and water quality. The presence and health of organisms reflect the state of the environment. If the environment is polluted then characteristic "tolerant" species are present while "sensitive" less tolerant species are absent. The functioning and effectiveness of a constructed wetland can be evaluated in terms of its biotic components.

Constructed wetlands are an effective technology for improving storm water quality and attenuating flow rates. Because each watershed is unique, exact prediction of constructed wetland efficiencies is not possible at this time with the available information. However, with experience developed in designing, building and operating such structures and with careful monitoring programs, it will be possible to provide a sound quantitative basis for the emerging technology of constructed wetlands in stormwater management.

TABLE OF CONTENTS

1.	Introduction	1
2.	Wetlands	2
	Structure of Wetlands	2
	Function and Values of Wetlands	4
3.	Hydrology of Wetlands	7
	Soil and Subsoil Material, Soil Permeability	7
	Superficial Topography, Velocity and Flow Rate	7
	Size of Wetland	8
	Ground Water Conditions, Recharge or Discharge Area	8
	Seasonal Distribution of Precipitation, Intensity and	8
	Water Depth and Fluctuation	9
	Detention Time	9
	Urban Hydrology	10
4.	Contaminant Loadings in Wetlands, Vegetation and Wildlife	12
	Bioaccumulation of Contaminants	13
	Transfer of Contaminants to Other Ecosystems	21
5.	Public Perceptions of Wetlands	23
	Wetlands in Residential Areas	23
	Wetlands in Industrial Commercial Areas	24
6.	History of Constructed Wetlands	24
	Constructed Wetlands for Municipal Sewage Treatment	24
	Constructed Wetlands for Treatment of Mine Wastewater	25
	Constructed Wetlands for Industrial Wastewater	26
	Constructed Wetlands for Wildlife Enhancement Projects	27
	Constructed Wetlands for Stormwater Management	27
7.	Development of Constructed Wetlands	28
	Design Criteria	28
	Size	29
	Area and Shape	30
	Depth	31
	Soil Preparation	31
	Planting	33

8.	Maintenance and Operation of Constructed Wetlands	39
	Water Level Controls	39
	Sediments	40
	Harvesting Organic Material	40
9.	Performance and Monitoring of Constructed Wetlands	40
	Frequency of Monitoring	41
	Spatial Monitoring	42
	Water Quantity	42
	Water Quality	45
	Nutrients	47
	Microbes	48
	Heavy Metals	48
	Organic Compounds	48
	Biotic Components	52
10.	Summary	53
11.	References	54

1. Introduction

In May, 1991, Mark E. Taylor and Associates was contracted by the Metropolitan Toronto and Region Conservation Authority (MTRCA) to provide an annotated bibliography and review paper on "*Constructed Wetlands for Stormwater Management*". The goal of this review paper is to provide an overview on the use of constructed wetlands for stormwater management with particular reference to southern Ontario.

Stormwater management is more of a concern in urban than in rural areas, though it is by no means confined to urban areas. Changes in hydrology occurred in southern Ontario when the original forests were cleared for agriculture. The result was increased siltation of streams, increased peak flows, the presence of fertilizers, herbicides, pesticides, and other substances of anthropogenic origin in the water.

The severity of storms, the natural topography and land use are all factors which determine whether stormwaters present a threat or hazard to human and biological communities. The degree of urbanization and the location and extent of an urban area within a watershed has a profound effect on stream flow.

The re-introduction of wetlands as a component in the hydrologic system of an area has been proposed as a way of reducing water pollution and bank erosion as well as attenuating stream flows. However, the location of a constructed wetland within a watershed, the periodicity and severity of rain events, and the pollution loading from the urban environment are all important in determining whether the introduction of new wetlands into a watershed is a suitable remedy.

The cost of land is an important consideration when proposing constructed wetlands for stormwater control. In dense urban areas where land values are high, it may not be possible to purchase sufficient land for flood control using wetlands and a dam might be more appropriate. If stormwaters can be diverted to constructed wetlands, for partial storage and partial treatment, the wetland begins to perform multiple functions. When a constructed wetland performs multiple functions such as water storage, reduction of stream erosion, cleansing of water and providing habitat for wildlife, then the cumulative value of the wetland is much higher than if only flood control is the goal. It does, however, become increasingly difficult to determine a dollar value for a constructed wetland with multiple functions.

The climate in which a constructed wetland is built is also important. If winter precipitation is mainly snow and covers the wetland, water polishing of ground water and some meltwater can continue through the winter beneath the snow. If the wetland is a wooded swamp, it may function better than a marsh in winter but not so well as a marsh in summer. Wetlands with little snow or vegetative cover and severe winters may freeze completely and wetland function is then curtailed. If the requirement of the constructed wetland is to maintain

summer flows for downstream aquatic habitats, water storage and slow release is an important criterion.

Therefore, the success of a constructed wetland depends on what the goals are, whether it be water quality improvement, attenuation of flood peaks, minimizing erosion, providing aesthetic habitats, providing wildlife and fisheries habitats, or any combination of such functions.

The scope of this review appeared endless, because of the large number of parameters which may affect the functioning of a constructed wetland. The total literature on the subject is vast and representative papers have been utilized wherever possible. A balance has been attempted, but because readers come with different backgrounds and different interests and expectations, biases undoubtedly remain.

2. Wetlands

Wetlands evolved in response to historic, topographic, climatic, geologic and hydrologic factors, and biotic communities. The type of wetland and its functions are a reflection of these parameters. Before attempting to construct artificial wetlands it is important to obtain information about the natural wetlands of an area and the factors which caused them. The hydrologic characteristics of an urban area are different from those in natural or agricultural areas and this must be taken into consideration in the design stage so that adequate storage volumes can be adjusted to expected runoff volumes.

2.1 Structure of Wetlands

There are five general classes of wetland in southern Ontario: bog, fen, swamp, marsh and shallow open water (National Wetlands Working Group, 1988). Details on classifying and evaluating the importance of wetlands in southern Ontario are available (Ontario Ministry Natural Resources 1984).

Bog

This is a peat-covered wetland in which the vegetation shows the effects of a high water table and a general lack of nutrients. The surface waters of bogs are strongly acidic ($\text{pH} < 4.6$) and the upper layers of peat are deficient in nutrients. Bogs are characterized by *Sphagnum* mosses, heath shrubs and in some cases low stunted trees. The mineral content of the water is below $80 \mu\text{S/cm}$ indicative of low calcium and magnesium levels. The mineral values of the peat in the root zone are also low (National Wetlands Working Group, 1988).

Fen

This is a wetland characterized by a high water table, a peaty soil and generally mineral rich waters. Water movement is usually very slow and originates from mineral rich areas with alkaline properties and high levels of calcium and magnesium. The vegetation in fens is a reflection of water chemistry, giving rise to graminoid fens, shrub fens and treed fens (National Wetlands Working Group, 1988).

Swamp

This is a wetland where standing or gently moving waters occur, either seasonally or for long periods of time such that the subsurface is waterlogged. The water table may drop seasonally below the root zone allowing the surface layers to become aerated. Swamp waters are approximately neutral to slightly acid and have moderate mineral loadings. The vegetation is usually woody with deciduous or coniferous trees or shrub thickets. The soils in swamps may be peaty or mineral and the overall nutrient status is high with good vegetation growth (National Wetlands Working Group, 1988).

Marsh

This is a wetland which is periodically inundated and is characterized by moving waters high in nutrients. Marshes occur on wet mineral soils, although a peat layer may be present. Water is approximately neutral with high oxygen concentrations. Surface waters may fluctuate daily as in coastal marshes, or for longer periods as on the Great Lakes, and they may dry up occasionally. The vegetation is characterized by floating aquatics and emergents including reeds, sedges or rushes. The vegetation shows distinct zonation due to the frequency of drawdowns and the depth profile of the area (National Wetlands Working Group, 1988).

Shallow Open Water

Areas of shallow open water may be subject to distinct changes in water level but are sufficiently shallow to be characterized by floating aquatics. They are usually less than two metres deep in midsummer and are roughly neutral in pH. They usually occur adjacent to marshes or lakes (National Wetlands Working Group, 1988).

The area of natural wetlands in southern Ontario has decreased substantially with the development of agriculture in the province and approximately 70% have been drained or lost in one way or another to agriculture or development (Curtis 1989); in southwestern Ontario this value is between 90 and 100% (Snell 1987).

It is helpful to consider wetlands in a watershed as being distributed along a continuum. Wetlands in upland areas are generally associated with small streams. As water passes into higher order streams (rivers) the proportion of water that passes through wetland decreases (Figure 2.1). Lower down in a watershed, most of the water contacts wetlands during periods of flooding. Therefore, the most effective place to have wetlands which affect water quality is in the upland catchment areas or at the end of tributaries (Whigham et al. 1988). These are also the areas most likely to be filled in or drained in urban developments because they present fewer engineering difficulties. It may be that wetlands constructed in high order streams nearer the mouth of a river should be treed swamps while wetlands constructed near catchment areas could be bogs or marshes.

2.2 Function and Values of Wetlands

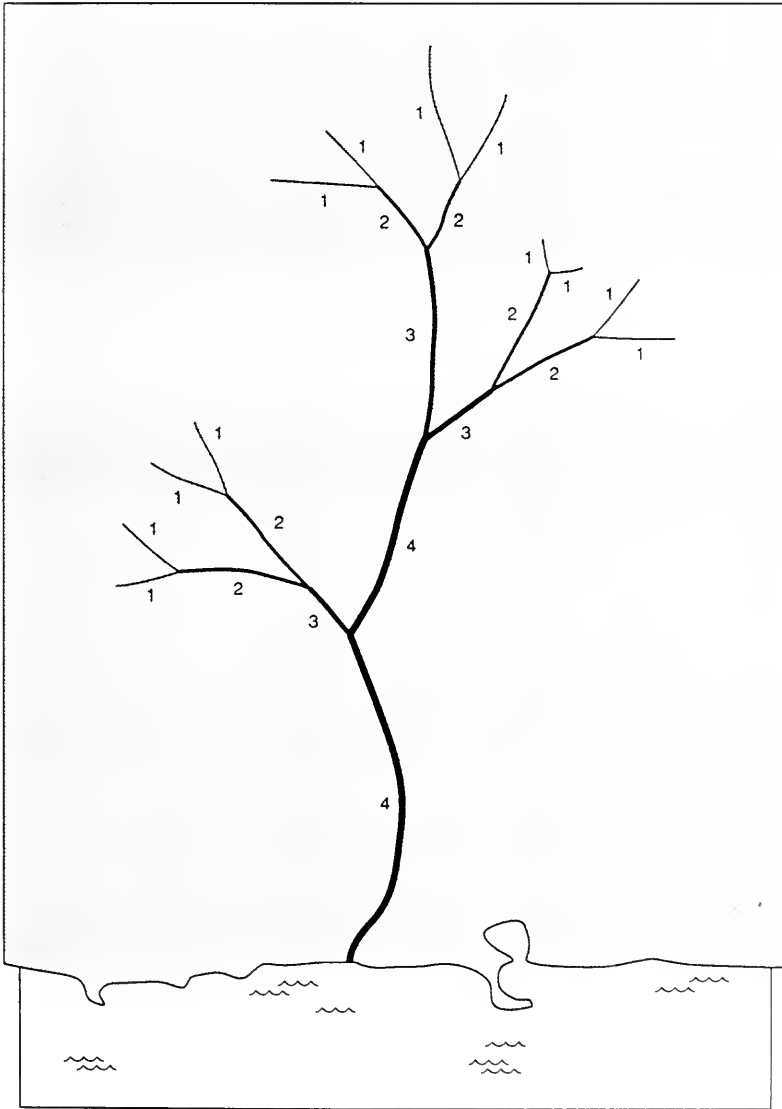
Wetlands perform many functions and some of these we may value more highly than others (Bond et al. 1988, Bradley and Cook 1951, Demgen 1979, Parsons and Aufmuth 1990, Stewart 1990). We can estimate the economic value of some of these functions while others are more difficult. Although we have difficulty putting a dollar value on some of them, we should not understate their value either economically or ecologically.

The following are major functions and values of wetlands.

Biophysical oriented functions and values

- 1) flood storage
- 2) flood conveyance
- 3) water supply as a source of ground and surface water
- 4) water quality improvement
- 5) barriers to waves and coastal erosion
- 6) sediment control
- 7) nutrient recycling

Figure 2.1 Dendrogram: tree layout of watershed systems. Adapted from stream ordering systems of Horton and Strahler (Fairbridge 1968). Numbers represent four orders of stream.



Biological and anthropogenic functions and values

- 8) habitat for rare and endangered species
- 9) habitat for waterfowl and other wildlife life cycles
- 10) fish and shellfish spawning and nursery areas
- 11) recreation sites for fishing, hunting, and observing wildlife
- 12) food production
- 13) timber production
- 14) historic, archaeological values
- 15) education and research
- 16) open space and aesthetic values

Not all the functions and values listed are of interest in this present study, and some may overlap one another. To deal comprehensively with all aspects is not within the scope of this review.

Climate

Climate affects the formation and/or maintenance of a wetland type and the following factors have a significant impact:

- 1) mean annual rainfall
- 2) distribution pattern of rainfall
- 3) mean annual temperature
- 4) length of growing season
- 5) length of frozen period
- 6) amount of snow cover

Much of the literature on wetlands and water management deals with their function in climates different from that of southern Ontario. However, there is some good data about wetlands and water quality in Ontario as well as adjacent States of New York, Wisconsin and Michigan where the climate is similar.

The climate in southern Ontario is characterized by moderate winters (mean daily January temperature -6°C), ameliorated by the Great Lakes, and hot summers (mean daily July temperature 20.3°C). Mean annual precipitation is around 900 mm and mean annual snowfall about 200 cm.

3. Hydrology of Wetlands

The hydrology of an area is a function of many parameters which include annual rainfall, annual evaporation, topography, soil type and parent rock material (Brodie 1989, Brown 1988, Colenbrander 1978, Livingston 1989, Sather and Smith 1984). Information on the following are required prior to constructing a wetland.

- 1) soil and subsoil material, soil permeability
- 2) superficial topography, velocity and flow rate
- 3) size of wetland
- 4) ground water conditions, recharge or discharge area
- 5) seasonal distribution of rainfall/snowfall, intensity and periodicity
- 6) water depth and fluctuation
- 7) detention time

3.1 Soil and Subsoil Material, Soil Permeability

The soil and subsoil influence the extent to which water moves both horizontally and vertically within the soil profile. The larger the particle size, the less resistance and more rapid the water movement. If permeable soils are underlain by impermeable clays or rock, water is forced to move laterally. The rate of movement is a function of slope of the water table and particle size through which the water is moving.

3.2 Superficial Topography, Velocity and Flow Rate

Superficial topography determines whether there is surface runoff or whether water tends to stand and enter the soil. Because the topography of southern Ontario is relatively flat, there is a tendency for water to penetrate the ground. However, on the edges of ravines and river valleys water moves more rapidly over the surface, causing erosion and carrying soil particles into waterways. This was particularly notable during the construction phase of the Don Valley Parkway in the 1960s, when large quantities of silt were carried into the Don River and so to the Keating Channel and Toronto Inner Harbour. Where the subsoil is permeable, as on the Oak Ridges moraine, water penetration is rapid even though the topography is rolling.

Flow rate depends upon the square of the depth and on the gradient, and in a natural marsh the majority of water flow is superficial and its rate is affected by the presence of emergent vegetation. Water flow may be sheet flow or in channels within a wetland. Channels may be formed by animal trails through a wetland (Kadlec 1987).

3.3 Size of Wetland

The size of a wetland is critical to its function. Because many of the functions occur around the edge, and the amount of edge is proportional to the area of the wetland, so the relative functioning of a wetland is proportional to its size (Millar 1971). Phreatic species are responsible for large amounts of evapotranspiration and because small wetlands have relatively more edge than large wetlands they are more effective at transferring water to the atmosphere than large wetlands. Small wetlands also slow surface water flow more than larger wetlands because their edges serve to slow water flow because of drag.

Marble and Gross (1984) found that of 385 wetlands studied in New Canaan, Connecticut, the majority (72%) were less than 1 ha and those that occurred in valley flat lands were more effective in flood control than those on slopes. From this one can deduce that a series of small wetland areas will have a greater effect on water flow and evapotranspiration than a single larger one.

3.4 Ground Water Conditions, Recharge or Discharge Area

If an area is a recharge area, then water in a wetland contributes to the recharge and polluted or nutrient rich waters may disappear into the ground water. If an area is a discharge area then polluted waters in a wetland may be diluted with ground water coming to the surface. In either case the measured efficiency of a wetland in improving water quality is distorted by such water flow (Gehrels and Mulamottil 1990, Gosselink and Turner 1978).

3.5 Seasonal Distribution of Precipitation, Intensity and Periodicity

In southern Ontario rainfall is fairly uniformly distributed through the summer months. During the winter, most precipitation falls as snow. Additional snow may accumulate on wetlands because the emergent vegetation acts as a trap for drifting snow. Deep snow in wetlands insulates the surface and allows water to move below the snow surface, permitting wetland functions to continue (Geis 1979).

Generally, major water flows are associated with spring runoff and summer storms. An average year in southern Ontario might include 40 storms (Gehrels and Mulamottil 1990).

Areas closer to the Great Lakes receive more precipitation than do areas inland, but large urban areas such as Toronto cause heat islands with distinctive temperature profiles. These result in modified climatic conditions such that the amount of rainfall in a city may be greater than in the surrounding rural/agricultural areas. Likewise, because of the higher average temperatures, the rainfall season in a city lasts longer than in the surrounding areas which receive more snowfall.

3.6 Water Depth and Fluctuation

The water depth of a wetland affects the type of vegetation which grows there and is the single most important variable in defining the extent, species composition and stability of wetlands along Lake Ontario (Geis 1979, Gosselink and Turner 1978, Weller 1978). Water depth is responsible for the zonation of plant species, since some plants are better adapted to deeper water than others (Figure 7.2, Table 7.1).

The frequency of change of water levels also has an effect on the functioning of a wetland. If an area is inundated continuously to a depth of approximately 50 cm, emergent vegetation will be replaced by floating aquatics. Likewise, if a woodland swamp has no periods when the water level drops below the soil surface, it is unlikely to remain a swamp and will become a pond. This is illustrated when beavers dam up wet areas along rivers resulting in the death of bottom land trees unless the dam is removed.

3.7 Detention Time

The length of time that water is detained in a pond affects water quality. Even relatively short periods of two or three days will improve water quality significantly and for longer periods this improvement is even more pronounced. If water is detained in a marsh, numerous physical, chemical and biological activities occur which modify the water chemistry (Table 4.1). Livingston (1987b) suggests that constructed wetlands be designed so that they can hold the one-year storm for 24 hours.

Glooschenko et al. (1987) showed that wetlands detain floodwaters by absorbing water during high flow periods and then gradually releasing it. Studies carried out on swamps in southern Ontario indicate that their ability to provide storage and gradual release of floodwaters is spatially and temporally variable. One swamp was found to have little effect on stream flow rates (Prasad 1961, Rai 1962) while two others were effective when the water table was low (Woo and Valverde 1981, Taylor 1981). In the Beverly Swamp, Ontario, regulation of stream flow merges with ground water storage (Woo and Valverde 1981).

Detention time also has an effect on the productivity of a wetland. As the water flow rate increases, so productivity may increase due to the constant supply of nutrients (Gosselink and Turner 1978). The time that water is held in a wetland has a significant impact on the flow rates of downstream portions of a watershed. Flow peaks are reduced with the greatest effects being observed closest to the wetland.

3.8 Urban Hydrology

Cities affect the local hydrology in three major ways. The permeability of the land surface is altered radically such that more water is diverted to water courses than in non-urban areas, and thus the streams and rivers are affected. Secondly, the actual weather is changed in cities. The effect of large expanses of asphalt, concrete and brick changes the heat retaining ability resulting in different air movements with increased rainfall. Lastly, the urban fabric and human activities result in a contamination of water falling as rain. When water passes over urban surfaces it picks up a wide variety of contaminants (Marsalek 1977, Marsalek and Greck 1984, Marsalek and Schroeter 1984). It has been suggested that urban runoff is as contaminated as municipal sewage water after primary treatment for many pollutants (Livingston 1989b, Theil pers. comm.).

Surface Permeability in Cities

The flow of water in an urban environment is modified by the degree or extent of impermeable surfaces in the city (Brown 1988, Scheuler 1987). In densely built downtown areas, shopping centres and heavy commercial areas, 100% of the surface is impermeable and rain water cannot penetrate the soil. Any water in the soil of such areas comes via aquifers or old stream courses, or from leaking water or sewage pipes. Rainfall or snowmelt water in such areas is either carried off in storm drains or it evaporates.

In low density housing areas there may be only 5-10% impermeable surfaces and with roadside swales and minimal storm drains most rain penetrates the ground or evaporates.

Most cities have a mix of residential, industrial and commercial with varying degrees of permeability of the surface. The level of contamination of runoff water is affected by landuse and some data for Washington are provided in Table 3.1 (Scheuler 1987). Values for other major centres in the United States are provided in the National Urban Runoff Program (EPA NURP, 1983).

The effect of urbanization on a watershed is to change the discharge profile of water, such that it peaks sooner and at a higher intensity than in a rural area (Brown 1988, Colenbrander 1978). Therefore, the effects of a comparable storm in an urban area will be more severe than in a rural area. This explains some of the differences between the effects of Hurricane Hazel and the Harrow storm. The latter storm was more intense but because it occurred in a largely rural area and the soil was dry before the event, its flooding effect was less severe than if the rain had fallen in an urban area (Dillon 1990). Watersheds which contain large areas of impervious land and small areas of wetland have higher runoff amounts than watersheds with small areas of impervious land and large wetland areas (Brown 1988).

Table 3.1 Annual storm pollutant export for selected values of impervious cover (modified from Scheuler 1987).

LAND USE	SITE IMPERV	TOTAL P	TOTAL N	BOD-5	EXTRACT ZINC	EXTRACT LEAD
RURAL	0	0.11	0.8	2.1	0.02	0.01
RESIDENTIAL	10	0.3	2.3	5.8	0.04	0.02
LARGE LOT, SINGLE FAMILY	10	0.3	2.3	5.8	0.04	0.02
MEDIUM DENSITY SINGLE FAMILY	20	0.49	3.8	9.6	0.07	0.04
TOWNHOUSE	20	0.49	3.8	9.6	0.07	0.04
GARDEN	35	0.07	6.0	15.2	0.11	0.06
APARTMENT	35	0.77	6.0	15.3	0.11	0.06
HIGH RISE	50	1.06	8.2	20.8	0.15	0.08
LIGHT COMMERCIAL	50	1.06	8.2	20.8	0.15	0.08
HEAVY COMMERCIAL	60	1.25	9.6	24.6	0.18	0.09
SHOPPING CENTRE	60	1.25	9.6	24.6	0.18	0.09
	80	1.63	12.6	32.0	0.23	0.11
	100	2.0	15.4	39.2	0.28	0.14

Storm Events, Urban Weather

The flow of water in cities is heavily modified by man's built environment. The importance of this is that in designing wetlands to treat stormwaters, one must recognize that occasionally storms will be intense, with potentially very high runoffs (450 mm in 30 hours for the Harrow Storm; 285 mm in 48 hours for Hurricane Hazel)(Dillon 1990). Constructed wetlands should be designed to moderate water quality and quantity of smaller storms but be designed to allow for water in high level storms to bypass them.

Water Quality in an Urban Environment

The water quality of storm runoffs has been well documented and the type and amount of pollutants is closely related to land use and rainfall characteristics (Table 3.1)(Johnson 1986, Scheuler 1987). Generally the "first flush" of storm water carries the highest pollution loadings. Studies have shown that the first inch of rainfall carries 90% of the pollution load. This shock loading of the water can have severe effects on aquatic organisms and is comparable to the intermittent discharges of polluted water from chemical plants (Dickman 1987).

In the Great Lakes Basin the annual loadings of 51 persistent toxic substances has been estimated. About 70,000 tons of solids are discharged annually in the Lake Ontario sub-basin alone (Marsalek 1977, Marsalek and Greck 1984). In stormwater samples, the highest frequencies of occurrence were found for some trace metals (Hg - 100%, Zn - 40%), two pesticides (a -BHC - 98%, lindane 87%) and 1,2 dichlorobenzene (68%). However, the amount of persistent toxic substances found in sediments were much greater, at least by several orders of magnitude, and the most widespread substances were trace elements (100% frequencies observed for As, Cu, Pb, Se, and Zn), PCB's, some organochlorine pesticides (p,p' -DDE -59%, a-BHC - 53 %, a-chlordane - 50% - 50% y - chlordane - 40% and p,p' DDT - 35%), and several chlorinated benzenes (Marsalek and Greck 1984).

4. Contaminant Loadings in Wetlands, Vegetation and Wildlife

There are different kinds of contaminants which may enter wetlands and their relative importance is attributable as to whether they break down or not and whether they are broken down by biological, chemical or physical processes (Table 4.1). Commonly recognized contaminants include excessive nutrient loadings, particularly phosphorus and nitrogen, many organic compounds such as phenols, oils and greases and some pesticides, bacteria and viruses, heavy metals including Cd, Pb, Hg, Cu, and Zn, strong acids or bases and persistent toxic substances such as PAHs and PCBs.

The effects of contaminants may vary depending on whether they are produced as single isolated spills, short bursts of contaminants from chemical factory outputs or chronic long term, low level releases.

Contaminants which are short lived may have severe immediate impacts if they enter a wetland but their effects diminish as their concentrations decrease with time. Other contaminants such as pathogenic bacteria and viruses can have severe effects on human water users, but bacteria are readily broken down in wetlands and in a few days rendered harmless (Gersberg et al. 1987, Palmateer et al. 1985). Some aquatic plants including *Scirpus lacustris* and *Phragmites communis* produce root excretions which can kill bacteria such as *E. coli* and *Salmonella* (Gersberg et al. 1987). There is no long term problem of bioaccumulation with microbial contamination.

Some contaminants may be toxic to the wetland organisms, whether they be plants or animals, resulting in change in the wetland structure (Burk 1977). Other contaminants may not be obviously toxic to the wetland community but may be hazardous chemicals which enter food webs and have effects elsewhere, such as the effect that DDT had on many bird species (Carson 1962).

There are few well documented cases of the effects of contaminants on wetlands and their transfers to other ecosystems and this is an area where a significant research effort is required (Odum 1987).

4.1 Bioaccumulation of Contaminants

There is particular concern that contaminants which are released to the environment can accumulate in organisms and either harm the organisms directly or harm other organisms higher in the food chains. Man consumes fish, fowl and other organisms which may spend a part of their time in contaminated environments. Therefore it is necessary that we are well informed as to the pathways and fate of contaminants which are taken up by other organisms.

Nutrients

An increase in phosphorus and nitrogen can have a significant impact on the structure and functioning of aquatic ecosystems. Experiments have shown the effects of fertilizers on aquatic plant communities and that phosphorus is the limiting nutrient in freshwater ecosystems (Schindler 1974). Increases in phosphorus generally cause excessive plant growth, often of blue green algae, and eutrophication of the waters. Phosphorus is taken up by plants for use and a small amount may be stored. Once their needs are met, phosphorus is either bound to organic materials or sediments or passes through the wetland. It has been found that with high phosphorus loadings, wetlands may become saturated with the nutrient in a few years, and if it is not bound to sediments, it passes through. Glooschenko et al.

(1987) cite a study of one freshwater wetland near Dundas, Ontario that has been receiving treated wastewater for over 60 years and reduces the BOD by 80%, removes 83% of the nitrate, 88% of the total nitrogen and 87% of the total phosphorus. However, caution must be used in interpreting data because of inadequate hydrologic information which may significantly affect the calculation of such removal rates (Gehrels and Mulamootil 1990).

Nitrates, nitrites and ammonia may also be superabundant in inflowing waters, but they do not accumulate. In a normal functioning wetland, denitrification of these nutrients by denitrifying bacteria occurs and free nitrogen is released to the air (Howard-Williams 1985). It does not, therefore, present the same problem as phosphorus.

Organic Compounds

Oils and greases from roads, parking lots, service stations and refineries are perceived to be a serious contaminant of wetlands. Oils are mixtures of hydrocarbons, either straight chains from C₁₁ to C₂₆ or aromatic hydrocarbons such as naphthalene. These constituent molecules vary in molecular weight, reactivity and toxicity. In an analysis of the effects of Prudhoe Bay crude oil on marine benthic organisms, it was found that numerous physical factors affected the toxicity and biological effects of this oil. The extent that the oil is mixed with the sediment, the temperature and the oxygen tensions all affect the long term toxic effects. The oils become depurated with time and this appears to depend upon oil degrading microorganisms. Oils also affect the vegetation of wetlands and some species are sensitive to oils (Table 4.2). However, the majority of the sensitive species are annuals and their percentage cover is low (Burk 1977). Seven years after the oil spill in Nova Scotia in which the Arrow lost *Bunker 2* oil, components of the oil were still present in Chedabucto Bay and contaminating molluscs. Krebs and Burns (1977) described the effect of an oil spill on fiddler crabs (*Uca pugnax*). The crab populations had not totally recovered after seven years, and it was found that concentrations of >1000 ppm were toxic to adults and 100-200 ppm were toxic to juveniles. After a spill of 3,800 litres of oil in the Arcadia Wildlife Sanctuary in Massachusetts, species diversity decreased particularly in the low marsh zone and the effect of the oil spill persisted for at least four years (Table 4.3)(Burk 1977).

Pesticides, herbicides and fungicides are known to have marked impacts on aquatic organisms. Of six pesticides tested, atrazine, fonofos and triallate had significant impacts on invertebrates and plants, concentrations of less than 10 µg/L affecting both producers and consumers (Johnson 1986). In Ontario the use of atrazine was by far the highest of these pesticides and in 1988 1,045,110 kg was used on field crops, fruits and vegetables while 710 kg of triallate and 18,370 kg of fonofos were used (Moxley 1989).

Table 4.1 Contaminant removal mechanisms in aquatic systems employing plants and animals (P = Primary Effect; S = Secondary Effect; I = Incidental Effect; SS settleable solids, CS colloidal solids, BOD biological oxygen demand, N nitrogen, P phosphorus, HM heavy metals, RO refractory organics, B&V bacteria and viruses)(From Tchobangolous et al. 1979).

Mechanism	Contaminant Affected										Description	
	SS	CS	BOD	N	P	HM	RO	B&V				
Physical												
Sedimentation	P	S	I	I	I	I	I	I	I			Gravitational settling of solids (and constituent contaminants) in pond/marsh settings.
Filtration	S	S										Particulates filtered mechanically as water passes through substrate, root masses, or fish.
Adsorption		S										Interparticle attractive force (van der Waals force).
Chemical												
Precipitation									P	P		Formation of or co-precipitation with insoluble compounds.
Adsorption					P	P			P	S		Adsorption on substrate and plant surfaces.
Decomposition									P	P	P	Decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation, and reduction.
Biological												
Bacterial metabolism		P	P	P							P	Removal of colloidal solids and soluble organics by suspended, benthic, and plant-supported bacteria. Bacterial nitrification/denitrification.
Plant metabolism											S	Uptake and metabolism of organics by plants. Root excretions may be toxic to organisms of enteric origin.
Plant absorption				S	S	S	S					Under proper conditions significant quantities of these contaminants will be taken up by plants.
Natural die-off											P	Natural decay of organisms in an unfavorable environment.

Other organic compounds such as PCBs have entered food chains in aquatic systems and the levels of some of them have been monitored by the Ministry of Natural Resources. With the reduction of the release in PCBs to the environment there has been a steady reduction in their accumulation in fish tissue (Figure 4.1) and in mammal tissue in the beluga whales of the St. Lawrence. Likewise, reducing the discharge of hexachlorobenzene to the environment has resulted in a reduction of its presence in food chains. Figure 4.2 shows the decline in levels over 11 years in herring gulls on Lake Ontario (Clark et al. 1988).

Heavy Metals

Heavy metals are present in stormwater outfalls and much of it is either bound to organic and inorganic sediments or taken up in plants (Allan 1986, Marsalek and Greck 1984, Schueler 1987, Stinson and Eaton 1983, Wieder et al. 1990). The majority of heavy metals are adsorbed on to sediments and may become buried with time, the sediments acting as a sink for these contaminants. Particle size of sediments is an important factor in heavy metal deposition, with fine particles such as clays and silts and organic matter adsorbing heavy metals to their surfaces to a much greater extent than sands (Little et al. 1987). On the other hand, the contaminated sediments may provide a source of heavy metals to benthic organisms which consume and bioturbate the sediments, adsorbing metals or bringing contaminated sediments to the surface. Aquatic invertebrates are eaten by a variety of organisms including crayfish, fish, amphibians, mammals and birds resulting in uptake of heavy metals. Changes in industrial practices have led to the decrease in some of these metals in the past 20 years (Figure 4.3, 4.4).

The literature on heavy metal movements in the environment is extensive and there are over 50,000 publications on mercury alone as an environmental pollutant (Hakanson 1990). The heavy metals commonly encountered in aquatic ecosystems include mercury, cadmium, chromium, lead, copper and zinc (Hynes 1960). The sources of these metals may be storm runoff from contaminated surfaces, old pipes and solder, industrial plants and aerial deposition (Marsalek and Greck 1984, Stinson and Eaton 1983). In urban environments where hunting is not a major source of lead contamination, levels have generally decreased with the removal of lead additives from petroleum.

Crayfish (*Pacifastacus leniusculus*) exposed to stormwater runoff accumulated mercury for whole body concentrations of 0.22 to 0.28 $\mu\text{g/g}$. Lead concentrations were highest in the exoskeleton (17.49 $\mu\text{g/g}$) while copper levels were highest in the viscera (245 $\mu\text{g/g}$, dry weight). The levels of accumulation in crayfish from "contaminated" locations were not much higher than those from uncontaminated locations or from laboratory controls (Stinson and Eaton 1983).

Table 4.2 Changes in the abundance of plant species within the Arcadia Wildlife Sanctuary marsh complex between summer 1971, before an accidental oil spill, and summer 1972 following the spill (from Burk 1977). (* = annual species; † = increasing).

Species not recorded after oil spill	Species reduced after oil spill	Species apparently unaffected or increasing after oil spill
<i>Acer rubrum</i>	<i>Cephalanthus occidentalis</i>	<i>Acer saccharinum</i>
<i>Bidens cernua</i> *	<i>Eleocharis acicularis</i>	<i>Alisma subcordatum</i>
<i>B. connata</i> *	<i>Galium trifidum</i>	<i>Carex lurida</i>
<i>B. frondosa</i> *	<i>Leerzia oryzoides</i>	<i>Ceratophyllum demersum</i> †
<i>Echinochloa walteri</i> *	<i>Lindernia dubia</i> *	<i>Dulichium arundinaceum</i> †
<i>Eleocharis obtusa</i>	<i>Luswigia palustris</i>	<i>Eleocharis palustris</i>
<i>Galium tinctorium</i> *	<i>Marsilea quadrifolia</i> †	<i>Elodea uttallii</i>
<i>Hypericum mutilum</i>	<i>Najas flexilis</i> *	<i>Equisetum fluviatile</i>
<i>H. virginicum</i>	<i>Onoclea sensibilis</i>	<i>Lemna minor</i>
<i>Iris versicolor</i>	<i>Pilea fontana</i> *	<i>Lysimachia terrestris</i>
<i>Lycopus uniflorus</i>	<i>Pontederia cordata</i>	<i>Nuphar variegatum</i>
<i>Mimulus ringens</i>	<i>Scirpus pedicellatus</i>	<i>Polygonum coccineum</i>
<i>Polygonum punctatum</i> *	<i>Sparganium androcladum</i>	<i>Potamogeton crispus</i>
<i>P. sagittatum</i> *	<i>Zizania aquatica</i>	<i>P. epiphydrus</i>
<i>Sparganium americanum</i>		<i>Sagittaria graminea</i>
<i>Spirodela polyrhiza</i>		<i>S. latifolia</i>
<i>Vallisneria americana</i>		<i>Salix nigra</i>
<i>Verbena hastata</i>		<i>Scirpus cyperinus</i>
		<i>S. validus</i>
		<i>Scutellaria lateriflora</i>
		<i>Sium suave</i>
		<i>Veronica scutellata</i>
		<i>Vitis vabrusca</i>

Table 4.3 Comparison of vegetation in three zones before and after the spillage of fuel oil January 10, 1972 (after Burk 1977).

	1971	1972	1973	1974	1975
High marsh					
Species richness	34	25	18	27	27
Mean species/quadrat (\pm S.E.)	8.3 (\pm 0.31)	5.6 (\pm 0.21)	5.3 (\pm 0.23)	6.6 (\pm 0.32)	7.9 (\pm 0.42)
Shannon-Wiener function	3.714	3.257	3.186	2.914	3.117
Total cover (\pm S.E.)	144 (\pm 3.83)	95 (\pm 3.16)	93 (\pm 5.66)	124 (\pm 6.20)	126 (\pm 9.65)
Mid marsh					
Species richness	24	17	12	22	17
Mean species/quadrat (\pm S.E.)	5.9 (\pm 0.41)	4.8 (\pm 0.32)	3.2 (\pm 0.25)	4.5 (\pm 0.25)	3.9 (\pm 0.22)
Shannon-Wiener function	3.053	2.380	2.074	2.185	2.522
Total cover (\pm S.E.)	97 (\pm 4.22)	70 (\pm 4.32)	57.8 (\pm 5.44)	87 (\pm 4.81)	86 (\pm 5.09)
Low marsh					
Species richness	12	15	12	6	5
Mean species/quadrat (\pm S.E.)	2.5 (\pm 0.21)	3.4 (\pm 0.22)	2.5 (\pm 0.21)	1.5 (\pm 0.11)	1.2 (\pm 0.12)
Shannon-Wiener function	2.677	2.126	1.804	1.255	0.573
Total cover (\pm S.E.)	43 (\pm 4.04)	40 (\pm 4.29)	41 (\pm 5.73)	51 (\pm 5.77)	43 (\pm 6.09)

Figure 4.1 Decrease in PCBs in rainbow trout over thirteen year period (from Ministry of the Environment and Ministry of Natural Resources 1990).

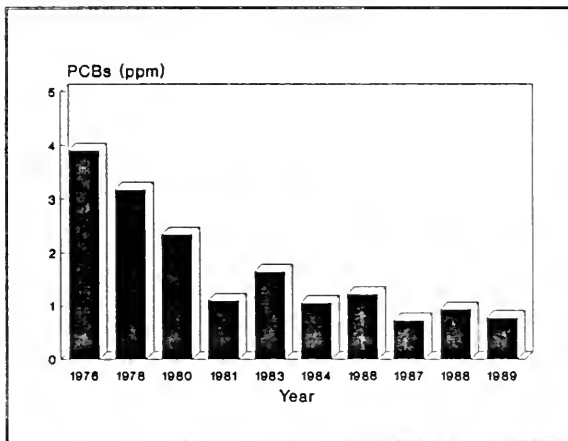


Figure 4.2 Hexachlorobenzene residues in herring gull eggs (from Clark et al. 1988).

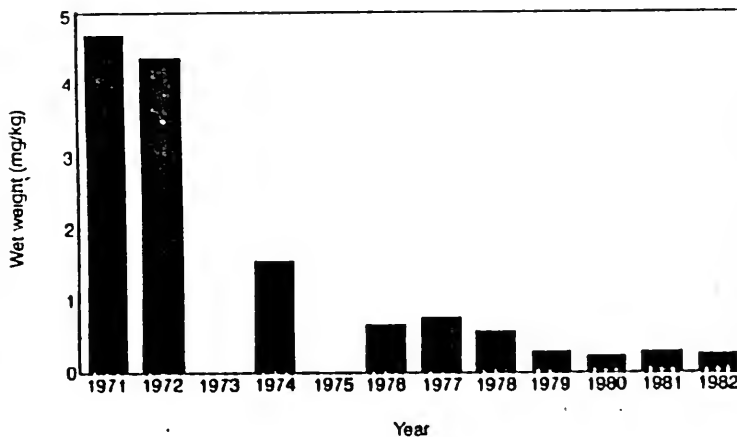


Figure 4.3 Decline in mercury in walleye in Lake St. Clair over 18 years (modified from Cox and Ralston 1990).

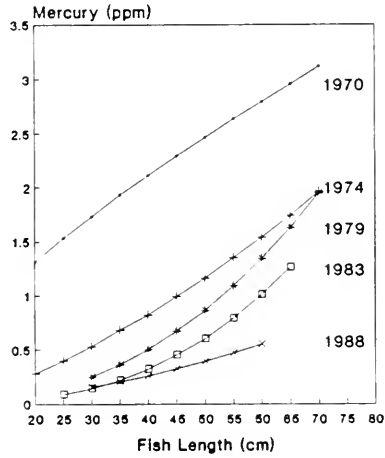
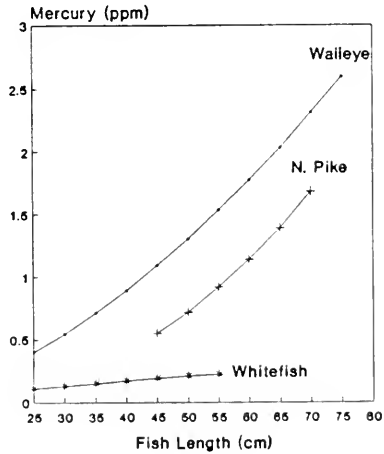


Figure 4.4 Differences in mercury concentration in relation to length of three species of fish (from Cox and Ralston 1990).



4.2 Transfer of Contaminants to Other Ecosystems

The transfer of contaminants from wetlands to other ecosystems is not well documented, though the principles are reasonably well understood. Contaminants may be transferred from a wetland via the water supply or outflow, and this may be into a stream or river flowing from the wetland or into groundwater. Alternatively, contaminants may be taken up by organisms living in the wetland and transferred in food chains. Aquatic invertebrates provide food for a variety of fish, amphibians, reptiles, birds and mammals and while some of these animals may be residents, others spend only short periods of time in the wetland breeding or feeding. Many visitors may be present for only a few days, such as waders on migration which utilize sewage lagoons (Goodwin 1982), while others such as muskrat or mink may only use a wetland as part of their home range. Some contaminants may be excreted by the visiting or resident animal while others may be transformed into more toxic forms such as the methylation of mercury by fish.

Transfer of Organic Compounds

The majority of organic contaminants are probably retained by wetlands and buried in sediments and slowly degraded. Some long lived pesticides such as DDT, DDE, BHC and chlordane present in urban stormwater may be assimilated by organisms. The importance of bioaccumulation and transfer were brought to the world's attention by Carson (1966) and involved DDT and the effect it had on top predators. Because of the ban on the use of long lived pesticides and the curtailment of the use of many other organic contaminants such as PCBs, their presence in aquatic ecosystems is declining. Nevertheless, many of them bioaccumulate in fatty tissue and their concentration fluctuates through the year with changes in total body fat (Clark et al. 1988) and restrictions on the consumption of larger and older carnivorous fish are recommended (Figure 4.4)(Ministry of the Environment and Ministry of Natural Resources 1990). Other organic contaminants such as furans and dioxins are released to the atmosphere in incinerators and other industrial plants and present an ongoing problem.

Transfer of Heavy Metals

Shorebirds consume large proportions of the annual production of benthic intertidal invertebrates in temperate estuaries which are exposed to heavy metal loadings from industries, agriculture and urban storm runoff. These metals may accumulate in waders or be lost to the environment through excretion or feather moult. A curlew (*Numenius arquata*) requires about 1200 polychaete worms (*Nereis diversicolor*) of 50 mg average dry mass to satisfy its daily energy needs. From analysis of heavy metal concentrations in these worms, Evans and Moon (1981) calculated that such a bird ingests about 12 mg of zinc and 0.5 mg of lead each day. During the eight months they would spend feeding on contaminated marshes they would ingest about 3 g of zinc and 0.12 g of lead. If the lead and zinc were

not excreted and were evenly distributed in the 850 g body this would yield concentrations of 3.5 g kg⁻¹ of zinc and 140 mg kg⁻¹ of lead. If we assume that only 10% of the ingested metals were absorbed through the gut wall, concentrations of 350 mg kg⁻¹ of zinc and 14 mg kg⁻¹ of lead should have been present by the end of the winter. Actual levels obtained from two curlews in March yielded levels of 18 mg kg⁻¹ of zinc and 1.2 mg kg⁻¹ of lead. The birds that were analyzed had spent more than a single winter on the estuary and could be expected to have higher levels than they did, thus it appears that curlews retain much less than 1% of the heavy metals they ingest (Evans et al. 1987).

Heavy metals are concentrated more in certain parts of the body (Table 4.4) and the skeleton or exoskeleton show higher levels than other tissues. When birds moult they may lose much of their body burden of heavy metals (Stickel et al. 1977). Shorebirds may transfer heavy metals obtained from one estuary to another when they moult (Evans et al. 1987). Metals which are concentrated in the exoskeleton of crayfish are lost when the animal moults (Stinson and Eaton 1983). When crayfish are consumed by either man or other predators such as otters or mink, it is likely that little of the heavy metals in the exoskeleton are passed on to the consumer, as the exoskeleton is not digested.

Table 4.4 Affinities of four heavy metals for different tissues in dunlin (*Calidris alpina*) from the River Mersey (from Evans et al. 1987)

Decreasing concentration ----->						
Cadmium	Bone	Bill	Kidney	Feet	Liver	Pectoral muscle
Copper	Bone	Pectoral muscle	Liver	Kidney	Bill	Feet
Lead	Bill	Bone	Kidney	Liver	Feet	Pectoral muscle
Zinc	Bill	Bone	Feet	Liver	Kidney	Pectoral muscle

5. Public Perceptions of Wetlands

The public perception of wetlands has shifted radically in the last twenty to thirty years such that their function in maintaining water quality and their recreational values are better known. This changed perception does not include everyone by any means and there are still powerful pressures to drain land and use it for one purpose or another. To obtain an indication of this pressure one need only examine the large number of environmental assessments which are carried out on wetlands to determine their significance. However many people are now more aware of the value of wetlands, and the role they play in maintaining ecosystem functions than in previous decades.

All levels of government and many non-government organizations can take credit for these changed perceptions. The value of wetlands has already been outlined in previous sections, but the perception of this value is another matter. It is most important when contemplating the construction of wetlands that this information about the value and function of a wetland is provided to the public (Grisham 1988, Stewart 1990).

The traditional use of many wetlands has been for duck hunting (Glooschenko et al. 1987), but this is an incompatible activity in an urban context so it is necessary to emphasize the other uses and values of a wetland. The use of wetlands for passive recreation such as bird watching (Goodwin 1982), nature walks, photography, as well as the value they have for improving water quality should be emphasized. Also, the relationship between a wetland and down river water quality is not immediately obvious to many people. If, for instance, all the water outflows in the Toronto area had previously passed through wetlands, it is not necessarily apparent to many people that this would alleviate water contamination and beach closure for swimming. To convince people that wetlands have an effect on water quality one has to explain and provide details of how this works. One cannot assume the public will accept such concepts without supporting information (Weller 1978). It is therefore essential to incorporate a strong research component into any pilot constructed wetland project so that fears and concerns about heavy metal accumulation, or safety, or mosquitoes can be addressed.

5.1 Wetlands in Residential Areas

Wetlands are often perceived to be a breeding place for mosquitoes and midges, and as these are considered a nuisance or worse by most people there is a certain antipathy towards creating wetlands in residential areas. However, by introducing mosquitofish (*Gambusia*) (Demgen 1979) or by providing nesting boxes for swallows (Brodie 1990) the numbers of insects may be significantly reduced. It would be inappropriate to introduce non-native species of fish such as *Gambusia* to constructed wetlands. Use of small native fish such as minnows should be effective at controlling mosquitoes providing suitable habitat is developed and stocking is undertaken. Much of the literature is concerned with wetlands for treating

municipal sewage where the water levels are relatively constant. If a wetland system is designed such that drawdown of water occurs between major rain events, breeding of mosquitoes can be controlled.

5.2 Wetlands in Industrial Commercial Areas

Wetlands created in industrial areas can generally be designed with specific groups of chemicals in mind and therefore be more effective. Many wetlands have been created to treat mine wastes, storm runoff on refinery sites, and for other chemical and manufacturing areas.

Many companies have taken the opportunity to involve the public in these activities and have by their remedial actions both improved water quality and enhanced the local wildlife and in some cases won awards for their innovative and successful attempts (Litchfield and Schatz 1989).

6. History of Constructed Wetlands

Constructed wetlands have existed for thousands of years. They have been an integral part of agriculture, flood control, pisciculture and, more recently, have been used to treat contaminated waters (Seidel 1976). Wetlands have also been constructed extensively for wildlife enhancement projects.

The type of wetland constructed reflects the goal of the builders, and the success of the wetland is generally measured in terms of those goals. However, wetlands may have effects which were not part of the original goals, and the values of a constructed wetland may exceed those of the original goals.

In general, constructed wetlands are built for either quantity control to ameliorate flooding and to regulate downstream flows, or for quality control to reduce biological or chemical substances in water. Water quantity controls include construction of dams, flood gates, drainage ditches, water storage ponds and lakes. Water quality controls involve the use of various chemical or biological additives or processes in an engineered structure such as a sewage treatment plant or the use of natural and constructed lakes, ponds, marshes, bogs and swamps to improve water quality.

6.1 Constructed Wetlands for Municipal Sewage Treatment

Many wetlands have been constructed for the treatment of wastewater or municipal sewage (Conway and Murtha 1989, Demgen 1979, Miller 1989, Herskowitz 1986). A brief overview is provided by Fetter et al. (1977), Neil and Graham (1989) and Wile et al. (1981). Most

such constructed wetlands are marshes, but ponds, meadows or swamps may be built and complete systems may be any combination of these wetland types.

There are two general types of artificial marsh used for treatment of wastewaters.

- 1) Surface flow marshes where the wastewater flow moves over the top of the marsh and pollutants are removed by emergents and aquatic plants and their associated microflora. Sediments are deposited and may contain unwanted contaminants.
- 2) Subsurface flow marshes where wastewater flows below grade through substrates of high hydraulic conductivity. Emergent aquatic species are planted on the surface and their roots serve to transfer oxygen into the anaerobic zone facilitating microbial activity. The roots and associated microbes remove and fixate contaminants in the water column.

In Europe and the U.K. the present emphasis is on the use of reeds (*Phragmites*) for wastewater treatment. The Krefeld or subsurface flow system was developed in Germany to improve the efficiency of nutrient and contaminant removal in constructed wetlands. In the United States, reeds (*Phragmites*), bullrushes (*Scirpus*) and cattails (*Typha*) are used. Usually sewage has preliminary separation of solids in lagoons (primary treatment) before the water is introduced to the wetland. After passing through a wetland the water quality appears to be generally related to the relative loading of the wetland. Many of these systems are fairly new, but those which have operated for many years indicate that although certain functions of the wetland, such as removal of phosphate, diminish with time (Richardson and Davis 1987), other functions such as nitrogen and microbe removal continue to be effective.

Kadlec (1987) describes the cost of modifying existing wetlands in Michigan for wastewater treatment. They found that the cost of construction was \$397,900 for two lagoons, a 12 ha pond and a distribution system to a 700 ha natural peatland. The operation of the wetland portion of the system costs \$12,600 per year. They found that the dechlorination pond was unnecessary, and that the 1978 construction cost could have been about \$206,100. The operating cost in the mid 1980s was \$2,600 per year.

In Ontario experimental wetlands for municipal sewage treatment have been in operation in Listowel (Herskowitz 1986, Wile et al. 1981), in Cochrane (Miller 1989) and more recently in Port Perry. Small wastewater operations have been developed for campgrounds and other locations where there is a seasonal production of sewage and the cost of installing a standard sewage treatment system is high.

6.2 Constructed Wetlands for Treatment of Mine Wastewater

Water from coal preparation plants, ore processing plants, refuse disposal areas and tailings impoundments all produce acid leachates. Bactericides may be used to reduce the activity of

iron oxidizing bacteria resulting in significantly improved water quality (Benedetti et al. 1990).

It was found that wetlands created in western Pennsylvania to treat water from old mine sites resulted in improved water quality as well as furnishing habitat for birds, mammals, reptiles and amphibians (Brenner and Hofius 1990). Five passive wetland sites in the Tennessee Valley resulted in improved water quality which met all water quality guidelines. It was found that such wetlands were suitable for treating weak to moderate acid drainage waters (Brodie 1990). However, it is possible that the positive results of such wetlands are due to other mitigating factors such as dilution with rain water or ground water and laboratory experiments have not confirmed all the positive benefits attributed to wetlands by some authors (Wieder et al. 1990). It may be that the laboratory wetlands do not mimic constructed wetlands in the field settings and that these constructed wetlands are as effective as the various authors claim.

Wetlands created for improving water quality from mine drainage may not have such a diverse invertebrate fauna as natural wetlands in the same area. Lacki et al. (1990) showed that substrates from constructed wetlands contained significantly fewer taxonomic families of benthic invertebrates than natural wetlands, though the diversity in the constructed wetland did increase substantially during the period of study. Longer term studies may show an increase in the faunal diversity with time.

6.3 Constructed Wetlands for Industrial Wastewater

Many industrial plants have discharged their effluents directly into water courses and there is considerable literature available on the effects of such discharges to waterways.

Dickman (1987) describes the effect of industrial chemicals on wetland flora in the Niagara area. He shows that immediately below storm/industrial waste outfalls there is a dead zone with no aquatic plants and there is also an upstream eddy effect. The first major plants to survive near the outfall are large emergents such as *Typha* and *Phragmites*. A second recovery zone is characterized by short Higher Aquatic Plants (HAPs) (*Pontenaria*, *Sagittaria*, *Sparganium*) as well as floating leaved HAPs (*Potamogeton*, *Nuphar*, *Nymphaea*). A tertiary recovery zone was characterized by submersed HAPs (*Elodea*, *Ceratophyllum*, *Myriophyllum*). He shows that occasional bursts or peaks of toxic chemicals are just as deleterious to aquatic plants as continuous pollution. He points out that shock loading is the rule rather than the exception due to the way industrial plants operate.

However, an increasing number of industrial operations are implementing various strategies for waste reduction including using constructed wetlands for wastewater management.

6.4 Constructed Wetlands for Wildlife Enhancement Projects

Numerous constructed wetlands have been created for wildlife in North America (Adams et al. 1982, Bishop et al. 1979, Bond et al. 1988, Bradley and Cook 1951, Emerson 1961, Fredrickson and Taylor 1982, Greer 1979, Korschgen and Green 1989, Meeks 1969, Weller 1975, 1988). Consequently a lot of information is available on seeding and planting wetlands for purposes other than stormwater control (Anderson and Omhart 1985, Korschgen and Green 1989, Kubichek 1940, Weaver 1988).

The flora and fauna of constructed wetlands have been poorly studied and although specific goal oriented wetlands have been examined with respect to their increased use by wildfowl, the large diversity and concentration of invertebrates is not well documented (Kadlec 1987, Sather and Smith 1984). These invertebrates in turn provide food for fish, amphibians, birds and mammals and are an essential part of food chains.

6.5 Constructed Wetlands for Stormwater Management

The requirements for constructed wetlands to handle stormwaters are quite different from those designed to handle municipal, mine or industrial wastewaters. Likewise, the goals of constructing and managing wetlands for wildlife are very different, though a wetland created for one purpose may very well end up being effective for others (Stewart 1990). The flow rate of stormwater cannot be predicted on a daily basis in the same way as the wastewater from municipal treatment plants. Average flow rates can be estimated based on catchment area and expected frequency of rain events and annual rainfall, but the frequency of storm events is unpredictable. A major advantage of creating wetlands for stormwater control is that treatment of water can be very thorough. Because storm events are pulsed, there is opportunity for drawdown of water through the soil and/or subsoil, allowing an aerobic environment to alternate with an anaerobic one. Also, the residence time between storms permits the virtual elimination of all anthropogenic bacteria in a wetland. One important criterion which must be considered is the provision of overflow spillways for major storms such that the wetland is not damaged.

Urban stormwater is characterized as having:-

- 1) high pollutant concentrations because of more intensive development and large areas of imperviousness (Table 3.1),
- 2) erosion and sedimentation during construction resulting in high loadings of suspended solids,
- 3) stormwater pollutant levels comparable to secondarily treated wastewater for many constituents (Livingston 1989a).

Considerable data on urban runoff is available for Ontario cities bordering the Great Lakes (Marsalek 1977, 1978, Marsalek and Greck 1984, Marsalek and Schroeter 1984). Water quality from urban stormwater is as contaminated as that from municipal waste after primary treatment (Theil pers. comm.). Therefore information from constructed wetlands which have been used for improving municipal waste can be used as a guide for those which might be designed for stormwater management, with the proviso that the actual flow rates and periodicity will be quite different.

The mechanisms for treating urban stormwater are both chemical and physical (Livingston 1989, Tchobanglous et al. 1979) and include:-

- 1) volatilization - many pollutants may be dispersed by evaporating. They include oils, mercury and some chlorinated hydrocarbons,
- 2) sedimentation - this is a principal mechanism for removal of particulate pollutants. The deposition is affected by flow rates, paths and storm size. Sedimentation is important also in removing suspended solids, particulate nitrogen, oils, chlorinated hydrocarbons and most heavy metals,
- 3) adsorption - dissolved pollutants adhere to suspended solids which settle out. It is also the primary viral removal mechanism,
- 4) precipitation - many ions precipitate in response to changes in pH, oxygen concentration, etc. in wetlands,
- 5) filtration - many particulate pollutants may be filtered through the vegetation and soils of wetlands.

7. Development of Constructed Wetlands

7.1 Design Criteria

The design of a constructed wetland for dealing with urban stormwater requires a detailed study to determine from the outset what the goals of the wetland are (Bond et al. 1988). If the function is to primarily store water during storm events and release it later, then the size of the catchment area, permeability of the urban surfaces and recorded flow rates will be utilized to determine the water volume storage capacity required. This, together with the expected frequency of large storm events, will provide an indication of the suggested drawdown rates for the wetland and the diameter of outflow pipes. If, on the other hand, improving water quality is a major goal, then subsurface water flow through one or more cells may be worth incorporating into the design specifications. Should the wetland operate

in the fall, winter and early spring as well as in summer? If so, then a configuration of wetland which is deep and permits water flow during low winter temperatures may be appropriate.

Several goals may be identified for a constructed wetland, but the available site may limit the achievement of all the goals. In this case priorities must be set. The general location of a constructed wetland is an important consideration. Is it to be constructed in a residential, industrial or rural area? Considerations such as safety, aesthetics, potential toxic spills or wildlife mean that different design criteria must be considered. To achieve water management goals, social as well as technical issues must be addressed, for "social" problems may be more difficult to solve than physical and technical ones, and managers should involve local interest groups in the early planning stages of projects (Adams et al. 1982, Colenbrander 1978, Stewart 1990).

It is important that a pretreatment area be provided for the collection of sediment (Livingston 1989b) and for the protection of the constructed wetland from accidental spills (Burk 1977, Nawrot and Klimstra 1990, Wenck 1981). Wenck (1981) provides data on the construction of a pretreatment area for oil separation and sediment removal prior to allowing water to flow into a wetland. There are few reports on the impacts of oil spills on wetlands to indicate how oil may affect wetland communities. One oil spill occurred on a freshwater marsh in Massachusetts and its effect was to reduce the number of a few largely annual plants for a few years. However, none of these annuals were very abundant (having cover abundance indices of less than 5%) and recovery of the marsh species occurred within three years. Several species such as *Eloдея nuttallii*, *Potamogeton crispus* and *P. epihydrus* actually increased their growth and abundance after the spill (Burk 1977). It would therefore seem that marsh communities are resilient to occasional spills.

A constructed wetland could contain a number of cells, either of similar construction and function, or of different structure and purpose. Figure 7.1 illustrates the major components of a constructed wetland and is a composite derived from several sources (Conway and Murtha 1989, Watson et al. 1987). It shows water flowing into an aeration/sedimentation cell, across a marsh draining into a pond which then drains into a meadow or swamp.

7.2 Size

The size of a constructed wetland must be determined at the outset and is a function of many parameters. The size and number of wetland cells, spillways and dikes for acid mine drainage in the Tennessee Valley were designed to accommodate flow from the 100-year, 6-hour rainfall event based on site flow monitoring (Brodie 1990). Spillways were over-designed by factors up to three and protected with either large (> 30 cm) riprap or non-biodegradable erosion control fabric planted with *Scirpus* or *Carex* (Brodie 1990). For a suburban shopping mall in Massachusetts wetland design was based on the 100-year, 24-hour event (Daukas et al. 1989).

Design sizes are also dependent upon water quality characteristics and land availability (Brodie 1990). Information for sizing for municipal wastewater treatment is approximately 2.5 cm per week or the amount produced by 60 people for every hectare of wetland (U.S. EPA 1985, Kadlec and Tilton 1979). However, the requirements of size for stormwater management depend largely on the local climate and the degree of urbanization of the area. For storm events, Scheuler (1987) suggests that the constructed wetland should hold water for a ≤ 20 mm storm event. He also suggests that a water quality parameter be used in the design stage and that the average annual watershed loading does not exceed 45 pounds of phosphorus or 225 pounds of nitrogen per surface acre of wetland. Depending on water quality, the wetland may be designed to hold water for 24-48 hours or longer if the water is highly contaminated. The Tennessee Valley Authority's wetlands ranged in size from 7.8 m² to 82.2 m² per average flowing litre per minute, and 2.2 m² to 24.5 m² per maximum flowing litre per minute. Cell areas were arbitrarily increased in size if very poor water quality was to be treated (Brodie 1990). Livingston (1989b) suggests that the size of the constructed wetland should be as large as possible to provide benefits for both pollution control and wildlife.

7.3 Area and Shape

The area and shape of constructed wetlands is largely dictated by existing topography, geology and land availability. Irregular shapes for wetland cells enhance their natural appearance and provide hydraulic discontinuity. Configurations that could increase flow velocities and cause channelization, scouring and bank erosion are avoided. Level sites are amenable to large cells which may be chambered with rock or earthen finger dykes. Steeper gradients require more grading or a system of terraces. Staged treatment using several cells may provide a more efficient system since the water levels can be manipulated more easily (Brodie 1990). In North Dakota a series of cascading ponds were built across natural drainage streams, and overflow structures and spillways were provided to permit high water volumes to pass through with minimum damage to the wetland during major storm events (Litchfield and Schatz 1989).

Some general criteria for wetland creation in New York State (Bradley and Cook 1951) are:-

- 1) the area must have a small enough watershed to permit building a structure which comes within the standard design tables,
- 2) it must have at least 20 acres of drainage area for each acre impounded to ensure adequate water during dry periods,
- 3) it must contain a minimum of one acre of water surface with the maximum limited by watershed and drainage-impoundment ratio,

- 4) the soil must be tight enough to hold water,
- 5) it must form a natural basin which would permit the impoundment of water to a level not exceeding 18 to 24 inches over three quarters of the surface area.

Criteria for the shape of ponds can be obtained from the US EPA which provides many helpful hints on design (Middlebrooks 1987). The shape of constructed wetlands, whether ponds, marshes or swamps, should consider the position of inflow and outflow and what happens in between. Irregular shapes for wetlands enhance their natural appearance and can be used to decrease flow velocities and channelization. Depending upon the drainage characteristics and the age of the urban watershed, one may wish to have a sediment trap pond as the first part of a wetland. This should be easily accessible for dredging when necessary without damaging the vegetation. Livingston (1989b) suggests that the incoming water should flow into the shallow vegetated area of the wetland rather than a pond, to decrease flow velocities.

7.4 Depth

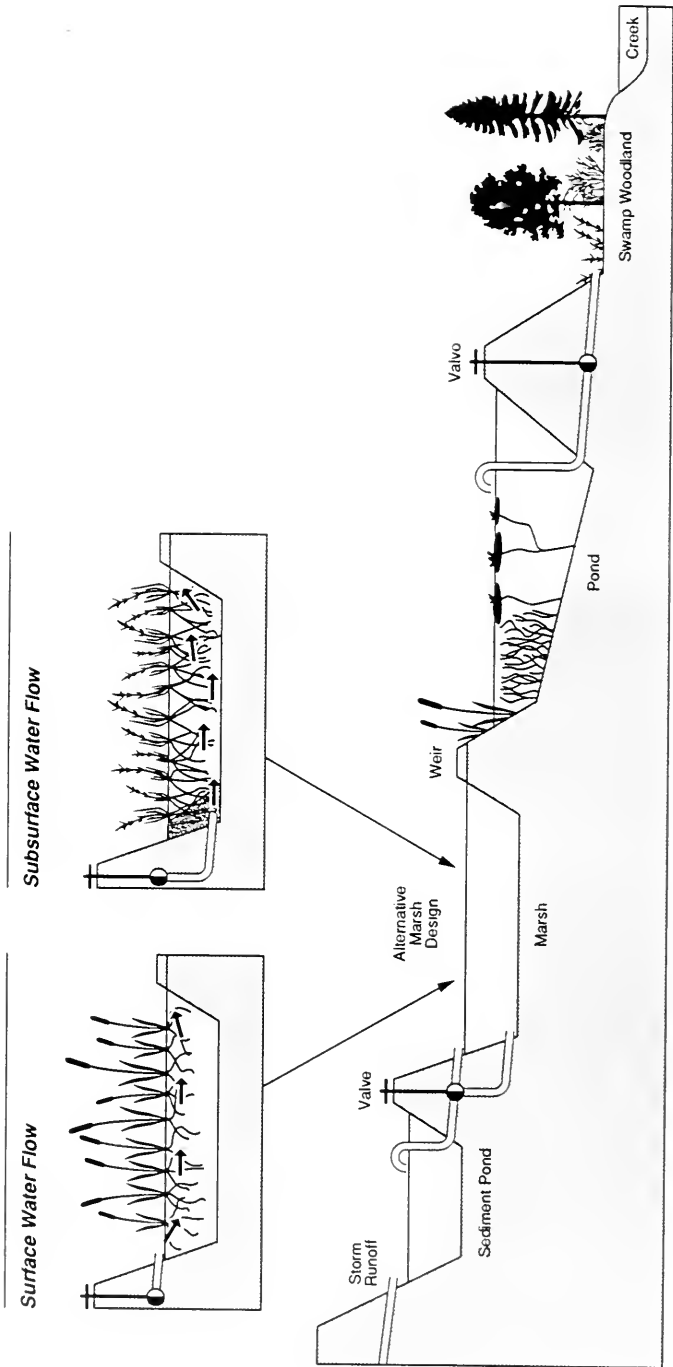
The depth of a constructed wetland depends on the desired plant species, though generally levels of between 15-180 cm are used for emergent species (Brodie 1990, Litchfield and Schatz 1989). Deep pockets where water depth is always at least two metres are included to provide refugia for aquatic species in times of low water levels (Brodie 1990). The guidelines for constructed wetlands in Maryland suggest that 25% of the wetland area should be 2-3 feet deep while the rest should be less than one foot deep (Livingston 1989b). This might be acceptable in the warmer climate of Maryland but the deep areas should probably be deeper in southern Ontario to provide refugia in cold winters when there is little snow cover.

7.5 Soil Preparation

Soil preparation will depend on whether the wetland cell is designed for surface or subsurface flow. For subsurface flow the soil must be permeable to water and the water encouraged to move down through the soil column. In this case it is essential that the stormwater is as free of sediment as possible, so that the pores between the soil/rock layer are kept open. If the intent is to provide a surface treatment of water then the soil must have a sufficiently high mineral component to hold plants and be tight enough to prevent leakage of water into groundwater. The type of soil to be used for wetlands depends on the nutrient status of the waters entering the wetland. If runoff is from an urban area, nutrients will be available in the influent waters.

Figure 7.1

Schematic View of Constructed Wetland



Surface Treatment Marsh

A peaty loam provides both organic material and sufficient holding characteristics for clay soils inhibit root spreading but are useful in providing a seal if the ratio of catchment area to wetland is not high enough to maintain water levels. At least four inches of soil should be provided to anchor plants well. If bottomland soil is available in the area it can be preserved and stockpiled and used as a top layer when the structure of the wetland has been created. Wetland soil containing plant propagules is the preferred base for new wetlands though this is not always possible (Livingston 1989b).

The calcium content of the soil is important for some aquatics such as muskgrass (*Chara* spp.) and sago pondweed (*Potamogeton pectinatus*) which are calcifiles, while other species (*Sphagnum*) are restricted to acidic soils. Peaty soils are generally not advisable as they do not provide enough holding capability while the wetland is becoming established.

Subsurface Marsh

The flow rates of subsurface water depend upon the particle size of the sand or gravel used. Subsurface flow is also dependent upon the slope. The advantage of sand is that it presents a much larger surface area for microbial activity, though it has the potential to become clogged with sediments. On the other hand gravels are less homogeneous and may not provide such an effective filtering mechanism but they are less likely to clog with fine sediments. Gravel size is selected using Darcy's Law to determine the hydraulic conductivity after the required area and desired cross sectional area and slope have been chosen. For a 0.6 m deep bed, gravel sizes of 12-25 mm for the lower horizon and pea gravel 6-12 mm for the top 0.15 m are recommended (Steiner and Freeman 1989).

The Water Research Board (U.K.) specifies 3-5 m² of Krefeld or Root Zone Method marsh planted with *Phragmites* as adequate to treat the sewage from one person, with prior settling and screening (Cooper and Hobson 1989). Most Root Zone Method marshes have been developed for treating sewage and whether they are effective in treatment of urban stormwater remains to be seen. However, because of the periodicity of storm events, and the fact that drawdown can occur between major rain events, the potential for developing a marsh which is alternately flooded and then oxygenated during a drawdown presents excellent opportunities for treating contaminants in runoff waters.

7.6 Planting

Constructed wetlands are usually planted with at least several species, and the range of species depends upon the configuration and the number of cells. Plant material may be dug from nearby wetlands (Miller 1989), obtained from nurseries or grown from seed (Korschgen and Green 1989, Kubichek 1940). It is most important when obtaining plant material from

local wetlands that they are not damaged in the process, nor that too much material is removed. If the site has been a wet area previously it may contain propagules of wetland plants. Obtaining "wild" material from nearby wetlands is the best method for obtaining wetland plants. There is greater genetic diversity in such material and it has a better chance of surviving as it is adapted to local conditions (Allen et al. 1989). It may require some organization to ensure that enough wetland material is available, and temporary holding beds be used for propagating plants such that there is sufficient stock when planting proceeds. There are several advantages to using seeds from natural wetlands as little disturbance need result in the collection activities. However, it is recommended that such seed be germinated in the nursery and grown to small plants to ensure successful introduction of the species to the constructed wetland.

Planting the right kind of wetland species is important and although each species can grow in a range of conditions, under competition from other plants it will do well within a limited part of a wetland. Because the growth of species in a constructed wetland is dependent upon many factors, it is prudent to plant a variety of species in each major hydrologic area to ensure success (Figure 7.2). Wetlands are best planted in early summer and material is hand-dug to obtain complete root balls/rhizomes and planted on the same day as digging. Plants should not be subjected to extreme temperatures, drying or wind during transport (Brodie, 1990). Complete wetlands installations can be operating in six to ten weeks depending upon their complexity. In southern Ontario a slightly longer settling in period may be required, but planting at the end of May and in early June will result in rapid growth and stabilization of the substrate in two months.

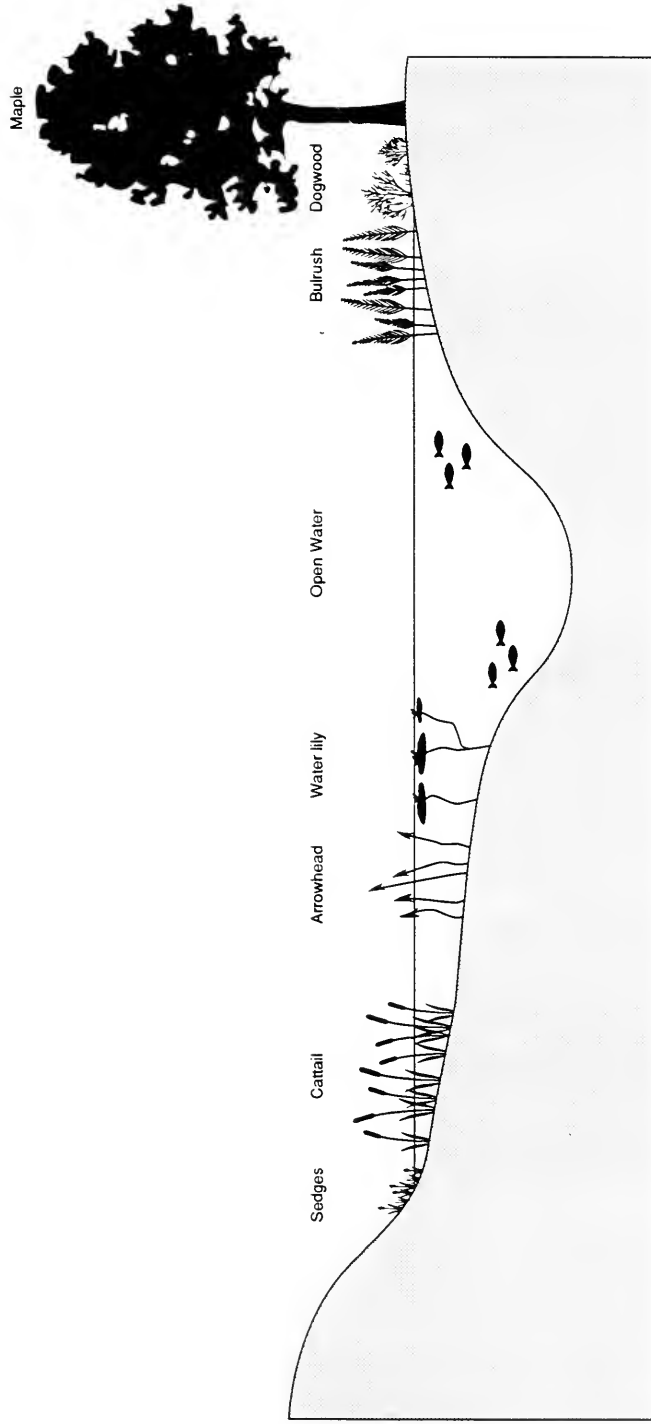
Semi-aquatics/emergents

The most commonly occurring species in North America are cattails (*Typha latifolia*, *T. angustifolia*), reeds (*Phragmites maximus*) and bulrushes (*Scirpus validus*, *S. fluviatis*) (Beule 1979, Brodie 1990, Emerson 1961, Herskowitz 1986, Lahiti 1977, Pullin and Hammer 1991). The recommended technique is to use rhizomes from nearby wetlands and to plant them out as soon as possible (Miller 1989). The tops can be bent over at water level to prevent wind blow and this also stimulates new growth from the rhizomes. Clumps of *Scirpus*, *Carex*, and *Juncus* are easy to plant in the desired location while *Eleocharis* and *Equisetum* require more care (Brodie 1990). Depending upon the weather, it is advantageous to water them or flood them briefly after planting (Weaver 1988).

Cattails grow readily in constructed wetlands as demonstrated in Listowel and Cochrane (Herskowitz 1986, Miller 1989). In many areas, emergents like cattails and rushes will invade an area fairly quickly and it depends on how quickly the wetland must be operational as to how much effort is expended in planting and how much can be left to natural

Figure 7.2

Schematic View of Wetland Planting



colonization. Livingston (1989a, 1989b) recommends against using either species of cattail (*Typha*) or reed (*Phragmites australis*) because of their aggressive nature. Monocultures are susceptible to disease and Brodie (1990) described problems with an infestation of cattail armyworms (*Simyra henrici*) which damaged 60-80% of the cattails in one wetland. The infestation was attributed to the rapid development of the monocultural nature of the cattails. It is therefore advisable to plant groupings of several species in each hydrologic zone to ensure that some species will do well. Neil and Graham (1989) found that bulrush (*Scirpus validus*) and common reed (*Phragmites australis*) were better at removing nutrients than cattails (*Typha angustifolia*), so depending on the water quality of stormwater, one may wish to use either of these species or some combination. Providing a variety of depths and flow conditions in the constructed wetland should encourage a number of species to flourish.

Soil plugs (8-10 cm diameter) from natural wetlands may also be used as they contain rhizomes, seeds or other propagules of native species (Allen et al. 1989, Smith and Kadlec 1983). Caution will have to be exercised, however, to prevent the introduction of noxious species such as purple loosestrife (*Lythrum salicaria*). If the flora of the wetland from which the soil plugs are taken is well known and free of noxious species, then this is an inexpensive and productive method.

Seeding of semi-aquatic plants is another option and may be considerably less expensive for large areas. Germination of seeds is better under moist soil conditions, rather than in completely inundated conditions (Smith and Kadlec 1983). Where salinity is a problem an inch or two of water assists germination. If one is dependent on natural seed banks in soils it is better to obtain the soil from the marsh part rather than from the open water part of a wetland as there will be more seeds of the desired species present in the soil. Plant material may be available from nurseries if advance notice is provided, and Lahiti (1977) successfully used nursery stock of *Acorus calamus*, *Eleocharis acicularis*, *Iris sheveri*, *Sagittaria latifolia*, *Scirpus fluvialis*, *Scirpus validus*, *Sparganium eurycarpum* and *Typha latifolia* in four small wetlands in Wisconsin.

Aquatics

Floating aquatics should be planted in deep areas. Some recommended species are waterweed (*Eloдея canadensis*), coontail (*Ceratophyllum demersum*), bulhead lily (*Nuphar variegata*) and curly pondweed (*Potamogeton crispus*). It is important that the plants are not exposed to air during a drought in their first year of growth. Aquatic plants provide an important additional assimilative surface for nutrients and toxic compounds, though they lose them when the leaves break down during the winter (Peeverly 1985).

Riparian Species

Riparian species consist of herbaceous plants, shrubs and trees. It is generally recommended that they be planted in clumps in a variety of locations. Trees planted along the edge of wetlands provide cover and the leaves falling in the water provide food for a variety of organisms (Greer 1979). Some commonly occurring species in wet areas include sensitive fern (*Onoclea sensibilis*), skunk cabbage (*Symplocarpus foetidus*), rushes (*Juncus* spp.) and sedges (*Carex* spp.). Dogwoods (*Cornus* spp.), black willow (*Salix nigra*) and button bush (*Cephalanthus occidentalis*) are common shrubs and trees of riparian areas (Brenner and Hofius 1990). Seeds or root stocks present in soil from nearby wetlands may provide other species in addition to the nursery stock planted out.

Wetland Trees

If a swamp is to be developed as a constituent part of a constructed wetland, a variety of trees and shrubs are required. A list of suitable species is given in Table 7.1. If trees and shrubs have adequate moisture they will become established quickly. The species composition, abundance and distribution of lowland forested areas is based on flood frequency and duration and the physiological response of each species to flooding and saturated soil. The periodic alteration between flooded and non-flooded conditions is important and it is advisable to ensure drawdown at least annually to allow aerobic reactions to take place in the soil profile (Winger 1986). This is not a problem if the swamp is designed to be flooded only with major storm events. Trees which are amenable to flooding include red ash (*Fraxinus pennsylvanicus*), willow (*Salix* spp.), eastern cottonwood (*Populus deltoides*), Manitoba maple (*Acer negundo*), red maple (*Acer rubrum*), silver maple (*Acer saccharinum*), pin oak (*Quercus palustris*) and sycamore (*Platanus occidentalis*) (Silker 1948, Winger 1986). These trees can be planted in and around constructed marshes or used as swamp species. Coniferous species characteristic of southern Ontario include black spruce (*Picea mariana*), tamarack (*Larix laricina*) and eastern white-cedar (*Thuja occidentalis*) (Environment Canada and Ontario Ministry of Natural Resources 1984).

Table 7.1 Plants suitable for wetland plantings (from Brenner and Hofius 1990, Lahiti 1977, Livingston 1989a, Winger 1986).

Plant name	Habitat	Comments
Trees and shrubs		
Black willow (<i>Salix nigra</i>)	Deciduous tree 30-50'	rapid growth, stabilizes streambanks
Buttonbush (<i>Cephalanthus occidentalis</i>)	Deciduous shrub 6-9'	full sun to partial shade
Dogwood (<i>Cornus</i> spp.)	Deciduous shrub 4-8'	bank stabilization, shade tolerant
Red ash (<i>Fraxinus pennsylvanicus</i>)	Deciduous tree 30-60'	rapid growing stream bank stabilizer
Red maple (<i>Acer rubrum</i>)	Deciduous tree 40-70'	rapid growth
Silver maple (<i>Acer saccharinum</i>)	Deciduous tree 60-80'	weak wood
Eastern White cedar (<i>Thuja occidentalis</i>)	Coniferous tree	grows in swamps, bogs and fens
Eastern cottonwood (<i>Populus deltoides</i>)	Deciduous tree 75-100'	rapid growth
Black spruce (<i>Picea mariana</i>)	Coniferous tree 30-50'	slow growing, usually acidic soils
Tamarack (<i>Larix laricina</i>)	Coniferous tree 20-40'	rapid initial growth
Pin oak (<i>Quercus palustris</i>)	Deciduous tree 50-90'	valuable mast for wildlife
Buttonbush (<i>Cephalanthus occidentalis</i>)	Emergent shrub	tolerant to submergence to 2 ft.
Herbaceous plants		
Common Arrowhead (<i>Sagittaria latifolia</i>)	Emergent	slow colonizer, marsh plant
Reed canary grass (<i>Phalaris arundinacea</i>)	Narrow-leaved emergent	good for erosion control, swales
Coontail (<i>Ceratophyllum demersum</i>)	Submergent	1-6 ft.
Bulrush (<i>Scirpus</i> spp.)	Robust emergent	provide food and cover for waterfowl and other wildlife
Sedges (<i>Carex</i> spp.)	Emergent	tolerant to shallow inundation (3")

Sweet flag (<i>Acorus calamus</i>)	Perimeter emergent	tolerant to drying,
Curly-leaved pondweed (<i>Potamogeton crispus</i>)	Emergent herb	rooted vascular hydrophyte
Rice cutgrass (<i>Leersia oryzoides</i>)	Emergent grass	Shade tolerant
Bulhead lily (<i>Nuphar variegata</i>)	Floating plants	rooted vascular hydrophyte
Spikerush (<i>Eleocharis acicularis</i>)	Emergent	good for binding soil
Pickerel weed (<i>Pontederia cordata</i>)	Broad-leaved emergent	marsh plant
Giant Bur-reed (<i>Sparganium eurycarpum</i>)	Robust emergent	marsh plant 1m tall
Cattail (<i>Typha angustifolia</i>)	Robust emergent	1.5-3m tall, invasive marsh plant
Cattail (<i>Typha latifolia</i>)	Robust emergent	1.5-3m tall, invasive marsh plant
Reed (<i>Phragmites</i> spp.)	Robust emergent	tall marsh plant
Waterweed (<i>Elodea canadensis</i>)	Submerged aquatic	grows readily

8. Maintenance and Operation of Constructed Wetlands

8.1 Water Level Controls

The maintenance of constructed wetlands is considerably easier when the water level can be controlled (Miller 1989). It is necessary to ensure that water levels in constructed wetland cells can be increased or decreased to control species composition. The abundance of species such as cattails can be reduced by prolonged flooding, and likewise the proportion of trees, shrubs, emergents and aquatic plants can be controlled by the periodicity and length of flooding (Lyon et al. 1986). The availability of nutrients is also a function of the oxygen status of the substrate and if conditions become anaerobic, more nutrients are available for plant uptake (Lyon et al. 1986).

8.2 Sediments

The accumulation of sediments is in large part a function of the watershed use and in an area undergoing development there may be a considerable quantity of sediments in urban runoff. On the other hand, in older established urban areas the majority of sediments may be a result of aerial deposition and use of sand on streets in the winter. A reduction in sediment loading may be obtained by various street cleaning regimes (Marsalek 1978). Numerous authors recommend incorporating a catchbasin type of pond at the water outfall point in which water velocity is slowed down and the majority of particulates can settle. In such cases it is preferable to have easy access for mechanized equipment to the pond so that it can be dredged when the capacity of the pond prevents its functioning as a sediment trap. It may be that by the time the pond is largely full of sediments, the sediment flow in inflow water is substantially reduced. The pond can then develop into a wetland dominated by emergents, allowing the natural process of succession to occur. Generally sediments in an urban area trap a wide variety of pollutants (Marsalek and Greck 1984) and the disposal of such contaminated sediments may present problems.

8.3 Harvesting Organic Material

An urban wetland is exposed to large quantities of nutrients and growth of the vegetation may be prolific. The carbon budget changes as the constructed wetland develops, and as dead organic material builds up there is less assimilative capacity (Bouldin et al. 1973). To reduce the rate of buildup of organic material, harvesting leaves and stems may be undertaken. How this is performed depends upon the type and size of wetland. For emergent vegetation such as cattails and sedges this may involve cutting with swathers and using the cut vegetation as fodder. However, the annual growth of emergents is as much below ground as above, so less than 50% of the annual production of such plants can be harvested. The use of this vegetation for fodder depends upon whether it is contaminated with heavy metals or toxic chemicals and whether these represent a health hazard or not. Wetland vegetation has also been used for biogas generation. If the constructed wetland includes treed swamps, trees may be harvested and generate significant additional revenues.

9. **Performance and Monitoring of Constructed Wetlands**

The performance or effectiveness of constructed wetlands in improving water quality or modifying water flow rates can only be evaluated with appropriate monitoring. The parameters to be monitored must be decided upon at the outset and be linked to the reasons why the constructed wetland has been built. If the major function of the constructed wetland is to remove toxic contaminants such as heavy metals, then it makes sense to monitor heavy metals in inflow and outflow waters, in the sediments and in the plants and animals which might be contaminated. There are innumerable chemicals of anthropogenic origin and many

programs have sought to measure large numbers of them. The task, however, is to choose indicator chemicals which represent specific pathways or bio-magnification concerns, and focus on the ones which will provide the most information.

Sometimes specific problems have not been identified and a more general monitoring program is required. A synoptic list of parameters is given in Table 9.1. In general, the more information which can be collected the better the database for future projects. However, common sense and available funding are important in determining which parameters should be measured.

9.1 Frequency of Monitoring

The frequency of making observations is very much dependent on the parameter in question. If one is monitoring the contaminant uptake in nesting birds, such as the uptake of pesticide residues in gull eggs, then the sampling period is circumscribed by the nesting periods and the number of birds nests one can sample. However, for monitoring chemical contaminants in the water inflow, sampling at weekly or biweekly intervals is important. If the need is to monitor contaminant loadings in first flushes, then sampling water during each significant rain event as well as on a regular basis is necessary. There may be a serial correlation between samples if the samples are taken at close intervals. This means that, when samples are taken within a short time period of one another, the values will be more similar than if they are taken at longer time intervals. This is illustrated in Figure 9.1 where one sees the seasonal means shown by the dashed line overlain by short term fluctuations. When serial correlation plays a significant role, the sampling frequencies should be more than 30 times a year. When the effects of serial correlation and seasonal variation cancel each other out, one can take samples between 10 and 30 times a year. Where seasonal variation is more important, ten or so samples a year are sufficient to monitor changes (Loftis and Ward 1980).

Another example of the importance of frequent sampling is concerned with measuring the effectiveness of bacterial removal in wetlands. Short interval monitoring is required because of the short life span of bacteria and the irregular pulses due to rain events (Figure 9.2). At Listowel sampling occurred weekly from April to November (Herskowitz 1986). If, on the other hand, one is measuring phosphorus retention, much larger time intervals are perfectly adequate as the major changes will be over several years (Figure 9.3).

There is relatively little information available on wetland function during the winter in northern climates. Some wetlands may freeze up but others, particularly swamps, function in winter with water flowing below the ice. It is necessary to obtain information on winter function whenever possible. Data at Listowel were collected between December and March biweekly and indicated that although the marsh cells were not as effective as in summer, some cleansing activities were going on (Herskowitz 1986). It is during the winter months

that there may be a major outflow of nutrients from a wetland due to slow decomposition of wetland plants.

Information on ongoing maintenance costs, monitoring and research costs, as well as the perceived values by the public of such places, are all important factors which may need to be assessed and be included in a monitoring program.

9.2 Spatial Monitoring

Most monitoring programs measure the concentrations of pollutants before they enter a wetland and at the outflow point. This is the simplest level of monitoring and it provides little information as to what is going on within the wetland. It has been argued that to understand wetland function it is necessary to make measurements across the wetland at several distances away from the inflow, because in this way one can obtain a more accurate idea of what part of the wetland is working and where changes are occurring (Kadlec 1987).

Phosphorus removal from wastewaters in constructed wetlands is initially rapid but with time, areas near the inflow become saturated and phosphorus removal occurs at a greater distance from the inflow water (Figure 9.3). Eventually the whole wetland becomes saturated with phosphorus and there is no long term retention but only seasonal retention associated with growth and loss from senescent stages of the vegetation (Gehrels and Mulamootil 1990). There are significant differences in the ability of different types of wetland to absorb phosphorus. A swamp may become saturated relatively quickly, a bog has greater capacity than a swamp and a fen a greater capacity than a bog (Figure 9.4)

Monitoring water flow in a constructed wetland is important because often the hydrology in an area is complex. Ground water may enter a wetland, diluting contaminated surface inflow waters indicating that pollutant removal is better than it is (Gehrels and Mulamootil 1990).

9.3 Water Quantity

The effect of wetlands on modifying water flow has been noted by several authors and there are several general principles operating (Glooschenko et al. 1987). Vegetation in a wetland impedes surficial water flow and attenuates peak flows. A wetland may serve as a water storage area, and the drawdown between recharge events results in increased stream flow downstream between rain events. However, the general capacity of a wetland to store water is restricted to the top 50 cm so that if a wetland is to perform a major water storage function, areal extent is of greater importance than depth.

Table 9.1 Summary of Synoptic Survey Monitoring (modified after Horner 1988).

CATEGORY	MEASUREMENT
Qualitative observations	Miscellaneous characteristics
Soils	Texture Organic content pH Oxidation-reduction potential Metals (Pb, Cd, Zn, Cu, Hg) Total phosphorus Total nitrogen Carbon dioxide evolution Microfauna
Water column	pH Fecal coliform Enterococci
Plants	Cover abundance Metals (Pb, Cd, Zn, Cu, Hg)
Animals	Aquatic invertebrate counts Sighting of others

Figure 9.1 Conceptual illustration of seasonal variation and serial correlation (After Loftis and Ward 1980).

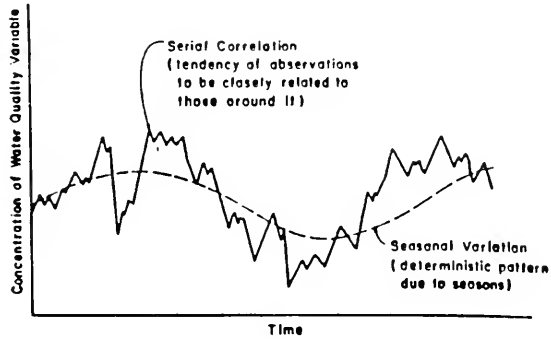
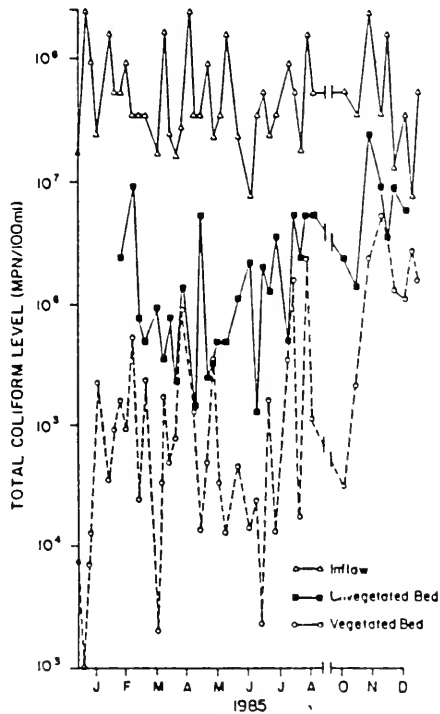


Figure 9.2. Concentration of total coliform bacteria in the applied primary municipal wastewater and in the effluent of a vegetated bed and an unvegetated bed. Hydraulic application rate was 5 cm d^{-1} for both beds (from Gersberg et al. 1987).



Significant amounts of water may be lost from a wetland by evaporation or evapotranspiration and it is necessary to monitor these quantities so that one can correct for changes in the concentration of pollutants leaving a wetland. Kadlec (1987) noted in the Houghton Lake wetland in Wisconsin that rainfall was approximately equivalent to water lost by evaporation and evapotranspiration.

Measurements of water flow are necessary to measure the attenuation of flood flows, the provision of increased flow during dry periods and the maintenance of flow under the snow or ice in winter. There is little information available for this last parameter and data on water flow throughout the year in different types of constructed wetland would be most useful.

9.4 Water Quality

Monitoring constructed wetlands for anthropogenic substances is essential. The performance of many wetlands has been measured and some average values of water quality before and after treatment are given (Table 9.2). Care is required in interpreting some of the values because many traditional water quality tests, such as BOD, estimate the oxygen demand on the water by decomposing organic matter. This organic matter may be of anthropogenic origin or it may be produced by the wetland itself. A high BOD in an outflow does not signify that the marsh has not been effective in treating sewage or other organic matter inputs, the BOD may represent marsh derived organic matter (Demgen 1979, Miller 1989). Likewise the flow of phosphate out of a wetland may represent phosphate released from the breakdown of organic matter (orthophosphate) and not phosphate flowing directly through the wetland (Gehrels and Mulamootil 1990).

A monitoring program may focus on the effect of contaminants on the organisms utilizing the constructed wetland and include measurements of species diversity and abundance, or focus on the level of contaminant uptake by specific indicator organisms (Clark et al. 1988). The advantages to biotic component analysis of wetlands include:-

- 1) some pollutants, notably heavy metals and organochlorine compounds, occur in much higher concentrations in aquatic organisms than in sediments or water, by as much as a factor of 10^3 - 10^6 , which can make chemical analysis much easier,
- 2) analysis of organisms measures the availability of the pollutants which is a better indication of biological effects than a measure of the total amount of pollutant in the environment,
- 3) organisms assimilate the pollutant present during time. Each combination of species and pollutant is unique, with its own degree of assimilation over time.

Figure 9.3 Phosphorus concentration profiles parallel to flow in Houghton Lake Wisconsin from 1978 to 1985 (from Kadlec 1987).

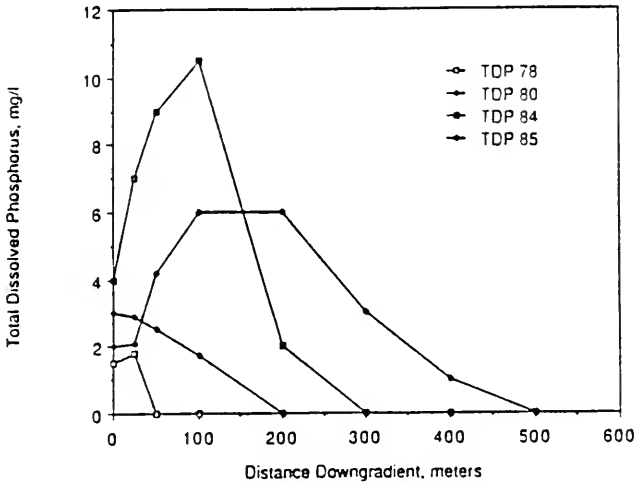
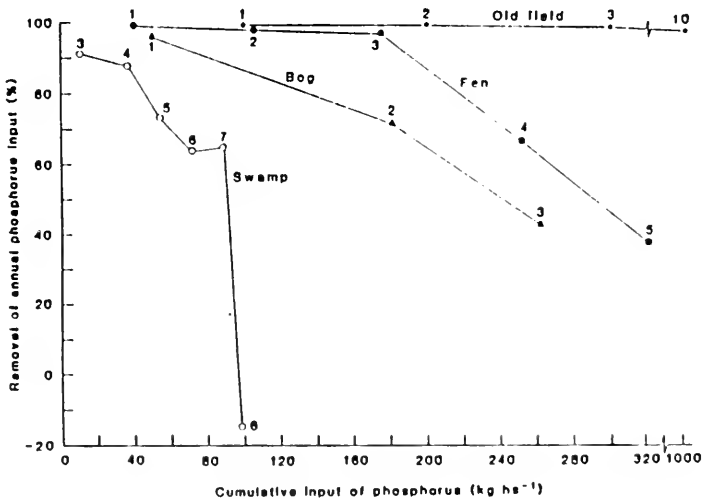


Figure 9.4 The change in phosphorus removal efficiency for the Houghton Lake fen, a white cedar swamp forest, an Irish blanket bog, and an abandoned old field in Pennsylvania as a function of cumulative phosphate inputs. The numbers along each line indicate the number of years of phosphorus addition (after Richardson 1985).



Because organisms concentrate contaminants differently, what may affect one organism will not be taken up by another and it is then advantageous to sample the general abiotic environment. Also, consistency is required in sampling and it is important when using species for monitoring that they should be:-

- 1) widely distributed and abundant when they occur,
- 2) easy to identify and collect,
- 3) of convenient size for collection,
- 4) generally sedentary at most life stages,
- 5) easy to assign to age classes,
- 6) contain levels of pollutants which are not so low that they cannot be measured nor so high that the animals are killed.

There are many other factors which can be monitored depending on the goals of the program. The transfer of contaminants to other organisms in the food web is important for they may ultimately end up in humans.

9.5 Nutrients

The major plant nutrients, nitrogen and phosphorus, are essential for healthy plant growth and urban waters are characterized by elevated levels of nutrients. This often results in more prolific growth of marsh and swamp vegetation, but often leads to eutrophic conditions in limnetic systems. This can result in considerable blue green algal blooms, with subsequent die back later in the summer causing anoxic conditions in waters resulting in fish asphyxia. Nitrogen is present as nitrate, nitrite and ammonium as well as other complex forms. Microorganisms denitrify nitrates and nitrites under anoxic marsh conditions, releasing nitrogen gas to the atmosphere.

Phosphorus is critical for plant growth and is usually abundant in runoff waters. Wetland plants use phosphorus in building new tissue, but in aquatic and semi-aquatic species, breakdown of tissue occurs in the fall and winter, releasing phosphorus to the water column. Phosphorus may also be bound in sediments and removed temporarily or permanently from the ecosystem. The degree of nutrient removal depends upon the size of the wetland and varies inversely with distance from the inflow (Fig. 9.5).

9.6 Microbes

Bacteria and viruses are removed from runoff waters by wetlands (Herskowitz 1986, Gersberg et al. 1987, Gersberg et al. 1989). Efficiencies of removal vary but many wetlands achieve 99% or better reduction of bacteria. It would be expected that bacterial removal from stormwaters in constructed wetlands involving marsh systems would be excellent because of the pulsed nature of storm events with longer average residence time and the presence of a large surface area of plants to trap microbes. Normally bacteria do not last more than two or three days in wetlands while viruses last longer (Gersberg et al. 1989). Measurement of bacterial levels often includes only fecal coliforms (*E. coli*) but these may be produced by other vertebrates as well as man. An indication of the anthropogenic bacteria can be obtained by examining the ratio of *E. coli* to *Streptococcus* (Stockdale 1986b). Other bacteria such as *Salmonella* may also be removed from wastewaters by wetlands (Gersberg et al. 1989).

9.7 Heavy Metals

Heavy metals are usually bound to sediments which accumulate in wetlands. They may subsequently be taken up by plants and animals. It is necessary to determine the amount of metals which enters the biotic and abiotic compartments. Monitoring heavy metals such as lead, zinc, cadmium, copper and mercury in plants, animals, sediments and inflow and outflow waters provides sufficient information to monitor the major toxic metals. There has been concern over the potential hazard of heavy metals to animals and Evans et al. (1987) studied metal uptake, excretion and movement in waders and Stinson and Eaton (1983) studied uptake of heavy metals from stormwater by crustacea.

Under anaerobic or reducing conditions metals are precipitated as insoluble sulphides and become complexed with organic matter thus limiting their bio-availability (Winger 1986). However, metals may become complexed with superficial organic sediments and be washed out of the wetland or taken up by benthic and filter feeding invertebrates.

9.8 Organic Compounds

If urban runoff drains industrial areas, water quality is generally worse than in commercial or residential districts, and the spectrum of chemicals different (Scheuler 1987). The range of potential organic compounds which might occur in urban wetlands is large and compounds such as PCBs, organochlorine pesticides and several chlorinated benzenes are widespread (Clark et al. 1988, Marsalek and Greck 1978). The general intent of constructed wetlands is to trap and if possible facilitate the destruction of these compounds.

Table 9.2 Typical composition of domestic wastewater before and after treatment (all values except settleable solids and coliform bacteria are expressed in mg/L)(from Tchobangolous et al. 1979).

CONSTITUENT	CONCENTRATION			
	Before treatment		After secondary treatment	After advanced treatment
	Range	Typical		
Solids, total	350-1200	720		
Dissolved, total	250-850	500		
Fixed	145-525	300		
Volatile	105-325	200		
Suspended, total	100-350	220	20	<3
Fixed	20-75	55		
Volatile	80-275	165		
Settleable solids, mL/L	5-20	10		
Biochemical oxygen demand, 5 day (BOD, 20 C)	110-400	220	20	1
Total organic carbon (TOC)	80-290	160		
Chemical oxygen demand (COD)	250-1000	500	80	10
Nitrogen (total as N)	20-85	40	30	2
Organic	8-35	15		
Free ammonia	12-50	25		
Nitrites	0-0	0		
Nitrates	0-0	0		
Phosphorus (total as P)	4-15	8	2	
Organic	1-5	3		
Inorganic	3-10	5		
Chlorides	30-100	50		
Coliform bacteria, MPN/100 mL	10 ⁵ - 10 ⁹	10 ⁷	20	<2
Heavy metals	0.1-2.5	1.3	0.8	<0.1
Refractory organics	0.2-7.4	1.4	0.2	<0.1
Alkalinity (as CaCO ₃)	50-200	100		
Grease	50-150	100		

Sampling for hydrocarbons such as petroleum, phenols, oils and grease provides an indication of the efficiency of microbial decomposition. These contaminants may evaporate from the surface or they may be metabolized by microbes and plants and the rates of disappearance depend upon the organic compounds concerned, the nature of the marsh and the previous exposure of microbes to the specific contaminant (Table 9.3).

At an oil refinery in North Dakota, constructed wetlands were used to reduce contaminants entering the Missouri River. Water was sampled at the inflow American Petroleum Institute (API) separator, at the lagoon outflow and at the final discharge point to the river. The parameters tested for included BOD, COD, $\text{NH}_3\text{-N}$, sulphides, phenols, oil-grease, hexavalent chromium, total chromium and TSS (Litchfield and Schatz 1989). The constructed wetlands reduced the levels of these organics well below the standards set by the National Pollutant Discharge Elimination System (NPDES).

In urban residential areas a wide spectrum of compounds is produced from vehicle use, from garages and oil change operations. Constructed wetlands may be used to treat these contaminants in the urban context. Oil spills may occur resulting in major releases of hydrocarbons to the aquatic environment. After an initial reduction in the diversity and number of organisms, there is a slow recolonization of the contaminated area (Tables 4.2, 4.3)(Anderson et al. 1978, Burk 1977). The effect of such oils on organisms has been studied largely in marine settings and there is little information on spills on wetlands of the Great Lakes.

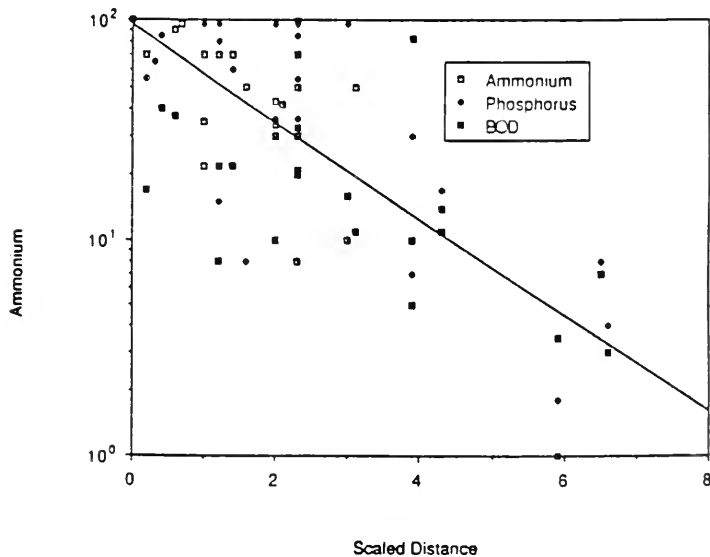
Monitoring the benthic fauna may be an appropriate way of tracking the effectiveness of a wetland in reducing organic compounds. Because of the large number of factors affecting the health of organisms, the individual effects of single chemicals are not analyzed but rather the combined effects they and the physical parameters have on the wetland biota. Two or more compounds may have a synergistic effect well above their individual toxic levels and therefore have a significant effect on the health of a wetland. It is therefore appropriate to ensure that organisms as well as chemical levels are monitored.

Pesticides entering aquatic environments from golf courses, gardens and farms can also have a deleterious effect on aquatic organisms. Pesticides may be adsorbed onto particulates and humic and fulvic acids are important carriers of some pesticides, while clay and silts carry others. Loss of pesticides from sediments is slow or does not occur and many of them are broken down by microbes within the wetland (Winger 1986).

Table 9.3 Disappearance of various organics in systems containing *Scirpus lacustris* (from Kadlec and Kadlec 1978).

Compound	Concentration mg/l	Days to Extinction
Phenol	100	15-29
p-Cresol	30	15-52
Pyrogallol	100	15-52
Pyridine	400	7-9
Quinoline	20	7-9
Aniline	20	15-52
p-Chlorophenol	10	14-52

Figure 9.5 Nutrient removal versus distance, selected data points from ten wetland systems (from Kadlec 1987).



9.9 Biotic Components

The presence and health of organisms reflect the state of the environment. If an environment is polluted, then characteristic "tolerant" species are present, usually in larger numbers, while "sensitive" species are absent. The biology of many polluted waters has been documented and Hynes (1960) provides a good overview of this subject. The functioning and effectiveness of a constructed wetland can be evaluated in terms of its biotic components.

Most constructed wetlands attract a variety of wildlife which may be a nuisance or a benefit. Wetlands provide good feeding and nesting opportunities for birds, mammals, amphibians and reptiles (Demgen 1979, Litchfield and Schatz 1989), and the diversity increases as the wetlands become more established. The outflow from wetlands also produces considerable quantities of phytoplankton and zooplankton which provide food for fish and other organisms downstream (Stewart 1990). Monitoring several wildlife species on the Great Lakes has provided a useful measure of the health of the lakes, and it is important that wetland animals be monitored to ascertain contaminant pathways and assess the effectiveness of wetlands in improving water quality without impairing the other biota.

10. Summary

The function and values of wetlands can be summarized by the following points:-

- 1) Wetland types differ greatly in their ability to store and release nutrients.
- 2) Wetlands can be a source or sink depending on the nutrient and season.
- 3) Wetlands are an efficient filter for suspended solids and organic matter.
- 4) Wetlands are efficient transformers for N.
- 5) Soil adsorption chemistry (Al, Fe) and microbial activity are the key to storing P.
- 6) Many wetlands do not have the potential for high levels of nutrient storage.
- 7) Wetland discharge systems should be designed to utilize conservative loading rates, adjusted to seasonal variations in wetland hydrology.
- 8) Wetlands that are threatened or endangered ecosystems should not be used for wastewater discharge.
- 9) Monitoring of constructed wetland discharges should be extensive and include biological information, hydrologic data and water nutrient budgets.
- 10) Artificial wetlands may have greater potential than natural wetlands as treatment systems, because they have
 - a. lower area requirements
 - b. better hydrologic control
 - c. good removal of BOD, SS, and N
 - d. low P removal capacity, unless water infiltrates soil and aeration is increased, but
 - e. annual plant storage of nutrients is low due to dieback and mineralization.
- 11) Pre-treatment of effluent is often required
 - a. Al (alum) or Fe to remove P
 - b. aeration to decrease BOD, SS.
- 12) Research is needed on
 - a. loading designs.
 - b. soil infiltration and nutrient sorption capacity.
 - c. root zone methodology
 - d. cumulative loading impacts.

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