MODELLING APPLICATIONS FOR WETLAND RESTORATION

THE APPLICATION OF MASS BALANCE AND HYDRODYNAMIC/POLLUTANT TRANSPORT MODELS FOR WETLAND RESTORATION

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Abstract

This study deals with the use of mass balance and hydrodynamic/pollutant transport models for wetland restoration. The models were applied to Cootes Paradise marsh, located at the western end of Hamilton Harbour, Lake Ontario. Regulated water levels, excess nutrients and high suspended solids have contributed to declining vegetation and a subsequent change in wildlife in this wetland ecosystem. The Royal Botanical Gardens (RBG), which manages Cootes Paradise, has developed goals for the restoration of this wetland which focus primarily on improving water quality.

A mass balance approach was applied to Cootes Paradise in order to gather more information on the inputs of phosphorus and suspended solids to the ecosystem. Although data were not complete for many aspects of the model, the mass balance calculations provided an acceptable agreement with field values. The mass balance models also revealed that more than 50% of the inputs of phosphorus and suspended solids were being contributed by the internal sediments.

A two-dimensional depth averaged hydrodynamic/pollutant transport model provided an explanation for the movement of substances through the marsh as a result of wind and inflow generated currents. The resulting pollutant distribution patterns could be explained by environmental conditions in the marsh ecosystem. The computer model predicted phosphorus concentrations reasonably well, both for an overall average of the entire marsh and for individual sites. The model also simulated suspended solids and accounted for contributions of particulate matter due to carp and due to wind resuspension of the bottom sediments. Both overall averages and sample site comparisons for suspended solids were within one standard deviation of field values. According to data generated by the computer model for suspended solids, carp and wind are contributing to the concentrations in Cootes Paradise on an almost equal level; both contribute approximately one third to the overall concentration for suspended solids based on the available data. Further information is needed, however, to improve on the data set for Cootes Paradise in order to better validate the results produced by the mass balance and computer models.

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List of Symbols

A_x, A_y	= eddy viscosities
C	= mean concentration
C_f	= field concentration
$\overline{C_f}$	= mean field concentration
C_c	= computer predicted concentration
d_p	= particle diameter
D	= eddy diffusion coefficient
D_s	= deposition to bottom sediments
D_x, D_y	= horizontal eddy diffusivities
E_{cr}	= convergence level
f	= Coriolis factor
F	= flushing coefficient
g	= gravitational acceleration
H	= water depth
H_{max}	= maximum water depth
i, j, n	= indices for x, y and time dimensions
L	= characteristic length of the flow domain
L_i	= input loads for mass balance calculations
M, N	= vertically integrated water transport per unit with in x- and y-directions, respectively
n_x	= sample size for standard deviation calculations
n_M	= Manning's coefficient
p_d	= probability of settling

P_e = Peclet number

R = reflux coefficient

s = sedimentation coefficient in mass balance calculations

S = source term for pollutant transport

S_{flow} = net contribution for inflows and outflows in pollutant transport

S_{dep} = loss of suspended solids due to deposition

S_{res} = contribution to suspended solids due to resuspension

u, v = depth-averaged velocities in x- and y-directions, respectively

U = characteristic velocity of transport fluid

U_* = bottom shear velocity

w_s = settling velocity

w_x, w_y = components of wind speed

x = values for standard deviation calculations

$\bar{z}$ = mean depth

α_1 = spatial variability in field concentrations

α_2 = the difference between field and computer simulated concentrations

α_3 = the ratio of the root mean square value of simulated concentrations to the root mean square value of field concentrations

ε = resuspension rate

γ_a = surface drag coefficient

γ_b = bottom drag coefficient

μ = dynamic viscosity

ρ_a = density of air

ρ_d = particle density

ρ_w = density of water

σ_P = sedimentation rate for phosphorus

τ_b, $\tau_x(b)$, $\tau_y(b)$ = bottom shear stresses

τ_{cd} = critical shear stress for deposition of suspended solids

τ_{cr} = critical shear stress for resuspension of bottom sediments

$\tau_x(s)$, $\tau_y(s)$ = wind shear stresses

ζ = water surface elevation

Δt	= time step
Δx, Δy	= grid cell dimensions
st.dev.	= standard deviation
AMP	= amplitude of sine function for water levels
BIOMASS	= biomass density of carp
LEVEL	= water level
MEAN	= water level at midpoint between minimum and maximum water levels
MONTH	= numerical representation of month
SS	= concentration of suspended solids

List of Acronyms

CSO	= Combined Sewer Overflow
GIS	= Geographic Information System
HRCA	= Hamilton Region Conservation Authority
RAP	= Remedial Action Plan
RBG	= Royal Botanical Gardens
STP	= Sewage Treatment Plant
WSC	= Water Survey of Canada

1 Introduction

Wetlands are valuable ecosystems but their worth has been noticed only recently. They were once regarded as a nuisance, making land unsuitable for agriculture and development due to wet conditions, mosquitoes and foul odours (Weller, 1981; Houser, 1974). Now, after many of the world's wetlands have been drained and filled, important benefits of wetlands have been recognized and more is being done to protect and restore these precious ecosystems.

1.1 What is a Wetland?

Wetland ecosystems include swamps, bogs, marshes, mires, fens, and other wet environments (Mitsch and Gosselink, 1993; Williams, 1990). These environments cover approximately 6% of the Earth's land surface (8.6 million km^2) and can be found from tropics to tundra and on every continent except for Antarctica (Mitsch and Gosselink, 1993; Williams, 1990). Wetland definitions, however, vary depending on the field of interest; hydrologists, geologists, ecologists, and managers will each define a wetland based on information specific to their area of study. In general, though, wetlands are transitional ecosystems located between terrestrial and aquatic environments and they are loosely defined as areas of land that are covered with water for a period of time over the year (Canadian Wildlife Service, 1989). A more detailed definition of wetlands, which includes many of the common properties of these environments, is given by Tarnocai (1979) and states that wetlands are "lands having a water table at, near or above the land surface or which are saturated for a long enough period to promote wetland or aquatic processes as indicated by hydric soils, hydrophilic vegetation and various kinds of biological activities which are adapted to a wet environment".

1.2 Functions and Benefits of Wetlands

When the benefits are taken all together it becomes very clear that wetlands are too precious to be destroying. In the past, the economics of the situation were considered first and foremost and more times than not wetlands were deemed less valuable than other uses. The many qualities of wetlands - scientific, social, economic, educational, recreational, and aesthetic - all prove that the advantages to preserving and protecting wetlands far outweigh the advantages to draining and infilling.

1.2.1 Ecosystem Functions

Wetlands have many physical, hydrological, chemical, and biological functions as well as several social and economic values. Like giant sponges, wetlands soak up surface water runoff and attenuate flood peaks and storm flows (Mitsch and Cronk, 1992; Williams, 1990; Canadian Wildlife Service, 1989; Russell, 1987), and they slowly release stored water during times of drought (Canadian Wildlife Service, 1989; Van Patter and Hilts, 1985). Wetland water storage allows groundwater recharge to occur (Mitsch and Cronk, 1992; Williams, 1990) and flood prevention contributes to reducing downstream soil erosion (Russell, 1987). Wetlands also trap and retain sediments (Williams, 1990; Russell, 1987). The presence of vegetation slows the flow of water and promotes the settling of suspended particles. Pollutants and toxic substances are removed via plant uptake, settling to the sediments, ion exchange, and bacterial metabolism (Williams, 1990; Glooschenko and Grondin, 1988). Wetlands are also capable of processing human and animal waste material, mainly as a result of primary productivity, sediment deposition and bacterial action (Williams, 1990). This capacity to remove sediments and pollutants has earned wetlands the title "nature's kidneys" (Kusler *et al.*, 1994; Mitsch and Gosselink, 1993).

1.2.2 Productivity and Biodiversity

Wetlands are among the most productive and the most biologically diverse ecosystems of the world (Kusler *et al.*, 1994; Williams, 1990). Wetlands provide habitats for a wide variety of plants and animals during all stages of their life cycle. Many fish, birds, mammals, and reptiles rely on wetland areas for breeding, nesting and feeding needs (Kusler *et al.*, 1994; Environment Canada, 1991; Williams, 1990; Canadian Wildlife Service, 1989; Glooschenko and Grondin, 1988; Houser, 1974).

1.2.3 Economics

Wetlands provide many economic and social benefits. The vegetation provides people with food and other valuable resources. Wild rice and cranberries are among the foods that are produced in northern wetland environments, and timber and peat are important natural resources (Kusler *et al.*, 1994; Environment Canada, 1991; Williams, 1990; Glooschenko and Grondin, 1988). Wetland animals are important for both commercial and recreational fishing and hunting (Kusler *et al.*, 1994; Environment Canada, 1991; Canadian Wildlife Service, 1989).

1.2.4 Education

While sustaining human populations nutritionally, recreationally and economically, wetlands can also contribute to the educational well-being of people (Environment Canada, 1991; Williams, 1990; Van Patter and Hilts, 1985; Bardecki, 1982). Wetlands provide a natural scientific laboratory for research and learning at all academic levels. A study by Bardecki (1982) showed that wetlands are a part of educational programs at the public elementary and secondary school levels and at the university level. Involvement at the lower educational levels tends to be much less than at the university level, however interest in the area of wetlands is growing as it becomes more apparent that these ecosystems require attention.

1.2.5 Aesthetics

Finally, wetlands have a remarkable amount of aesthetic value (Environment Canada, 1991; Williams, 1990), which is something that is all too often overlooked as an important aspect of these ecosystems. The beauty of these wetland systems shows through in the vast diversity of plants and animals thereby providing a scenic landscape for enjoyment by naturalists, photographers and canoeists, as well as many others (Houser, 1974). Not only are the sights something to behold but the sounds that emanate from the wide variety of insects, amphibians, mammals, and birds provide a symphony for the ear. Furthermore, these environments are rich in natural heritage and they have many historical benefits (Williams, 1990).

1.3 Wetlands in Canada

In Canada, wetlands are found along the shores of oceans, lakes and rivers, across the prairies and in poorly-drained depressions in the Canadian Shield (Canadian Wildlife Service, 1989). Canada contains one-quarter of the world's wetland area (Environment Canada, 1991) falling second only to the former Soviet Union in richness of wetland resources (Zoltai and Pollet, 1983). Approximately 127.2 million hectares, or 14%, of Canada's land surface is classified as wetland, with the greatest concentration in Ontario and Manitoba (Zoltai, 1988). In general, though, wetlands in Canada occur in a broad belt which extends from central Labrador, passing south of Hudson Bay and reaching northwesterly across the northern prairie provinces and along the Mackenzie Valley (Zoltai and Pollet, 1983).

Since 1800, an estimated 20 million hectares, or approximately one seventh of Canada's wetlands, have been drained or lost to other functions and millions more hectares have been seriously degraded (Environment Canada, 1991). About 65% of Atlantic coastal salt marshes are gone, 80-90% of wetlands immediately adjacent to urban centres have been lost, over 50% of potholes in the central prairies no longer exist, and 70% of Pacific estuary marshes are lost or degraded (Environment Canada, 1991). In Southern Ontario alone, it is estimated that 70-80% of the approximate 2.4 million hectares of wetlands that existed historically have been severely altered or have disappeared altogether (Snell, 1987). When the aforementioned benefits of wetlands are considered it becomes overwhelmingly apparent that these rates of loss cannot continue.

Wetland areas are lost as a result of natural processes of formation, change and degradation (Gosselink and Maltby, 1990), but humans have generated the greatest impacts in the modern era. Conversions for agricultural and urban development, recreation, lake level management, landfilling, forestry, and peat mining are responsible for most wetland losses (Environment Canada, 1991; Canadian Wildlife Service, 1989; Van Patter and Hilts, 1985). Agricultural development is the dominant reason for wetland destruction. According to Snell (1987), 81% of land drainage in Southern Ontario between 1967 and 1982 was for agricultural purposes. Port expansion, industrialization and urbanization are also very strong forces placing pressure on wetland environments (Pinder and Witherick, 1990). In addition to the numerous hectares of wetlands destroyed, degradation and negative impacts on remaining wetlands cannot be ignored. Many activities may not destroy wetlands but instead have indirect effects on reducing water, soil and air quality in and around the wetland ecosystems (Environment Canada, 1991).

1.4 Wetland Restoration

As outlined above, wetlands possess many valuable qualities which have been ignored in earlier efforts to create more land for human exploitation. Now that the beneficial properties of wetland environments are better known, efforts to protect remaining wetlands and restore degraded wetlands are increasing. Since 1986 the Federal Government of Canada has been working with many committees on the issues surrounding wetland management (Environment Canada, 1991). By 1991, a Federal Policy on Wetland Conservation had been developed in an effort to protect these precious ecosystems. The main objective of the policy is to promote the conservation of Canada's wetlands to sustain their ecological and socio-economic functions (Environment Canada, 1991). Several goals have been outlined to support this objective. The goals include 1) no net loss of wetland functions on federal lands and water, and 2) enhancement and rehabilitation of wetlands in areas where continuing loss or degradation have reached critical levels (Environment Canada, 1991). The no net loss goal strives to protect remaining wetland areas in Canada and the rehabilitation goal aims to restore degraded wetland environments. Public education and awareness and simple laws and regulations can contribute to achieving the protection goal.

Restoration of degraded wetlands, however, has proved to be difficult. Wetlands, like other ecosystems, are complex and restoration is not simple (Roberts, 1993). In restoring wetlands, care must be taken to ensure that the system does not become overengineered through the addition of structures such as dams and channels and through the introduction of non-native species (Mitsch and Gosselink, 1993). It is better to give the system a little kick-start and then leave it to regenerate on its own. Extensive study and thought must also be put into a restoration project otherwise the risk of failure is high. It has been noted that some restored wetlands disappear shortly after completion, others persist but bear little resemblance to natural wetlands and still others are close mimics with look-alike vegetation but fail to support the plants and animals that they were intended to support (Roberts, 1993). In the long run it is much easier to protect a wetland before it reaches the state of severe degradation than to restore or recreate a wetland later (Canadian Wildlife Service, 1989; Weller, 1981).

1.5 Goals of this Study

This study examines a degraded marsh ecosystem at the western end of Lake Ontario and provides a modelling approach for restoration. Mass balance models for phosphorus and suspended solids were used to identify the relative importance of sources contributing to degraded water quality and hydrodynamic and pollutant transport models were used to study the movement of substances through the aquatic system.

Models are useful in simulating different conditions and hence predicting the outcomes of different restoration options. The models are therefore valuable tools for ecosystem restoration projects. Once information is gained from the models on the relative importance and distribution of phosphorus and suspended solids, a strategy for revegetation and restoration can be developed. With careful planning, in addition to the modelling results, seeds and seedlings can be placed strategically throughout the marsh to enhance the success of vegetation growth and wetland restoration.

2 Area of Study

2.1 Cootes Paradise

2.1.1 General Information

Cootes Paradise is a wildlife sanctuary owned and managed by the Royal Botanical Gardens (RBG). It is located in the Dundas Valley at the western end of Hamilton Harbour, Lake Ontario (Figure 2.1). Approximately 250 ha of Cootes Paradise is wetland (Painter *et al.*, 1989), the majority of which is open water surrounded by marshy areas and woodland (Mudroch, 1981). The open water area has a mean depth of 0.5 m and a maximum depth of 2 m (Holmes, 1988; Mudroch, 1981; Sims, 1949). Cootes Paradise is connected to Hamilton Harbour by the Desjardins Canal which, in the past, allowed the passage of boats from the harbour to the Town of Dundas.

Several streams and creeks drain into Cootes Paradise but many of these inputs dry up soon after spring runoff (Bacchus, 1974). The three creeks contributing most to the water quality of the marsh are Spencer Creek, Chedoke Creek, and Hopkins Creek (Figure 2.2). Hopkins Creek joins with Borer's Creek before discharging into Cootes Paradise (Semkin *et al.*, 1976). The Dundas Sewage Treatment Plant (STP) also drains into Cootes Paradise via the Desjardins Canal and West Pond. In the past, the Dundas STP was a major source of organic matter and nutrients entering Cootes Paradise (Mudroch, 1981; Semkin *et al.*, 1976; Sims, 1949).

2.1.2 Changes in Cootes Paradise

Cootes Paradise was once a healthy wetland ecosystem supporting many plants and animals. Through time, many changes have occurred in this wetland. Cootes Paradise was once home to many different species of fish and supported successful fisheries for species such as pike (*Esox lucias*) and bass (*Micropterus* spp.) (Holmes, 1988; Lavender, 1987). At present, the fish community is dominated primarily by common carp (*Cyprinus carpio*). Cootes Paradise was also home to many large mammals such as the black bear (*Ursus americanus*), bobcat (*Lynx rufus*), lynx (*Lynx canadensis*), mountain lion

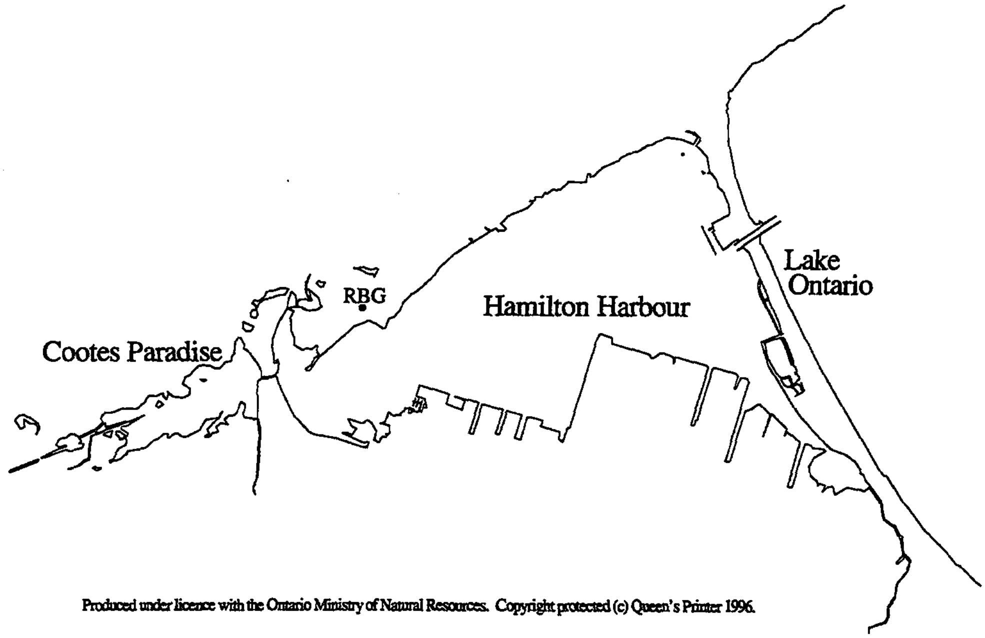

Figure 2.1 The location of Cootes Paradise with respect to Hamilton Harbour, Lake Ontario.

(*Felis concolour*), grey wolf (*Canis lupus*), and wolverine (*Gulo gulo*) (Lavender, 1987). These mammals are no longer present in this area. Many other organisms, though, continue to live in and make use of Cootes Paradise. They include white-tailed deer (*Odocoileus virginianus*), raccoons (*Procyon lotor*), muskrats (*Ondrata zibethica*), turtles, several species of birds, countless insects, and many different species of zooplankton (Lavender, 1987; Simser, 1980; Cockman, 1955).

Probably more obvious than the changes in animal species diversity and abundance in Cootes Paradise are the changes in the vegetation. In the late 1700's and early 1800's Cootes Paradise was nearly 100% covered with emergent vegetation (Painter *et al.*, 1989). A large decline in vegetation cover occurred from the mid-1930's into the 1950's (RAP, 1992). This was followed by a slight increase into the 1960's and another decrease in the early 1970's. At the present only about 1% of the marsh is covered with emergent vegetation (Simser, 1994) and little submergent vegetation exists in Cootes Paradise (Painter *et al.*, 1989).

2.1.3 Consequences of a Loss of Vegetation

Vegetation forms an important link in the food webs of ecosystems and its loss can lead to several problems. The most obvious loss associated with a decrease in vegetation is a loss of wildlife.

Many animals rely on vegetation for both food and shelter. When these resources are removed, the wildlife may move elsewhere to find these necessities or die off by staying in the affected area.

A loss of vegetation also leads to decreased cleansing of the water. Many microorganisms which have an important role in metabolizing compounds and nutrients in a body of water are associated with aquatic plants (DeJong, 1976). If the plant population decreases then so also will the population of these important microorganisms. The plants themselves are also capable of taking up nutrients and compounds from the water (Boyt *et al.*, 1977). Without these breakdown and removal mechanisms the waters may become unsuitable for other forms of life to exist.

Plants play an important role in the hydrodynamics of an aquatic system by retarding the flow of water through a basin and dampening the impact of wind and wave action. A decrease in the amount of plants in a body of water can lead to an increased water flow which in turn may lead to an increase in the resuspension of sediments (Carpenter and Lodge, 1986; Dean, 1979). Dieter (1990) showed that resuspension of sediments due to wind action is also increased in areas which lack vegetation, and shoreline erosion is higher when plants are not present to increase the durability of the substrate through the soil/root matrix and to dampen the impact of waves (Dean, 1979).

With the increase in resuspended material, a loss of vegetation leads to decreased accretion of sediments (Carpenter and Lodge, 1986; Boto and Patrick, 1979). In the absence of plants, particulate

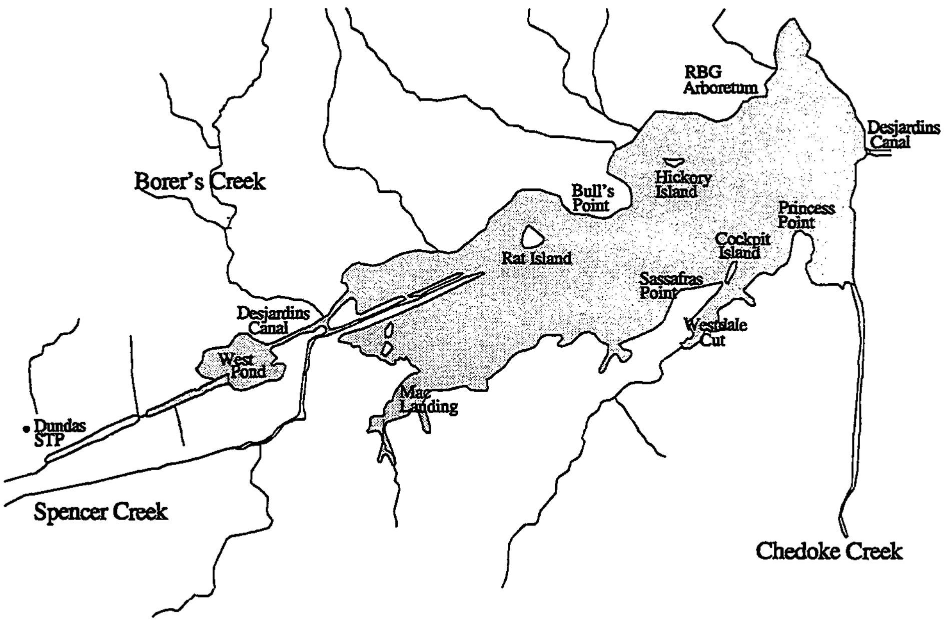

Figure 2.2 The three main creeks of Cootes Paradise along with other landmarks in and around the marsh.

matter remains suspended in the water column. This can lead to a decrease in ecological succession by preventing the expansion of the littoral zone. Furthermore, high levels of suspended solids produce a turbid environment which is not conducive to submergent plant growth. Conditions which are unfavourable for the growth of vegetation will also contribute to a decrease in the plant population and consequently decrease succession.

2.1.4 Goals for the Restoration of Cootes Paradise

The RBG developed goals and objectives for Cootes Paradise to address the serious decline in the state of the marsh ecosystem (Laking, 1976; RAP, 1992). These are summarized below:

1. Maintain the water and marsh habitat as a wildlife sanctuary by protecting the flora and fauna from all activities which interfere with ecological interactions.
2. Provide limited public access and interpretive facilities for public education and quiet appreciation.
3. Provide natural aquatic and terrestrial habitats for studies in environmental science
4. Achieve diversity in flora and fauna through water quality improvement.
5. Reduce coliform counts to allow for safe handling of specimens and to allow for safe activities such as quiet boating.

The RBG clearly recognized the value of protecting Cootes Paradise as an important marsh ecosystem. The wording of the goals and objectives indicate much needs to be done to protect the remaining flora and fauna. Coincident with these goals are those outlined by the Hamilton Harbour Remedial Action Plan (RAP) under which Cootes Paradise falls (RAP, 1992). The RAP was developed for Hamilton Harbour to improve the water quality, sediment quality and health of wildlife in the watershed. As a result of the RBG and RAP goals and objectives, many programs have been carried out in the past, are underway presently and are planned for the future which attempt to restore lost features of the marsh. The ultimate goal for Cootes Paradise is to restore this wetland to something approaching its original state.

The restoration of degraded aquatic environments, particularly wetlands, has already been shown to be challenging (Chapter 1), and great care must be taken to ensure that the resulting ecosystem will be able to continue to function with little human interference. In order to do this successfully, it is important to evaluate the situation in order to determine the best place to start. Since vegetation is often an important part of an aquatic ecosystem and its loss can lead to many detrimental consequences, the most logical place to start in restoring a wetland would be with the vegetation.

2.2 Factors Affecting Vegetation in Cootes Paradise

In order for restoration to be successful, the root causes of the problems must first be identified and remedial actions must occur at this bottom level. In Cootes Paradise, three main factors appear to be impacting vegetation: regulated water levels, high concentrations of nutrients, and high concentrations of suspended solids. These factors do contribute to a decrease in vegetation however they may not be the root causes of the vegetation problems in Cootes Paradise. They may be the consequences of other factors in and around the marsh. The problem is complex.

2.2.1 Water Level Fluctuations

Water level fluctuations can dramatically alter plant communities in marsh areas (Kusler *et al.*, 1994; Mitsch, 1992; Keddy, 1990; Burton, 1985; Hardy, 1982). High water levels eliminate woody plants thus increasing the marsh area, they kill dominant species such as *Typha* thereby increasing marsh diversity, and they also eliminate emergent plants allowing temporary replacement by floating and submergent species (Wilcox, 1993, 1990; Keddy, 1990; Busch *et al.*, 1990; Keddy and Reznicek, 1985). Low water levels kill submergent plants and expose seeds buried in the sediment allowing them to germinate and grow into dense stands of emergents (Wilcox, 1993, 1990; Keddy, 1990; Busch *et al.*, 1990; Keddy and Reznicek, 1985). These natural fluctuations between highs and lows in an aquatic ecosystem can be very healthy and non-threatening to the survival of the plant community and in many cases are important to the function of the wetland (Keough, 1990). If water level fluctuations are altered, the healthy pattern of high and low water levels can be drastically changed and major transformations may result (Yonker, 1993; Wilcox, 1993, 1990; Keddy, 1990).

Great Lakes wetlands experience water level fluctuations over several time scales including annual and seasonal cycles, and shorter term seiches (Keough, 1990). When these phenomena occur under natural conditions wide fluctuations can occur thereby contributing to vegetation changes such as those described above. In Lake Ontario, the St. Lawrence Seaway Commission has regulated water levels (since 1959) (i) to prevent extreme high-water levels from increasing shoreline erosion and (ii) to maintain a level high enough to permit commercial navigation and hydropower production (Wilcox, 1993; Busch *et al.*, 1990). After regulation began, the range of water levels in Lake Ontario decreased from about 2 m to approximately 0.9 m in the late 1970's (Wilcox, 1993). Wilcox (1993) noted that with the disappearance of alternating flooded and dewatered periods that were once common in Lake Ontario many superior plant competitors such as cattail (*Typha* spp.) and purple loosestrife (*Lythrum salicaria*) have established thriving populations disrupting the growth of the original diverse wetland plant community.

Water levels in Cootes Paradise are determined by water levels in Lake Ontario. The regulation of Lake Ontario has contributed to the decline in vegetation in this marsh. Painter *et al.* (1989) outline the historical fluctuations in water levels in Lake Ontario between 1840 and 1986 in a discussion of the impacts of these fluctuations on the vegetation in Cootes Paradise. During the time periods 1857-1865, 1943-1956, and 1972-1976 the water levels of Lake Ontario were higher than normal, and data presented in Painter *et al.* (1989) and RAP (1992) show that low levels of emergent vegetation correspond to these high water level periods. Between 1895 and 1907, Lake Ontario experienced low water levels and the marsh saw the return of emergent vegetation (Painter *et al.*, 1989), as expected. During the low water level period of 1920-1942, however, vegetation was absent at the eastern end of Cootes Paradise and it appears that the vegetation has lost its ability to recolonize this part of the marsh (Painter *et al.*, 1989). Painter *et al.* (1989) infer that the cause for this decrease in vegetation is a result of water level fluctuations. This is likely, however excess nutrients (Section 2.2.2) and the carp population (Section 2.2.3) may have also contributed to the loss in plant cover at this time. After 1959, the regulated water levels of Lake Ontario may have played a more significant role in the continuing decline of Cootes Paradise due to a decrease in the number of dewatered events and an increased low water level.

Clearly, water level changes can affect aquatic plant communities and this has occurred in Cootes Paradise. The regulated water levels, however, are not the root cause of the problem. In this situation, the root cause is the St. Lawrence Seaway Commission. Changes to amend the problems occurring in Cootes Paradise must therefore be made through the appropriate channels for this government organization. Since regulation of the water levels of Lake Ontario was established for navigation, it is unlikely water level controls will be removed.

2.2.2 Excessive Nutrient Loadings

Phosphorus and nitrogen are nutrients necessary for successful growth of vegetation. High concentrations, however, can lead to uncontrolled growth and excessive levels may even create an unsuitable growing environment for plants. In aquatic ecosystems, excess nutrients can affect the plant community in a number of ways. Initially, high nutrient concentrations alleviate stresses that may be associated with limiting conditions thereby producing a favourable environment for growth (Wisheu *et* *al.*, 1990). Unfortunately, such favourable conditions can lead to further problems. The primary response to excess nutrients is an increase in algal biomass. Algal blooms, however, increase turbidity in turn decreasing the amount of light available for submergent plant growth. Furthermore, the presence of high concentrations of nutrients intensifies competition between species for available elements. Under such circumstances, those species that are superior competitors (primarily emergent plant species) tend to overcome the available space, producing a plant community with lower species richness (Grime, 1973). Decreases in the number and the diversity of plants can affect higher trophic levels of the ecosystem and may ultimately lead to a decrease in wildlife populations. In order to avoid the problems associated with algal blooms and decreased species diversity in response to increased levels of nutrients, water quality must be maintained to provide favourable conditions for the growth of a more diverse plant population.

Maintaining a certain water quality for nutrients is difficult, particularly when nutrient loadings come from both non-point sources and point sources. Non-point sources are very diverse and not easily identifiable. These sources include storm runoff, precipitation and dry fallout. It is important to know the contribution of these sources to the overall loadings, although they are hard to control. Attention is therefore best directed at point sources for which improvement can be seen on a much smaller and much faster scale. This does not mean, however, that non-point source inputs should be ignored. Improved agricultural techniques and construction methods are needed to avoid increased inputs of solids, nutrients and other pollutants associated with erodable material. Global standards must also be enforced to avoid the input of pollutants from distant sources via precipitation and dry-fallout

In contrast to non-point sources, point sources are described as those which can be identified and which can be improved through various immediate actions. Examples include municipal and industrial effluent pipes, combined sewer overflows (CSOs), as well as rivers and streams. Of these point source examples, inputs from tributaries would be the most challenging to remediate. Excess nutrients in municipal and industrial effluent can be decreased through changes in system processes, and CSO loadings can be reduced with the addition of holding tanks or the implementation of separated sewer systems. Care must be taken in these types of remedial actions, though, to find the most economic yet most effective solution.

In Cootes Paradise, nutrient concentration levels are very high. Painter *et al.* (1989) suggested that excessive nutrients, which lead to algal blooms, are contributing to high turbidity thereby limiting submergent plant growth. Before aquatic vegetation can return to Cootes Paradise, the excess nutrient loadings must be reduced. High nutrient concentrations must be reduced at the primary sources. For

Cootes Paradise, excess nutrients enter the marsh from the Dundas STP, surrounding creeks, combined sewer overflows (CSOs), and stormwater runoff. Of these nutrient sources, the most important one is the Dundas STP (Painter *et al.*, 1989; Painter and Hampson, 1990; McLarty and Thachuk, 1986; Mudroch, 1981; Semkin *et al.*, 1976; Bacchus, 1974; Sims, 1949). The Dundas STP has undergone several system improvements, however, and it is possible that this source is not as large a contributor as it once was. An evaluation of the potential sources would provide such information. One method used to determine from where the majority of the loadings are coming is a nutrient mass balance model. Such a model for phosphorus was developed and is discussed in Chapter 3.

2.2.3 Suspended Solids

High concentrations of suspended solids create several problems in an aquatic ecosystem. The most obvious effect of high suspended matter is turbidity (Boto and Patrick, 1979). As already mentioned, high turbidity decreases light penetration which in turn leads to a decrease in photosynthesis and changes in the temperature regime of the water (Semkin *et al.*, 1976). Solid particles also carry adsorbed nutrients and pollutants which can create an unsuitable environment for plant growth. Further, when the particles settle they fill the interstices of the bottom sediments creating an unstable substrate for rooted macrophytes (Lavender, 1987). In addition, particulate matter can negatively impact other aquatic organisms. High suspended solids can affect aquatic wildlife by clogging respiratory membranes and feeding structures, by reducing feeding efficiency and growth rates, and by interfering with egg and larvae development (Newcombe and MacDonald, 1991; McKee and Wolf, 1963).

In Cootes Paradise the root causes of high suspended solids appear to be a result of carp activity, wind action and high suspended solid loadings. Due to the fine particle size of the sediments on the bottom of the marsh (Mudroch, 1981), resuspension occurs quite readily and the particles tend to remain in the water column for long periods of time. In the open areas of the marsh resuspension is due to actions of carp (*Cyprinus carpio*) and of the wind (Semkin *et al.*, 1976). Carp are very destructive in their feeding and spawning actions. They uproot vegetation thereby destroying plant beds (Crivelli, 1983), and their winnowing process during feeding and their thrashing during spawning promote the resuspension of the bottom sediments (Breukelaar *et al.*, 1994; Semkin *et al.*, 1976; Threinen and Helm, 1954; Cahn, 1929). In the 1950s, the RBG was aware that the carp were having a negative impact on the marsh vegetation and they carried out a removal program (Lamoureux, 1961). Although the effort proved beneficial, this program was time consuming and laborious, and soon ended. Recently, a barrier was built on the marsh side of the Desjardins Canal at Hamilton Harbour to exclude large carp from Cootes Paradise.

Resuspension due to wind action is also important in Cootes Paradise due to the shallow nature of the marsh and its orientation to the predominate wind directions (Painter *et al.*, 1989). The openness of Cootes Paradise also contributes to the potential for resuspension of bottom sediment (Dieter, 1990). The problem is further complicated by the fact that the surficial sediment of the marsh is comprised primarily of sand, silt and clay (Mudroch, 1981). These grain sizes are easily resuspended and once in the water column tend to stay there for long periods of time. Unfortunately, a solution is not easily found for reducing the resuspension of sediments due to wind action in order to decrease turbidity enough to allow for the growth of submergent macrophytes. Once vegetation begins to establish itself in Cootes Paradise, however, protection of the sediments will be an accompanying factor and further benefits will accrue.

Although carp and wind actions appear to be significant contributors to high suspended solids in Cootes Paradise, they are not the only root causes of the problem. A large portion of suspended solids in Cootes Paradise is also coming from outside sources. The main sources of suspended solids loadings have been recorded as the creeks (49%), urban runoff (24%), and combined sewer overflows (19%) (RAP, 1992). Clearly the input from the creeks is the primary outside source of suspended solids and Spencer Creek is noted as contributing the largest amount out of the three major creeks (Semkin *et al.*, 1976). Spencer Creek flows through a highly agricultural area (Lavender, 1987) and gathers a large amount of solids from exposed fields and pastures. Erosion from poor development practices (i.e. pregrading of construction sites) and poor site management in the watershed area will also contribute to high suspended solids loads.

2.3 Conclusions

Clearly, the above three factors, regulated water levels, excess nutrients and high concentrations of suspended solids, have in the past and are presently affecting vegetation in Cootes Paradise. Each factor, however, is not necessarily the root cause of the problem. Water level fluctuations depend on the regulation of the water levels of Lake Ontario and changes in this area would have to be made through the authorities responsible for controlling the regulation. Excess nutrients are entering Cootes Paradise from the Dundas STP, surrounding tributaries and CSOs, as well as all activities in the watershed that lead to contaminated urban and rural stormwater runoff. Contaminants in stormwater runoff are the result of such things as the use of fertilizers and pesticides on fields, crops and lawns, and the operation of motorized vehicles which produce air pollutants that ultimately settle onto the ground to be washed into receiving bodies by rain. Finally, the root causes of excess suspended solids include agricultural and construction processes leading to extensive soil erosion, dry fallout of particulate matter, wind action, and the spawning and feeding behaviours of carp.

Since the loadings to Cootes Paradise of phosphorus and suspended solids have yet to be effectively addressed in the restoration plans for the marsh, further examination has been given to these factors through the use of a system modelling approach. This approach focused on mass balance models and hydrodynamic and pollutant transport models.

3 Mass Balance Modelling

Systems modelling provides an excellent basis for evaluating environmental problems and allows the user to simulate different remediation scenarios. The results of modelling studies can help in making decisions about the effectiveness of different remedial actions. For the restoration of Cootes Paradise it is important to identify from where the excess nutrients and suspended solids are coming and to where they are going once they have entered the ecosystem. For evaluating the sources of these substances, a mass balance model was used (this chapter), and a hydrodynamic/pollutant transport model was used to follow the path of the phosphorus and suspended solids once they entered the marsh (Chapter 4).

3.1 Mass Balance Modelling

The role of excess nutrients as a factor controlling the productivity of aquatic ecosystems has become central in limnological studies (Ahlgren *et al.*, 1988) and mass balance models are valuable in the analysis of the nutrient status of such environments. The mass balance approach enables the investigator to determine if a particular system annually accrues substances, is at steady state or releases substances to receiving bodies (Whigham and Bayley, 1979). This approach is also useful for identifying the various inputs to the system and for determining the relative degree of importance of each source. The information then becomes valuable in the restoration and the management of degraded aquatic environments.

Mass balance models are based on the theory of the conservation of mass (Vollenweider, 1975; Tchobanoglous and Burton, 1991; Van Huet, 1992; Prairie, 1989; Ahlgren *et al.*, 1988; Golterman, 1980). In general, this theory states that whatever enters the system must be accounted for in the output and in the internal system combined. Most mass balance models consider the system of interest as one compartment, but due to changes within the system itself (i.e. due to lake stratification) this approach may produce oversimplified results. Imboden (1974) addresses this issue by indicating that regions of homogeneous chemical and biological conditions should be separated into different compartments of the model. He goes on to develop a mass balance model which applies to a stratified lake with the epilimnion as one compartment and the hypolimnion as another. Using an approach similar to that outlined by Imboden (1974), Lorenzen *et al.* (1976) and Minns (1986) developed lake models which separate the water column and the sediments into two compartments. Since Cootes Paradise is too shallow to become stratified, the water column could be considered one homogeneous region and the sediments a second region. Therefore the water-sediment approach used by Lorenzen *et al.* (1976) and Minns (1986) was applied to the calculations for the Cootes Paradise data.

3.2 Inputs and Outputs for Cootes Paradise

Phosphorus and suspended solids loadings to Cootes Paradise come from both external and internal sources (Figure 3.1). External loads include the surrounding tributaries, the Dundas STP, stormwater runoff, CSOs, and precipitation, and internal loads come primarily from the sediments. Of the many creeks which empty into the marsh most are insignificant contributors as they dry up soon

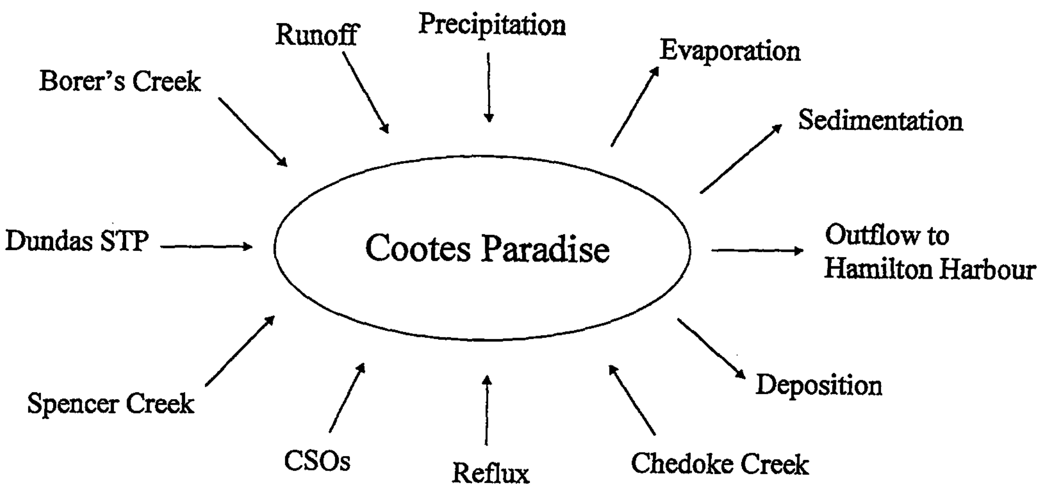

Figure 3.1 A schematic representation of the inflows and outflows considered in the phosphorus and suspended solids mass balance models for Cootes Paradise.

after spring runoff (Bacchus, 1974), therefore only the three main creeks, Spencer Creek, Borer's Creek and Chedoke Creek, were considered.

The inputs of pollutants to the system are modified by internal and outflow losses to produce an overall final concentration in the water. Upon entering the water column, phosphorus and suspended solids are subject to the forces of gravity and therefore settle to the surface of the sediments. The amount of pollutant lost due to sedimentation depends on the particle settling velocity and on the depth of the water column. A certain portion of the surface sediments will continue to be active in resuspension whereas those sediments below the active layer will be permanently lost to surface forces. Phosphorus and suspended solids will also be lost due to the natural outflow of the system (flushing). Finally, a proportion of the water in Cootes Paradise will be removed by evaporation. It was assumed, however, that no pollutants were lost by evaporation therefore this component only affected the overall flow of the system.

3.3 Mass Balance Calculations

Several restrictions and assumptions were made for the overall mass balance calculations in order to keep the model as simple as possible. As is done with most mass balance models, a fully mixed system was assumed. Equilibrium concentrations were therefore taken to be uniform throughout the entire waterbody. It was also assumed that no backflow occurred from Hamilton Harbour into Cootes Paradise. Furthermore, the time period for the mass balance was restricted to the months of May to September. In most cases, these were the only months for which data were collected and limiting calculations to this time frame meant that factors such as snow melt and ice cover could be ignored.

In addition to the above mentioned assumptions many individual components of the model calculations required assumptions and estimations. This was largely due to the fact that the data set for Cootes Paradise is incomplete. Details regarding these assumptions and estimations are described, as necessary, in the following sections.

3.3.1 Dundas STP, Creeks and Rainfall

In order to determine the load of pollutant contributed by each external source, flow rates and pollutant concentrations were required. For the Dundas STP, the flow rates and concentrations of the final effluent were obtained from annual operating reports maintained by the plant staff.

Spencer Creek has been observed by several organizations for many years and the data set is therefore quite extensive. The flow rate is monitored on a continuous basis by the Water Survey of

Canada (WSC) and water quality data have been collected by the Hamilton Region Conservation Authority (HRCA) and the Royal Botanical Gardens. The concentration data collected by the HRCA, however, are very sporadic and the statistical validity is questionable (Prent, 1994). The data collected by the RBG were therefore used in the mass balance calculations.

Unlike Spencer Creek, virtually no data have been collected for either Chedoke Creek or Borer's Creek. Studies which have included these two creeks (D. W. Draper & Associates Ltd., 1993; Paul Theil Associates Limited and Beak Consultants Limited, 1991; Robinson and James, 1984; James, 1980) have focused primarily on stormwater management. The data set for Borer's Creek remains sparse. As a result of the data limitations for these two tributaries, estimations were made based on the available sources (D. W. Draper & Associates Ltd., 1993; Paul Theil Associates Limited and Beak Consultants Limited, 1991; Robinson and James, 1984; James, 1980).

Rainwater has been shown to contain a small amount of phosphorus and particulate matter (Pareja *et al.,* 1994; Likens *et al.,* 1985; Schlesinger, 1978; Junge, 1963; Herman and Gorham, 1957) and as a result, rain was considered as an input load to Cootes Paradise. The flow rate for rain was determined from the average amount of rain falling on the surface of Cootes Paradise. Concentrations for phosphorus and suspended solids were estimated based on data contained in Pareja *et al.* (1994) and Herman and Gorham (1957).

3.3.2 Runoff

Watershed landuse can be broadly separated into rural and urban, both of which have different characteristics with respect to stormwater runoff. For the mass balance calculations the runoff component of the model included only the portion of the Cootes Paradise watershed which was comprised of rural land. A study done by Meikle (1985) indicated that approximately 24% of the Spencer Creek watershed was considered urban in 1984. Accounting for the other subwatersheds of Cootes Paradise (i.e. Chedoke and Borer's watersheds) as well as further development from 1984 to the present, the urban component of the Cootes Paradise watershed was assumed to be 30%. Therefore 70% was taken to be rural land which thereby contributed to rural runoff.

Runoff flow rates were then determined based on the amount of rain falling on the rural portion of the watershed. Due to the processes of infiltration, storage and evaporation, though, the actual flow was taken to be a percentage of the total flow. The percentages used varied with month and were calculated based on a comparison between estimated creek baseflows and storm flows. The concentrations for phosphorus and suspended solids in rural runoff were taken from the Regional Municipality of Hamilton-Wentworth Pollution Control Plan (Paul Theil Associates Limited and Beak

Consultants Limited, 1991), and the rainfall data were taken from meteorological reports available from the Royal Botanical Gardens.

3.3.3 Combined Sewer Overflows (CSOs)

Inputs from the CSOs were determined in the same manner as used for runoff. Since 30% of the Cootes Paradise watershed was taken to be urban land, rain falling on this area was assumed to contribute to CSOs. Not all rain events, however, create overflows from the sewer systems, therefore only a percentage of the rain falling on the urban areas was used in the loading calculations. Based on Paul Theil Associates Limited and Beak Consultants Limited (1991), the percentage of rainfall contributing to CSOs was taken to be 5%.

The CSO flow was divided further to account for differing contributions from sanitary sewage and stormwater. According to Paul Theil Associates Limited and Beak Consultants Limited (1991), stormwater comprises about 93% of CSOs with a phosphorus concentration of 0.33 mg/L and a suspended solids concentration of 100 mg/L. Sewage makes up the remaining 7% with phosphorus and suspended solids concentrations of 6.0 mg/L and 302 mg/L respectively.

3.3.4 Sedimentation, Deposition and Reflux Coefficients

Internal loads and losses must be considered in order to make the mass balance as complete as possible. These components were incorporated in the calculations using coefficients which represented each relevant process; sedimentation, deposition and reflux (Minns, 1986). The sedimentation coefficient was determined from settling velocities and the mean depth of the marsh. Procedures outlined in Vollenweider (1975) suggested that the settling velocity of phosphorus was about 0.027 m/day (10 m/yr.). Dillon and Kirchner (1975) recorded a higher settling rate of 0.036 m/day (13.2 m/yr.) and Chapra (1975) stated an even higher value of 0.044 m/day (16 m/yr.). It should be noted that the settling velocities presented in each of these studies were based on procedures centered around a net sedimentation loss. Therefore the settling rates were not separated from a reflux component and thus do not apply to the method used for Cootes Paradise. In contrast, Imboden (1974), who separated sedimentation from reflux, gave a range of actual phosphorus sedimentation velocities between 0.1 - 0.4 m/day, an order of magnitude higher than the apparent settling velocities given by Vollenweider (1975), Dillon and Kirchner (1975) and Chapra (1975). Since the settling velocity used by Minns (1986) fell within the range given by Imboden (1974), it was also used in the Cootes Paradise calculations.

The settling velocity for suspended solids was calculated using Stokes' Law,

$$w_s = \frac{g(\rho_p - \rho_w)d_p^2}{18\mu} \qquad \textbf{(3.1)}$$

where w_s is the settling velocity (m/s), g is acceleration due to gravity (m/s^2), ρ_d is the particle density (kg/m^3), ρ_w is the density of water (kg/m^3), d_p is the diameter of the particles (m), and μ is the dynamic viscosity of the liquid (kg/m·s). Suspended solids data collected for Cootes Paradise during the summer of 1995 indicated that approximately 78% of the suspended material was inorganic. Furthermore, the majority of the surface sediments in the marsh are comprised of silt particles (Mudroch, 1981). It was therefore assumed that the average suspended solid particles were silt, and a settling velocity was determined based on size and density values for this type of solid.

The process of deposition was taken to mean the permanent loss of phosphorus and particulate material to the sediments below the active layer. According to Mudroch (1981), the top 10 cm of sediment in Cootes Paradise were soft and aerated by disruption and mixing. A depth of 10 cm was therefore taken to be the depth of the active sediment layer. This coincides with Chapra and Reckhow (1983) who said that the thickness of the surficial sediment layer is typically 1 to 10 cm. Below the first 10 cm of sediment, then, particles become removed from the actions occurring in the water column and become unavailable to reflux generating forces.

In a study discussing the isostatic rebound of the Earth's crust below Lake Ontario, Smith (1995) indicated that the water levels in Cootes Paradise were rising at an approximate rate of 1.8 to 3.0 mm/yr. He also suggested that the rate of sediment deposition in Cootes Paradise was keeping pace with the lake level rise. The depositional coefficient was therefore calculated based on a depositional rate that was assumed to be equivalent to the rate at which sediments were accumulating in the marsh. An intermediate value for Cootes Paradise provided a rate of sediment accumulation of 2.4 mm/yr. This value is not unreasonable as Chapra and Reckhow (1983) indicate that the rate of build up of a lake's sediment is typically 1 to 10 mm/yr.

A portion of the settled phosphorus and the settled suspended materials will be returned to the water column from the sediments as a result of several actions (i.e. diffusion, wind resuspension, biological activity, etc.), collectively taken to be termed reflux (Minns, 1986). The reflux term is difficult to measure in the field, therefore if the external load contributions and the rates at which phosphorus and suspended solids are removed via settling and deposition are known, the reflux coefficient can be calculated using field concentrations and Equation 3.2:

$$R = -D_s + \frac{s \cdot D_s}{\left(\frac{\sum L_i}{C} - F\right)} \tag{3.2}$$

where R is the reflux term (s^{-1}), D_s is the deposition term (s^{-1}), s is the sedimentation term (s^{-1}), L_i are the input loads (mg/L·s), C is the overall concentration (mg/L), and F is the flushing coefficient (s^{-1}). This procedure, along with RBG field data from 1990 to 1992, was used for determining the reflux coefficients for phosphorus and suspended solids in Cootes Paradise.

The sedimentation, deposition and reflux coefficients used for the phosphorus and suspended solids mass balance calculations are summarized in Table 3.1. It should also be noted that the volume of Cootes Paradise (1.63 x 10^6 m^3), and the areas of Cootes Paradise (2.08 x 10^6 m^2) and the watershed (2.82 x 10^8 m^2) were determined using a geographic information system (GIS).

Table 3.1 The values of the sedimentation, deposition and reflux coefficients for the mass balance calculations.

Coefficient	Phosphorus	Suspended Solids
Sedimentation (s^{-1})	2.62 x 10^{-6}	1.66 x 10^{-5}
Reflux (s^{-1})	2.92 x 10^{-9}	2.39 x 10^{-8}
Deposition (s^{-1})	7.61 x 10^{-10}	7.61 x 10^{-10}

The input data (i.e. flows, concentrations), and the coefficient values were substituted into Equation 3.3, which was used to calculate the overall concentration in the marsh:

$$C = \frac{\sum L_i}{F + \left(\frac{s \cdot D_s}{R + D_s}\right)} \tag{3.3}$$

where C is the overall concentration (mg/L), L_i are the input loads (mg/L·s), F is the flushing coefficient (s^{-1}), R is the reflux term (s^{-1}), D_s is the deposition term (s^{-1}), and s is the sedimentation term (s^{-1}). The data used in solving this equation were contained in spreadsheet files and outputs from these files are included in Appendix I.

3.4 Results

3.4.1 Overall Concentrations

Table 3.2 outlines the total flows determined by the mass balance as well as the results of the concentration calculations for Cootes Paradise. Field values are also included in Table 3.2 for comparison with the model values. The field values were based on 1989-1992 data from the RBG sampling stations, numbers 1 to 3 (Figure 3.2). Stations 4 to 6 were not included in the field value calculations as they are near the mouth of Spencer Creek, in West Pond and in the Desjardins Canal respectively; these stations were considered to be outside of the system of concern (i.e. not in the main body of Cootes Paradise).

The total flow through the system was the greatest in May and decreased over the summer to a low in August. An increase in flow then occurred from August to September.

In all but four cases (May and June for phosphorus, and July and August for suspended solids), the mass balance model predicted concentrations within one standard deviation from the field values. The percentage error between the model concentration values and the field concentration values fluctuated greatly on a monthly basis from values lower than 1% to those as high as nearly 43%. The average values, however, differed by less than 12% for both phosphorus and suspended solids. Although a percentage error of 12% may seem high, it was considered to be acceptable due to the fact that many assumptions had to be made in order to keep the mass balance model simple, as well as the fact that the data set for Cootes Paradise is incomplete.

For the phosphorus concentrations in the marsh, the model predicted values less than those reported by the field data, with the exception of the concentration for May. The mass balance results for June, July and August agreed very well with the field values, but May and September differed greatly. The phosphorus concentrations also showed an increase from May to June followed by decreases through to August. In September, however, the model showed a decrease in concentration whereas the field data indicated an increase in concentration.

The percentage errors for the suspended solids values were very high, with the exception of September for which the model and field values differed by only 0.31%. For May and June, the model predicted values higher than those which occurred in the field whereas in July and August the opposite was true. For the model values, suspended solids concentrations increased from May to June, decreased over the summer and then increased again from August to September. The field data, however, showed an increase in concentrations from May to August and a decrease from August to September.

Table 3.2 A summary of the mass balance results for phosphorus and suspended solids compared with field values.

Month	Flow (m^3/s)	Phosphorus (mg/L)			Suspended Solids (mg/L)		
		Model	Field†	% Error‡	Model	Field†	% Error‡
May	3.366	0.256	0.206 ± 0.026	24.27	64.98	48.14 ± 19.79	34.98
June	2.403	0.302	0.313 ± 0.049	3.51	83.97	75.35 ± 10.23	11.44
July	1.682	0.291	0.307 ± 0.010	5.21	63.67	91.98 ± 8.75	30.78
August	1.495	0.231	0.238 ± 0.011	2.94	54.87	95.96 ± 13.42	42.82
September	2.210	0.225	0.360 ± 0.340	37.50	60.69	60.88 ± 3.67	0.31
Average	2.231	0.261 ± 0.035	0.285 ± 0.062	8.42	65.64 ± 10.96	74.46 ± 20.29	11.85

† the values listed are average ± standard deviation; the monthly values were calculated from a sample set of field data for each month and the overall average and standard deviation were determined using the monthly values as the sample set.

the standard deviation was calculated using: $st.dev. = \sqrt{\frac{n_x \sum x^2 - \left(\sum x\right)^2}{n_x (n_x - 1)}}$

‡ the percentage errors were calculated between the model values and the field values using: $\%Error = \frac{|Field - Observed|}{Field} x100$

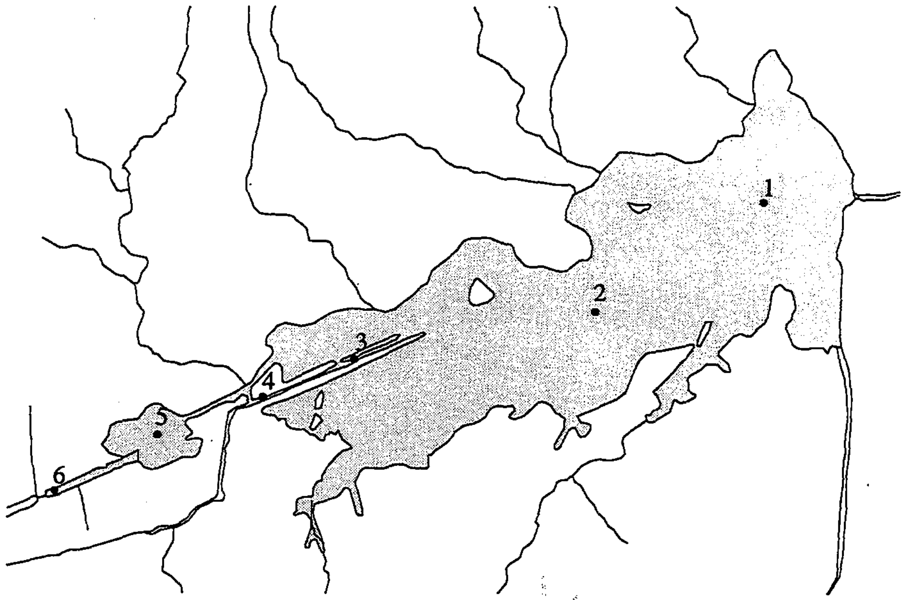

Figure 3.2 The locations of the Royal Botanical Gardens water quality sampling sites in Cootes Paradise.

3.4.2 Relative Loadings

When the loadings to Cootes Paradise were separated into individual source contributions, reflux was shown to account for an average of over 50% of the loadings for both phosphorus and suspended solids (Tables 3.3 and 3.4). As with the overall concentrations determined by the mass balance models, the percentage loadings varied slightly from month to month, however the importance of each source with respect to the others generally did not change. During the spring, snowmelt and high rainfall contribute to large amount of runoff, to CSOs and to higher creek flows. As a result, the combined inputs from these sources during May were expected to be higher than reflux, which is in fact what the mass balance revealed. For the summer months, hotter temperatures and drier conditions contribute to decreased external flows thereby decreasing the relative contributions from the STP, the creeks, CSOs, and runoff. These decreases, in combination with high carp activity, resulted in a larger contribution to the loadings from reflux alone.

Rural runoff followed reflux with approximately 26% of the phosphorus contributions and 33% of the suspended solids loadings. After runoff, the relative importance of each source for the two parameters of interest changed. CSOs were the next important contributor of phosphorus to Cootes

Table 3.3 Percentage loadings (%) for each source of phosphorus to Cootes Paradise.

Month	Rain	STP	Creeks			CSOs		Runoff	Reflux
			Spencer	Chedoke	Borer's	Sewage	Stormwater		
May	0.32	3.79	6.98	1.10	0.05	5.89	4.30	33.19	44.38
June	0.13	2.65	7.28	1.07	0.05	4.00	2.93	31.11	50.78
July	0.17	2.99	11.55	1.24	0.05	7.20	5.26	14.58	56.95
August	0.18	3.82	4.51	1.61	0.07	7.69	5.62	17.82	58.68
September	0.15	3.34	4.39	1.47	0.06	5.23	3.82	29.29	52.24
Average	0.19	3.27	7.94	1.27	0.05	5.88	4.30	25.85	51.25

Table 3.4 Percentage loadings (%) for each source of suspended solids to Cootes Paradise.

Month	Rain	STP	Creeks			CSOs		Runoff	Reflux
			Spencer	Chedoke	Borer's	Sewage	Stormwater		
May	0.14	0.12	4.92	0.87	0.09	1.17	5.14	42.65	44.92
June	0.08	0.08	7.19	0.77	0.08	0.72	3.19	36.49	51.40
July	0.19	0.12	10.12	1.13	0.11	1.66	7.29	21.73	57.64
August	0.19	0.09	5.46	1.36	0.14	1.63	7.17	24.46	59.51
September	0.11	0.09	4.99	1.09	0.11	0.98	4.29	35.41	52.93
Average	0.14	0.10	7.45	1.01	0.10	1.18	5.18	33.51	51.33

Paradise thereafter followed by the creeks, the STP and finally rain. For suspended solids, rural runoff was followed by the creeks, then CSOs, then rain, and finally the STP. Examination of Tables 3.3 and 3.4 indicates that Spencer Creek contributed the majority of the creek loadings for phosphorus and suspended solids, however due to the lack of data, the values for Chedoke and Borer's Creeks could be underestimated.

3.5 Discussion

Many factors, such as temperature, wind and precipitation, are working together in Cootes Paradise to create the trends presented in the results above. At different times, however, one factor may be more prominent than the others in producing the observed conditions.

Several of the monthly variations can be explained by precipitation patterns and since the mass balance model was based heavily on rainfall (i.e. to determine CSOs, runoff and precipitation contributions) this is not surprising. For both phosphorus and suspended solids, the model calculated higher concentrations in May than actually occurred in the field. During the spring, high rainfall and snowmelt increase the flows entering the marsh and as the ground thaws, groundwater contributions increase the flows in the creeks. As a result of these increased flows, the total flow for Cootes Paradise in May was higher than in other months (Table 3.2). High flow will decrease the residence time for substances in Cootes Paradise thereby resulting in a lower overall concentration in comparison to other months. Discrepancies between the field and model values may have resulted from short circuiting of the flow through the marsh. The mass balance model assumes that the system of interest is a fully mixed basin. This condition is not always met, however, and areas may occur for which velocities are lower and recirculation patterns exist (Thackston *et al.,* 1987). Under such circumstances, the volume of the basin through which water flows is much less than the total volume and the resulting residence time is therefore smaller (Thackston *et al.,* 1987). In the mass balance calculations, a shorter residence time means a greater flushing rate and hence a smaller overall concentration.

Increased flows in the spring also explain the resulting relative loadings for May. Reflux alone was the largest loading for every month, but when the May contributions from the sources affected by rainfall, snowmelt and ground thaw (runoff, CSOs, creeks) were combined, they surpassed reflux in relative loadings. This is not true for June, July, August, and September. In addition to higher flows, the phosphorus and suspended solids concentrations of the inputs were also higher in May, and when higher flows are multiplied by higher concentrations a greater mass loading results.

The phosphorus concentrations over the summer were greater in the field than predicted by the mass balance, although the percentage difference was not great. The relative loadings indicate that the major input for June, July and August was reflux from the sediments. Most models describing phosphorus exchange with sediments relate phosphorus release to anoxic conditions in the overlying waters as a result of thermal stratification. Since Cootes Paradise is shallow and generally well mixed due to wind action, anoxic conditions would be rare.

According to Bostrom *et al.* (1982), though, many factors contribute to phosphorus release from the sediments under aerobic conditions. This transport from the sediments to overlying water occurs primarily from dissolved phosphorus existing in the pore water (Bostrom *et al.,* 1982). The amount of phosphorus in the pore water is generally only a small portion of the total sediment phosphorus (Bostrom *et al.,* 1982), however it is the most important; phosphorus in solution is directly exchangeable with the overlying water and it has the highest chemical mobility (Syers *et al.,* 1973). The release of phosphorus from the bottom of shallow, aerobic bodies of water, like Cootes Paradise, is therefore easily induced by factors such as diffusion, wind disturbance and bioturbation (Bostrom *et al.,* 1982).

Diffusion of phosphorus from the sediments will occur when a concentration gradient exists between the sediment and overlying water. Over the summer months, the mass balance for Cootes Paradise indicated that the primary source of phosphorus was from the internal system. Schindler *et al.* (1977) suggest that release from sediments such as this may occur in systems which have a history of high nutrient loading. The sediments act as a buffer by capturing phosphorus from external sources and removing it from the system. Following several years of high loading, the sediments reach a saturation point after which if external source loadings are decreased, release from the sediments occurs (Schindler *et al.,* 1977; Bostrom *et al.,* 1982; Rossi and Premazzi, 1991). The Dundas STP has discharged sewage effluent to Cootes Paradise since 1919. Changes to the plant to improve water quality have occurred several times over the past with the most recent being the addition of tertiary treatment in 1988. Even with these modifications to the STP, the overall water quality of Cootes Paradise has not greatly improved (Painter *et al.,* 1991; Painter and Hampson, 1990). The slow recovery is likely due to continual enrichment of the waters from the sediments, as has been shown in several studies (Ryding, 1981; Ryding and Forsberg, 1977; Ahlgren, 1980, 1977).

Release of dissolved phosphorus from sediments also occurs as a result of wind disturbance and bioturbation (Bostrom *et al.,* 1982). Mixing or stirring due to wind has been mentioned in several studies (Bostrom *et al.,* 1982; Ryding, 1981; Ahlgren, 1980; Holdren and Armstrong, 1980; Sonzogni *et al.,* 1975; Andersen, 1974) as a factor contributing to increased phosphorus release from the sediments. In shallow bodies of water, wind energy is easily transferred to the bottom sediments and mixing may extend throughout the water mass considerably increasing the impact of sediments on water quality (Ryding, 1981). According to Andersen (1974), the stirring of sediments reduces the diffusion distance at the sediment-water interface thereby increasing phosphorus exchange rates. In addition to increasing the diffusion surface, mixing exposes the sediments to chemical changes in the water which may in turn promote increased phosphorus release (Bostrom *et al.,* 1982).

Often more important than wind disturbance, though, is phosphorus release due to bioturbation (Holdren and Armstrong, 1980). Benthic invertebrates contribute to phosphorus release from sediments by increasing mixing of the sediment surface through burrowing, and disturbance by benthivorous fish during feeding and spawning contributes to the overall bioturbation effect (Breukelaar *et al.,* 1994; Bostrom *et al.,* 1982; Holdren and Armstrong, 1980; Sonzogni *et al.,* 1975). Since Cootes Paradise has a large population of carp, bioturbation resulting from carp activities may be contributing significantly to the high summer reflux loading of phosphorus.

Also affecting phosphorus release from sediments are temperature changes. Andersen (1974) noted that temperature increases will liberate inorganic phosphorus from sediments directly, however the release is generally small. He suggested that indirect temperature effects may be more important because of increased biological activity at increased temperatures. Microbial and bacterial activities change the chemical environment in the sediments by consuming oxygen (Bostrom *et al.,* 1982; Holdren and Armstrong, 1980). The decrease in oxygen leads to the release of phosphorus during the reduction of Fe(III) to Fe(II) (Holdren and Armstrong, 1980). Perhaps more important in Cootes Paradise than increased microbial activity with increased temperatures, though, is increased carp activity. Swee and McCrimmon (1966) showed that carp spawning activity increased with temperature and as the water temperatures in Cootes Paradise increase over the summer, increased bioturbation from carp may release sediment phosphorus.

Factors such as those mentioned above (diffusion, wind disturbance, bioturbation) can be used to explain the increase in phosphorus concentrations in Cootes Paradise between May and the summer months, as well as the internal dominance in the relative loadings. It was assumed, however, that in calculating the reflux coefficient, all factors contributing to phosphorus release would have been taken into consideration. Since the percentage errors between field and model values were so close, this estimate was likely a good one. The discrepancies may have been due to inaccurate estimations in other aspects of the model (i.e. estimated concentrations and flows for unknown sources).

The decreasing trend in phosphorus concentrations from June to August, though, is not as easily explained. As temperatures increase over the summer, and as chemical reactions, microbial processes and carp activity correspondingly increase, the release of phosphorus from the sediments would be expected to increase the overall concentrations from June to August. This trend, however, was not observed in Cootes Paradise. It is possible that the decline over the summer may have been due to uptake and trapping by algae and macrophytes or perhaps due to increased flushing of phosphorus from Cootes Paradise to Hamilton Harbour as a result of hydraulic short circuiting.

In September, phosphorus concentrations increased greatly in the field whereas a decrease was predicted by the mass balance model. The increase in field concentrations may be explained by decreased water levels in Cootes Paradise which occur during the fall months. Kadlec (1986) noted that phosphorus levels in small diked marshes decreased when water levels increased, which suggests that if water levels decreased, the phosphorus concentration would increase. This is a reasonable conclusion based on a couple of points. First, lower water levels mean a smaller volume of water in Cootes Paradise. As a result of the decreased volume, little dilution would occur thereby producing a higher concentration. Second, lower water levels would decrease the depth of the water in the marsh. In shallower waters, wind energy would be more easily transmitted to the bottom sediments which in turn would promote phosphorus release due to stirring and mixing. Since the mass balance model does not account for water level changes, the predicted concentration likely underestimated reality.

For suspended solids, the model predicted a decreasing trend in concentrations from June to August whereas the field data indicated an increasing trend. Decreasing water levels over the summer may have contributed to the discrepancies in the trends for the same reasons as mentioned above. It is also possible that the external suspended solids loadings were underestimated in the assumptions thereby creating total loads smaller than actuality. Furthermore, even though carp and wind effects were assumed to be accounted for in the calculations for reflux, it is possible that this method underestimated their contribution.

In the field, the increasing suspended solids concentrations were most likely due to wind and bioturbation effects of carp (Meijer *et al.,* 1990a; Painter *et al.,* 1989). The sediments in Cootes Paradise are primarily comprised of silt and clay sized particles (Mudroch, 1981) which are easily resuspended by both wind and biological activity. According to Lam and Jaquet (1976), velocities of only 2-3 cm/s are sufficient to resuspend similar sediment. As indicated by meteorological data collected by the RBG, the average wind speeds for May to September 1995 were high enough to resuspend the bottom sediments, however the average speeds did not fluctuate greatly from month to month over the given time span. Although periods may have existed for which wind was the major factor causing resuspension (i.e. during storm events), carp were likely more important.

As already mentioned, carp play an active role in bioturbation, and an increase in turbidity has been attributed to carp activity in many studies (Roberts *et al.,* 1995; Breukelaar *et al.,* 1994; Meijer *et al.,* 1990a, b; Threinen and Helm, 1954; Cahn, 1929). Since carp activity has been noted to increase under warmer conditions (Swee and McCrimmon, 1966), increased water temperatures over the summer may account for the larger concentrations of suspended solids in July and August.

The decrease in field suspended solids concentration from August to September may be a result of less carp activity due to cooling temperatures but the increase seen from August to September in the model results is inconclusive. This increase, though, is not large and the value for September still falls within one standard deviation of the average. The increase in the model results was therefore determined to be insignificant.

3.6 Conclusions

On a month to month basis, concentrations for phosphorus and suspended solids as predicted by the mass balance model differed from the field data within a range of approximately 1% to 43%. Variations could be attributed to wind and carp action and to model estimations and assumptions. The mass balance models, however, predicted the average concentrations of phosphorus and suspended solids in Cootes Paradise with a percentage error of less than 12%. This was considered an acceptable level based on the assumptions and estimations necessary for the calculations. Separation of the individual source contributors to Cootes Paradise revealed that over 50% of the phosphorus and suspended solids loadings was contributed to the water column of Cootes Paradise by the marsh sediments. After reflux, the next largest contributor for both phosphorus and suspended solids was rural runoff. The relative percentage of the remaining inputs differed slightly for the two parameters studied.

The mass balance models provided further information on the water quality of Cootes Paradise, however this modelling approach was constrained by many assumptions and estimations. More complex computer models, which eliminate the need for some assumptions thereby producing more detailed results, were next applied to Cootes Paradise. The results follow in Chapter 4.

4 Computer Modelling

Ecosystems are complex environments with many interactions between physical, chemical and biological compartments. This large degree of interconnectedness within ecosystems makes the modelling of such environments challenging. Assumptions can be made to simplify the models greatly, however this is generally done at the expense of a more accurate representation of the ecosystem. As was shown in Chapter 3, a mass balance approach to the water quality of an aquatic environment can provide an acceptable representation of the conditions of the system. Mass balance models, however, are not without limitations; assumptions and estimations required to produce the model and maintain its simplicity reduce the degree of accuracy of the predicted results.

Computers are valuable tools for system modelling as they allow for a more complex representation of the area of concern. Assumptions are still required in computer models, however many of the limitations of the mass balance models can be overcome quite easily in the computer simulations. For example, physical factors such as lake topography and wind-generated currents can be incorporated into the computer models so as to eliminate the generally unreasonable assumption of a fully-mixed system.

For Cootes Paradise, a two-dimensional depth averaged hydrodynamic model was applied to the system in order to determine the likely path that substances would take upon entering the marsh. This model was coupled with a pollutant transport model in order to simulate the distribution of phosphorus and suspended solids throughout the marsh. Further modifications made to the model allowed for the incorporation of inputs from carp resuspension and from wind resuspension due to scouring of the bottom sediments.

4.1 Overview of the Computer Model

The hydrodynamic and pollutant transport models are based on mathematical equations for the conservation of mass, the conservation of momentum and the state of the system (Wu, 1993; Simons, 1980). Assumptions are used to simplify the equations in order to suit the conditions of the specific environment of concern. The equations are then solved using an appropriate numerical method. For Cootes Paradise, a vertically integrated two-dimensional model was used, the details of which are included in Appendix II. Models of this type have also been described by Simons (1980), Simons and Lam (1986), Schwab *et al.* (1989), and Wu and Tsanis (1995). The shallow, well mixed nature of the marsh allowed for the elimination of detailed three-dimensional analyses which consider changes in the vertical dimension such as those arising from thermal stratification.

The body of water is divided into a grid system for which the size of grid cells depends on the degree of acceptable accuracy for the results and on computer time limitations (i.e. smaller grid cells require more computing time). The depth and lateral boundary conditions of the cells are dependent on the topography and location of each cell with respect to its position in the system. The surface and bottom boundaries are dependent on wind and bottom shear stresses. Initial conditions are usually set to zero (Wu, 1993) and input data for wind speed and direction and for input flows and concentrations are supplied to the model by the user. Energy changes in the system as a result of wind, inflows and outflows, in combination with the depth and topography, create a current distribution.

The resulting current distribution may then provide information on the location of eddy circulation patterns, well mixed zones and stagnant zones. The patterns can also identify the potential for short circuiting of flow in the system which becomes important in examining pollutant transport. In addition to current patterns, pollutant distributions can be developed based on the hydrodynamics of the system and the mass loading of a pollutant from various sources. Plots of the pollutant distribution in the system of concern are valuable for use in developing restoration plans. Attention for remediation can be given to those areas which are high in concentration in order to decrease the pollutant levels or actions can be taken to remediate areas for which the pollutant impact is low.

4.2 Application to Cootes Paradise

The data for the computer model of Cootes Paradise were set up to include the same inputs as the mass balance model, however some inputs were altered slightly to accommodate the input format needed by the computer. Since the computer model could more easily accommodate time changes in the data, wet events were separated from dry events rather than incorporate an averaged storm contribution over a whole month as was done in the mass balance calculations in Chapter 3. Rainfall contributing to rural runoff was assumed to be incorporated in increased flows and concentrations in the creeks during storm events. Combined sewer overflow inputs that discharged into creeks were also assumed to be incorporated into the tributary loadings. A separate loading was created for the one CSO which discharges directly into the marsh (Sterling Street CSO). Individual contributions for precipitation, runoff and the CSOs were therefore eliminated while similar information was still included in the overall calculations. Figure 4.1 shows the location of each input source for the computer model and Table 4.1 outlines the flows and concentrations used for wet and dry conditions. Comments are also included in Table 4.1 which indicate the sources that contain the information from which the values were estimated. Plots of the source input data files are included in Appendix III.

The occurrence of rain events was based on meteorological reports produced by the Royal Botanical Gardens for the months of May to September, 1995. The data were organized on an hourly basis with dry weather conditions pertaining to days where no rain data were indicated in the RBG reports and with wet weather conditions on days when rain was recorded. Since no details were

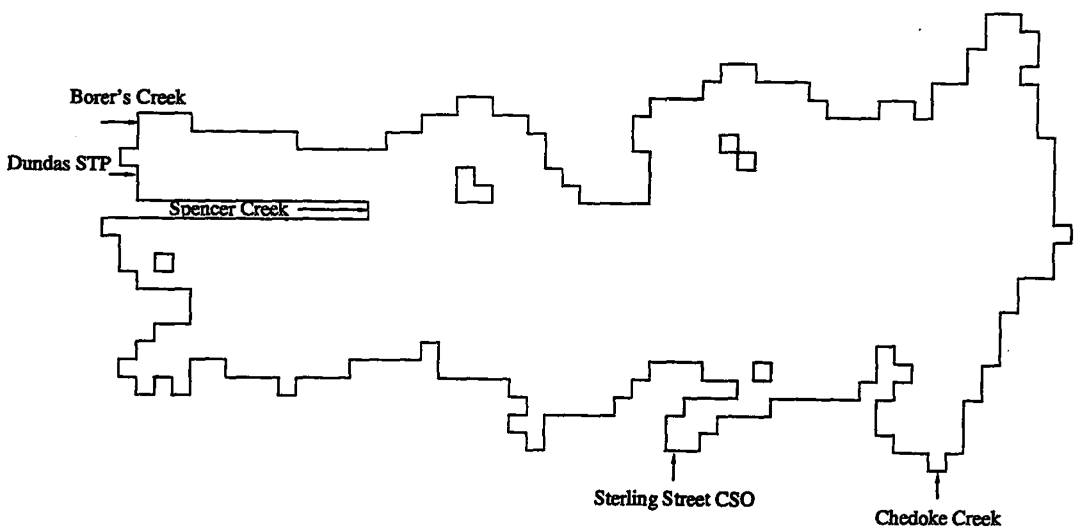

Figure 4.1 The location of the inputs for the computer model of Cootes Paradise.

Table 4.1 Flows, phosphorus concentrations and suspended solids concentrations for Cootes Paradise under dry and wet conditions.

Source	Flow (m^3/s)	Phosphorus (mg/L)	Suspended Solids (mg/L)	Comments
Dry Conditions				
Spencer Creek	0.844	0.145	37.4	- flow based on data from the Water Survey of Canada and concentrations based on RBG data from 1989-1992 and 1995
Chedoke Creek	0.086	0.250	50.0	- James, 1980; Robinson and James, 1984
Borer's Creek	0.013	0.070	33.1	- D. W. Draper & Associates Ltd., 1993
Dundas STP	0.139	0.190	1.5	- estimated from plant reports
Wet Conditions				
Spencer Creek	3.130	0.144	40.0	- flow based on data from the Water Survey of Canada and concentrations based on RBG data from 1989-1992 and 1995
Chedoke Creek	0.759	0.600	150.0	- James, 1980
Borer's Creek	0.700	0.213	113.7	- D. W. Draper & Associates Ltd., 1993
Dundas STP	0.300	0.340	5.0	- estimated from plant reports
CSO	0.247	0.727	114.1	- based on data from Paul Theil Associates Limited and Beak Consultants Limited, 1991

provided in the meteorological reports on the starting or ending times of each rain event, the data were inputted as if the rain event occurred over a full 24 hours of each day that it rained. This assumption does not represent reality but it could be taken to be a worst case scenario for the storm event contributions.

Wind energy is the primary driving force for the computer model and variable wind conditions were based on wind data taken from the RBG meteorological reports. The wind data file was created to provide wind speed (m/s) and wind direction (degrees) in hourly increments for each day of May to September, 1995. The wind patterns are shown in Figure 4.2.

Hydrodynamic patterns for May 1995 were developed at various times throughout the month such that dry and wet conditions would be represented. Corresponding pollutant distributions were also created for phosphorus and suspended solids. Overall average concentrations were determined for the two parameters of concern and modifications were made in an attempt to calibrate the concentrations to field data. A decay component was incorporated in the phosphorus simulations and contributions to suspended solids due to carp and wind scouring of the marsh bottom were included in the suspended solids scenarios.

The contributions to suspended solids concentrations due to carp activity required extra calculations and assumptions, the results of which are shown in Table 4.2. Average carp biomasses for the whole of Cootes Paradise during the summer of 1995 were provided by Theijsmeijer (personal communication). These values were uncorrected for sampling efficiency therefore an efficiency of 20% was assumed. Carp densities were approximately four times greater in nearshore areas than in open water. Inputs from carp were thus assumed to be limited to the outer grid cells of the model (i.e. simulated shoreline areas) and the nearshore biomasses were used. Finally, carp were noted to be present primarily in the first 10 m from shore (Theijsmeijer, personal communication). Since the grid cells for the computer model were 50 m by 50 m, the nearshore biomasses were further adjusted to account for the grid size. The monthly biomass values were then used to determine a concentration of suspended solids produced by carp. Breukelaar *et al.* (1994) found that a significant positive relationship existed between carp and suspended solids and that the relationship could be represented by the following equation:

$$SS = 0.07724 \bullet BIOMASS \quad \textbf{(4.1)}$$

where SS is the concentration of suspended solids (mg/L) and BIOMASS is the biomass density of carp (kg/ha). Concentrations of suspended solids contributed by carp were therefore estimated using the above equation and the calculated nearshore carp biomass densities from Cootes Paradise.

Determination of overall averages from the computer generated data were based on the five month time period, however the first 10 days of values were eliminated in the calculations. Based on the

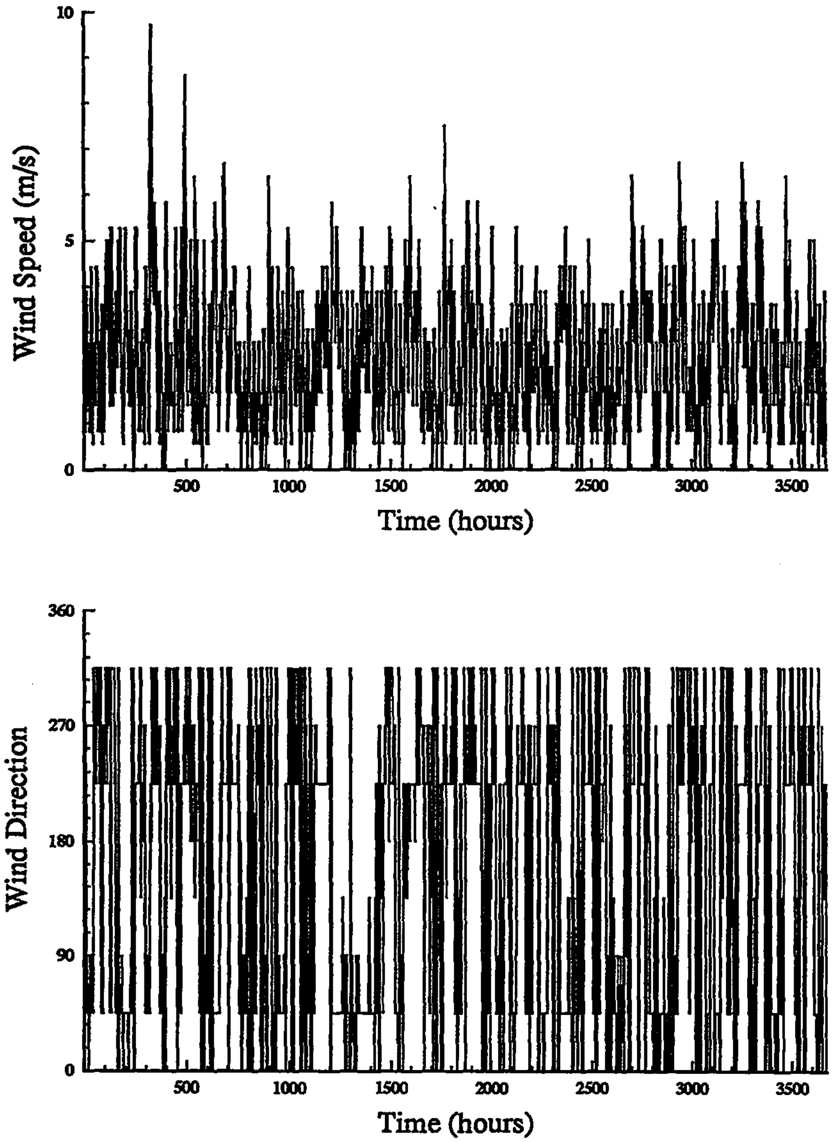

Figure 4.2 Plots for the wind speeds (m/s) and directions (degrees) used in the computer model for Cootes Paradise.

Table 4.2 Determination of suspended solids concentrations contributed to Cootes Paradise by carp.

Month	Biomass[†] (kg/ha)	Corrected for Efficiency[‡] (kg/ha)	Inshore Biomass (kg/ha)	Corrected for Grid[††] (kg/ha)	Concentration[‡‡] (mg/L)
May	118.27	591.35	2365.4	473.08	36.54
June	240.01	1200.05	4800.2	960.04	74.15
July	258.87	1294.35	5177.4	1035.48	79.98
August	477.28	2386.4	9545.6	1909.12	147.46
September[*]	276.83	1384.15	5536.6	1107.32	85.53

[*] a biomass was not available for September therefore a value was determined by averaging data from August and October.
[†] from Theijsmeijer, personal communication
[‡] efficiency was assumed to be 20%
[††] grid cell size of 50 m by 50 m
[‡‡] based on regression relationship in Breukelaar *et al.*, 1994

NOTES:

1. Column 2 (Biomass) was multiplied by 5 to account for 20% electrofishing efficiency in order to obtain the values in column 3.
2. Column 4 was obtained by multiplying column 3 by 4 to account for greater inshore biomasses.
3. Column 4 was divided by 5 to give values corrected for grid cell size in column 5.
4. Values in column 5 were substituted into Equation 4.1 to give concentrations in column 6.

volume of and the total flows through Cootes Paradise, the residence time for the marsh is approximately 8 days. Preliminary work with the computer model for Cootes Paradise indicated that it took 8 to 12 days for the system to reach steady state conditions under variable winds if a continuous input of pollutant was added to the marsh starting with a concentration of zero. The same amount of time was required to completely eliminate a substance from the basin if the continuous input was stopped. On account of these points, the first 10 days of data were considered "warm-up" for the computer model and were not included in the average concentration calculations.

4.3 Results from the Computer Simulations

4.3.1 General Current Patterns and Pollutant Distributions

The current patterns in Cootes Paradise are dynamic and will change continuously based on input flows and on wind speeds and directions. Computer simulations were completed which produced current distributions for the marsh during wind and precipitation conditions for May 1995. The distribution plots corresponding to various times throughout the month are included in Appendix IV.

Pollutant distribution plots for phosphorus and suspended solids are given in Appendix V. Similar patterns resulted for both phosphorus and suspended solids with greater concentrations occurring near the CSO and Chedoke Creek inputs during storm events. Concentrations were typically higher at the east-central and south-easterly areas of the basin. Winds from the southwest and northwest promoted lower concentrations in the western portions of the basin whereas northeasterly and southeasterly winds appeared to encourage higher concentrations in these areas.

4.3.2 Phosphorus

Simulations were run for phosphorus with and without a loss term. Figure 4.3 presents the results from these scenarios. Although phosphorus can be removed from the internal system by settling, by chemical processes, and by biological uptake, the loss term was based on sedimentation only. The measurement of sedimentation rate coefficients is extremely difficult and it is therefore generally determined using models and mathematical relationships (Vollenweider and Dillon, 1974). Vollenweider (1975) suggested that sedimentation rates for phosphorus ranged from less than 0.1 to 1 yr^{-1} and slightly higher. With an increasing number of values, though, it became evident to him that the sedimentation rate coefficient depended on depth to a high degree and Vollenweider therefore established Equation 4.2 for determining the sedimentation rate for lakes:

$$\ln \sigma_P = \ln 5.5 - 0.85 \ln \bar{z} \quad \textbf{(4.2)}$$

where σ_P is the sedimentation rate coefficient (yr^{-1}) and $\bar{z}$ is the mean depth (m). Using an average depth of 0.5 m for Cootes Paradise, Vollenweider's relationship gave a sedimentation rate of approximately 10 yr^{-1} or 0.027 day^{-1} for phosphorus in the marsh. A removal rate of 0.03 day^{-1} was therefore used in the computer simulations for Cootes Paradise. Without removal, the overall computer concentration of phosphorus in Cootes Paradise was 0.334 ± 0.028 mg/L whereas a sedimentation rate of 0.03 day^{-1} decreased this value to 0.265 ± 0:038 mg/L. Field data collected by the RBG in 1995 indicated that the overall average for the marsh is approximately 0.285 ± 0.062 mg/L which encompasses the computer concentrations.

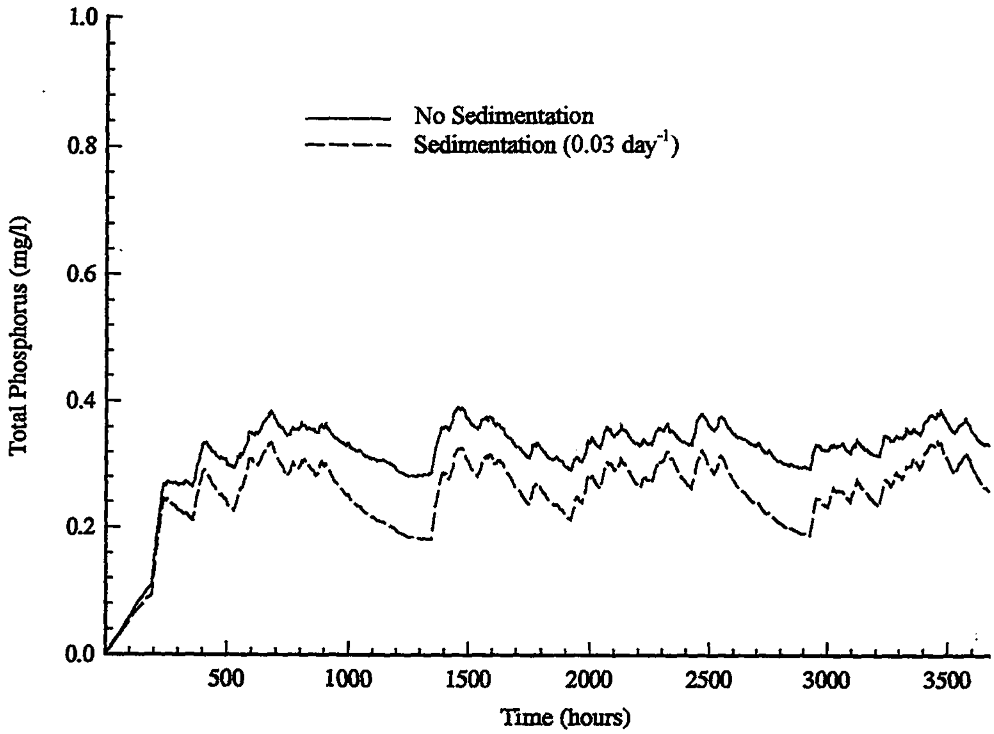

Figure 4.3 Computer simulated phosphorus concentrations in Cootes Paradise without sedimentation and with a sedimentation coefficient of 0.03 day^{-1}. The simulation encompassed May to September, 1995.

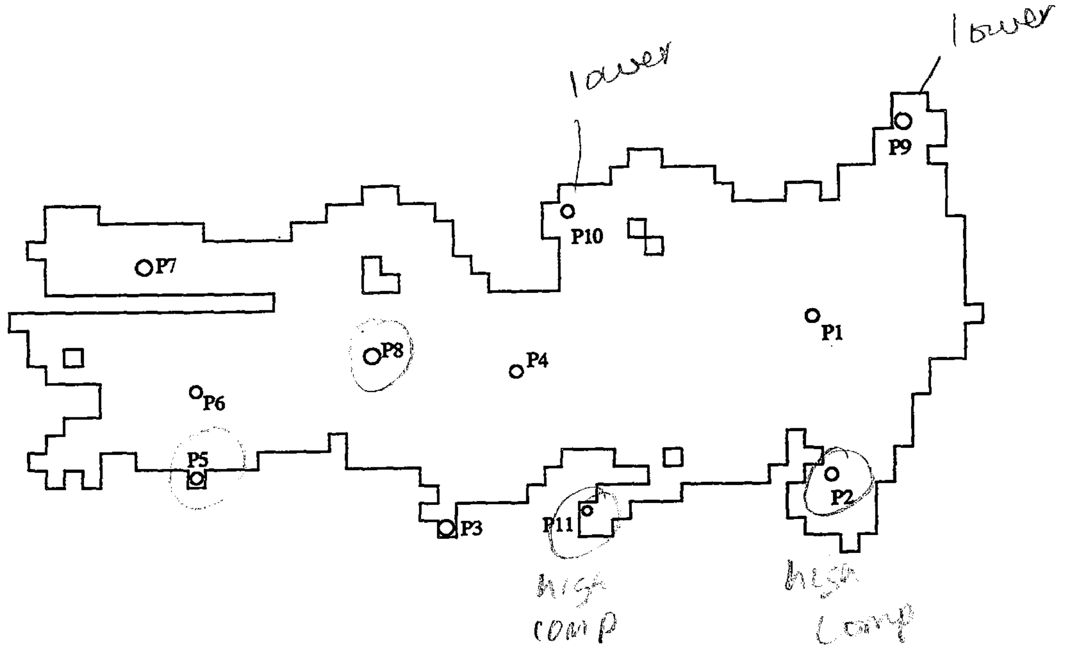

Figure 4.4 Points in Cootes Paradise for which data were saved during the computer simulations.

As shown in the pollutant distributions, phosphorus and suspended solids vary with time and with environmental conditions. Resulting data indicate that the concentration is not uniform throughout the basin (Appendix V). Eleven points were identified within Cootes Paradise for which concentration plots were created (Figure 4.4). Concentration plots for the 11 sites are included in Appendix VI and the average phosphorus concentrations from 9 of these 11 points are given in Table 4.3 along with field values. The field values were determined using chlorophyll *a* data which were collected during the summer of 1995. Chlorophyll *a* represents the presence of algae within an aquatic environment and is indicative of the amount of phosphorus in the system. Since the phosphorus data collected by the RBG for 1995 did not correspond to site locations over the entire marsh, they could not be used to compare with the computer model results. Instead, the RBG data were used to develop a relationship between chlorophyll *a* and total phosphorus from which phosphorus data could be inferred from the chlorophyll *a* data collected. A linear regression between the RBG chlorophyll *a* and total phosphorus data, as calculated using a spreadsheet program, indicated that a weak ($r^2 = 0.383$) but significant ($p < 0.0001$) relationship existed. This relationship was therefore used to determine field data for comparison with the 9 sites. An overall field average for the entire marsh using chlorophyll *a* data and the regression equation was calculated to be 0.263 mg/L.

Table 4.3 A comparison of the computer determined phosphorus concentrations with field values for nine sites in Cootes Paradise.

Site	Computer Concentrations (mg/L)	Field Concentrations (mg/L)
P1	0.342 ± 0.056	0.247
P2	0.421 ± 0.173	0.293
P3	0.156 ± 0.016	0.259
P4	0.200 ± 0.026	0.268
P5	0.176 ± 0.030	0.305
P8	0.200 ± 0.019	0.306
P9	0.251 ± 0.054	0.236
P10	0.158 ± 0.026	0.263
P11	0.590 ± 0.184	0.259
Average	0.277 ± 0.148	0.271 ± 0.025

4.3.3 Suspended Solids

A computer simulation was carried out such that the overall concentration of suspended solids in Cootes Paradise could be determined based on loads from the external sources only, with no settling

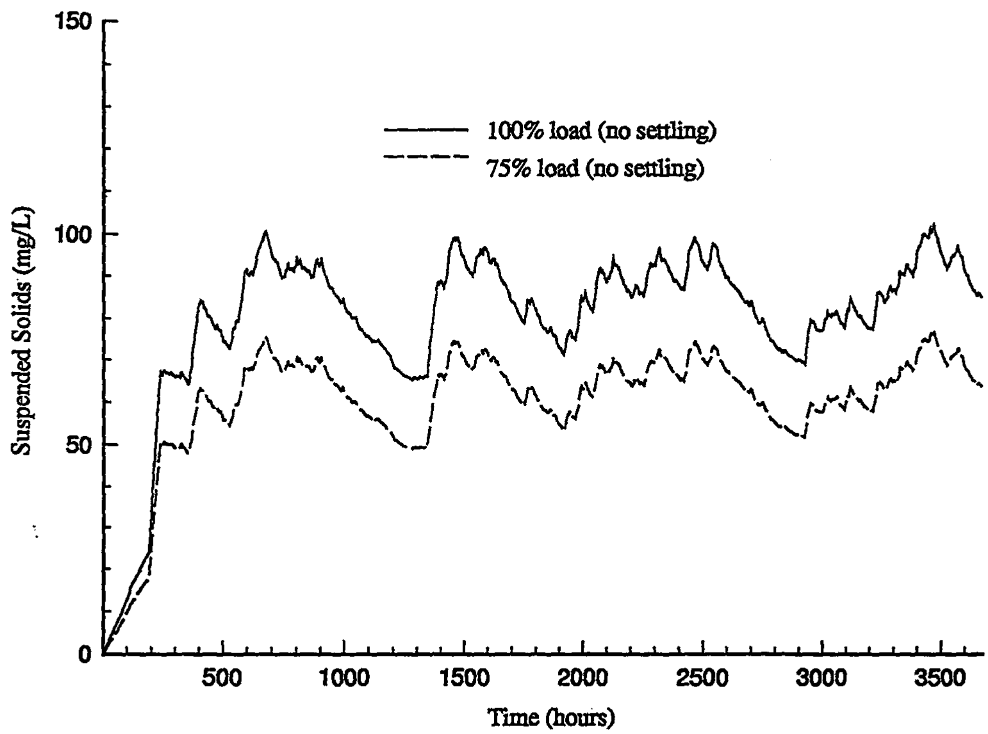

Figure 4.5 The suspended solids concentrations in Cootes Paradise predicted by a computer simulation which used 100% and 75% of the input loads for May to September, 1995.

included. When 100% of the inputs were used the resulting concentrations had an approximate average of 85 mg/L. A reduction to 75% for the inputs decreased the overall concentrations to levels around 60 mg/L (Figure 4.5).

Suspended particles entering the system will eventually settle, therefore simulations were run to determine the effect of different settling velocities on the concentrations in Cootes Paradise (Figure 4.6). Three settling velocities calculated using Stoke's Law (Equation 3.1) were tested, 2.079×10^{-6} m/s, 8.317×10^{-6} m/s and 1.331×10^{-4} m/s. These values corresponded to fine silt (0.002 mm - 0.006 mm), medium silt (0.006 mm - 0.02 mm) and coarse silt (0.02 mm - 0.06 mm) sized particles, respectively. A large drop in concentrations occurred between the curves for no settling and for a settling velocity of 2.079×10^{-6} m/s. Further decreases in concentrations occurred when the other settling velocities were applied, with almost complete removal of suspended solids under a settling velocity of 1.331×10^{-4} m/s. The majority of particles in Cootes Paradise are clay and silt sized (Mudroch, 1981). A settling velocity corresponding to fine silt was assumed to represent the distribution of sizes in the silt and clay particle categories and was therefore used in the simulations.

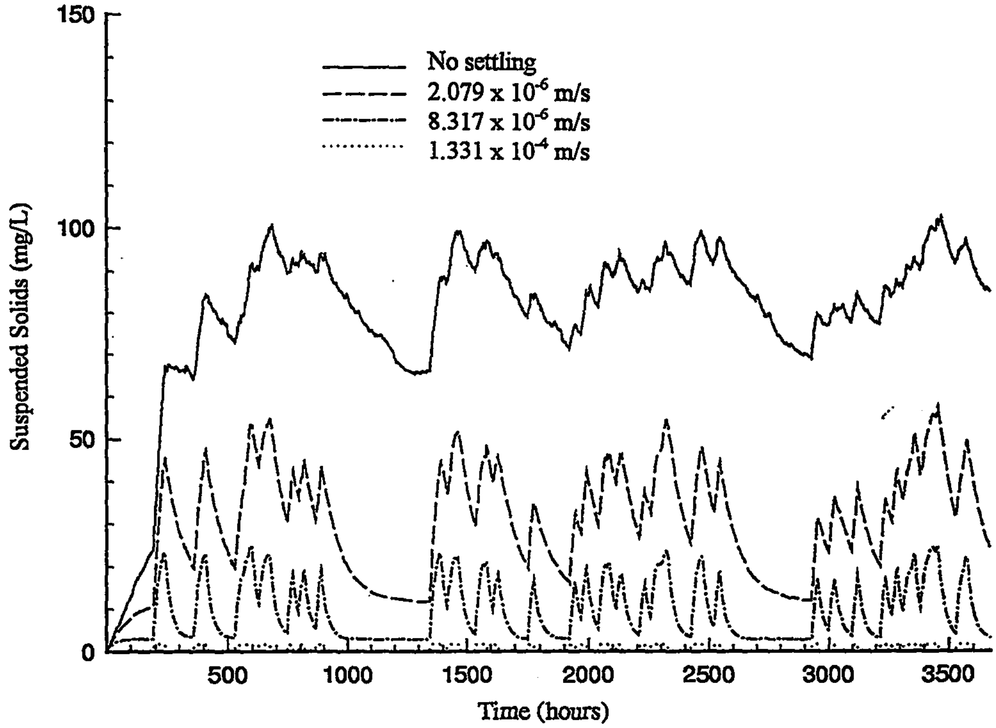

Figure 4.6 The resulting suspended solids concentrations in Cootes Paradise when different settling velocities were applied to the inputs. The settling velocities corresponded to fine silt (2.079×10^{-6} m/s), medium silt (8.317×10^{-6} m/s) and coarse silt (1.331×10^{-4} m/s).

Since Cootes Paradise has a large population of carp and since carp contribute to suspended solids through their spawning and feeding activities, an input which accounted for contributions due to carp was also included in the simulations. Figure 4.7 outlines the results of a simulation which used 75% of the external loads along with a settling velocity of 2.079 x 10^{-6} m/s and a carp contribution for 24 hours/day. Without the input from carp, the average concentration in the marsh was 24.24 ± 8.42 mg/L. Contributions from carp increased the average concentration to 110.80 ± 34.00 mg/L. Carp, however, are not likely active for 24 hours/day, but instead may be active for about 6 hours/day (Minns, personal communication). Figure 4.8 shows the resulting concentrations for 75% of the external loads, a settling velocity of 2.079 x 10^{-6} m/s and carp activity for 6 hours/day. The average concentration for suspended solids in Cootes Paradise with carp contributions for 6 hours/day was 45.48 ±10.83 mg/L, much less than the concentration for a 24 hour/day contribution.

Settling velocities, to this point, had been based on Stoke's Law (Equation 3.1) which estimates the settling velocity for a given particle size under ideal conditions and under gravitational forces only. Ideal conditions do not exist in Cootes Paradise. Currents will keep particles in suspension for a longer period of time thereby decreasing their effective settling velocity. A modified settling velocity which

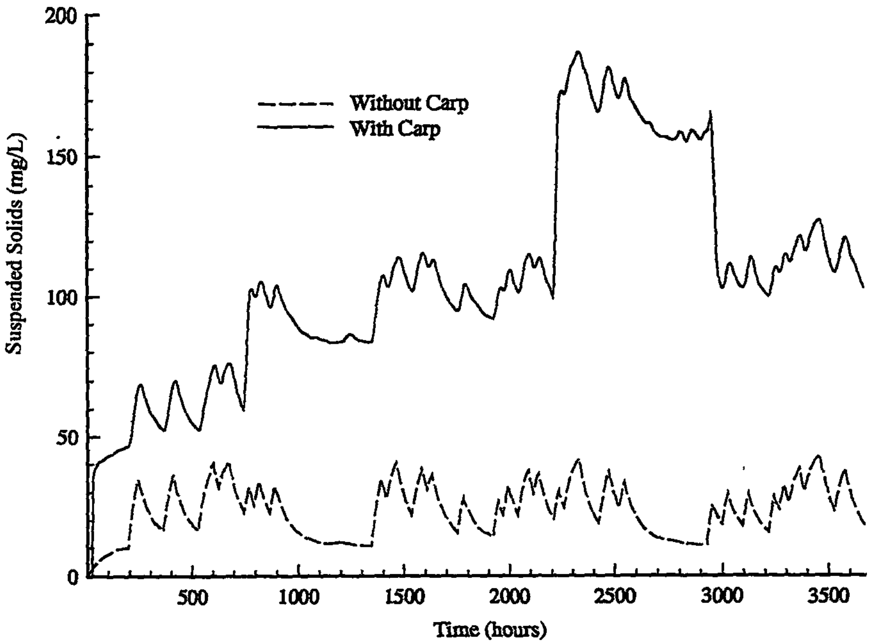

Figure 4.7 Results from a suspended solids simulation for which carp contributions were included for 24 hours/day.

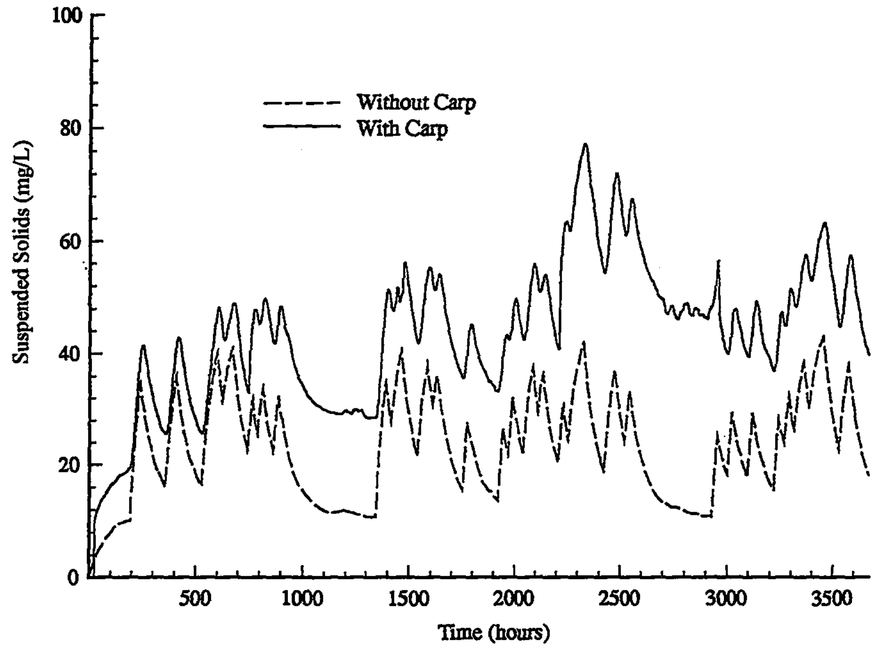

Figure 4.8 Results from a suspended solids simulation for which carp contributions were included for 6 hours/day.

incorporates the effects of wind on particle settling was therefore applied to Cootes Paradise. The modified settling velocity did increase the overall concentrations in the marsh, however the difference was not large (Figure 4.9). The average concentration with a settling velocity of 2.079 x 10^{-6} m/s was 24.24 ± 8.42 mg/L whereas the average concentration with the modified settling velocity was 27.08 ± 9.04 mg/L. Although the modified settling velocity did not affect the overall concentrations greatly, it was used for the final computer simulations.

Not only will external sources and carp contribute to suspended solids but the wind will contribute to loads via resuspension through scouring of the bottom sediments. Further modifications were made to the computer model to include resuspension due to wind. The final concentrations in Cootes Paradise with 75% of the external loads, carp contribution for 6 hours/day, a settling velocity of 2.079 x 10^{-6} m/s modified for current effects, and wind resuspension are shown in Figure 4.10. The overall average concentration for this simulation was 67.86 ± 18.93 mg/L.

As with the phosphorus scenarios, concentration plots at 11 points in the marsh were made for suspended solids. These plots are included in Appendix VII. Overall averages for the corresponding field sites are given in Table 4.4 along with field data which were collected during the summer of 1995.

Agreement with the field data is very good with only one site falling outside one standard deviation for the averages. The average for the entire marsh based on the field values was 79.31 ± 43.02 mg/L.

Table 4.4 A comparison of the computer determined suspended solids concentrations with field values for nine sites in Cootes Paradise.

Site	Computer Concentrations (mg/L)	Field Concentrations (mg/L)
P1	82.35 ± 25.23	61.84 ± 31.95
P2	80.20 ± 28.13	89.87 ± 70.83
P3	61.78 ± 17.66	89.99 ± 14.66
P4	64.90 ± 21.24	58.58 ± 39.16
P5	54.34 ± 13.16	120.26 ± 48.41
P8	74.02 ± 26.38	129.15 ± 55.54
P9	61.30 ± 17.50	62.49 ± 28.75
P10	60.49 ± 17.11	126.5 ± 91.70
P11	82.35 ± 25.23	83.21 ± 7.65
Average	69.08 ± 10.74	91.32 ± 28.17

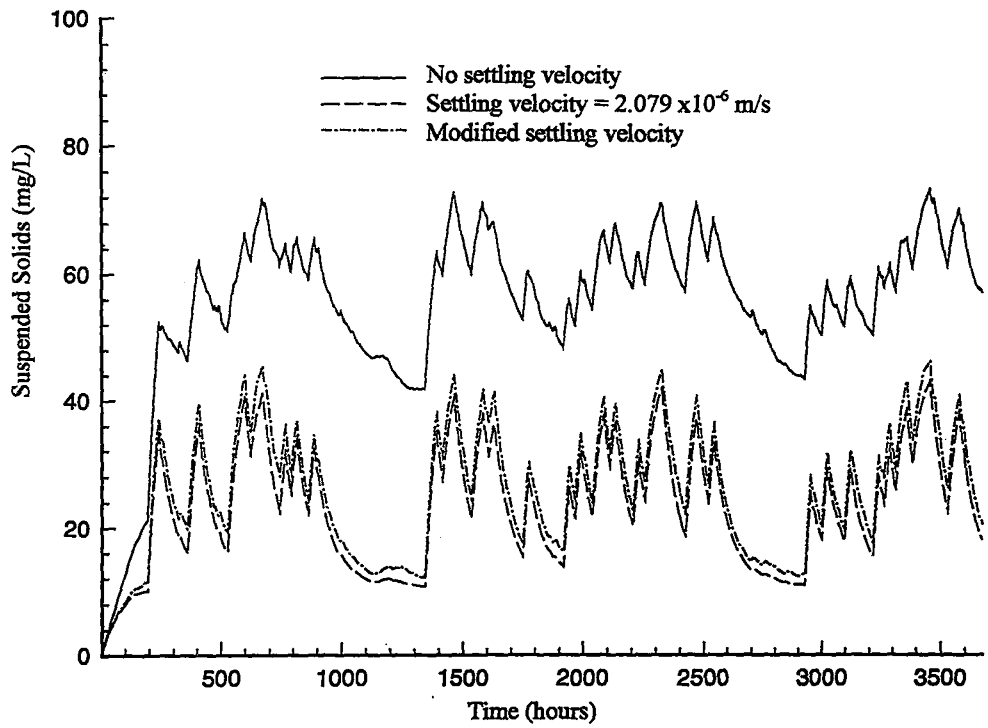

Figure 4.9 Changes to the suspended solids concentrations when a modified settling velocity is applied to the data. Curves with no settling and with a settling velocity of 2.079 x 10^{-6} m/s are shown for comparison. The modified settling velocity considers wind and current effects on the settling velocity of particles.

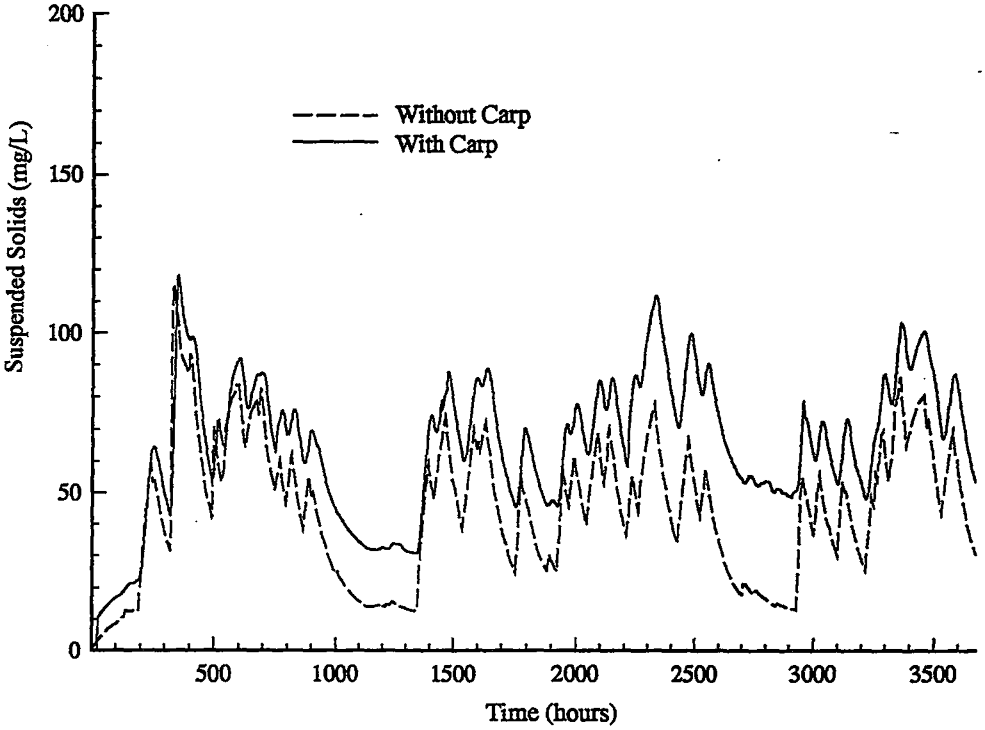

Figure 4.10 Suspended solids for Cootes Paradise with 75% of the input loads, a modified settling velocity and resuspension from wind. Curves are shown with and without carp contributions for 6 hours/day.

4.4 Discussion

4.4.1 General Current Patterns and Pollutant Distributions

The current patterns generally reflected the flow and wind conditions in the marsh. Thackston *et al.* (1987) noted that wind can significantly affect circulation patterns with its major effect being the promotion of mixing. Under dry flow conditions with a northeasterly wind, small eddy circulations were produced in Cootes Paradise, primarily along the south shoreline and near the centre of the basin. When the wind was from the southwest, however, eddies were not as evident and the flow line followed the south shore toward the outlet at the Desjardins Canal. Cootes Paradise is oriented in the same direction as the predominate winds, which are from the southwest and northeast (Painter *et al.*, 1989). When the wind is from the southwest, it would be blowing such that it would push the flow to the outlet, thereby discouraging mixing. When from the northeast, however, the wind would be resisting flow toward the outlet and would therefore promote the formation of circulation patterns.

Storm conditions increased the flows in the basin and the circulation patterns changed based on wind direction. Circulation zones were present under predominate wind conditions whereas a more direct flow with little circulation occurred during winds from the northwest and southeast. These results are not as would be expected. Perhaps during storm events the flows have more impact on the hydrodynamics of the basin than wind and the resulting patterns are influenced primarily by inflows and the topography of the marsh.

The pollutant distribution plots can be explained by the underlying hydrodynamics of Cootes Paradise. At steady state, the marsh is almost fully-mixed. Some areas do exist, though, for which concentration gradients exist. Under dry conditions, higher concentrations for both phosphorus and suspended solids result at the western end of the marsh near Spencer Creek and at the mouth of Chedoke Creek. These areas have high mass loadings and would therefore have higher concentrations at their input point. During storm conditions, inputs from the CSO and from Chedoke Creek are very evident. Combined sewer overflows are high in phosphorus and suspended solids and therefore contribute a large amount to the loadings during rain events. Chedoke Creek accepts discharges from three CSOs (Paul Theil Associates Limited and Beak Consultants Limited, 1991). This would explain the increase in loads from this source during storms. Higher concentrations are predominant at the eastern end of the basin near the outlet at the Desjardins Canal. Flows from the CSO and from Chedoke Creek have less distance to travel to the outlet and under favourable wind conditions the inputs will not become mixed with the entire basin but instead will exit early. This short-circuiting at the eastern end of the marsh will cause the concentration gradients which are evident in the plots (Appendix V), particularly during storm conditions.

4.4.2 Phosphorus

The phosphorus concentrations predicted by the computer model varied widely between sample sites. Only 2 (P2, P9) of the 9 sites had field data which fell within one standard deviation of the corresponding computer predictions (Table 4.3). Because the field phosphorus concentrations were determined using a linear regression relationship, standard deviations were not included. Tsanis *et al.* (1996) outlined statistical equations which can be used to evaluate comparisons between field data and computer predictions. These equations were modified for application to concentration data. Equation 4.3 represents the ratio of the spatial variability of the concentrations to the total concentration in the field data:

$$\alpha_1 = \frac{\sum (C_f - \overline{C_f})^2}{\sum C_f^{\,2}} \tag{4.3}$$

where α_1 is the ratio of the spatial variability in the field data; C_f is the field concentration; and $\overline{C_f}$ is the mean field concentration. A small α_1 implies a uniform spatial distribution of the concentrations. The difference between observed and simulated concentrations is represented by:

$$\alpha_2 = \frac{\sum (C_f - C_c)^2}{\sum C_f^{\,2}} \tag{4.4}$$

where α_2 is the difference between the observed and predicted data; and C_c is the concentration predicted by the computer model. The smaller the value for α_2, the better the agreement between the two sets of data. Finally, the ratio of the root mean square value of the simulated concentrations to the root mean square value of the field concentrations (Equation 4.5) is another measure of the agreement between field and simulated data. The closer α_3 is to 1, the better the agreement.

$$\alpha_3 = \frac{\sqrt{\sum C_c^2}}{\sqrt{\sum C_f^{\,2}}} \tag{4.5}$$

Using the phosphorus data in Table 4.3, $\alpha_1 = 0.008$, $\alpha_2 = 0.285$ and $\alpha_3 = 1.141$. These values indicate that there is little spatial variability in the field data and that there is good agreement between the model predictions and the field values. Closer examination of the computer results indicates that low values occurred at sites P3 and P5, and a high concentration occurred at site P11. These three sample sites were located in the outer grid cells of the model. The 50 m by 50 m grid cell size used for this study is large and the circulation patterns in the first row of cells is not well represented. As a result, in areas of the system with no input sources (i.e. P3, P5), low concentrations result; there is little or no circulation to move substances through these cells. In areas receiving inputs (i.e. P11), high concentrations occur because the circulation is not sufficient to move pollutants away from the source. If these three points are eliminated from the data set, $\alpha_1 = 0.008$, $\alpha_2 = 0.120$ and $\alpha_3 = 1.028$; the agreement between the field and computer data is improved.

Although the simulated data were determined to be a good representation of field data, the variation in the discrepancies between field and simulated values at each site needs explanation. The phosphorus cycle within an aquatic environment is very complex. As discussed in Chapter 3, phosphorus enters the system from external sources, but the internal system can be a significant contributor to the overall concentration as well. Phosphorus is taken up by biota and is released upon death and decay; for organisms such as algae this cycle can be very rapid. Suspended particles also carry phosphorus compounds adsorbed to their surface and phosphorus in the sediments may be permanently removed through further deposition or may be returned to the system through chemical and physical processes (Bostrom *et al.,* 1982; Syers *et al.,* 1973). As a result of these potential sinks and sources, the modelling of phosphorus is difficult. The computer model used for this study was not created to represent phosphorus in detail, therefore it is not surprising that the discrepancies between the computer predicted values and the field data fluctuated widely between sample sites. Furthermore, the site specific field values had to be estimated based on mathematical relationships. Although the linear regression was statistically significant and therefore deemed suitable to apply to the data, it may not have been an appropriate measure for the condition at hand. Nicholls and Dillon (1978) and Dillon *et al.* (1978) discussed the use of relationships between phosphorus and chlorophyll *a* for predictive means. Nicholls and Dillon (1978) compared several phosphorus-chlorophyll *a* relationships and noted many variations, both between relationships and within relationships. Furthermore, they suggested that total phosphorus may not be the best measure of available phosphorus and therefore should not be used on a universal basis for comparison purposes in relationships with chlorophyll *a*. In spite of the variation in discrepancies between field and computer simulated data at each sample site, the model was considered an adequate predictor for phosphorus concentrations.

4.4.3 Suspended Solids

The sediment of Cootes Paradise is primarily sand, silt and clay (Mudroch, 1981) which would infer that the inputs are comprised of similar sized particles. Assuming that all of this matter remains in suspension upon entering the marsh, the overall suspended solids concentration is high (Figure 4.5). A reduction in load to 75% decreased the overall average for suspended solids in Cootes Paradise. This reduction was based on 25% of the loads being sand (Mudroch, 1981) and the assumption that the sand particles would settle immediately and would therefore not contribute to the overall concentrations of suspended matter. Examining Figure 4.6 justifies this assumption. A settling velocity which corresponds to coarse silt removed almost all of the matter suspended in Cootes Paradise. Sand particles are larger than coarse silt and would therefore have greater settling velocities. If coarse silt can be expected to settle almost entirely from the system, then sand particles will likely settle immediately. Sand grains may be transported in suspension, however this is generally observed where currents and turbulence are high, such as in rivers and in the surf along beaches (Eisma, 1993).

In addition to particles being removed from the system via settling, suspended solids will be returned to the system as a result of disruption of the sediments causing resuspension. Two significant contributors to resuspension have been identified as carp and wind (Painter *et al.,* 1989). An attempt was made to incorporate a contribution for carp to suspended solids concentrations based on biomass data from Cootes Paradise for 1995. The initial assumption that carp would contribute to suspended solids 24 hours/day was unreasonable. The overall concentrations that resulted from this scenario exceeded concentrations observed in the field (Figure 4.7). Behavioural patterns or rhythms in fish have been well documented in the literature (Ali, 1992). Fish can dramatically change their behaviour within short periods of time from foraging to fighting, to mating, and even to periods of inactivity (Noakes, 1992; Reebs, 1992; Schwassmann, 1980). A better understanding of the daily behavioural patterns of carp is therefore needed in order to represent their contribution to suspended solids in Cootes Paradise. Since the feeding and spawning actions are the habits of carp which affect the turbidity of the marsh most significantly, patterns involving these behaviours should be determined. A study on the foraging behaviour of *Cyprinidae* revealed that stoneroller fish fed continually during daylight hours (Fowler and Taber, 1985). Since carp are cyprinoid fish, it could be assumed that their feeding actions would also occur during daylight hours, however it is unknown whether they feed continuously as do stonerollers. Also, the spawning actions of carp need to be considered in suspended solids generation. Carp typically spawn when the water reaches temperatures greater than 17°C (Swee and McCrimmon, 1966). This will occur during summer months and likely during the hottest parts of the day (i.e. mid-day). By trial methods, it was determined that a 6 hour/day contribution from carp, occurring during the morning, produced reasonable results (Figure 4.8), however more details are required to justify this time period. Carp activity may be longer or may be shorter, or perhaps may be equivalent to 6 hours/day but comprised of shorter instances at several times over a 24 hour period (i.e. 3 hours in the morning and 3 hours in the evening, or a few hours spread over the day for feeding with time during warmer parts of the day for spawning).

The calculation of suspended solids contributions due to carp may also be questionable. Equation 4.1, although deemed a significant relationship by Breukelaar *et al.* (1994), was based on a very small data set. In order to improve the estimations for carp contributions, studies are required which more accurately identify the nature of the relationship between carp activity and suspended matter.

Since Cootes Paradise is shallow, wind generated resuspension may have a large impact on the suspended solids concentrations (Eisma, 1993; Painter *et al.,* 1989). The computer model was modified to allow for the calculation of a contribution to suspended solids due to wind resuspension. Details pertaining to the sediment in Cootes Paradise which rely on specific particle size distributions (i.e. critical shear stresses) had to be estimated and were done so based on trials which brought the suspended solids concentrations in Cootes Paradise to equivalent levels with field data. The results were such that the final concentration for suspended solids in the marsh was very close to overall field averages (Figure 4.10) and site comparisons for the 9 points of interest agreed very well (Table 4.4).

Only one site out of the 9 points chosen had a suspended solids concentration that did not correspond to field data within one standard deviation. Comparisons of the computer predictions and the field data using Equations 4.3 to 4.5 revealed little spatial variability in the field suspended solids concentrations (α_1 = 0.078) and good agreement between field and simulation data (α_2 = 0.161, α_3 = 0.734). Removing sites P3, P5 and P11, as was done with phosphorus, indicated an increase in spatial variability (α_1 = 0.106) and a slight improvement in the agreement between field values and computer predictions for suspended solids (α_2 = 0.153, α_3 = 0.764).

Knowing the physical characteristics of the particles in the system allows for the determination of many of the required parameters for the model equations. Complex chemical and biological processes do not affect suspended solids the same as they would affect phosphorus. Complications do arise, however, when considering fine-grained material. Clay and silt particles tend to aggregate with other particles to form flocs (Eisma, 1993). The formation of these aggregates has further implications on the settling of these particles. As the flocs grow in size, their settling velocity will increase and they will be removed from the system at a faster rate (Eisma, 1993). Modelling flocs is difficult because of the scarcity of information on their composition and formation. In spite of the estimations with regards to carp and in spite of the potential for floc formation, the good agreement with field data, both on a sample site comparison and on an overall average comparison, would suggest that the model is an acceptable representation of the system. Of course, more detail with regards to the carp contributions, as well as with the particle characteristics, would improve the accuracy of the predictability of the model. Field data were not collected during time periods which corresponded to the suspended solids distribution plots given in Appendix VII. Direct comparisons with the distribution patterns and field values therefore could not be made.

Based on the available data and the corresponding overall average results, it appears that carp and wind each contribute suspended solids to Cootes Paradise on an equal level; approximately 20 mg/L each, or one third of the total concentration. Periods do occur, however, when each is more significant than the other. For example, Figure 4.2 indicates a high wind speed around 300 hours and a large concentration of suspended solids results in Figure 4.10 at the same time. Comparing the two curves in Figure 4.10 reveals that, around 300 hours, the contributions of suspended solids is primarily due to wind; only a very slight increase is seen in the curve for "with carp". Conversely, the contribution due to carp is large around 1100 hours and around 2700 hours, times which both correspond to low wind speeds.

Suspended solids concentrations must be below 15 mg/L in Cootes Paradise to achieve water clarity adequate enough for the growth of aquatic plants (Painter *et al.*, 1989). Figure 4.10 suggests that, even with no carp present in the marsh, wind will create suspended solids levels high enough to exceed this objective. High concentrations due to wind in the absence of carp, however, will likely occur in the open areas of Cootes Paradise. Inlets and bays which are sheltered from wind will be the most promising areas to begin revegetation. Once plants have become established, further improvements to water quality may be expected (Section 2.1.3). Care must be taken, though, to consider the potential for high loads in some protected areas. For example, the Westdale Cut might appear to be an ideal protected area, however discharges from the CSO (Figure 4.1) could prevent successful restoration in this location at this point in time; improvements to the CSO loads are first needed.

4.5 Parameter Variations

Since many estimates had to be made during the phosphorus and suspended solids simulations, the final results could vary significantly. As a result, consideration was given to several parameters in order to determine the sensitivity of the computer model to changes in values and conditions.

4.5.1 Dry and Wet Conditions

Field sampling is typically carried out during dry weather, a fact which may skew the field data in favour of dry conditions. Details regarding the environmental conditions at the time of sampling (i.e. time of sampling, cloud cover, wind speed and direction, duration since last rain event) are generally not available with field results, therefore comparisons with models and explanations for differences in values are not easily made. In the main simulations for this study, rain events were included in the overall concentration calculations, and these concentrations were in turn compared with field values which may have been a representation of primarily dry conditions. Comparing these values is not necessarily valid. Table 4.5 outlines the resulting concentrations when dry and wet events were separated from each other. Since a delay typically occurs between the start of a rain event and the expected increase in concentration, averages were also calculated with a 12 hour lag time for comparison purposes.

Table 4.5 Differences in concentrations when wet and dry conditions are separated from one another.

	Phosphorus (mg/L)	Suspended Solids (mg/L)
RBG Field Value	0.285 ± 0.062	74.46 ± 20.29
Overall Computer Average	0.265 ± 0.038	62.86 ± 18.94
No Lag		
Dry	0.256 ± 0.038	64.43 ± 19.04
Wet	0.286 ± 0.030	75.36 ± 16.03
12 Hour Lag		
Dry	0.252 ± 0.036	62.67 ± 18.14
Wet	0.295 ± 0.025	80.35 ± 14.08

Separating dry from wet conditions lowered the average computer concentrations thereby increasing the difference between these values and the field values. The wet weather averages were higher than the field and overall computer concentrations which is as would be expected. All values, however, still remained within one standard deviation of each other. Including a 12 hour lag time decreased the dry concentrations and increased the wet concentrations further. A delay therefore has an impact, although it appears to be small, on the final concentrations in Cootes Paradise.

These calculations identify a need for more information regarding concentration changes during rain events. To better represent the system, changes in flows and concentrations (i.e. pollutographs) need to be detailed in order to identify lag times and peak values during storm conditions.

4.5.2 Water Levels

Assuming that the field data were collected during dry conditions only, adjusting the computer values in order to better compare the results with field values identifies a larger discrepancy between the model and the field. The main simulations, though, did not take into consideration changing water levels over the season. When water levels are lower, the volume available for the dilution of pollutants is also lower and the overall concentration is therefore greater. The water levels in Cootes Paradise are at a peak in June and a low in December, and as dictated by the water levels in Lake Ontario; the water level changes in Cootes Paradise appear to follow a sinusoidal pattern (Painter *et al.*, 1989). Based on data for the depths of Cootes Paradise (Painter, personal communication), average water levels for the marsh under high and low conditions were determined by a GIS to be 0.745 m and 0.394 m, respectively. Assuming the water level changes follow a sinusoidal function

$$LEVEL = MEAN + AMP \cdot \sin\left(\frac{2\pi}{12}(MONTH - 3)\right) \quad \textbf{(4.6)}$$

where MEAN is assumed to be the midpoint between the high and low water levels; AMP is the amplitude of the function; and MONTH corresponds to the numerical representation of each month (i.e. May = 5), estimates can be made for the water levels during each month between May and September. The computer simulations were carried out as if the water levels were constant at the high level (0.745 m) for the 5 month period. By normalizing the water levels with respect to the high level, adjustment factors can be determined and these factors can be used to estimate the actual dry concentrations under varying monthly water levels (Table 4.6).

As shown in Table 4.6, taking water levels into consideration for the dry concentrations increases the overall phosphorus concentration to a value much closer to the field value (0.285 mg/L) and the overall suspended solids concentration increases, but only to a value similar to the original overall computer averages which included rain events. Other parameter variations need to be considered for suspended solids.

Table 4.6 The effects of water level changes on dry concentrations for phosphorus and suspended solids.

Month	Water Level (m)	Adjustment	Phosphorus (mg/L)	Suspended Solids (mg/L)
May	0.721	1.03	0.260	64.55
June	0.745	1.00	0.252	62.67
July	0.721	1.03	0.260	64.55
August	0.657	1.13	0.285	70.82
September	0.570	1.31	0.330	82.10
Average	0.683	1.10	0.277	68.94

4.5.3 Carp

For the original suspended solids computer simulations, a contribution from carp was assumed to occur for 6 hours/day. The actual daily duration of carp activity is unknown and may thus be different from the value used. Simulations were therefore performed for varying carp contributions. Durations of 4, 6 and 24 hours/day were tested. The results indicate a linear relationship between concentration and duration of activity (Table 4.7) with a slope of approximately 3.631. If, for example, carp are active for 10 hours/day instead of 6 hours/day, the suspended solids contribution due to carp could be expected to increase to approximately 36.31 mg/L. Furthermore, carp may be more active during May and June for spawning and less active the other months, therefore a monthly variation may occur. Assuming that carp are active 10 hours/day for May and June, and only 6 hours/day for July, August and September, gives an overall average contribution of 27.27 mg/L. The contribution to suspended solids due to carp is therefore variable based on the duration of activity for each month. When taken into consideration with water level changes, carp activity could in turn increase the computer dry concentrations to values closer to those seen in the field.

4.5.4 Wind Speed

Wind can impact the overall suspended solids concentration in several ways. The first method tested was wind speed. Simulations were run under constant west winds of 4 m/s and of 2 m/s. The critical shear stresses for deposition and resuspension were held constant at 0.01 N/m^2 and 0.04 N/m^2 (Ariathurai and Krone, 1976), respectively, and contributions from carp were not included. Table 4.7 shows the results for wind speed effects. With a slower wind speed, the concentration of suspended solids was expected to be lower; less wind will keep fewer particles in suspension and will resuspend fewer bottom sediments. A decrease in concentration was seen between 4 m/s and 2 m/s, however, decreasing the wind speed by 50% decreased the concentration by only 21%. Since variable wind data were available on an hourly basis for this study, changes in wind speed can be assumed to be adequately considered. The sensitivity of the overall concentration due to changes in the critical shear stresses for deposition and resuspension must therefore be examined.

4.5.5 Critical Shear Stress for Deposition (τ_{cd})

The critical shear stress for deposition (τ_{cd}) is important in the settling of particles from the water column. A larger shear stress means that a higher wind speed is necessary to keep particles suspended. For this scenario, critical shear stresses for deposition of 0.01 N/m^2 and 0.02 N/m^2 were tested. The wind speed and the critical shear stress for resuspension were held constant at 4 m/s and

Table 4.7 Changes in carp activity, wind speed and the critical shear stresses for deposition (τ_{cd}) and resuspension (τ_{cr}).

Effect	Suspended Solids (mg/L)	Change (%)
Carp		
4 hours/day	14.15 ± 21.65	-33
6 hours/day	21.24 ± 27.00	-
24 hours/day	86.69 ± 34.33	+400
Constant $\tau_{cd} = 0.01$ N/m^2, $\tau_{cr} = 0.04$ N/m^2		
4 m/s west wind	51.21 ± 20.58	-
2 m/s west wind	40.23 ± 17.47	-21
Constant 4 m/s west wind, $\tau_{cr} = 0.04$ N/m^2		
$\tau_{cd} = 0.01$ N/m^2	51.21 ± 20.58	-
$\tau_{cd} = 0.02$ N/m^2	47.03 ± 19.79	-8
Constant 4 m/s west wind, $\tau_{cd} = 0.01$ N/m^2		
$\tau_{cr} = 0.04$ N/m^2	51.21 ± 20.58	-
$\tau_{cr} = 0.08$ N/m^2	35.04 ± 11.07	-32

0.04 N/m^2, respectively, and a contribution from carp was not included. As expected, the higher critical shear stress resulted in a lower overall concentration (Table 4.7), however a doubling of the shear stress caused a decrease of only 8%. The computer model could therefore be assumed to be relatively insensitive to changes in the critical shear stress for deposition under the conditions used for Cootes Paradise.

4.5.6 Critical Shear Stress for Resuspension (τ_{cr})

As with deposition, larger values for the critical shear stress for resuspension (τ_{cr}) require larger wind speeds to resuspend material from the bottom. Under a constant west wind of 4 m/s, with a critical shear stress for deposition of 0.01 N/m^2 and with no contribution from carp, the concentration in Cootes Paradise would be expected to decrease with an increase in the critical shear stress for resuspension. Table 4.7 indicates that this does in fact occur when the critical shear stress for resuspension is increased from 0.04 N/m^2 to 0.08 N/m^2. A doubling of τ_{cr}, though, causes the concentration to decrease by only 32%. Changing this parameter appears to have a greater impact on the overall concentrations than changing wind speed or the critical shear stress for deposition.

4.6 Conclusions

The two-dimensional depth averaged hydrodynamic and pollutant transport model for Cootes Paradise provided good results for overall average phosphorus and suspended solids concentrations, as well as good agreement between field values and computer predictions for various sample sites throughout the marsh.

Current distributions generated from the hydrodynamics of the model were directly related to environmental conditions (i.e. wind, dry flows, wet flows). Circulation patterns near the central portion of the basin, typified by eddy formation and a meandering flow, were dominant in the current patterns. Variations in wind speed, wind direction and inflows altered these distributions. Correspondingly, the pollutant distribution patterns in Cootes Paradise reflected the underlying hydrodynamics of the basin, as well as the environmental conditions. During storm events, concentrations were higher at the eastern end of the basin near the CSO input and near Chedoke Creek, and the hydrodynamics were such that the flows from these two sources generally moved directly toward the Desjardins Canal with little mixing with the rest of the basin.

Since assumptions had to be made for many of the parameters in the computer model, the effects of variations in these parameters were tested in order to determine the sensitivity of the model to changes in these values. Dry weather concentrations were lower than the overall computer averages and also lower than the field data. When considering lower water levels, though, the dry concentrations increased to values which were more comparable to field data. For suspended solids, further adjustments in the contribution due to carp and in the critical shear stresses for deposition and resuspension caused variable changes in the overall concentrations. Carp contributions appeared to vary linearly with the daily duration of the contribution and the critical shear stress for resuspension seemed to have a greater impact on the concentrations than did the critical shear stress for deposition.

Although many aspects of the computer model could be improved through the collection of more detailed data, the model, as it exists right now, produces comparable results to field data and is therefore suitable for preliminary applications to restoration strategies.

5 Conclusions

5.1 Achievements of the Present Study

Two systems models were applied to Cootes Paradise marsh in an attempt to gain more knowledge of the ecosystem with respect to phosphorus and suspended solids concentrations, 1) a mass balance model and 2) a hydrodynamic/pollutant transport model. Phosphorus and suspended solids are impacting the water quality of Cootes Paradise and in turn are hindering the return of vegetation which is preventing marsh restoration efforts. As a preliminary step in the modelling exercises, attention was given to the conditions in the marsh in order to clearly define the problems and identify the underlying root causes. Based on studies in the literature, the root causes for phosphorus were described as point source and nonpoint source loadings, and those for suspended solids included loadings as well as a large population of carp. The Cootes Paradise ecosystem, though, needs to be re-evaluated, based on missing data, to determine if in fact the identified factors are the only factors affecting plant growth. Due to the lack of information on the sediments, it is impossible to say whether or not the sediment chemistry is inhibiting plant growth. Furthermore, the return of plants to Cootes Paradise may not correct nutrient problems but in turn may contribute to loads upon death and decay of the vegetation. Encouraging plant growth, therefore, may not be in the best interest of the system.

5.1.1 Mass Balance Model

* Research for information about the inputs to Cootes Paradise revealed that the available data set for the marsh is incomplete. Flow and water quality data have not been collected for Chedoke and Borer's Creeks, contributions of phosphorus and suspended solids during storm events are not well documented and internal sources and sinks have not been studied to any great extent.

* In spite of the data limitations, the mass balance results agreed well with field data for May to September, 1995. Large fluctuations occurred on a monthly basis (percentage differences

between the field and the model ranged from less than 1% to 43%), but the overall averages were predicted by the model within one standard deviation of the field values.

* Analysis of the relative loadings to Cootes Paradise identified the internal system as the largest contributor to phosphorus and suspended solids. Reflux from the bottom sediments accounted for more than 50% of the loads to the marsh. Following the sediments in importance for load contributions was rural runoff.

5.1.2 Computer Model

* Current distributions were generated for Cootes Paradise using data which corresponded to May 1995. Both dry conditions and storm conditions were represented in the output from the model simulations. The resulting current patterns were related to wind speed and direction and to changing flows in the system.

* Pollutant distributions resembled the underlying hydrodynamics in Cootes Paradise. The computer results identified higher concentrations of phosphorus and suspended solids in the eastern end of the basin. Higher concentrations were evident from Chedoke Creek and the Sterling Street CSO during storm events, and short-circuiting was apparent at several times throughout the simulation.

* Overall average concentrations for phosphorus as determined by the model agreed well with field averages, and comparisons between field data and computer predictions at nine sites in Cootes Paradise revealed good agreement between the model and the field concentrations.

* Components were incorporated into the suspended solids simulations to account for carp contributions to concentrations and for wind resuspension. Although good details pertaining to sediment characteristics and to carp behaviour were missing, the model produced reasonable results. Overall averages were predicted well by the model as were sample site concentrations.

* Results suggested that carp and wind contributed to suspended solids in Cootes Paradise on an almost equal level; concentrations due to wind were slightly higher.

* Since field data are generally collected during favourable weather conditions (i.e. not during rain events), averages for wet and dry concentrations as predicted by the computer model were determined. When compared to the field values, dry weather averages were lower and wet averages were higher. A delay of 12 hours in the calculations produced dry averages which were lower and wet averages that were even higher than without a lag period. Dry level averages increased to values closer to field data when low water levels were considered.

* Contributions to suspended solids by carp varied with the duration of activity on a linear scale; a doubling of the length of activity can be expected to double the contribution. Critical shear stresses for deposition and resuspension also caused changes in the suspended solids concentrations. An increase in both of these parameters resulted in a decrease in the suspended solids concentration. The critical shear stress for resuspension appeared to have a larger impact on the overall concentrations than did the critical shear stress for deposition. A doubling of the resuspension value resulted in a decrease in concentration by 32%, whereas a doubling of the deposition value caused a decrease in concentration by only 8%.

5.2 Recommendations for Restoration

Based on the results of this study, some preliminary suggestions for restoration strategies can be made. For a more detailed remedial plan, though, additional information is required to improve the accuracy of the models.

* Contributions of phosphorus to the system from sediments are difficult to address. The sediments could permanently be removed, however this would increase the depths in the marsh which is counterproductive for promoting emergent wetland vegetation growth. Treatment methods could be applied to remediate removed sediments and then return the sediments to the marsh, but these procedures can be expensive and disturbance to the ecosystem may be large.

* At this time, restoration strategies to decrease phosphorus in Cootes Paradise would best be focused on reducing the second largest contributor, rural runoff. This would require identifying specific landuses of the rural areas in the Cootes Paradise watershed that contribute phosphorus to the marsh. Actions could then be developed to address each area accordingly. For example, there are

many agricultural areas in the watershed and information sessions on "ecologically sound" farming practices would help to decrease nutrient laden runoff.

* For suspended solids, carp contributions are presently being addressed through the installation of the fish barrier across the Desjardins Canal between the marsh and Hamilton Harbour. Wind generated resuspension, however, is not easily remedied. As with phosphorus, loads from rural runoff should therefore be addressed in order to decrease external loadings to the best possible level. Strategies might include improving agricultural and construction practices that generally promote high suspended matter in runoff.

* While the issues of external loadings are being addressed, the computer model can be used to determine areas in the marsh which are not influenced significantly by currents and by high phosphorus and suspended solids concentrations. Attempts to revegetate these areas can then begin. Encouraging natural restoration through well-planned planting efforts will promote a sturdy plant population which in turn may contribute to further improvements in the water quality of Cootes Paradise.

* Although not considered appropriate for a "natural" approach to restoration due to the large human involvement, the introduction of engineered structures (i.e. dams) is a possibility for restoration. The computer models are excellent for simulating the resulting hydrodynamics, and hence the pollutant distributions, in an environment with the addition of structures, such as dams. The model could be used to simulate the conditions in Cootes Paradise under different design suggestions in order to determine the potential impact on the system as a result of the introduction of such structures.

5.3 Further Study for the Modelling of Cootes Paradise

Although the mass balance and computer models used in this study were concluded to be good representations of the conditions in Cootes Paradise, modifications can be made to improve the effectiveness of their applications for restoration.

* Improved data are required to validate the models. This includes data associated with the inputs and loss terms as well as field data for comparison with computer predicted results.

* Results from the hydrodynamic/pollutant transport model can be combined with a Geographic Information System (GIS) in order to spatially represent the conditions in the marsh and provide a link with a database containing information on vegetation. Files which contain information on the specific environmental conditions required by certain wetland plants for successful growth can be cross-referenced with the pollutant distributions from the computer model. Based on the results, vegetation can then be planted in areas suitable for each species, with the assumption that under conditions that are favourable for the plants they should have a greater success rate for growth and hence restoration could be expected to be more prosperous.

* The inclusion of a component to the computer model which would represent vegetation growth and expansion would be valuable. The hydrodynamics of the system will change with the addition of more vegetation which in turn will alter the behaviour of pollutants in the marsh. Since restoration is an ongoing process and changes occur continuously, the ability of the model to simulate changes and adapt to these changes would allow for improved decision making for future restoration plans.

* Finally, studies could be broadened to include aspects of the Cootes Paradise ecosystem as a whole rather than just the water quality of the marsh. This might include investigating the effects of development changes in the watershed or of global climatic fluctuations on the entire ecosystem, including vegetation and wildlife.

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Appendix I

~ Mass Balance Model Calculations ~

The mass balance calculations were done using a spreadsheet program and Equation 3.3. The flows (m^3/s) and the concentrations (mg/L) for phosphorus and suspended solids for each month are shown in Table A1.1. Where data were lacking (i.e. Chedoke Creek, Borer's Creek) estimates were used and they were kept constant for each month.

Table A1.1 Flow and concentration data for the mass balance calculations.

	Dundas STP			Spencer Creek		
Month	Flow	P	SS	Flow	P	SS
May	0.152494	0.486	4	1.453768	0.09375	16.7625
June	0.137785	0.3878	3.19	0.6857	0.21375	58.7
July	0.135909	0.381	3.48	0.649893	0.3075	58.95
August	0.131227	0.3872	2.14	0.545745	0.11	31.625
September	0.1349931	0.3608	2.69	0.8825	0.0725	22.2
Average	0.1384816	0.40056	3.1	0.8435212	0.1595	37.6475

	Chedoke Creek			Borer's Creek		
Month	Flow	P	SS	Flow	P	SS
May	0.08589	0.25	50	0.013	0.07	33.1
June	0.08589	0.25	50	0.013	0.07	33.1
July	0.08589	0.25	50	0.013	0.07	33.1
August	0.08589	0.25	50	0.013	0.07	33.1
September	0.08589	0.25	50	0.013	0.07	33.1
Average	0.08589	0.25	50	0.013	0.07	33.1

	Rain			Runoff		
Month	Flow	P	SS	Flow	P	SS
May	0.0677533	0.091	10	1.4096123	0.46	150
June	0.0474765	0.057	10	1.3621349	0.46	150
July	0.07338	0.04	10	0.5485526	0.46	150
August	0.060251	0.04	10	0.5153055	0.46	150
September	0.0448701	0.048	10	0.9276526	0.46	150
Average	0.0587462	0.0552	10	0.9526516	0.46	150

	CSO - Sewage			CSO - Stormwater		
Month	Flow	P	SS	Flow	P	SS
May	0.0191782	6	302	0.2547963	0.33	100
June	0.0134387	6	302	0.1785423	0.33	100
July	0.207709	6	302	0.2759564	0.33	100
August	0.0170546	6	302	0.2265829	0.33	100
September	0.0127009	6	302	0.1687405	0.33	100
Average	0.0166287	6	302	0.2209237	0.33	100

Table A1.2 contains rainfall and evaporation data as well as estimates for the percentage of runoff that occurred each month. These data, along with the data contained in Table A1.1 were used to calculate the loadings shown in Table A1.3. Loadings, the volume of Cootes Paradise, and values for the settling, deposition, and refulx terms were then substituted into Equation 3.3 to determine the monthly concentrations given in Table A1.4.

Table A1.2 Rainfall, evaporation and runoff information.

Month	Rainfall (mm)	Evaporation (mm)	Evaporation Flow (m^3/s)	% Runoff
May	87.3	117.15	0.09091984	22.05021
June	59.2	150.52	0.12071216	30.40782
July	94.55	156.82	0.12170764	7.922897
August	77.63	129.23	0.1002951	9.0645
September	55.95	74.63	0.05985084	21.9115
Average	74.9266	125.67	0.09869712	18.271385

Table A1.3 Total flows and loadings of phosphorus and suspended solids for each month.

Month	Total Flow (m^3/s)	Loadings ($mg \cdot m^3/L \cdot s$)	
		P	SS
May	3.3655723	1.0865246	273.09439
June	2.4032552	0.9912231	272.122633
July	1.6816442	0.7449664	160.39409
August	1.4947609	0.5497762	127.97193
September	2.2104963	0.695833	184.985739
Average	2.2311458	0.8265336	207.509977

Table A1.4 Resulting concentrations for phosphorus and suspended solids from the mass balance calculations.

Month	Phosphorus (mg/L)	Suspended Solids (mg/L)
May	0.256	64.976
June	0.302	83.970
July	0.291	63.671
August	0.231	54.871
September	0.225	60.692
Average	0.261	65.636

Appendix II

~ Details of the Computer Model ~

A vertically integrated two-dimensional model, which is obtained by integrating three-dimensional equations in the depth dimension, was used in the Cootes Paradise study. For well-mixed, shallow water bodies, the water movements in the horizontal plane usually predominate and the vertical velocity and density variations are small. Therefore adopting a vertically integrated two-dimensional model to simulate large-scaled flows is adequate. The details of the governing equations used in the Cootes Paradise model were excerpted from Tsanis and Shen (1994a, b) and are presented in the following discussion.

Hydrodynamic Model

As is done with most models, assumptions were applied to the Cootes Paradise model in order to simplify the equations. The equations of motion in the x-and y-directions and of mass continuity were developed under the assumptions that:

1. the density of water is constant
2. the pressure distribution in the vertical dimension is hydrostatic
3. the variations of velocity in the vertical dimension are negligible

The resulting equations are therefore given as:

Continuity Equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \qquad \textbf{(A2.1)}$$

Momentum Equations:

x-direction:

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x} uM + \frac{\partial}{\partial y} vM = fN - gH\frac{\partial \zeta}{\partial x} + A_x \frac{\partial^2 M}{\partial x^2} + A_y \frac{\partial^2 M}{\partial y^2} + \frac{\tau_x(s) - \tau_x(b)}{\rho} \qquad \textbf{(A2.2)}$$

y-direction:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} uN + \frac{\partial}{\partial y} vN = -fM - gH\frac{\partial \zeta}{\partial y} + A_x \frac{\partial^2 N}{\partial x^2} + A_y \frac{\partial^2 N}{\partial y^2} + \frac{\tau_y(s) - \tau_y(b)}{\rho} \qquad \textbf{(A2.3)}$$

where M (=uH) and N (=vH) are the vertically-integrated water transports per unit width in the x- and y-directions, respectively; u and v are the depth-averaged velocities in the x- and y-directions, respectively; ζ is the water elevation; f is the Coriolis factor, which is taken to be negligible in this study; g is the gravitational acceleration; H is the water depth; A_x and A_y are the eddy viscosities in the x- and y-directions, respectively; $\tau_x(s)$ and $\tau_y(s)$ are the wind shear stresses in the x- and y-directions, respectively; and $\tau_x(b)$ and $\tau_y(b)$ are the bottom shear stresses in the x- and y-directions, respectively.

Boundary Conditions

At the water surface, the wind shear stresses are expressed by the following equation:

$$(\tau_x(s),\tau_y(s)) = \rho_a\gamma_a^2(W_x,W_y)\sqrt{W_x^2+W_y^2} \qquad \textbf{(A2.4)}$$

where W_x and W_y are the components of wind speed in the x- and y-directions, respectively; γ_a^2 is the surface drag coefficient; and ρ_a is the density of air.

At the bottom, the friction stresses are expressed by the following equation:

$$(\tau_x(b),\tau_y(b)) = \rho\gamma_b^2(u,v)\sqrt{u^2+v^2} \qquad \textbf{(A2.5)}$$

where γ_b^2 is the bottom drag coefficient.

At the shore, the components of velocity perpendicular to the shore and the concentration fluxes through the shore are assumed to be zero. Where the shore has inflow or outflow sources, the velocity components normal to the shore are considered to be equal to the velocities of the inflows or outflows.

Pollutant Transport Model

Pollutant transport is accomplished by two distinct physical mechanisms, advection and diffusion. The first mechanism describes the bulk transport of the pollutant material by the mean component of the current and the second mechanism describes the spreading of the material as a consequence of the turbulence associated with the currents.

Diffusion also describes, in the case of laminar flow, the Brownian motion of the pollutant's molecules, resulting in the continuous increase of the area that the pollutant, originating from a local source. In the case of turbulent flow, the motions at a molecular level become negligible when compared to motions due to turbulence. The spreading of the pollutant is accomplished in the scale of the turbulent eddies formed as a consequence of the turbulence associated with the currents. The increase in the area that the pollutant occupies is done at a much faster rate.

The rate of diffusion, even in the case of turbulent flow, can be described by a diffusion coefficient according to the Boussinesq approximation. This is the eddy diffusion coefficient, D, analogous to the eddy viscosity coefficient and some orders of magnitude greater than the molecular diffusion coefficient. The contribution of the above two mechanisms, advection and diffusion, to the final pollutant transport can be quantified through the Peclet number:

$$P_e = \frac{UL}{D} \tag{A2.6}$$

where U is the characteristic velocity of the transporting fluid and L is a characteristic length of the flow domain. If the Peclet number has a value higher than one then advection dominates over diffusion.

Finally, in the analysis of the physical processes involved in the transport of pollutants, the distinction between conservative and non-conservative pollutants must be made. If the total mass of the advected-diffused pollutant is conserved during its transport, then it is characterized as a conservative one. Otherwise, if its discharge in the carrying fluid initiates physical, chemical or biological processes that result in a decrease or increase in its initial mass, then it is characterized as a non-conservative one.

For this study, pollutants were assumed to behave conservatively and the two-dimensional depth-averaged pollutant transport equation for a conservative pollutant is:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x} uC + \frac{\partial}{\partial y} vC = S + D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} \tag{A2.7}$$

where C is the mean concentration; D_x and D_y are the horizontal eddy diffusivities; u and v are the depth mean velocities in the x- and y-directions, respectively; and S is a source term. It is usually assumed that $D_x = D_y$ and is equal to a constant horizontal eddy diffusivity. The value of horizontal eddy diffusivity used in this study was 0.1 m^2/s.

Sediment Transport

For the Cootes Paradise suspended solids simulations, modifications were incorporated into the pollutant transport equations to account for contributions to and losses from suspended solids concentrations. The source term for suspended solids, S, includes suspended sediment inputs and losses from inflows and outflows, suspended sediment losses due to settling from the water to the bottom and sediment resuspension from the bottom to the water. This can be represented as:

$$S = S_{flow} - S_{dep} + S_{res} \qquad \textbf{(A2.8)}$$

where S_{flow} is the net contribution from the inflows and outflows, S_{dep} is the loss due to deposition and S_{res} is the contribution due to resuspension. The deposition component, S_{dep}, is based on the settling velocity of the suspended matter. Generally the settling velocity should depend on the sediment concentration and the particle size, however in this study settling velocity is assumed to be a function of particle size only. Deposition was therefore represented by (Hater and Pakala, 1989):

$$S_{dep} = \frac{p_d w_s C}{H} = \frac{\left(1 - \frac{\tau_b}{\tau_{cd}}\right) w_s C}{H} \qquad \textbf{(A2.9)}$$

where p_d is the probability of settling; w_s is the settling velocity; H is the water depth; τ_b is the bottom shear stress; and τ_{cd} is the critical shear stress for deposition. The critical shear stress for deposition was taken to be 0.01 N/m^2 (Ariathurai and Krone, 1976) and the bottom shear stress was calculated by:

$$\tau_b = \rho_w U_*^2 = \rho_w \frac{n_M{}^2 U^2 g}{H^{1/3}} \qquad \textbf{(A2.10)}$$

where ρ_w is the density of water; U_* is the bottom shear velocity; n_M is Manning's coefficient, n_M = 0.035; g is the acceleration due to gravity; U is the depth averaged velocity; and H is the water depth. Obviously, the larger the shear stress, fewer sediment particles will settle.

The contribution of suspended solids due to resuspension was represented by:

$$S_{res} = \frac{\varepsilon\left(\frac{\tau_b}{\tau_{cr}} - 1\right)}{H} \tag{A2.11}$$

where ε is the resuspension rate; τ_b is the bottom shear stress; τ_{cr} is the critical shear stress for resuspension; and H is the water depth. Both ε and τ_{cr} depend on the bed structure of the sediment. In this study, though, ε and τ_{cr} were taken as constants; $\varepsilon = 7.83 \times 10^{-3}$ g/m^{2}s and $\tau_{cr} = 0.04$ N/m^2 (Ariathurai and Krone, 1976). More sediments will be resuspended with larger bottom shear stresses.

Numerical Techniques

A large number of numerical schemes have been used to solve equation A2.7. A successful scheme is one that is accurate and stable, includes proper treatment of the propagation of concentrations with steep gradients, and avoids negative concentration values. In this study a numerical scheme in which advection terms are represented via a second order upwinding scheme and the diffusion terms via a centered difference scheme were used for the solution of equation A2.7. The flow patterns obtained from the hydrodynamic model were used as input to the pollutant transport model.

Cootes Paradise was discretized in square grids with grid size $\Delta x = \Delta y = 50$ m. Since an explicit numerical scheme was used for the pressure term, the time step, Δt, used in this study had to satisfy the Courant Criterion:

$$\Delta t < \frac{\Delta x}{\sqrt{2gH_{max}}} \tag{A2.12}$$

where $H_{max} = 2$ m is the maximum depth in Cootes Paradise. The Δt used in this study was 4 seconds and the leap-frog numerical scheme was used for the temporal differencing.

At each time step the model calculates the total kinetic energy in the flow domain from the sum:

$$E^n = \tfrac{1}{8}\sum_i \sum_j \left[\left(u^n_{i,j} + u^n_{i+1,j}\right)^2 + \left(v^n_{i,j} + v^n_{i,j+1}\right)^2\right] H_{i,j}\Delta x \Delta y \tag{A2.13}$$

where the i, j and n indices refer to the x, y and time dimensions, respectively. Steady state is reached when the difference in kinetic energy between time steps reaches a test convergence level:

$$\frac{\left|E^{n+1}-E^{n}\right|}{E^{n}}<E_{cr} \qquad \textbf{(A2.14)}$$

where E_{cr} is the convergence level and is typically 10^{-5}.

References

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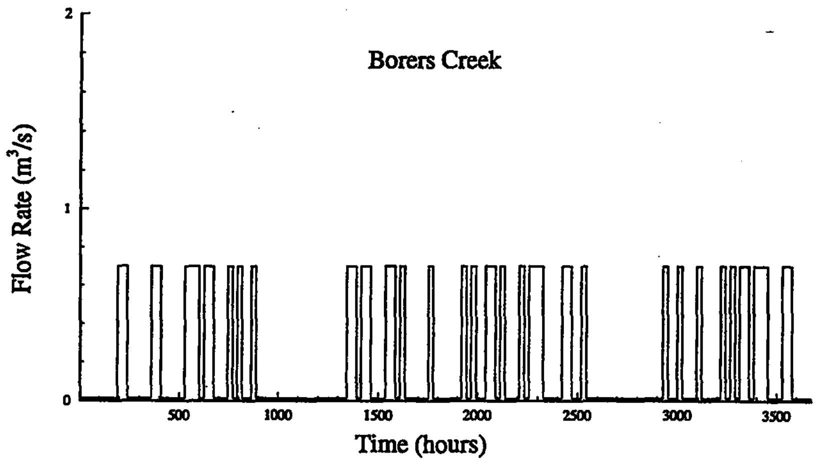
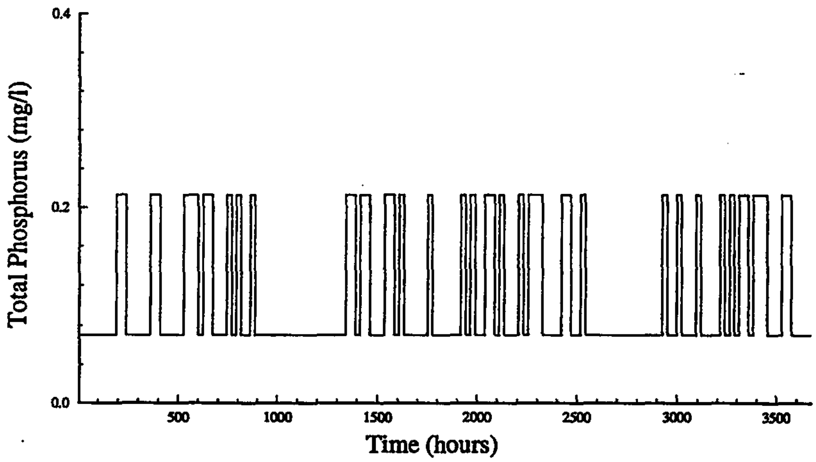
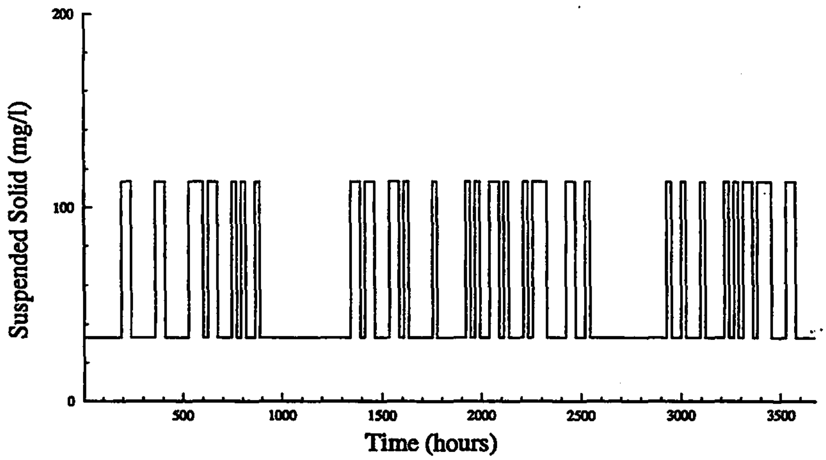
Tsanis, I. K. and H. Shen. 1994b. Modelling current movements in Cootes Paradise. Technical Report, Department of Civil Engineering, McMaster University, Hamilton, Canada.

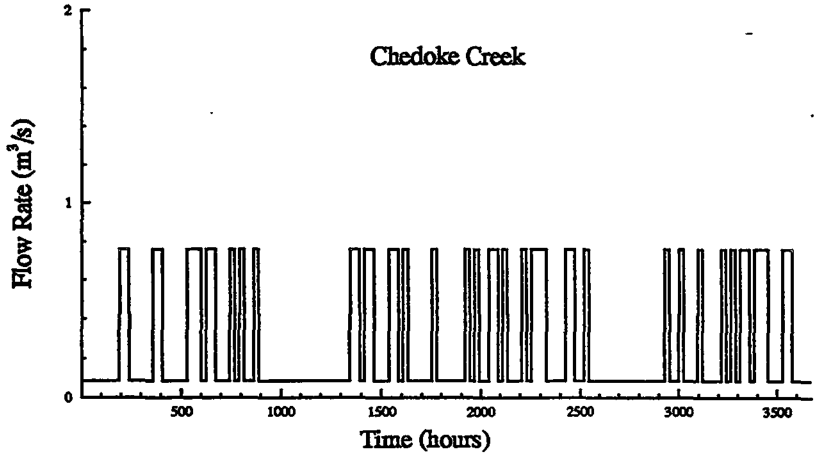
Appendix III

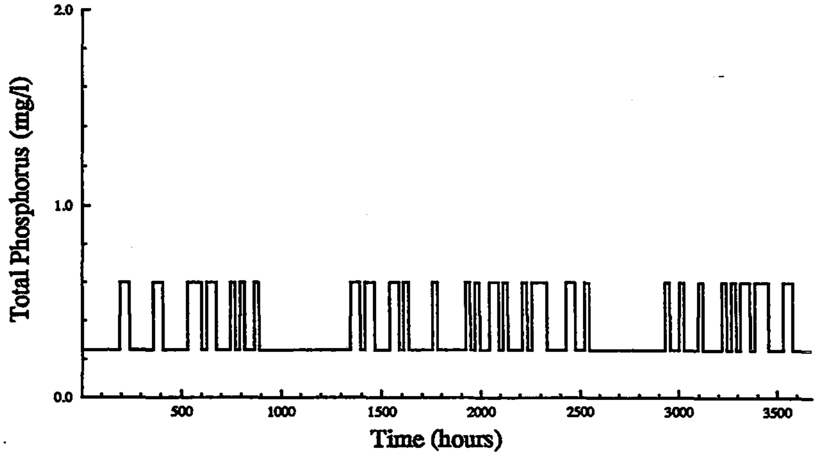
~ Input Data ~

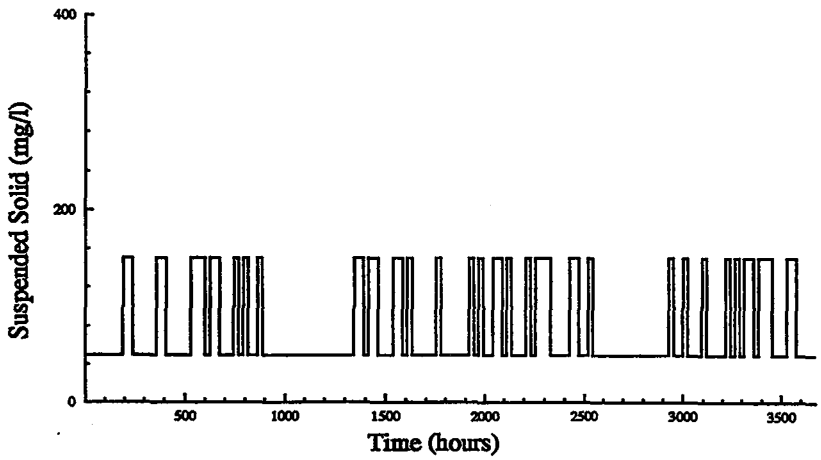

Borers Creek
Flow Rate (m³/s)
2
1
0
500
1000
1500
2000
2500
3000
3500
Time (hours)

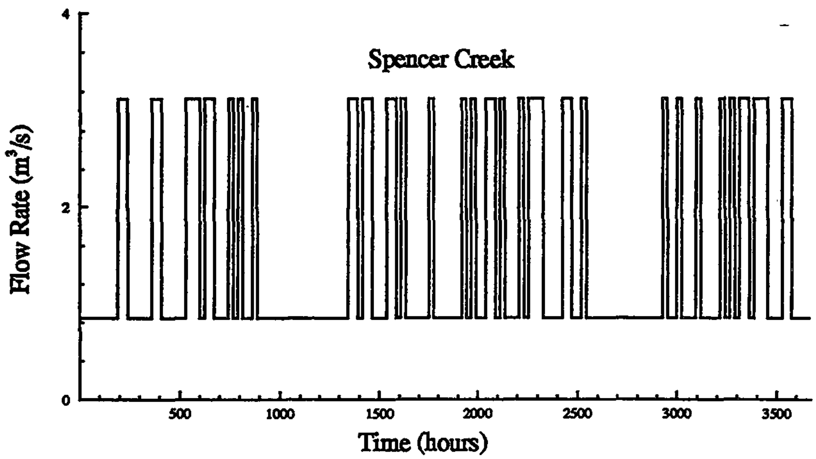

Total Phosphorus (mg/l)
0.4
0.2
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)

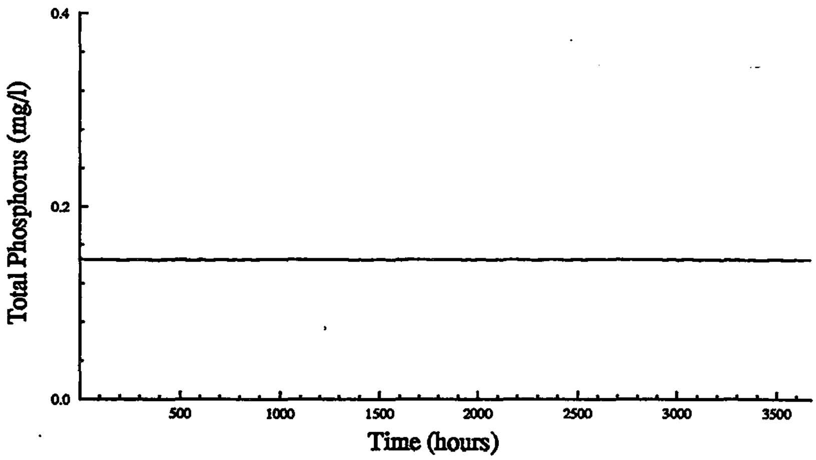

Suspended Solid (mg/l)
200
100
0
500
1000
1500
2000
2500
3000
3500
Time (hours)

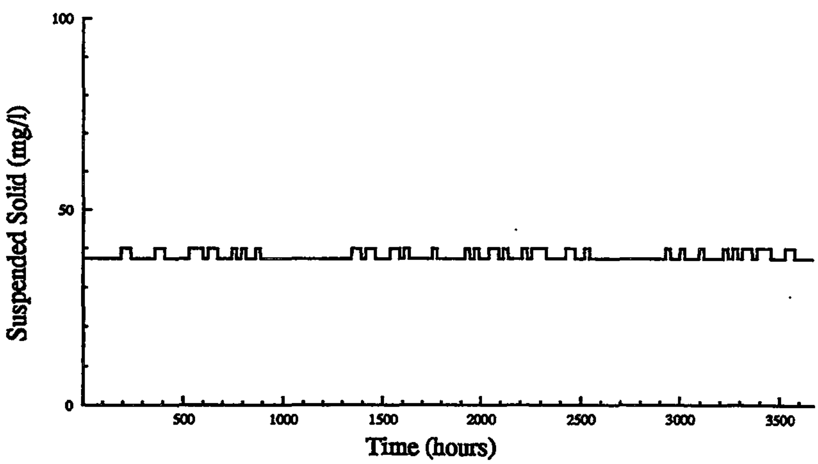

Chedoke Creek
Flow Rate (m³/s)
2
1
0
500
1000
1500
2000
2500
3000
3500
Time (hours)

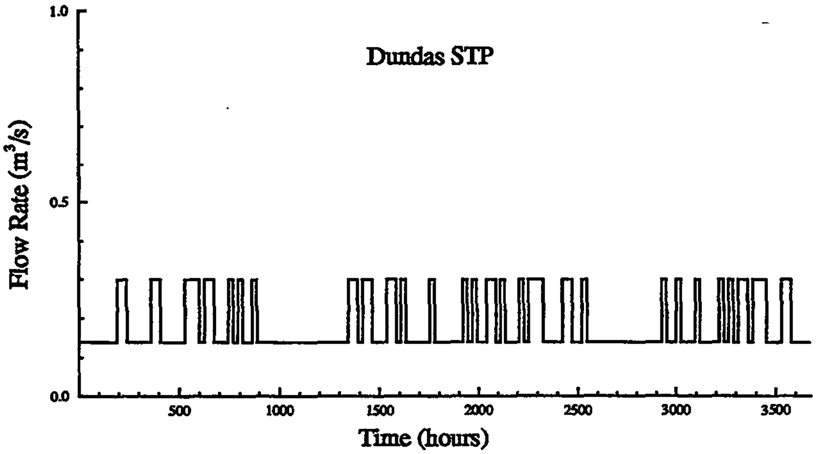

Total Phosphorus (mg/l)
2.0
1.0
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)


Suspended Solid (mg/l)
400
200
0
500
1000
1500
2000
2500
3000
3500
Time (hours)

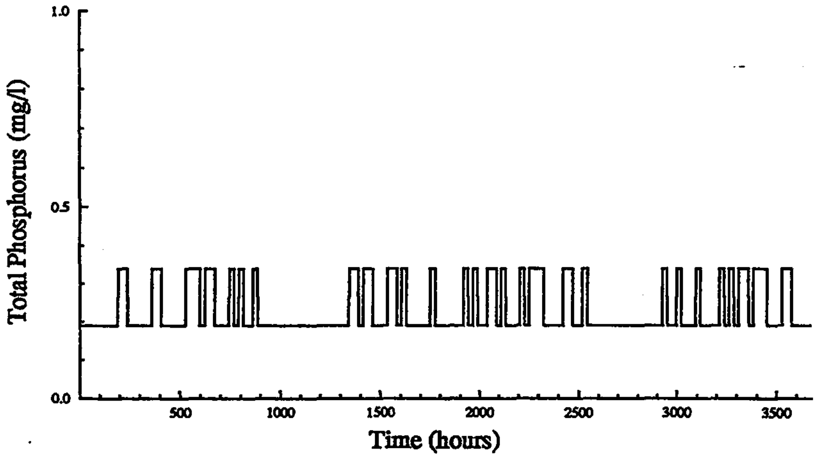

Spencer Creek
Flow Rate (m³/s)
4
2
0
500
1000
1500
2000
2500
3000
3500
Time (hours)


Total Phosphorus (mg/l)
0.4
0.2
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)

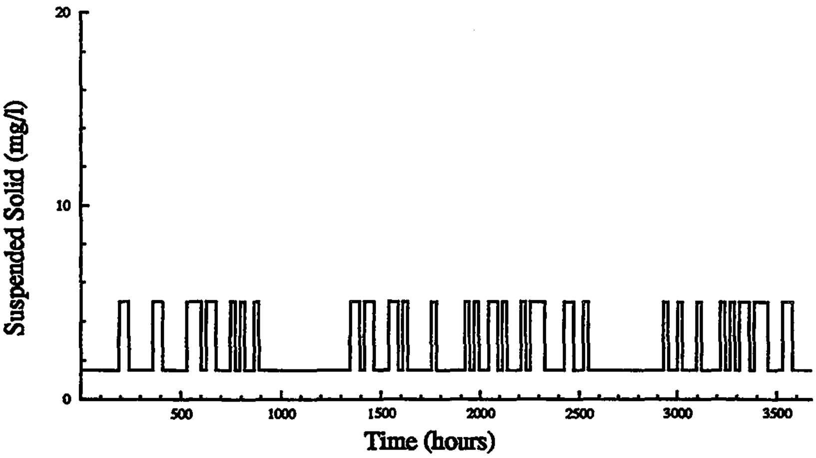

Suspended Solid (mg/l)
100
50
0
500
1000
1500
2000
2500
3000
3500
Time (hours)



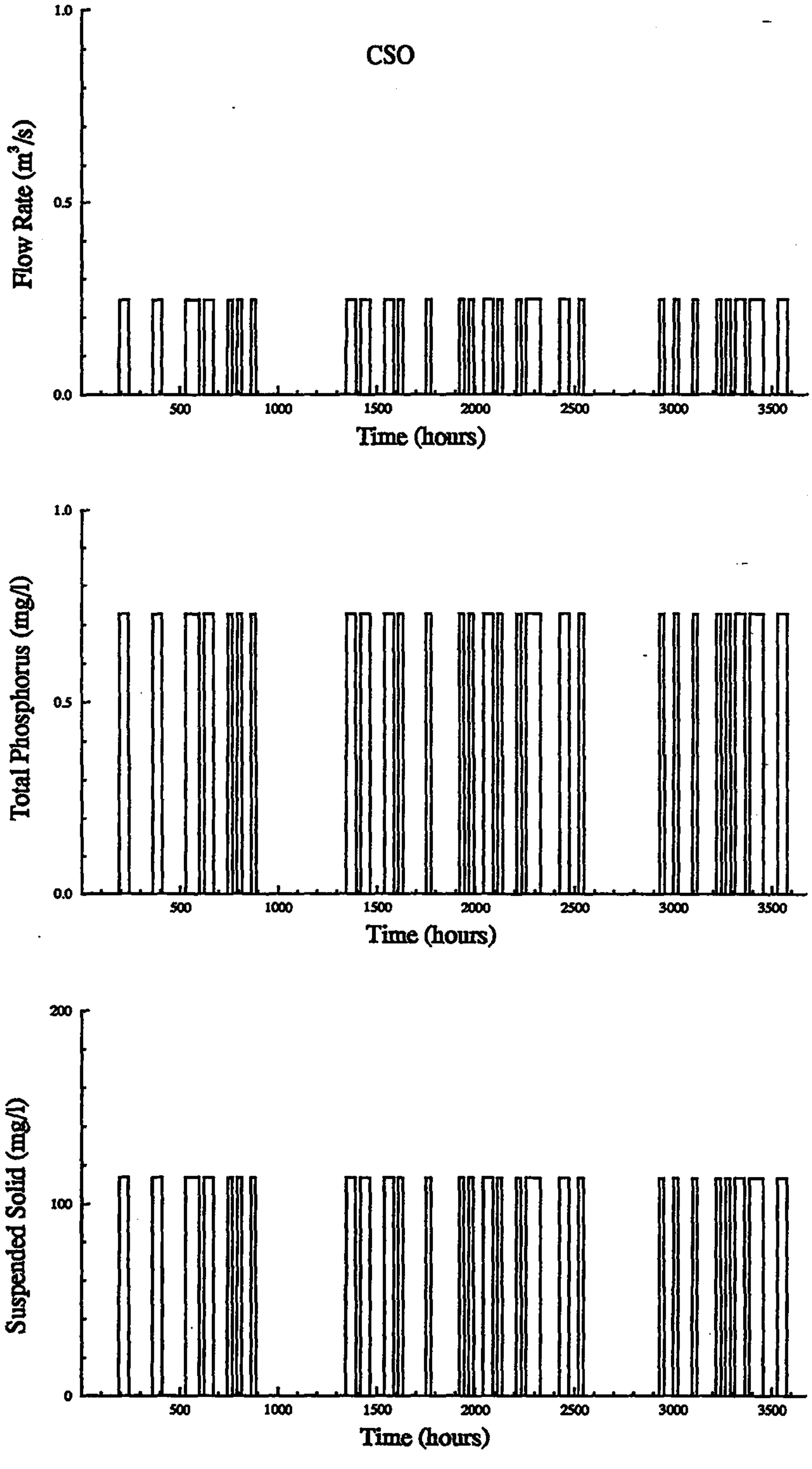
Dundas STP
Flow Rate (m^3/s)
1.0
0.5
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)



Total Phosphorus (mg/l)
1.0
0.5
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)



Suspended Solid (mg/l)
20
10
0
500
1000
1500
2000
2500
3000
3500
Time (hours)


CSO
Flow Rate (m³/s)
Time (hours)
Total Phosphorus (mg/l)
Time (hours)
Suspended Solid (mg/l)
Time (hours)

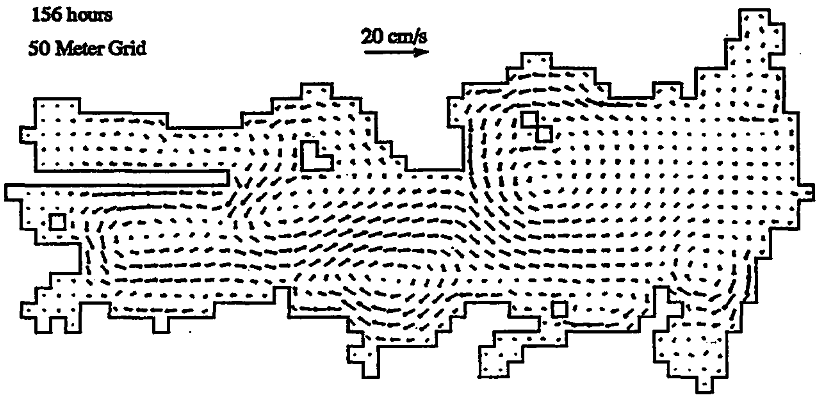
Appendix IV

~ Current Distribution Plots ~

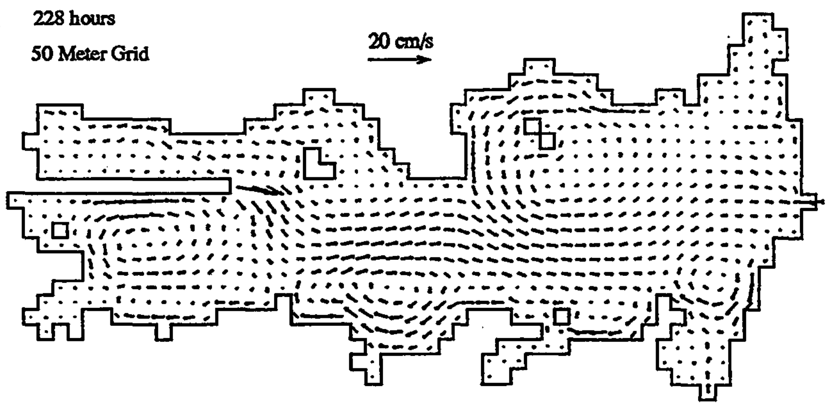
Table A4.1 Descriptions of the time periods in May 1995 for which hydrodynamic and pollutant distributions were plotted.

Time (hours)	Description
156	- dry conditions
228	- during the first storm of the month
252	- immediately after the first storm
348	- five days after the first storm; dry conditions
444	- two days after the second storm
516	- before the third storm
564	- during the third storm
612	- between the third and fourth storms
660	- during the fourth storm
732	- end of the month

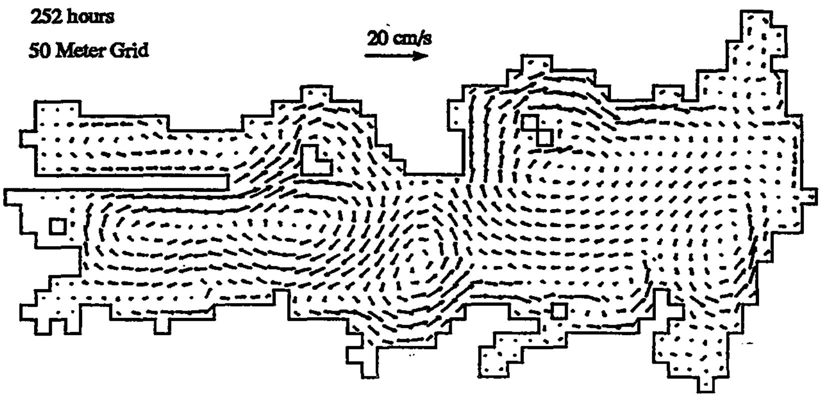
Cootes Paradise



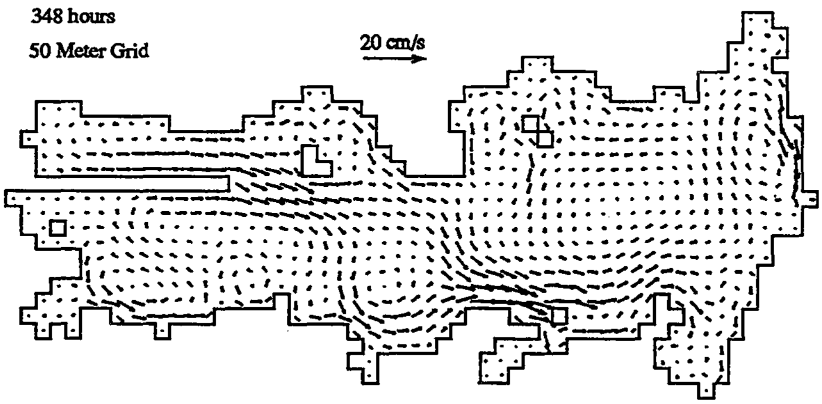
Cootes Paradise



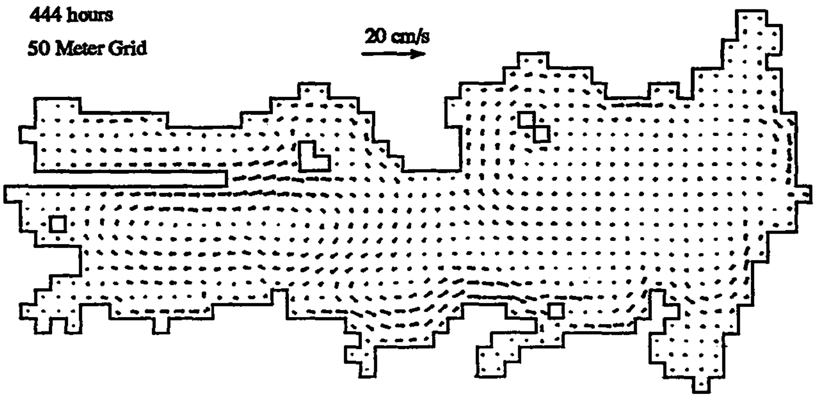
Cootes Paradise



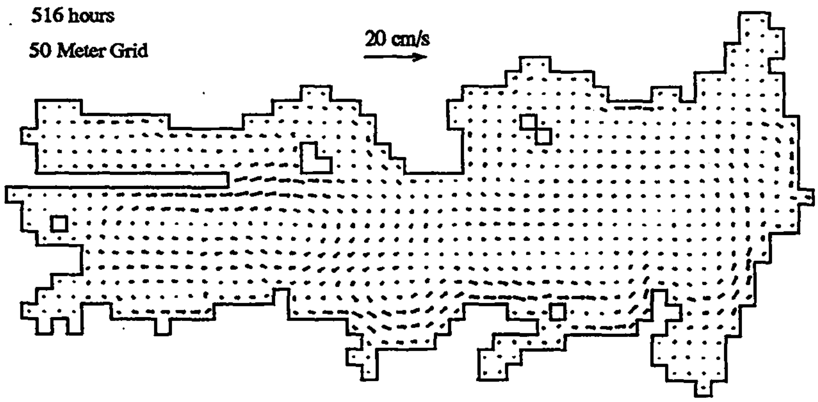
Cootes Paradise

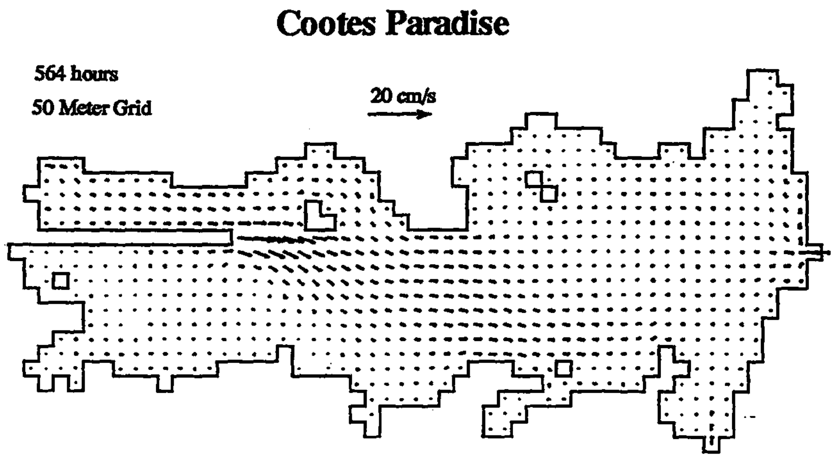


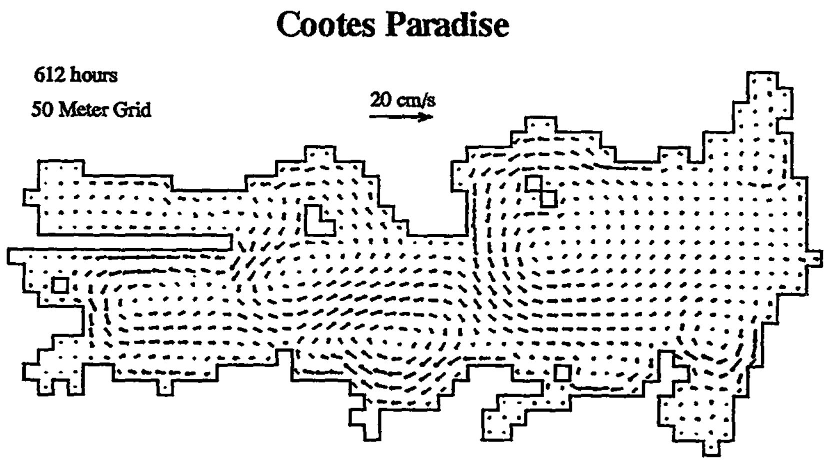
Cootes Paradise



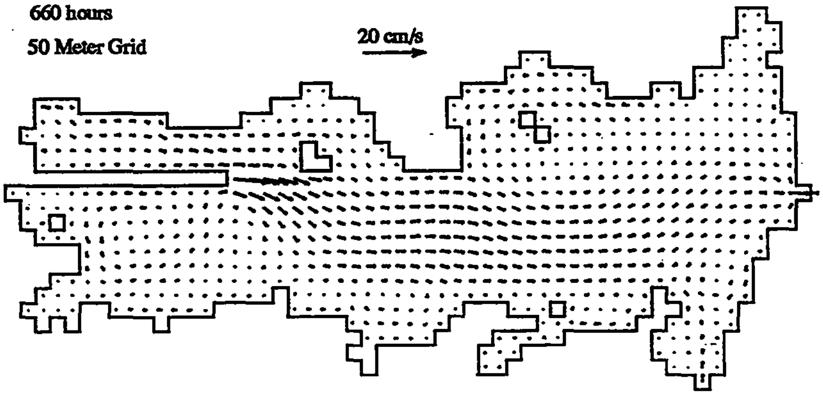
Cootes Paradise



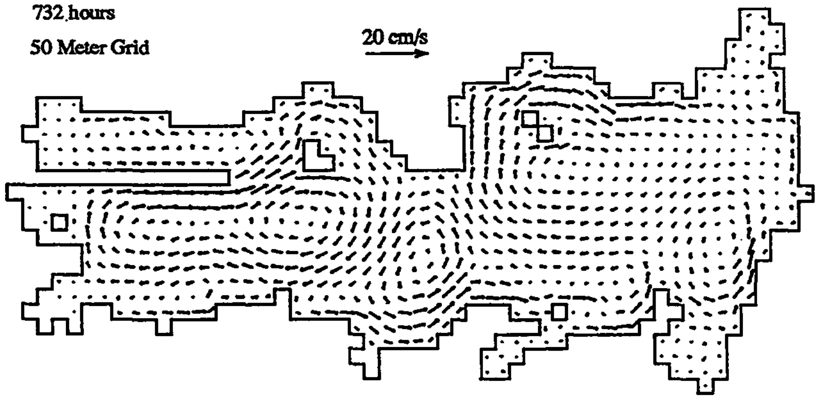

Cootes Paradise
564 hours
50 Meter Grid
20 cm/s


Cootes Paradise
612 hours
50 Meter Grid
20 cm/s

Cootes Paradise

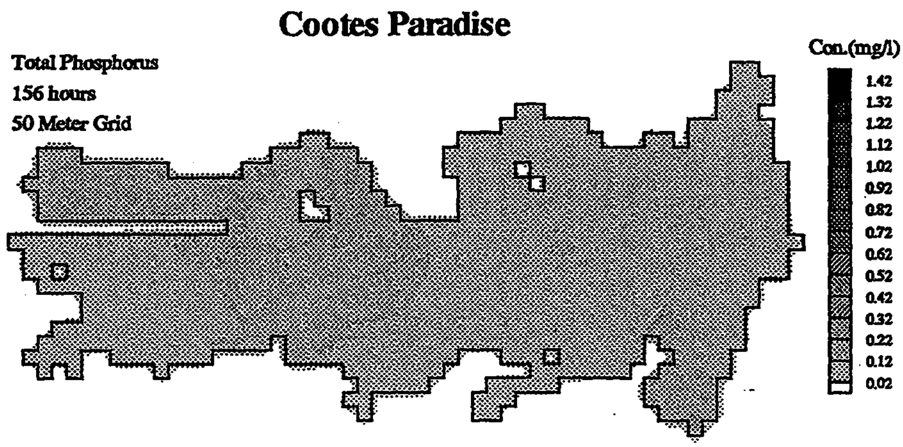


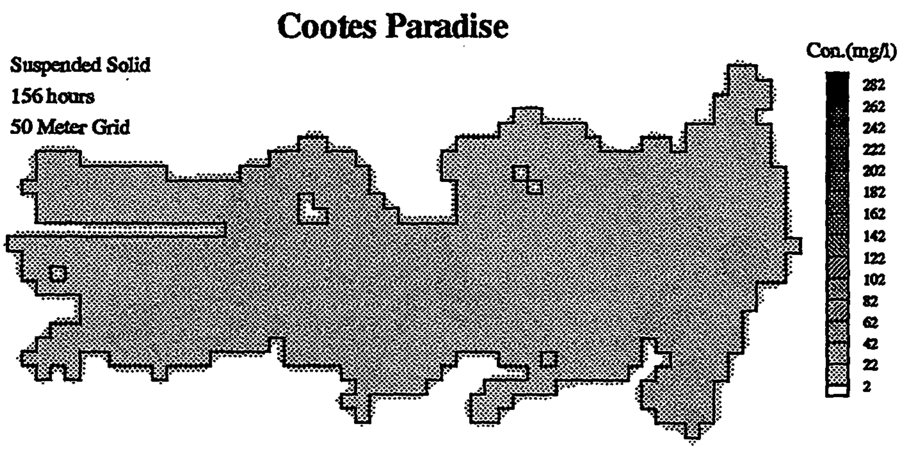
Cootes Paradise

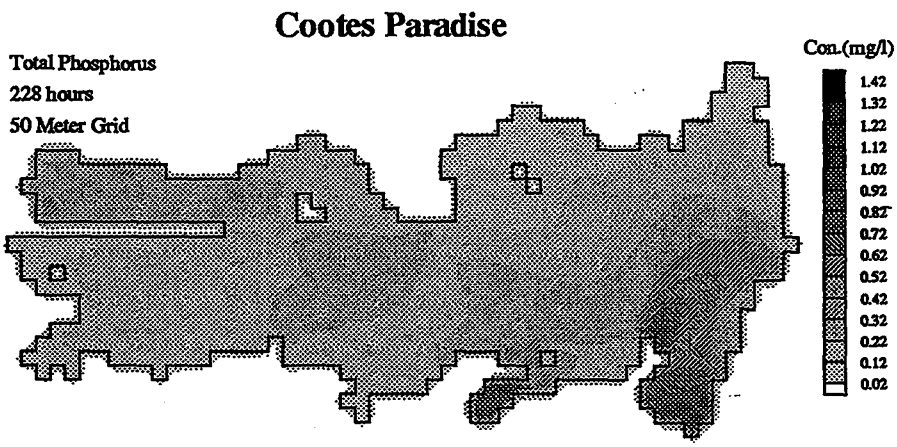


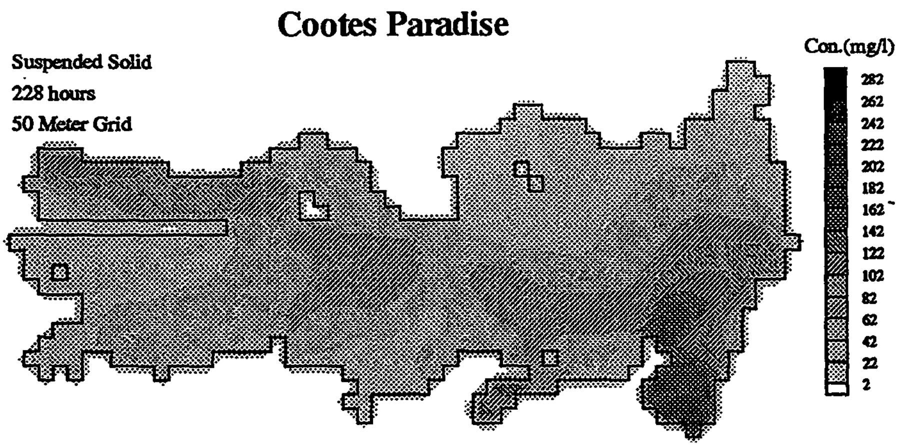
Appendix V

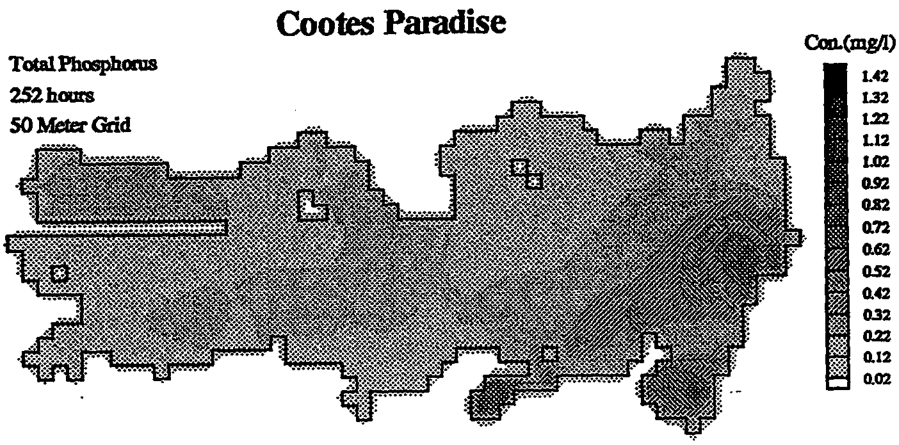
~ Pollutant Distribution Plots ~

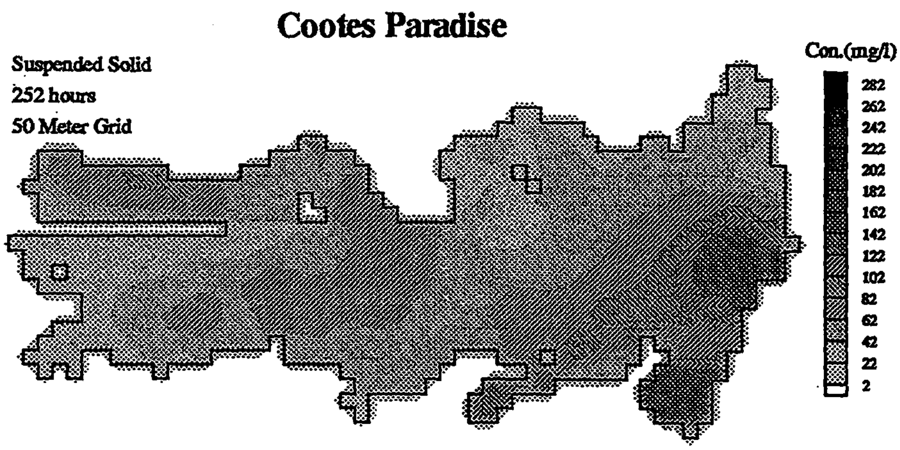

Cootes Paradise
Total Phosphorus
156 hours
50 Meter Grid
Con.(mg/l)
1.42
1.32
1.22
1.12
1.02
0.92
0.82
0.72
0.62
0.52
0.42
0.32
0.22
0.12
0.02

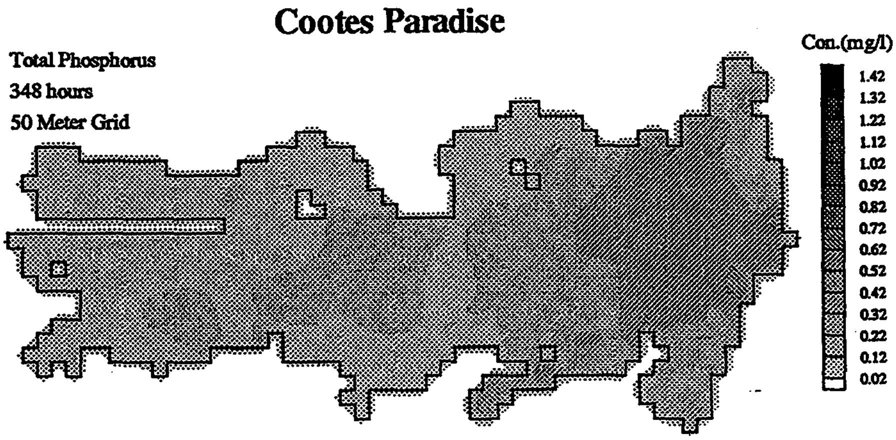

Cootes Paradise
Suspended Solid
156 hours
50 Meter Grid
Con.(mg/l)
282
262
242
222
202
182
162
142
122
102
82
62
42
22
2

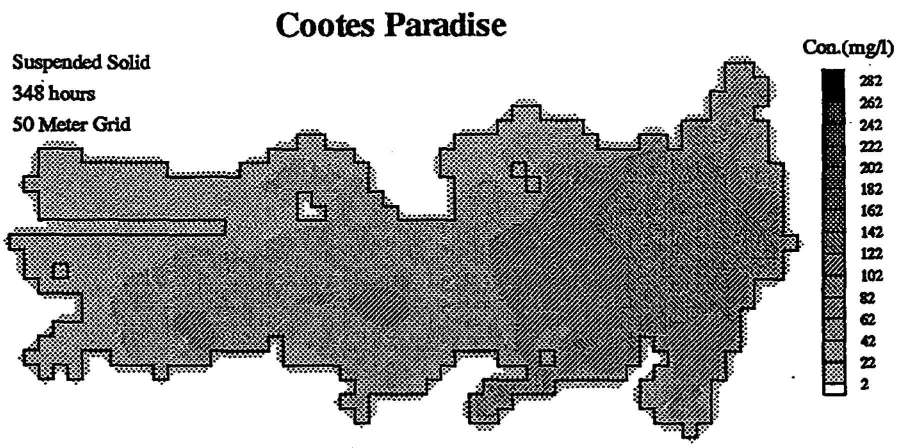

Cootes Paradise
Total Phosphorus
228 hours
50 Meter Grid
Con.(mg/l)
1.42
1.32
1.22
1.12
1.02
0.92
0.82
0.72
0.62
0.52
0.42
0.32
0.22
0.12
0.02

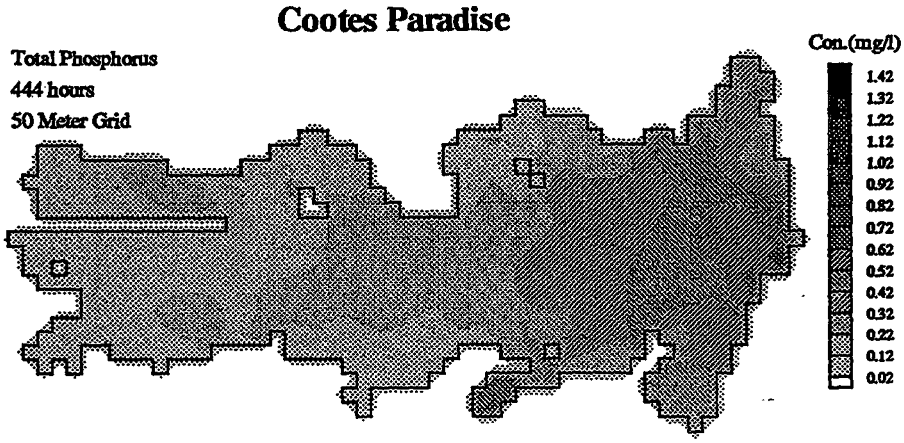

Cootes Paradise
Suspended Solid
228 hours
50 Meter Grid
Con.(mg/l)
282
262
242
222
202
182
162
142
122
102
82
62
42
22
2

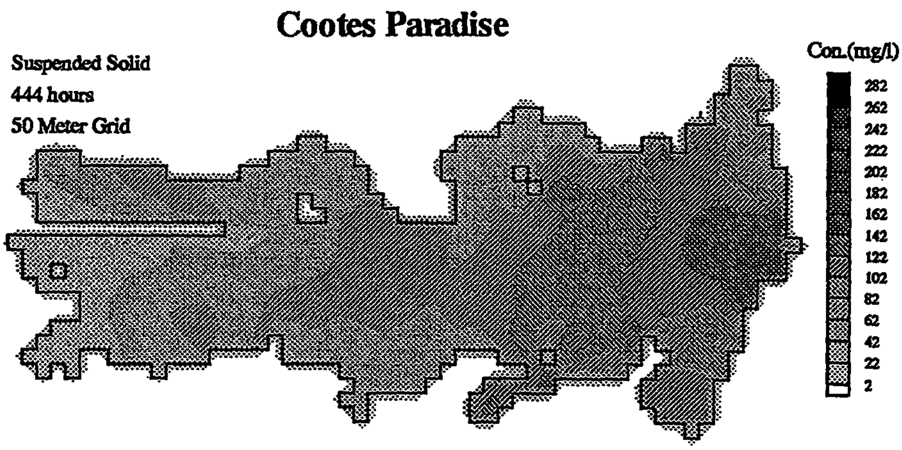

Cootes Paradise
Total Phosphorus
252 hours
50 Meter Grid
Con.(mg/l)
1.42
1.32
1.22
1.12
1.02
0.92
0.82
0.72
0.62
0.52
0.42
0.32
0.22
0.12
0.02

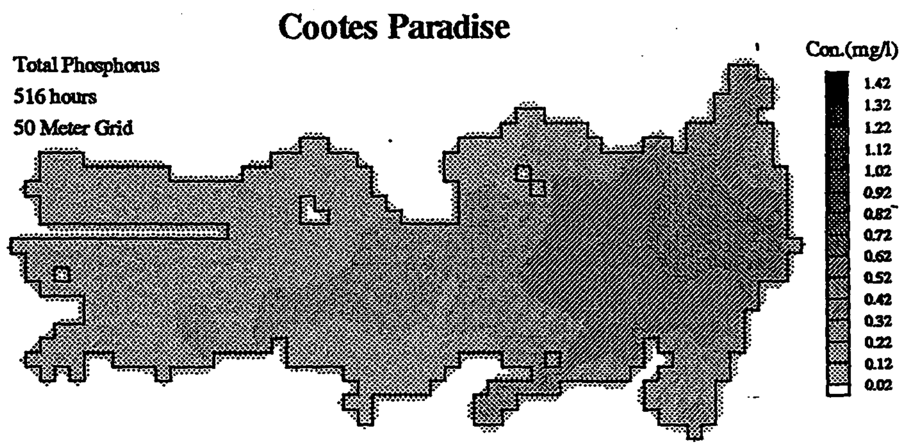

Cootes Paradise
Suspended Solid
252 hours
50 Meter Grid
Con.(mg/l)
282
262
242
222
202
182
162
142
122
102
82
62
42
22
2

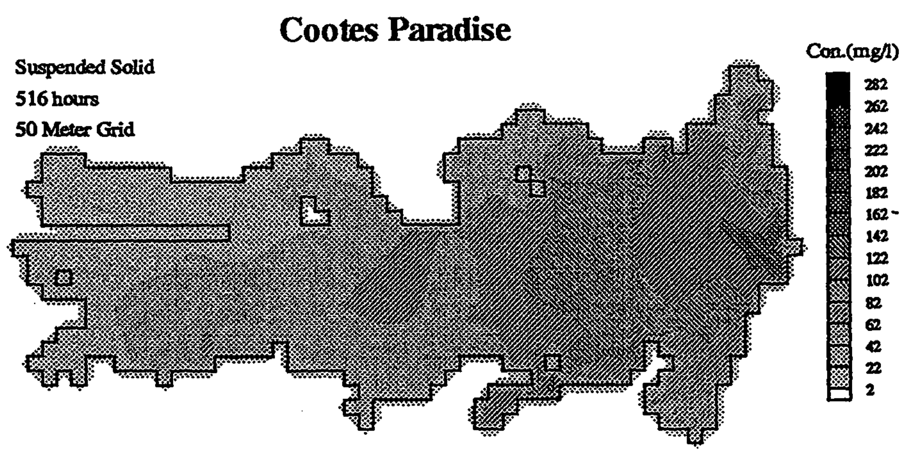

Cootes Paradise
Total Phosphorus
348 hours
50 Meter Grid
Con.(mg/l)
1.42
1.32
1.22
1.12
1.02
0.92
0.82
0.72
0.62
0.52
0.42
0.32
0.22
0.12
0.02

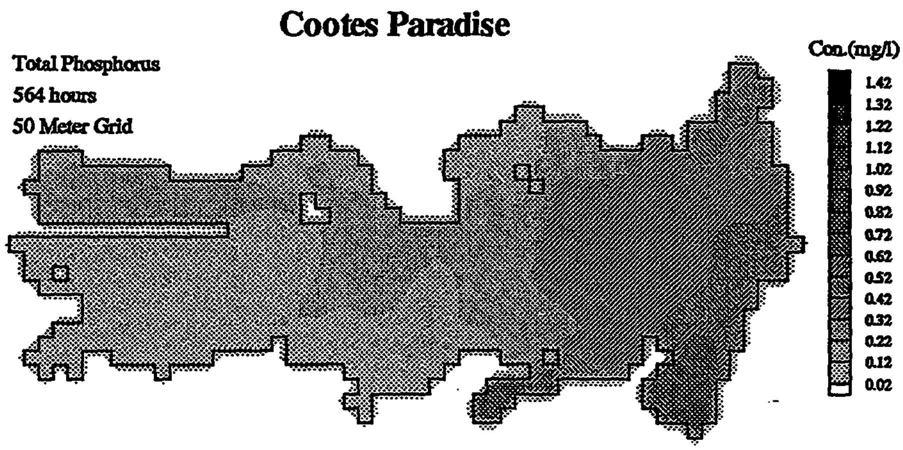

Cootes Paradise
Suspended Solid
348 hours
50 Meter Grid
Con.(mg/l)
282
262
242
222
202
182
162
142
122
102
82
62
42
22
2

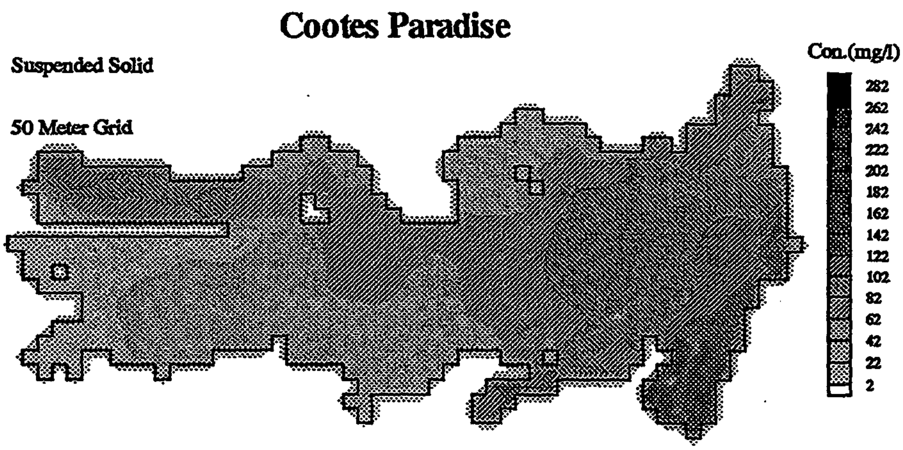

Cootes Paradise
Total Phosphorus
444 hours
50 Meter Grid
Con.(mg/l)
1.42
1.32
1.22
1.12
1.02
0.92
0.82
0.72
0.62
0.52
0.42
0.32
0.22
0.12
0.02


Cootes Paradise
Suspended Solid
444 hours
50 Meter Grid
Con.(mg/l)
282
262
242
222
202
182
162
142
122
102
82
62
42
22
2

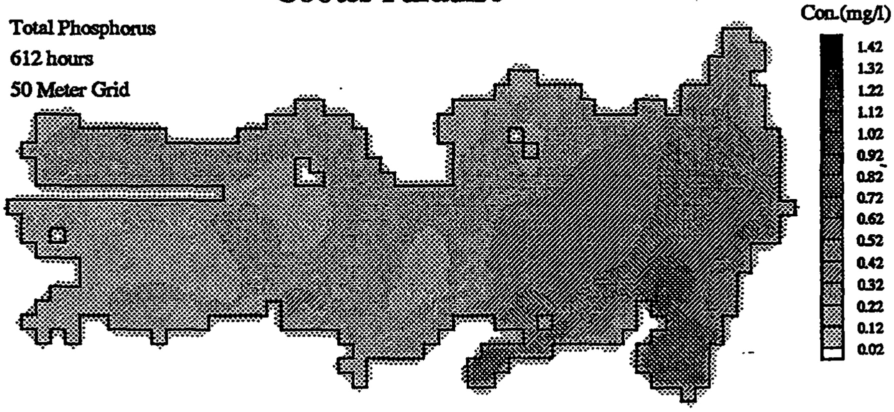

Cootes Paradise
Total Phosphorus
516 hours
50 Meter Grid
Con.(mg/l)
1.42
1.32
1.22
1.12
1.02
0.92
0.82
0.72
0.62
0.52
0.42
0.32
0.22
0.12
0.02


Cootes Paradise
Suspended Solid
516 hours
50 Meter Grid
Con.(mg/l)
282
262
242
222
202
182
162
142
122
102
82
62
42
22
2

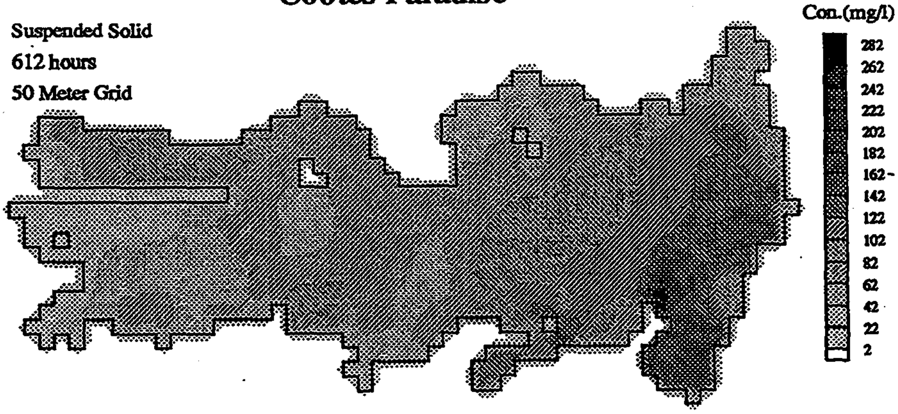

Cootes Paradise
Total Phosphorus
564 hours
50 Meter Grid
Con.(mg/l)
1.42
1.32
1.22
1.12
1.02
0.92
0.82
0.72
0.62
0.52
0.42
0.32
0.22
0.12
0.02

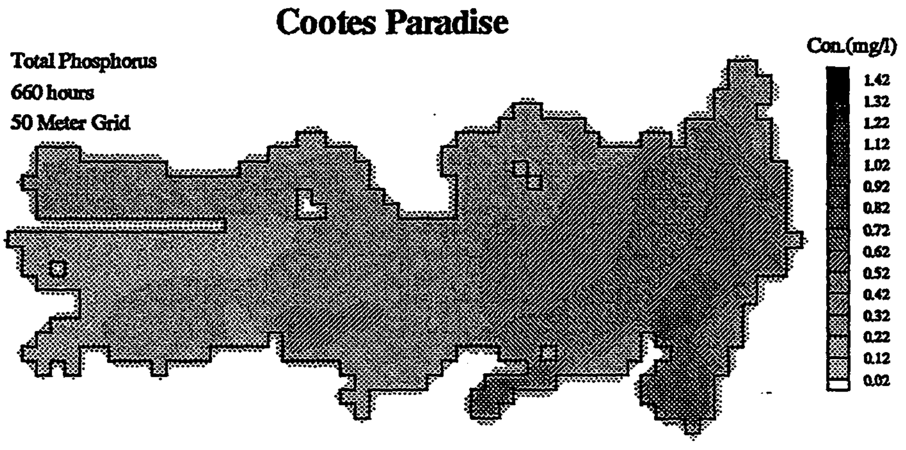

Cootes Paradise
Suspended Solid
50 Meter Grid
Con.(mg/l)
282
262
242
222
202
182
162
142
122
102
82
62
42
22
2

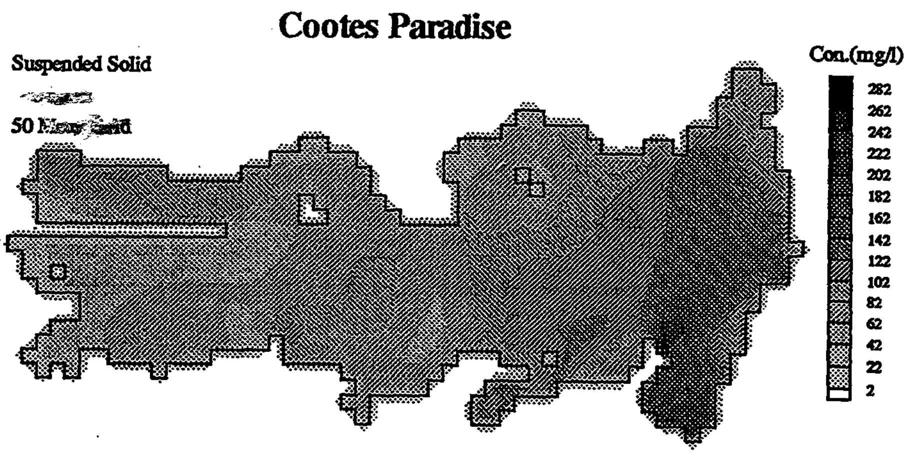
Cootes Paradise

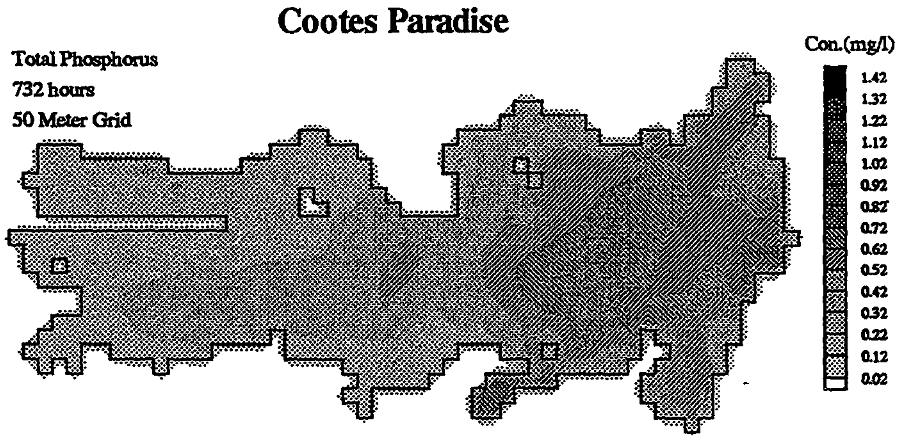


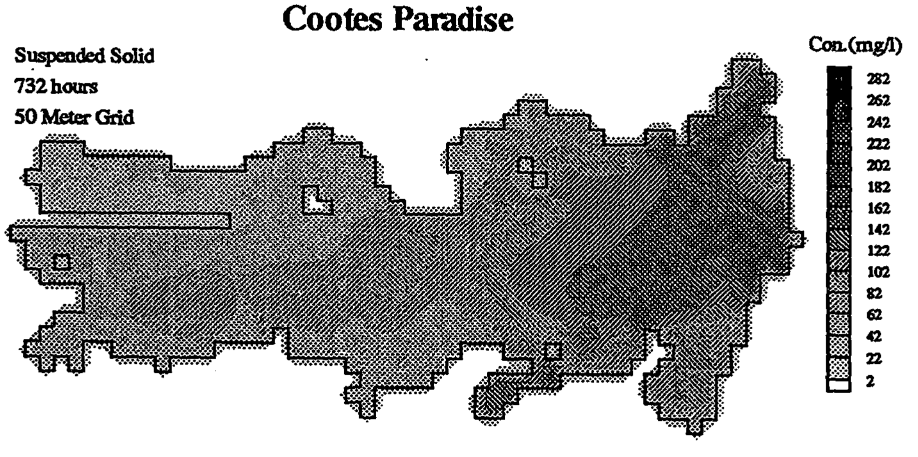
Cootes Paradise




Cootes Paradise
Total Phosphorus
660 hours
50 Meter Grid
Con.(mg/l)
1.42
1.32
1.22
1.12
1.02
0.92
0.82
0.72
0.62
0.52
0.42
0.32
0.22
0.12
0.02

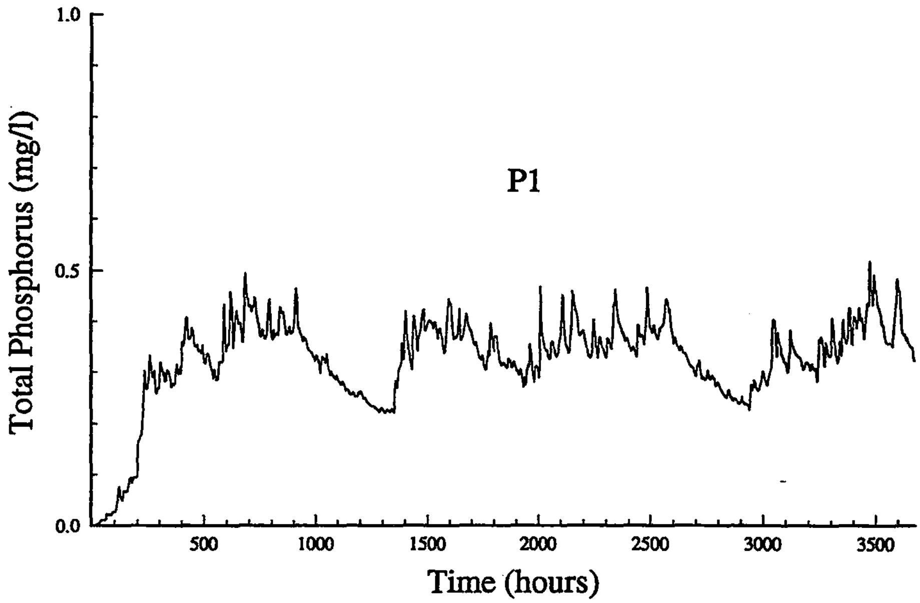

Cootes Paradise
Suspended Solid
Con.(mg/l)
282
262
242
222
202
182
162
142
122
102
82
62
42
22
2

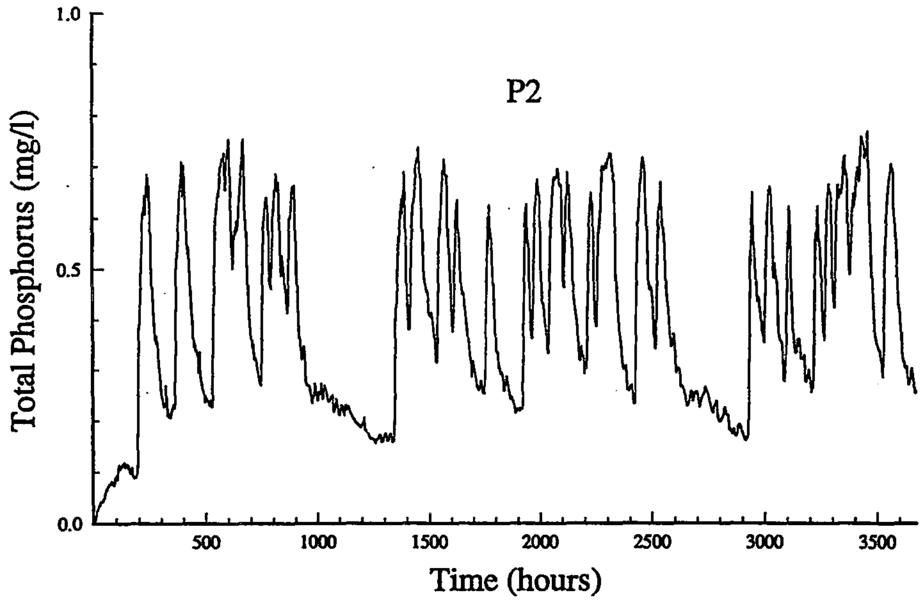

Cootes Paradise
Total Phosphorus
732 hours
50 Meter Grid
Con.(mg/l)
1.42
1.32
1.22
1.12
1.02
0.92
0.82
0.72
0.62
0.52
0.42
0.32
0.22
0.12
0.02

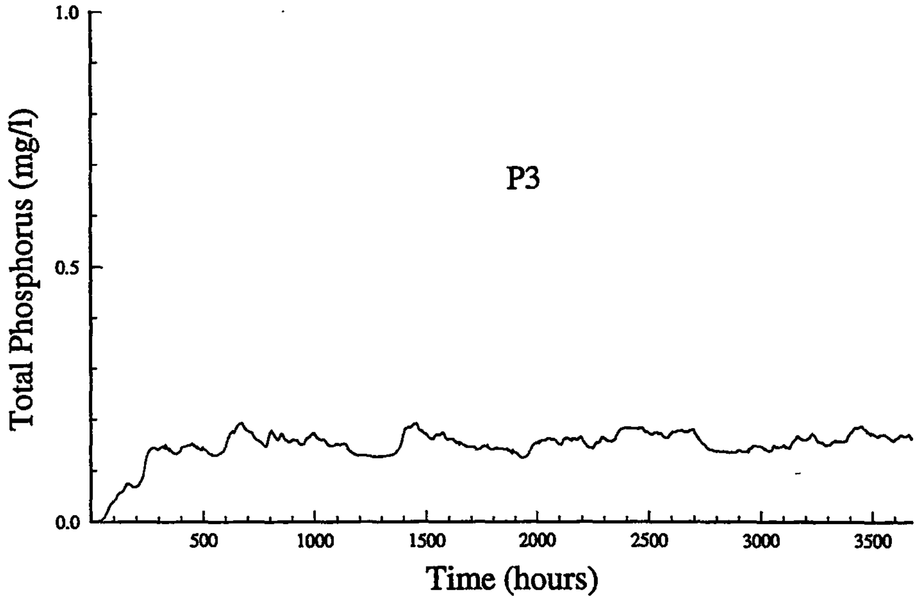

Cootes Paradise
Suspended Solid
732 hours
50 Meter Grid
Con.(mg/l)
282
262
242
222
202
182
162
142
122
102
82
62
42
22
2

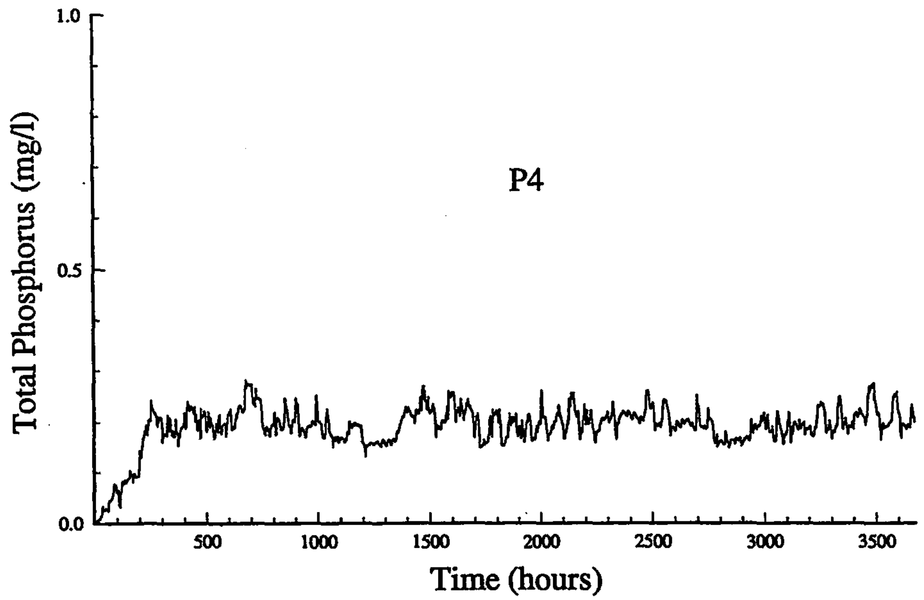
Appendix VI

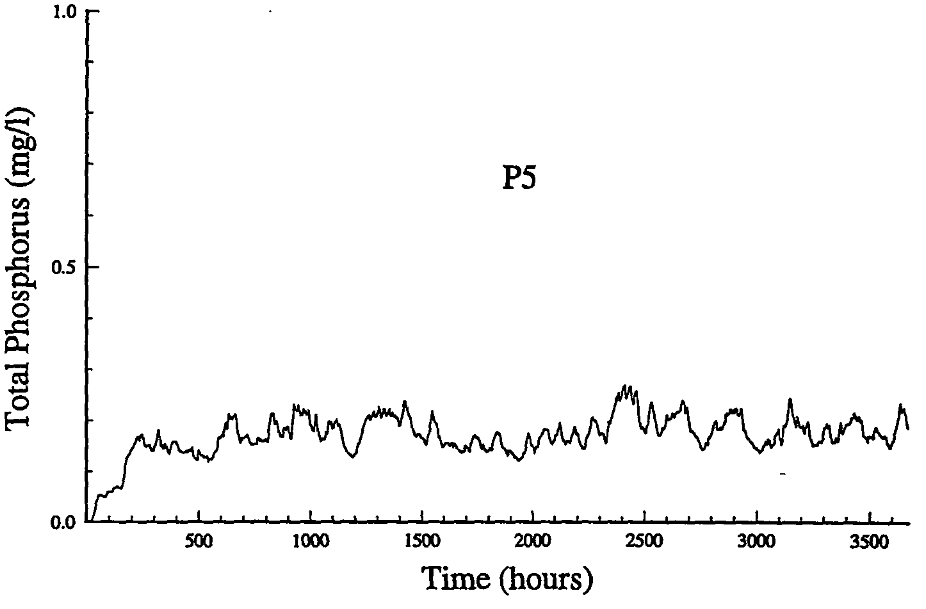
~ Concentration Plots for Phosphorus ~


P1
Total Phosphorus (mg/l)
1.0
0.5
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)

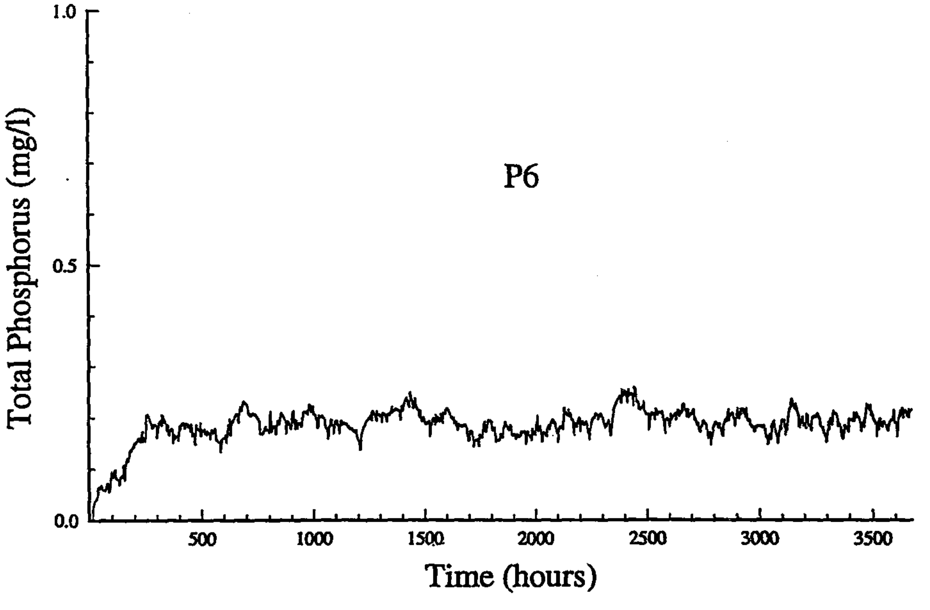

P2
Total Phosphorus (mg/l)
1.0
0.5
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)


1.0
0.5
0.0
Total Phosphorus (mg/l)
P3
500
1000
1500
2000
2500
3000
3500
Time (hours)

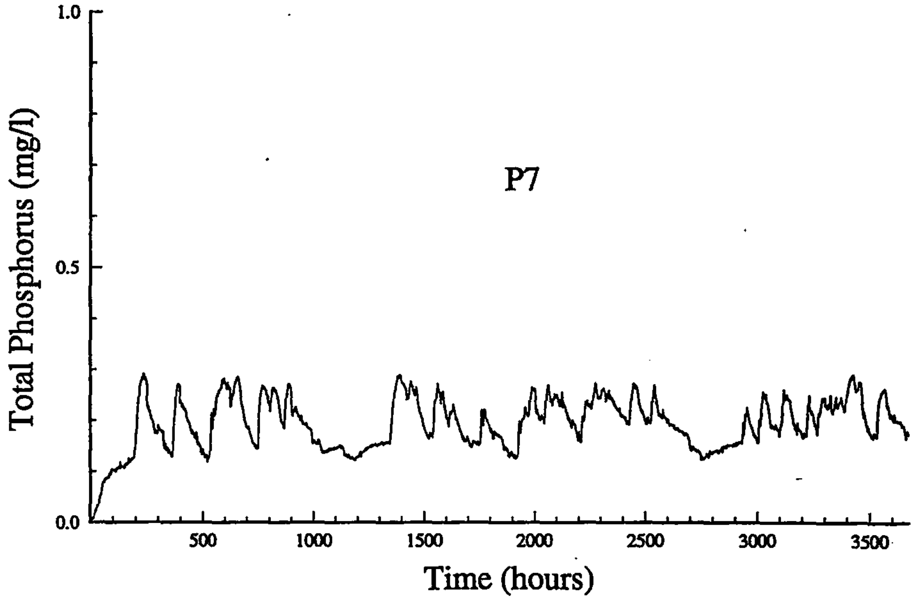

1.0
0.5
0.0
Total Phosphorus (mg/l)
P4
500
1000
1500
2000
2500
3000
3500
Time (hours)

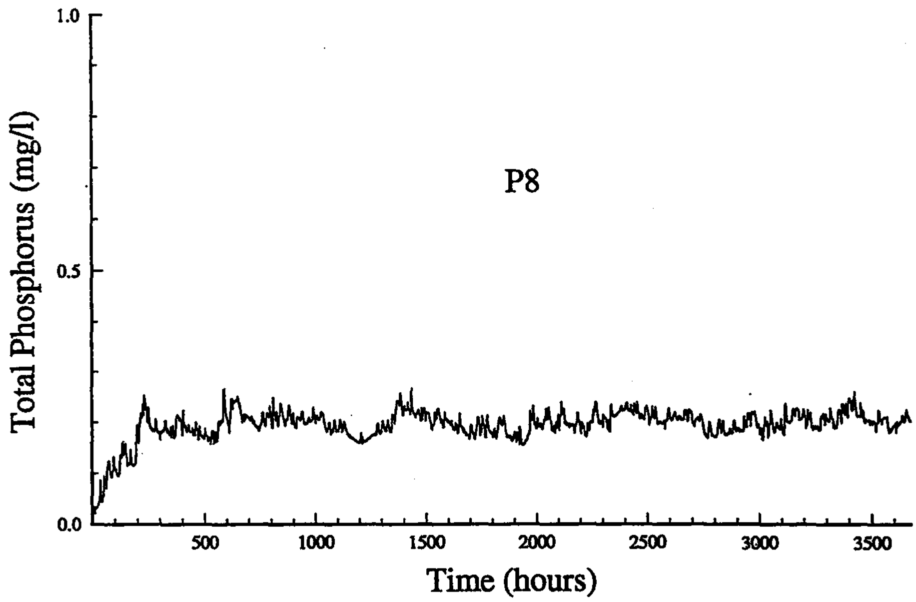


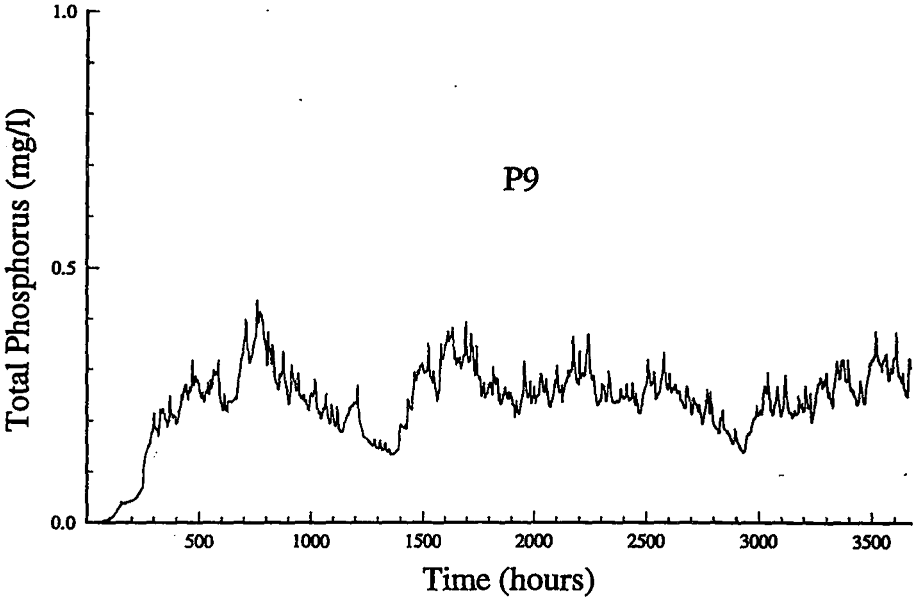
1.0
0.5
0.0
Total Phosphorus (mg/l)
P5
500
1000
1500
2000
2500
3000
3500
Time (hours)

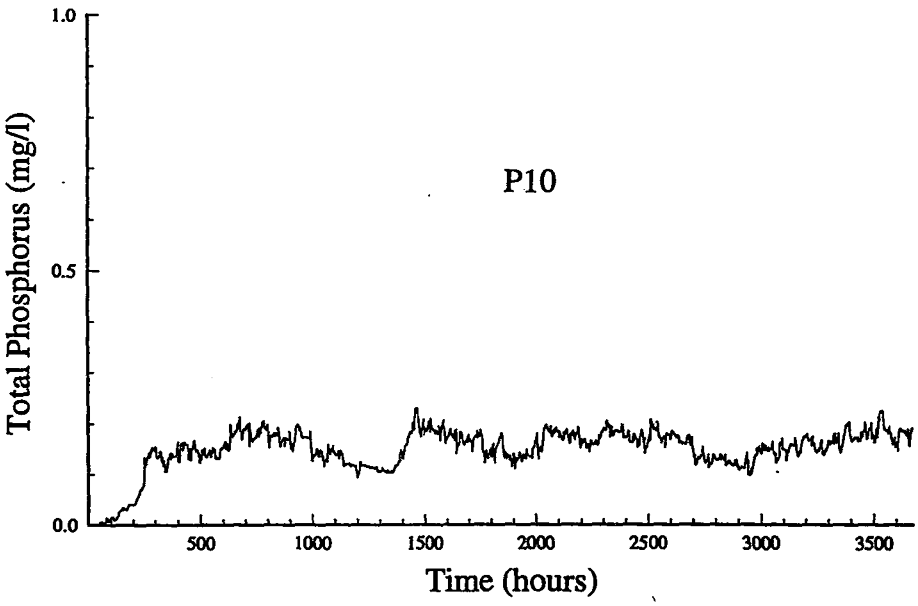


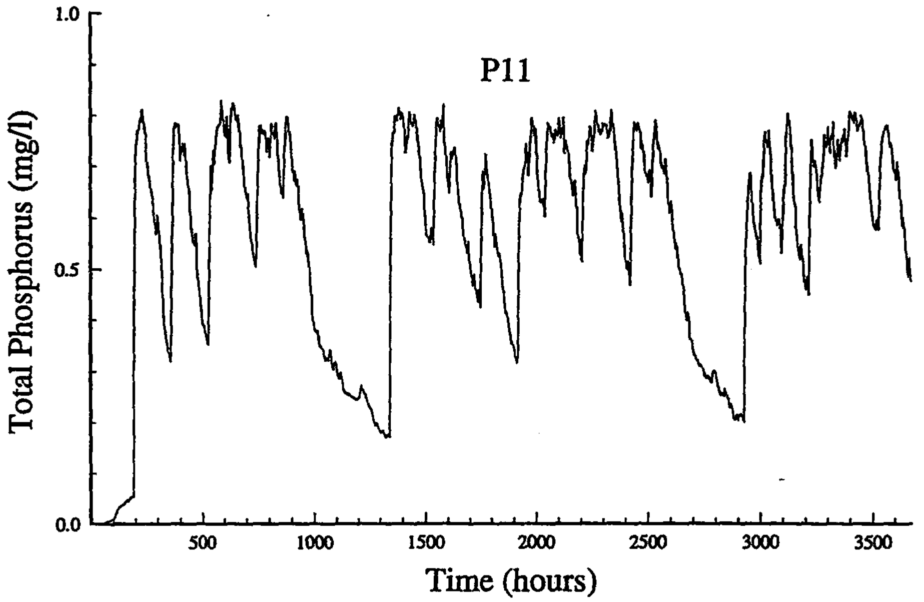
1.0
0.5
0.0
Total Phosphorus (mg/l)
P6
500
1000
1500
2000
2500
3000
3500
Time (hours)


1.0
0.5
0.0
Total Phosphorus (mg/l)
P7
500
1000
1500
2000
2500
3000
3500
Time (hours)


1.0
0.5
0.0
Total Phosphorus (mg/l)
P8
500
1000
1500
2000
2500
3000
3500
Time (hours)

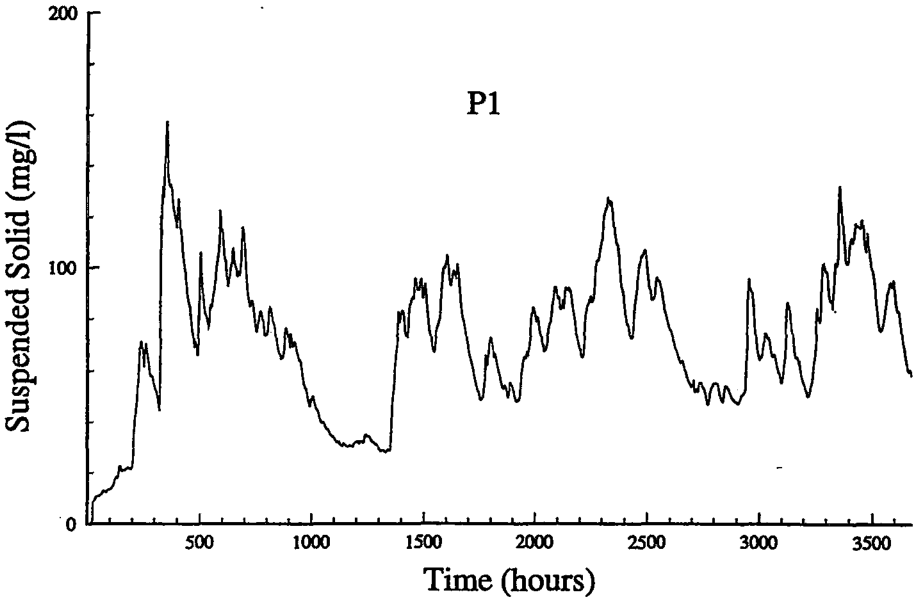

P9
Total Phosphorus (mg/l)
1.0
0.5
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)

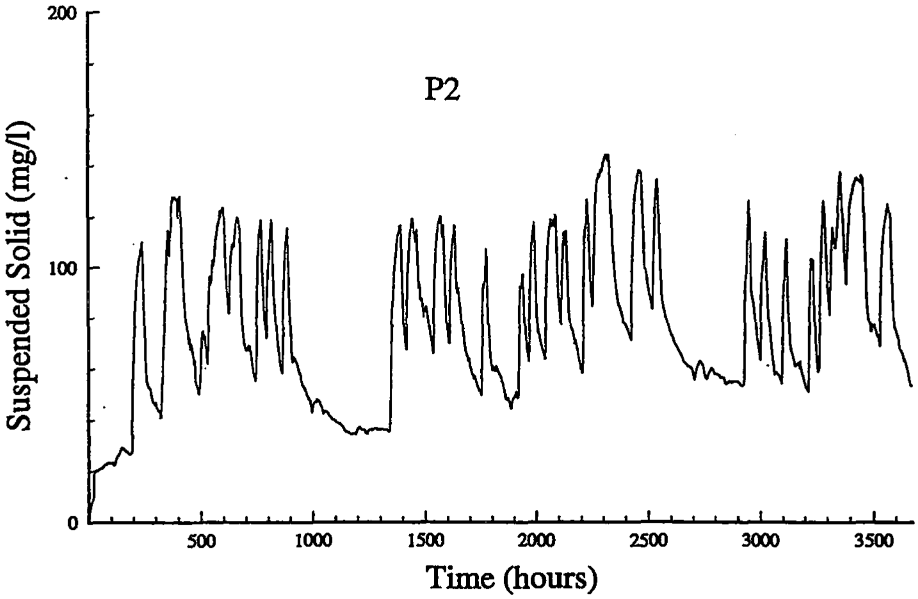

P10
Total Phosphorus (mg/l)
1.0
0.5
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)

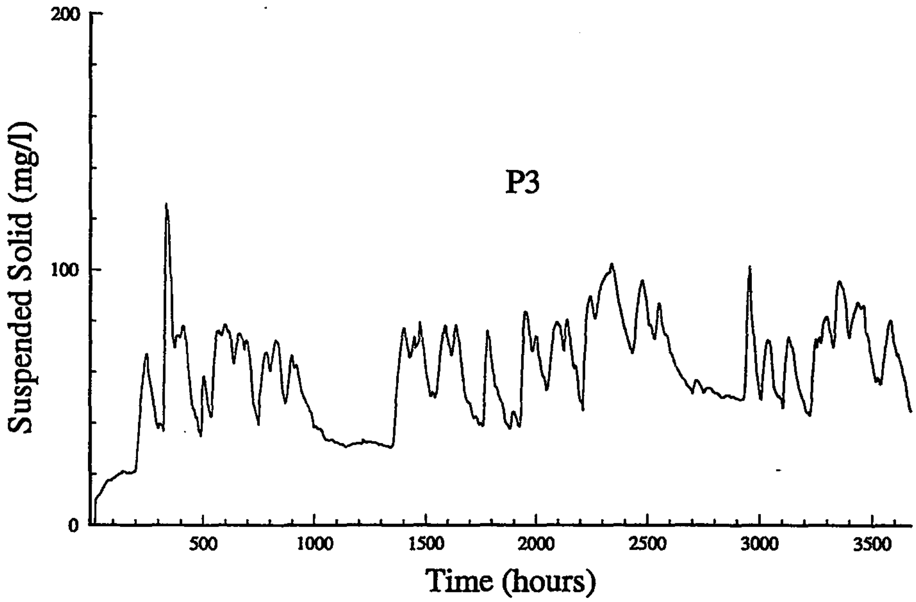

P11
Total Phosphorus (mg/l)
1.0
0.5
0.0
500
1000
1500
2000
2500
3000
3500
Time (hours)

Appendix VII

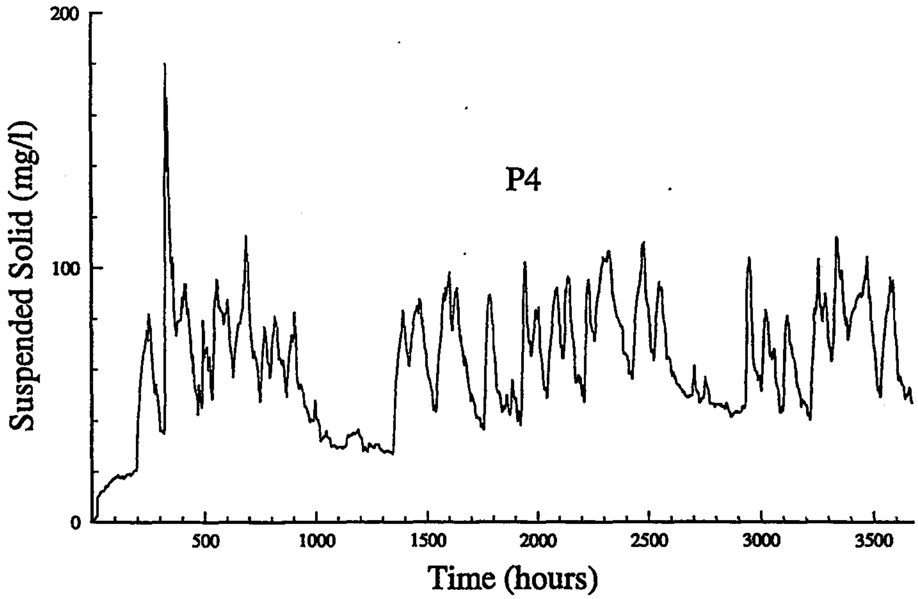
~ Concentration Plots for Suspended Solids ~


P1
Suspended Solid (mg/l)
200
100
0
500
1000
1500
2000
2500
3000
3500
Time (hours)

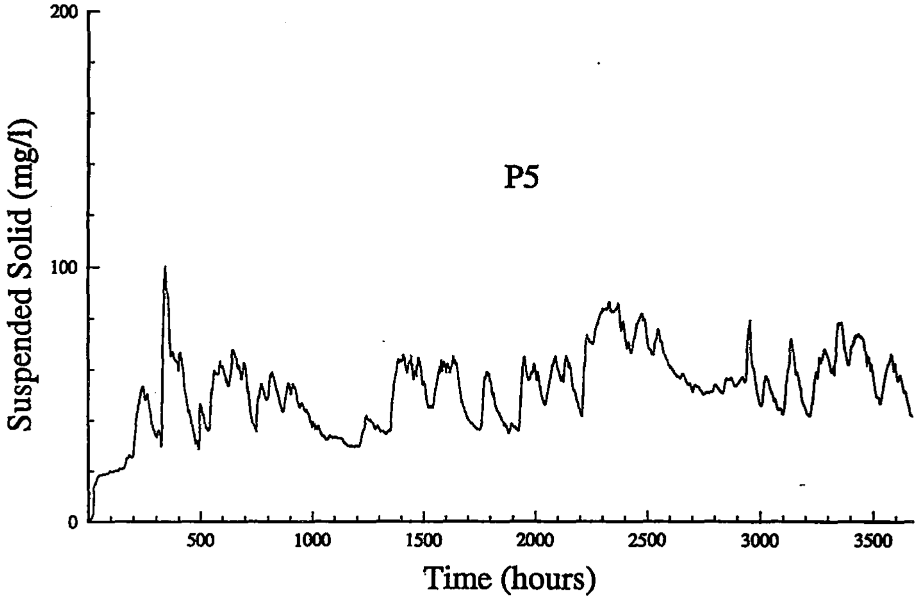

P2
Suspended Solid (mg/l)
200
100
0
500
1000
1500
2000
2500
3000
3500
Time (hours)

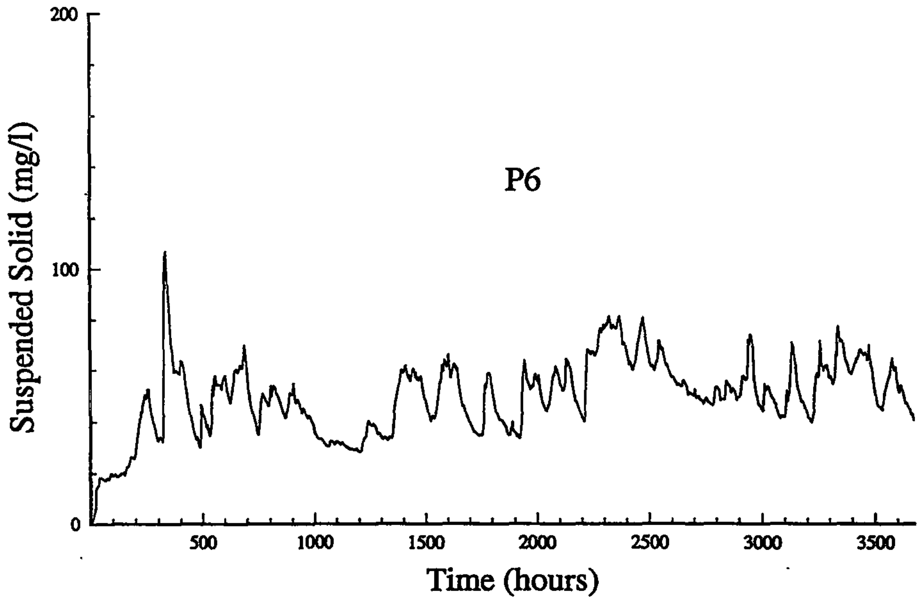


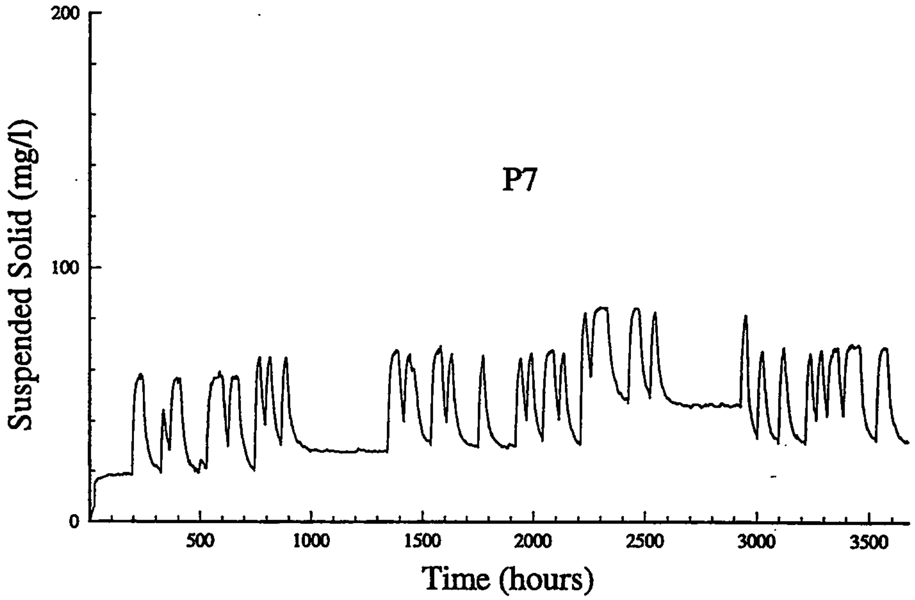
200
100
0
Suspended Solid (mg/l)
P3
500
1000
1500
2000
2500
3000
3500
Time (hours)

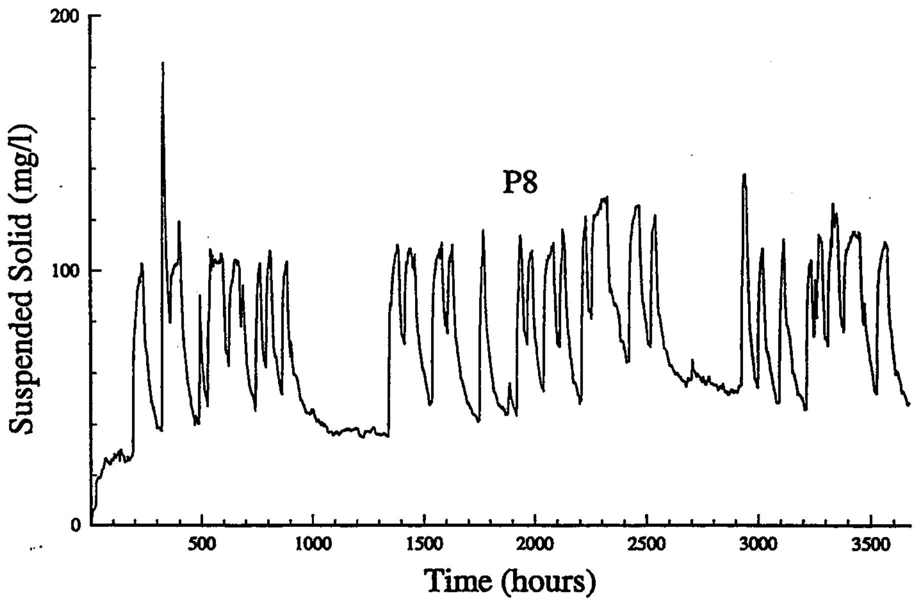


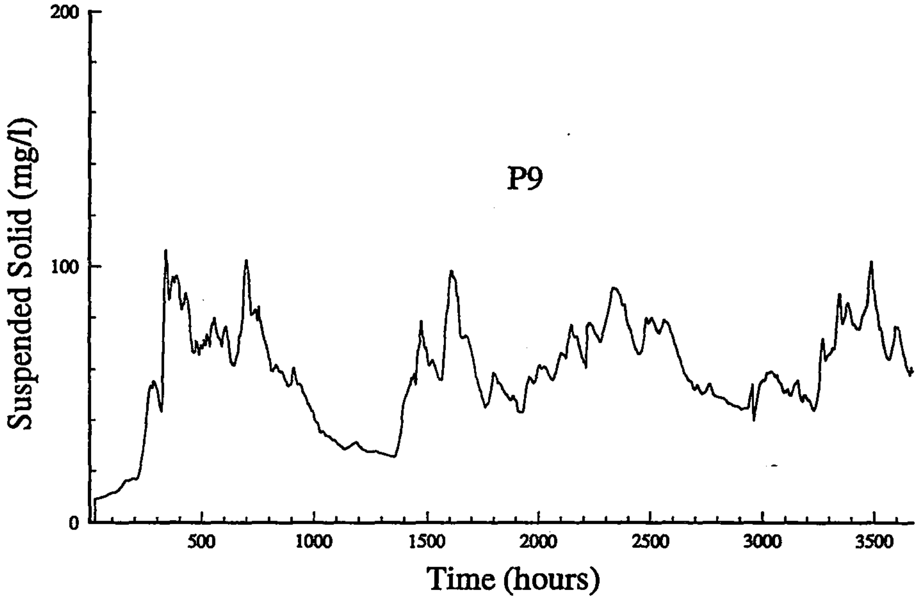
200
100
0
Suspended Solid (mg/l)
P4
500
1000
1500
2000
2500
3000
3500
Time (hours)

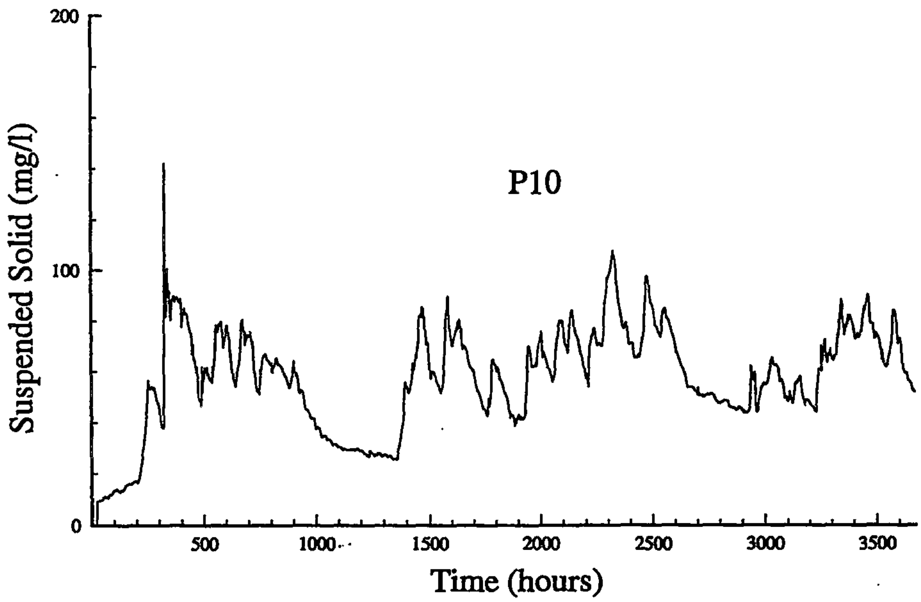

200
100
0
Suspended Solid (mg/l)
P5
500
1000
1500
2000
2500
3000
3500
Time (hours)

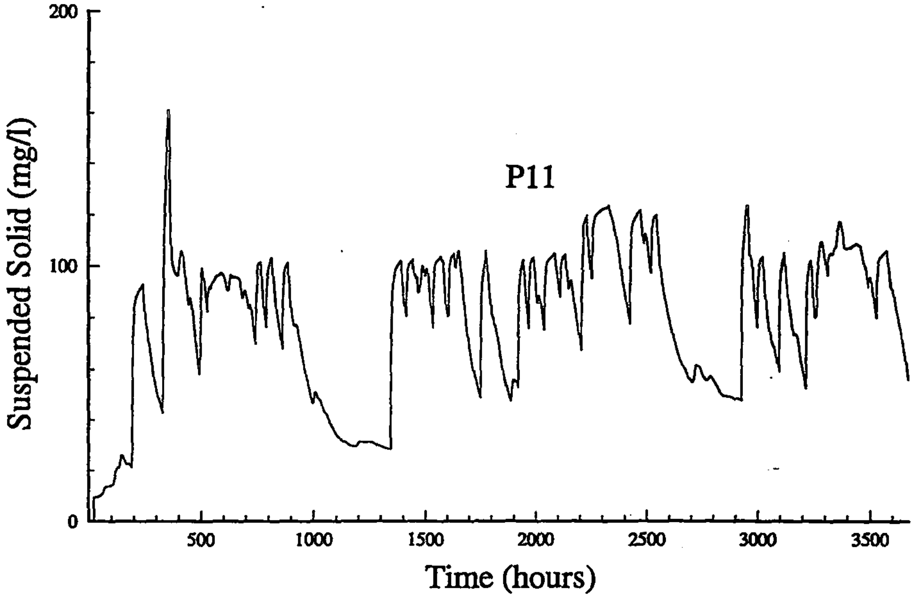

200
100
0
Suspended Solid (mg/l)
P6
500
1000
1500
2000
2500
3000
3500
Time (hours)


200
100
0
Suspended Solid (mg/l)
P7
500
1000
1500
2000
2500
3000
3500
Time (hours)


200
100
0
Suspended Solid (mg/l)
P8
500
1000
1500
2000
2500
3000
3500
Time (hours)


200
100
0
Suspended Solid (mg/l)
P9
500
1000
1500
2000
2500
3000
3500
Time (hours)


200
100
0
Suspended Solid (mg/l)
P10
500
1000
1500
2000
2500
3000
3500
Time (hours)



200
100
0
Suspended Solid (mg/l)
P11
500
1000
1500
2000
2500
3000
3500
Time (hours)

2198