ELSEVIER

Ecological Engineering 9 (1997) 1–18

ECOLOGICAL
ENGINEERING

Mass balance modelling and wetland restoration

K.L. Prescott, I.K. Tsanis *

Department of Civil Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L7, Canada

Received 24 June 1996; received in revised form 16 April 1997; accepted 24 April 1997

Abstract

As wetland ecosystems become degraded due to human actions, restoration efforts are becoming more pronounced. Developing a successful restoration plan, however, depends on a solid base of knowledge of the system. Mass balance models can provide valuable information about ecosystems with respect to input sources and the relative importance of each load. This study examined phosphorus and suspended solids loadings to Cootes Paradise marsh Hamilton Harbour, Lake Ontario, Canada, through the use of mass balance models. When compared to field data, the models predicted average concentrations well, however large variations occurred on a monthly basis. Relative loadings results suggested that 57% of phosphorus and 68% of suspended solids contributions to Cootes Paradise came from resuspension of the sediments. These inputs were followed in importance by rural runoff and combined sewer overflows for phosphorus and by rural runoff and the creeks for suspended solids. Data, though, are lacking in many areas related to these sources. Improved information is therefore necessary to confirm the contributions from the sediments, runoff and combined sewer overflows before restoration strategies are finalized. © 1997 Elsevier Science B.V.

Keywords: Mass balance models; Phosphorus; Suspended solids; Wetland restoration

---

* Corresponding author. Tel.: +1 905 5259140 (ext. 27176); fax: +1 905 5299688; e-mail: tsanis@water.eng.mcmaster.ca

PII S0925-8574(97)00015-3

1. Introduction

Wetlands are among the most important ecosystems on Earth. They provide habitats for a wide variety of flora and fauna, they perform valuable functions in hydrologic and chemical cycles by cleansing polluted waters, preventing floods, protecting shorelines and recharging groundwater aquifers and they have certain economic importance in food and energy production (Mitsch and Gosselink, 1993; Lavender, 1987; Kay, 1949). Unfortunately, many wetlands have been converted to agricultural fields, altered for port development, or filled for industrial, commercial and residential development (Mitsch and Gosselink, 1993; Whillans, 1982). Those wetland areas which still remain are faced with deteriorating water quality and subsequent changes in ecosystem function and structure (Mudroch, 1981; Bacchus, 1974).

Wetlands possess many valuable qualities which have been ignored in an effort to create more land for human exploitation. Now that information on the beneficial properties of wetland environments is becoming more available, concern is rising for the protection of remaining wetlands and for the restoration of degraded wetlands. Restoration of such systems, however, is not simple (Roberts, 1993). In restoring wetlands, extreme care must be taken to ensure that the system does not become over-engineered (Mitsch and Gosselink, 1993); it is more beneficial to do as little as possible to give the system a kick-start and then leave it to regenerate on its own. Extensive study and thought also must be put into a restoration project so as not to result in failure. 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 but fail to support the plants and animals that they were intended to support (Roberts, 1993).

Although it is much easier to protect a wetland before it reaches a state of severe degradation than to restore or recreate a wetland later, protection is no longer an option for many of these degraded environments (Canadian Wildlife Service, 1989; Weller, 1981). In the Great Lakes system, several wetlands have been completely destroyed but some still exist for which there is the potential of restoration. Cootes Paradise, a 250 ha wetland located at the western end of Hamilton Harbour, Lake Ontario, Canada (Fig. 1), is an example of such a marsh which has changed over the past several decades from a thriving wetland ecosystem to one which is degraded and which possesses the potential for restoration.

For Cootes Paradise, the most obvious change which has occurred is that which involves the vegetation. At one time this wetland was essentially 100% covered with emergent vegetation but today this percentage has dropped to near zero total emergent cover and the ability of the system to support submergent plants is minimized due to excessive turbidity (Painter et al., 1989). Vegetation is important to a wetland ecosystem and a decrease in the number and diversity of plants can lead to negative consequences. A loss of vegetation leads to a loss of wildlife due to a decrease in food and shelter, decreased cleansing and nutrient uptake by microorganisms associated with plants (DeJong, 1976), resuspension of sediments due to increased water flow (Carpenter and Lodge, 1986) and wind action (Dieter, 1990) and decreased accretion of sediments which leads to decreased expansion of the littoral zone and decreased ecological succession (Carpenter and Lodge, 1986).

The decrease of vegetation in Cootes Paradise can be attributed to several possible explanations among which are regulated water levels (Painter et al., 1989; Semkin et al., 1976; Bacchus, 1974), carp behaviour (Painter and Hampson, 1990; Painter et al., 1989; Kay, 1949), high suspended solids (Painter et al., 1989; Semkin et al., 1976; Bacchus, 1974) and excessive nutrient loadings (Painter and Hampson, 1990; Semkin et al., 1976; Bacchus, 1974). This paper focuses on the use of mass balance modelling to obtain information on nutrient and suspended solids loadings to Cootes Paradise. A mass balance modelling approach is a valuable tool for identifying the inputs to a system and for determining the relative degree of importance of each source. The information gathered from the mass balance models for Cootes Paradise can be used then in designing restoration and management strategies for the marsh.

2. Mass balance calculations

Mass balance models are based on the theory of the conservation of mass (Vollenweider, 1975). 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 sepa-

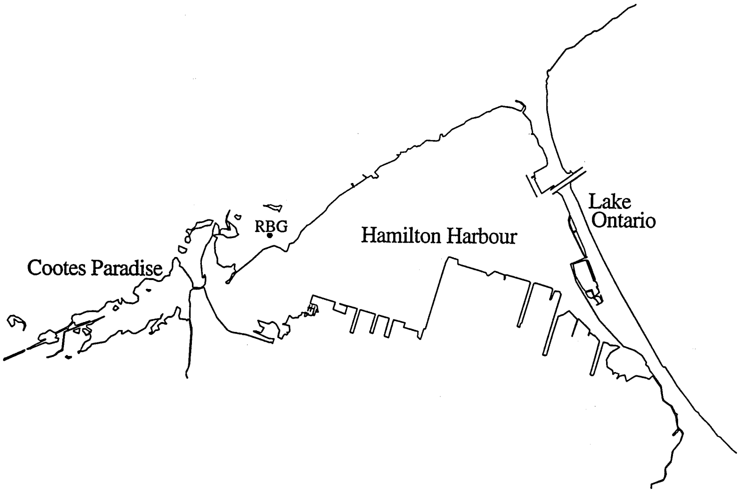

Fig. 1. Cootes Paradise marsh is located in the Dundas Valley at the western end of Hamilton Harbour, Lake Ontario, Canada.

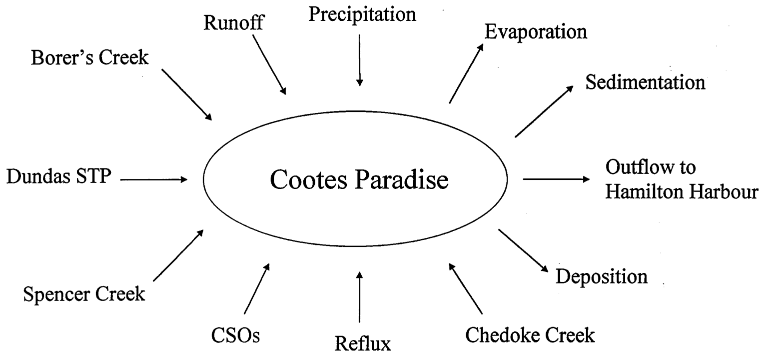

Fig. 2. Inputs and outputs for phosphorus and suspended solids in Cootes Paradise.

rated 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 and the overall concentration in the marsh was determined using Eq. (1):

$$C = \frac{\sum L_{\mathrm{i}}}{F + \left(\frac{s \cdot D_s}{R + D_{\mathrm{s}}}\right)} \tag{1}$$

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}).

Phosphorus and suspended solids loadings to Cootes Paradise come from both external and internal sources (Fig. 2). External loads include the surrounding tributaries, the Dundas Sewage Treatment Plant (STP), stormwater runoff, combined sewer overflows (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 after spring runoff (Bacchus, 1974), therefore only the three main creeks, Spencer Creek, Borer's Creek and Chedoke Creek, were considered (Fig. 3).

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. Hydrodynamic studies for Cootes Paradise indicated that this was not necessarily true, but for ease of calculations the fully mixed assumption was retained. Concentrations were therefore taken to be uniform throughout the entire water body. 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 available.

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 with respect to areas such as flows and concentrations for the creeks and storm event contributions.

3. 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.

The flow rate for Spencer Creek is monitored on a continuous basis by the Water Survey of Canada (WSC) and water quality data have been collected by the Royal Botanical Gardens (RBG) in Burlington, Ontario. Unlike Spencer Creek, though, virtually no data have been collected for either Chedoke Creek or Borer's Creek. Studies which have included these two creeks (D.W. Draper and Associates Ltd., 1993; Paul Theil Associates Ltd. and Beak Consultants Ltd., 1991; Robinson and James, 1984; James, 1980) have focused primarily on storm water management. The

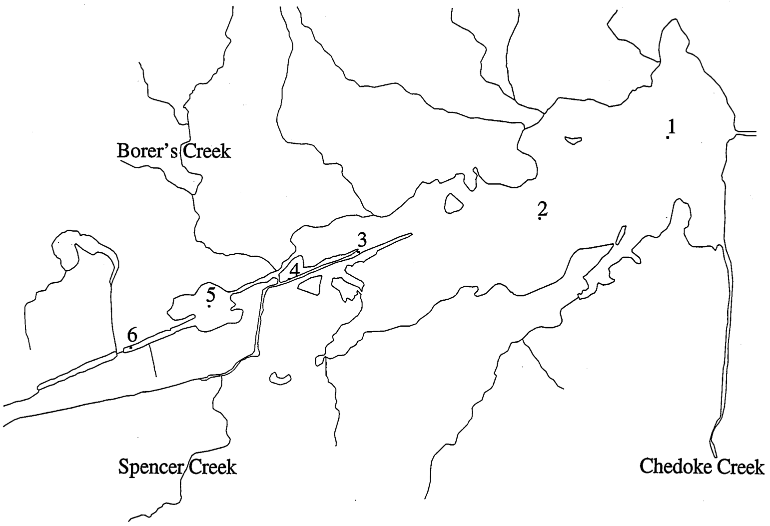

Fig. 3. The location of the water quality monitoring sites in Cootes Paradise which are sampled by the Royal Botanical Gardens, Burlington, Ontario. The three main tributaries to the marsh are also labeled.

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 and Associates Ltd., 1993; Paul Theil Associates Ltd. and Beak Consultants Ltd., 1991; Robinson and James, 1984; James, 1980).

Rainwater contains 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 was therefore considered as an input load to Cootes Paradise. The flow rate 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). Since rainwater only contains a small amount of phosphorus and suspended solids, it was assumed that dry fallout would contribute an even smaller amount of these substances to Cootes Paradise. Consequently, dry atmospheric deposition was considered negligible and therefore ignored.

4. Runoff

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 determined based on the amount of rain falling on the rural portion of the watershed. Due to 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 base flows 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 Ltd. and Beak Consultants Ltd., 1991) and the rainfall data were taken from meteorological reports available from the Royal Botanical Gardens.

5. 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 5% of the rain falling on the urban areas was used in the loading calculations (Paul Theil Associates Ltd. and Beak Consultants Ltd., 1991).

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

6. Sedimentation, deposition and reflux coefficients

Internal loads and losses 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 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. Imboden (1974), who separated sedimentation from reflux, gave a range of actual phosphorus sedimentation velocities between 0.1 and 0.4 m/day. A settling velocity of 0.113 ± 0.064 m/day, given by Minns (1986), was used in the Cootes Paradise calculations.

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

$$v_s = \frac{g(\rho_p - \rho_w)d_p^2}{18\mu} \tag{2}$$

where v_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 surface sediments in the marsh are comprised of approximately 26% sand, 49% silt and 25% clay particles (Mudroch, 1981). Since no data were available for particle size distributions of suspended solids in the inflows, it was assumed that the distribution of sediment sizes within Cootes Paradise applied to the inputs. Furthermore, it was assumed that clay particles remained in suspension at all times and that sand and silt particles were subject to both settling and resuspension. Therefore, for suspended solids concentrations, Eq. (3) was used and the settling velocity was calculated based on size and density values for an average sand-silt particle (Craig, 1992; Rukavina and Versteeg, 1995).

$$C = \frac{0.25\sum L_{\mathrm{i}}}{F} + \frac{0.75\sum L_{\mathrm{i}}}{F + \left(\dfrac{s \cdot D_s}{R + D_s}\right)} \tag{3}$$

It should be emphasized here that Stoke's Law estimates settling velocities for particles under ideal conditions and under gravitational forces only. Ideal conditions do not occur in Cootes Paradise. Currents will keep particles in suspension and the flocculent nature of clays and silts will impact settling properties (Eisma, 1993). The mass balance calculations used in this study do not allow for the consideration of current effects on the settling of suspended matter, and information is scarce on the composition, formation and behaviour of flocs (Eisma, 1993). Settling velocities determined from Stoke's Law were therefore considered to be adequate estimates for suspended solids in Cootes Paradise, however studies should be done to gather information on the behaviour of suspended solids in this marsh.

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 1.8–3.0 mm/yr. For a marsh environment to be maintained in Cootes Paradise, sedimentation must therefore occur at the same rate to preserve the shallow depths (Smith, 1995). Smith (1995) suggested that the rate of sediment deposition in Cootes Paradise was keeping pace with the rate of 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 1–10 mm/yr, however this value for Cootes Paradise should be verified in future research.

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). Knowing the external load contributions and the rates at which phosphorus and suspended solids are removed via settling and deposition, the reflux coefficient can be calculated using field data. This procedure, along with RBG field data from 1990 to 1992, was used for determining estimates for the reflux coefficients for phosphorus and suspended solids in Cootes Paradise.

The values used for the phosphorus and suspended solids mass balance calculations are summarized in Table 1. It also should be noted that the volume of Cootes Paradise (1.63×10^6 m^3) and the areas of Cootes Paradise (2.08×10^6 m^2) and the watershed (2.82×10^8 m^2) were determined using a geographic information system (GIS).

7. Results

Table 2 outlines the total flows determined by the mass balance as well as the results of the concentration calculations for Cootes Paradise. Average field values

Table 1
Parameter used in the mass balance calculations for Cootes Paradise

Parameter	Value	Source
Borer's Creek		
Flow (m^3/s)	0.12	D.W. Draper and Associates Ltd., 1993
Phosphorus (mg/l)	0.07	
Suspended solids (mg/l)	33.1	
Chedoke Creek		
Flow (m^3/s)	0.086	Paul Theil Associates Ltd. and Beak Consultants Ltd., 1991; Robinson and James, 1984; James, 1980
Phosphorus (mg/l)	0.25	
Suspended solids (mg/l)	50.0	
Spencer Creek		
Flow (m^3/s)	0.55–1.45	Water Survey of Canada
Phosphorus (mg/l)	0.07–0.31	Royal Botanical Gardens
Suspended solids (mg/l)	16.8–59.0	
Dundas STP		
Flow (m^3/s)	0.13–0.15	Dundas STP annual operation reports
Phosphorus (mg/l)	0.36–0.49	
Suspended solids (mg/l)	2.1–4.0	
CSOs-sewage		
Flow (m^3/s)	0.01–0.02	Paul Theil Associates Ltd. and Beak Consultants Ltd., 1991
Phosphorus (mg/l)	6.0	
Suspended solids (mg/l)	302.0	
CSOs-stormwater		
Flow (m^3/s)	0.17–0.28	Paul Theil Associates Ltd. and Beak Consultants Ltd., 1991
Phosphorus (mg/l)	0.33	
Suspended solids (mg/l)	100.0	
Runoff		
Flow (m^3/s)	0.52–1.41	
Phosphorus (mg/l)	0.46	Paul Theil Associates Ltd. and Beak Consultants Ltd., 1991
Suspended solids (mg/l)	150.0	
Rainwater		
Phosphorus (mg/l)	0.04–0.09	Pareja et al., 1994; Herman and Gorham, 1957
Suspended solids (mg/l)	10.0	

Table 1 (continued)

Parameter	Value	Source
Deposition (mm/year)		
Phosphorus	1.8–3.0	Smith, 1995
Suspended solids	1.8–3.0	
Sedimentation (m/day)		
Phosphorus	0.113 ± 0.64	Minns, 1986
Suspended solids	0.46–25.87	
Reflux (s^{-1})		
Phosphorus	1.65×10^{-9}–1.14×10^{-8}	
Suspended solids	5.43×10^{-8}–9.05×10^{-8}	

are also included in Table 2 for comparison with the model values. The field values were based on 1989–1992 data from the RBG sampling stations, numbers 1–3 (Fig. 3). Stations 4–6 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 percentage error between the model concentration values and the field concentration values fluctuated greatly on a monthly basis from values as low as 5.75% to those as high as 53%. The average values, however, differed by less than

Table 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[a]	Error[b] (%)	Model	Field[a]	Error[b] (%)
May	3.473	0.275	0.206 ± 0.026	33.50	73.68	48.14 ± 19.79	53.05
June	2.510	0.331	0.313 ± 0.049	5.75	98.77	75.35 ± 10.23	31.08
July	1.789	0.327	0.307 ± 0.010	6.51	79.38	91.98 ± 8.75	13.70
August	1.602	0.264	0.238 ± 0.011	10.92	70.08	95.96 ± 13.42	26.97
September	2.317	0.249	0.360 ± 0.340	30.83	72.58	60.88 ± 3.67	19.22
Average	2.338	0.289	0.285 ± 0.062	1.40	78.78	74.46 ± 20.29	5.95

[a] Average ± S.D.

[b] Calculated between the model values and the average field values.

6% for both phosphorus and suspended solids. A percentage error of 6% is very good considering that many assumptions had to be made in order to keep the mass balance model simple and considering that the data set for Cootes Paradise is incomplete.

For the phosphorus concentrations in the marsh, the model predicted values greater than those reported by the field data, with the exception of the concentration for September. The mass balance results for June, July and August agreed well with the field values, but May and September differed by 33.5 and 30.8%, respectively. The phosphorus concentrations given by the model calculations also showed an increase from May to June followed by decreases through to September.

The percentage errors for the suspended solids values were high. For May, June and September, 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.

When the loadings to Cootes Paradise were separated into individual source contributions, reflux was shown to account for an average of over 57% (45 mg m^{-2} day^{-1}) of the loadings for phosphorus and 68% (18 g m^{-2} day^{-1}) for suspended solids. 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. Rural runoff followed reflux with approximately 23% of the phosphorus contributions and 21% 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 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. 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.

To clarify the potential range of values for reflux, sensitivity calculations were made. The settling and depositional parameters were varied and reflux values recalculated. Little change occurred in the predictions for the overall phosphorus concentrations, however changes were seen in the relative percentage contributions to the load by reflux. Although the contribution to phosphorus loads by reflux was typically near 57%, this value ranged from 33 to 69% (17–74 mg m^{-2} day^{-1}) when the other parameters were varied. As with phosphorus, the suspended solids concentrations varied slightly when the settling and deposition parameters were changed, however, the percentage contribution to reflux ranged from 65 to 72% (16–22 g m^{-2} day^{-1}).

8. Discussion

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 2). High flow will decrease the residence time for substances in Cootes Paradise thereby resulting in lower overall concentrations. Discrepancies between the field and model values may have therefore 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 for Cootes Paradise, 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).

The relative loadings for phosphorus indicated that the major input (approximately 57% or 45 mg/m^2 per day) was reflux from the sediments. Similar results were found by Søndergaard et al. (1990) for Lake Søbygård in Denmark. Their study identified a net summer sediment release of phosphorus of 40 mg m^{-2} day^{-1} which accounted for approximately two thirds of the total phosphorus load to the lake. 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 which is directly exchangeable and highly mobile and release is easily induced by diffusion, wind disturbance and bioturbation (Bostrom et al., 1982; Syers et al., 1973).

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 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).

Mixing or stirring due to wind has been mentioned in many reports (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 distance at the sediment–water interface over which phosphorus diffuses 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 (*Cyprinus carpio*), bioturbation resulting from carp activities may be contributing significantly to high summer reflux loads of phosphorus.

Temperature changes also affect phosphorus release from sediments. 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. Important in Cootes Paradise is increased carp activity with an increase in temperature. 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 from field data, all factors contributing to phosphorus release would have been taken into consideration. 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 over the summer, however, is not as easily explained. As temperatures increase, 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. This trend 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. Lower water levels mean a smaller volume of water in Cootes Paradise, less dilution and therefore a higher concentration. Also, lower water levels 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 for phosphorus. It is also possible that the external suspended solids loadings were underestimated in the assumptions thereby creating total loads smaller than actuality.

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 (between 2.28 and 2.83 m/s) 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, particularly in nearshore areas.

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, indirectly, account for the larger field concentrations of suspended solids in July and August. The decrease in field suspended solids concentration from August to September may be a result of changes in the carp population or of changes in carp behaviour due to cooling temperatures, but the increase seen from August to September in the model results is unexplainable.

9. 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 5.75–53%. 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 6%. Separation of the individual source contributors to Cootes Paradise revealed that 57% of the phosphorus and 68% of the suspended solids loadings were 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.

It became clear during this study that improved data are needed for a better representation of the water quality of Cootes Paradise. Therefore, to properly answer questions about the major influences to water quality, flow and concentration data are necessary for Borer's and Chedoke Creeks, monitoring during storm events is needed, sediment analyses should be performed and reflux, sedimentation and deposition rates should be validated. In addition to parameter verification, sensitivity analyses should be performed to determine the potential impacts of differing environmental conditions (i.e., wet/dry conditions, high/low water levels) on concentrations and relative loadings.

The mass balance modelling approach therefore identified gaps in the data set for Cootes Paradise and it provided information that could benefit restoration planning. The preliminary findings suggest that restoration efforts in Cootes Paradise need to focus on contributions to phosphorus and suspended solids from sediment reflux, rural runoff and CSOs. Although more information is needed, restoration strategies can incorporate components which aim to minimize sediment impacts on water quality. Studies which encourage the regrowth of vegetation through seeding and planting should continue, the populations of benthivorous fish (i.e., carp) should be monitored, and watershed management plans should address issues surrounding inputs to Cootes Paradise from rural runoff and CSOs. In addition, monitoring programs are needed to update information used in the models. These programs should incorporate a wide variety of sampling sites which cover both shoreline and open water areas of Cootes Paradise and data should be collected during the spring, fall and winter months in order to provide information on the concentration trends and load relationships of phosphorus and suspended solids.

Acknowledgements

The present work was supported by the Tri-Council (MRC, NSERC, SSHRC) McMaster Ecosystem Research Program, and NSERC Operating Grant No. OGP0157914. Comments from Dr C.K. Minns and two anonymous reviewers are greatly appreciated.

References

Ahlgren, I., 1980. A dilution model applied to a system of shallow eutrophic lakes after diversion of sewage effluents. Arch. Hydrobiol. 89 (1/2), 17–32.

Ahlgren, I., 1977. Role of sediments in the process of recovery of a eutrophicated lake. In: Golterman, H.L. (Ed.), Interactions Between Sediments and Fresh Water. Dr. W. Junk B.V. Publishers, The Hague, pp. 372–377.

Andersen, J.M., 1974. Nitrogen and phosphorus budgets and the role of sediments in six shallow Danish lakes. Arch. Hydrobiol. 74 (4), 528–550.

Bacchus, H.M., 1974. An Ecological Study of Phytoplankton in Cootes Paradise. M.Sc. Thesis. McMaster University, Hamilton, Ontario.

Bostrom, B., Jansson, M., Forsberg, C., 1982. Phosphorus release from lake sediments. Ergeb. Limnol. 18, 5–59.

Breukelaar, A.W., Lammens, E.H.R.R., Klein Breteler, J.G.P., Tatrai, I., 1994. Effects of benthivorous bream (*Abramis brama*) and carp (*Cyprinus carpio*) on sediment resuspension and concentrations of nutrients and chlorophyll a. Freshwater Biol. 32, 113–121.

Cahn, A.R., 1929. The effect of carp on a small lake: the carp as a dominant. Ecology 10 (3), 271–274.

Canadian Wildlife Service, 1989. Wetlands. Environment Canada, Ottawa, Ontario.

Carpenter, S.R., Lodge, D.M., 1986. Effects of submersed macrophytes on ecosystem processes. Aquat. Bot. 26 (3/4), 341–370.

Chapra, S.C., 1975. Comment on An empirical method of estimating the retention of phosphorus in lakes by W.B. Kirchner and P.J. Dillon. Water Resources Res. 11 (6), 1033–1034.

Chapra, S.C., Reckhow, K.H., 1983. Engineering Approaches for Lake Management. Vol 2: Mechanistic Modeling. Butterworth Publishers, Boston, pp. 492.

Craig, R.F., 1992. Soil Mechanics, 5th ed. Chapman and Hall, London, pp. 427.

D.W. Draper and Associates Ltd., 1993. Hamilton Harbour tributaries storm event monitoring study. D.W. Draper and Associates Ltd., Etobicoke Ont., Canada.

DeJong, J., 1976. The purification of wastewater with the aid of rush or reed ponds. In: Tourbier, J., Pierson, R.W., Jr. (Eds.), Biological Control of Water Pollution. University of Pennsylvania Press, Philadelphia, pp. 133–139.

Dieter, C.D., 1990. The importance of emergent vegetation in reducing sediment resuspension in wetlands. J. Freshwater Ecol. 5 (4), 467–473.

Dillon, P.J., Kirchner, W.B., 1975. Reply. Water Resources Res. 11 (6), 1035–1036.

Eisma, D., 1993. Suspended Matter in the Aquatic Environment. Springer-Verlag, Berlin, 315 pp.

Herman, F.A., Gorham, E., 1957. Total mineral material, acidity, sulphur and nitrogen in rain and snow at Kentville, Nova Scotia. Tellus 9 (2), 180–183.

Holdren, G.C. Jr., Armstrong, D.E., 1980. Factors affecting phosphorus release from intact lake sediment cores. Environ. Sci. Technol. 14 (1), 79–87.

Imboden, D.M., 1974. Phosphorus model of lake eutrophication. Limnol. Oceanogr. 19 (2), 297–304.

James, W., 1980. Hamilton stormwater modelling study. Report No. 2: 1980 summer field programme. Preliminary Draft. McMaster University Computational Hydraulics Group, Hamilton, Ontario.

Junge, C.E., 1963. Air Chemistry and Radioactivity. Academic Press, New York, pp. 382.

Kadlec, J.A., 1986. Effects of flooding on dissolved and suspended nutrients in small diked marshes. Can. J. Fish. Aquat. Sci. 43, 1999–2008.

Kay, E.R.M., 1949. Limnological studies of the Dundas Marsh region. M.A. Thesis. McMaster University, Hamilton, Ontario.

Lam, D.C.L., Jaquet, J.-M., 1976. Computations of physical transport and regeneration of phosphorus in Lake Erie, fall 1970. J. Fish. Res. Board Can. 33, 550–563.

Lavender, B., 1987. Historical geography of Cootes Paradise, Ontario. B. Env. Studies Thesis. University of Waterloo, Waterloo, Ontario.

Likens, G.E., Bormann, F.H., Pierce, R.S., Eaton, J.S., 1985. The Hubbard Brook Valley. In: Likens, G.E. (Ed.), An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer Verlag, New York, pp. 9–39.

Lorenzen, M.W., Smith, D.J., Kimmel, L.V., 1976. A long-term phosphorus model for lakes: application to Lake Washington. In: Canale, R.P. (Ed.), Modelling Biochemical Processes in Aquatic Ecosystems. Ann Arbor Science Publishers, Ann Arbor, Michigan, pp. 75–91.

Meijer, M.-L., de Haan, M.W., Breukelaar, A.W., Buiteveld, H., 1990a. Is reduction of the benthivorous fish an important cause of high transparency following biomanipulation in shallow lakes?. Hydrobiology 200/201, 303–315.

Meijer, M.-L., Lammens, E.H.R.R., Raat, A.J.P., Grimm, M.P., Hosper, S.H., 1990b. Impact of cyprinids on zooplankton and algae in ten drainable ponds. Hydrobiology 191, 275–284.

Meikle, J.C., 1985. Sediment flows in the Spencer Creek watershed, Hamilton-Wentworth, Ontario. B.Sc. Thesis. The University of Western Ontario, London, Ontario.

Minns, C.K., 1986. A simple whole-lake phosphorus model and a trial application to the Bay of Quinte. In: Minns, C.K., Hurley, D.A., Nicholls, K.H. (Eds.), Project Quinte: point-source phosphorus control and ecosystem response in the Bay of Quinte, Lake Ontario. Can. Spec. Publ. Fish. Aquatic Sci. 86, 84–90.

Mitsch, W.J., Gosselink, J.G., 1993. Wetlands, 2nd ed. Van Nostrand Reinhold, New York, 722 pp.

Mudroch, A., 1981. A study of selected Great Lakes coastal marshes. NWRI Scientific Series No. 122. National Water Research Institute, Burlington, Ontario.

Painter, D.S., Hampson, L., 1990. Cootes Paradise water clarity 1989 update. NWRI No. 90–24. National Water Research Institute, Burlington, Ontario.

Painter, D.S., Hampson, L., Simser, W.L., 1991. Cootes Paradise water turbidity: sources and recommendations. NWRI Contribution No. 91–15. National Water Research Institute, Burlington, Ontario.

Painter, D.S., McCabe, K.J., Simser, W.L., 1989. Past and present limnological conditions in Cootes Paradise affecting aquatic vegetation. Royal Botanical Gardens Technical Bulletin No. 13. Burlington, Ontario.

Pareja, B.L., Artola, C.G., Vera, F.L., 1994. Contribution of nitrogen and phosphorus by precipitation in the drainage basin of the Santillana Reservoir (Madrid). Environ. Geol. 23, 99–104.

Paul Theil Associates Ltd. and Beak Consultants Ltd. 1991. Regional Municipality of Hamilton-Wentworth Pollution Control Plan. Paul Theil Associates Ltd. and Beak Consultants Ltd., Brampton, Ontario.

Roberts, J., Chick, A., Oswald, L., Thompson, P., 1995. Effect of carp, *Cyprinus carpio* L., an exotic benthivorous fish, on aquatic plants and water quality in experimental ponds. Mar. Freshwater Res. 46, 1171–1180.

Roberts, L., 1993. Wetlands trading is a loser's game, say ecologists. Science 260, 1890–1892.

Robinson, M.A., James, W., 1984. Chedoke Creek flood storage computed by continuous SWMM and dynamic storms. Report R124 to the Hamilton-Wentworth Regional Engineering Department. Computational Hydraulics Inc., Hamilton, Ontario.

Rukavina, N.A., Versteeg, J.K., 1995. The physical properties of the surficial sediments of Hamilton Harbour. NWRI Contribution No. 95–150. National Water Research Institute, Burlington, Ontario.

Ryding, S.-O., 1981. Reversibility of man-induced eutrophication. Experiences of a lake recovery study in Sweden. Int. Rev. Gesamten Hydrobiol. 66 (4), 449–502.

Ryding, S.-O., Forsberg, C., 1977. Sediments as a nutrient source in shallow polluted lakes. In: Golterman, H.L. (Ed.), Interactions Between Sediments and Fresh Water. Dr. W. Junk B.V. Publishers, The Hague, pp. 227–234.

Schindler, D.W., Hesslein, R., Kipphut, G., 1977. Interactions between sediments and overlying waters in an experimentally eutrophied Precambrian shield lake. In: Golterman, H.L. (Ed.), Interactions Between Sediments and Fresh Water. Dr. W. Junk B.V. Publishers, The Hague, pp. 235–243.

Schlesinger, W.H., 1978. Community structure, dynamics and nutrient cycling in the Okefenokee Cyprus Swamp-forest. Ecol. Monogr. 48, 43–65.

Semkin, R.G., McLarty, A.W., Craig, D., 1976. A water quality study of Cootes Paradise. Ontario Ministry of the Environment, Water Research Assessment, West Central Region, Hamilton, Ontario.

Smith, D.G., 1995. Cootes Paradise marsh and stream restoration: a geomorphologic perspective. Unpublished Report.

Søndergaard, M., Jeppesen, E., Kristensen, P., Sortkjær, O., 1990. Interactions between sediment and water in a shallow and hypertrophic lake: a study on phytoplankton collapses in Lake Søbygård, Denmark. Hydrobiology 191, 139–148.

Sonzogni, W.C., Fitzgerald, G.P., Lee, G.F., 1975. Effects of wastewater diversion on the lower Madison lakes. J. Water Pollut. Control Fed. 47 (3), 535–542.

Swee, U.B., McCrimmon, H.R., 1966. Reproductive biology of the carp, *Cyprinus carpio* L., in Lake St. Lawrence, Ontario. Trans. Am. Fish. Soc. 95, 372–380.

Syers, J.K., Harris, R.F., Armstrong, D.E., 1973. Phosphate chemistry in lake sediments. J. Environ. Qual. 2 (1), 1–14.

Thackston, E.L., Shields, F.D. Jr., Schroeder, P.R., 1987. Residence time distributions of shallow basins. J. Environ. Eng. 113 (6), 1319–1332.

Threinen, C.W., Helm, W.T., 1954. Experiments and observations designed to show carp destruction of aquatic vegetation. J. Wildl. Man. 18 (2), 247–251.

Vollenweider, R.A., 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweiz. Z Hydrol. 37, 53–84.

Weller, M.W., 1981. Freshwater Marshes: Ecology and Wildlife Management. University of Minnesota Press, MN, pp. 146.

Whillans, T.H., 1982. Changes in marsh area along the Canadian shore of Lake Ontario. J. Great Lakes Res. 8 (3), 570–577.