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Water Quality Characterization and Mathematical Modeling of Dissolved Oxygen in the East and West Ponds, Jamaica Bay Wildlife Refuge

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ABSTRACT

The current study was undertaken to characterize the East and West Ponds and develop a mathematical model of the effects of nutrient and BOD loading on dissolved oxygen (DO) concentrations in these ponds. The model predicted that both ponds will recover adequately given the average expected range of nutrient and BOD loading due to waste from surface runoff and migratory birds. The predicted dissolved oxygen levels in both ponds were greater than 5.0 mg/L, and were supported by DO levels in the field which were typically above 5.0 mg/L during the period of this study. The model predicted a steady-state NBOD concentration of 12.0–14.0 mg/L in the East Pond, compared to an average measured value of 3.73 mg/L in 1994 and an average measured value of 12.51 mg/L in a 1996–97 study. The model predicted that the NBOD concentration in the West Pond would be under 3.0 mg/L compared to the average measured values of

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7.50 mg/L in 1997, and 8.51 mg/L in 1994. The model predicted that phosphorus (as PO_4^{3-}) concentration in the East Pond will approach 4.2 mg/L in 4 months, compared to measured average value of 2.01 mg/L in a 1994 study. The model predicted that phosphorus concentration in the West Pond will approach 1.00 mg/L, compared to a measured average phosphorus (as PO_4^{3-}) concentration of 1.57 mg/L in a 1994 study.

Key Words: Water quality characterization; Mathematical modeling; Dissolved oxygen; Nutrient loading; Jamaica bay wildlife refuge.

INTRODUCTION

Jamaica Bay is located at the southwestern end of Long Island, New York, and on the eastern end of New York Harbor, which dominates the lower Hudson River Estuary. Jamaica Bay Wildlife Refuge (JBWR) is recognized as part of the Western Hemisphere Shorebird Reserve system and has been designated a Significant Coastal Fish and Wildlife Habitat by the New York State Department of Environmental Conservation (NYSDEC). It is surrounded by the densely populated urban communities of New York City and is part of the Gateway National Recreation Area (GNRA), as designated by the US Congress in 1972. Since 1972 the National Park Service (NPS) has been charged with the responsibility to conserve Jamaica Bay, primarily as a wildlife refuge and as an integral part of the Atlantic Flyway.

Wildlife habitat and species diversity has been enhanced in the Jamaica Bay since the creation of the East and West Ponds, several decades ago.[1–3] Water in the ponds is fresh to slightly brackish. Small populations of fish, such as white perch, that have been recorded within the ponds presumably have introduced themselves by swimming through valves that are opened periodically. The quiescent ponds act as protection and nursery grounds for these fish. The ponds provide year-round foraging and resting habitat for breeding and migrant birds including thousands of waterfowl, herons, egrets, and ibis, and tens of thousands of migrant shorebirds. Locally threatened ospreys, least terns, common terns, black skimmer, federally endangered peregrine falcons, and several native species of fish and turtles also depend upon the ponds as the last remaining significant habitat of this type in otherwise highly urbanized areas. Quality of these ponds as fish and wildlife habitat is hampered by a number of presumably inter-related problems. The East and West Ponds are both shallow (less than two meters) and potentially eutrophic, the result of their origins and 40 years of nutrient inputs from high avian use. Harmonious manipulations of these components require an extensive inventory of natural systems through the establishment of a detailed database.[4,5] Characterization of the ponds in the current study contributes to this long-term goal.

Fish kills have generally proved to be a significant ecological and economic liability. Low DO conditions that develop between June through September lead to fish die-offs in both ponds periodically. The most recent fish die-off was recorded one year before this study began. Algal blooms, mats of filamentous green algae, and potentially toxic blue-green algae (*Microcystis seruginova*) have also been observed to occur annually. Historical data suggests that although at times a significant economic and ecological liability, fish populations have recovered from periodic fish kills. Though fish populations appear to recover, the fish die-off results in dramatic temporary declines in food availability for piscivorous birds, create a potential disease outbreak and have negative impacts aesthetically, as well as in the public's perception of NPS management of the Refuge.[6]

Current management practices include active water level manipulation through a valve, and pipeline systems valves prevent saltwater intrusion into the ponds and permit drawdown by draining into Jamaica Bay. Freshwater can be added, in severe drought periods, through a pipeline tied to the municipal water supply. Current management of the ponds involves maintaining high water levels are during the spring waterfowl breeding season, and drawing down water in late summer to provide mudflats for migrating shorebirds.

The major objectives of this study were (i) to obtain the physical, chemical, and biological characteristics for the East and West Ponds, and (ii) to develop a mathematical model to predict DO levels within the ponds. The objective of the modeling study was to determine if the ponds can cope with the current BOD and nutrient loads or if it was necessary to put in an aeration system in the ponds.

MATERIALS AND METHODS

In order to address the objectives identified, a field sampling and studies, and lab analyses were conducted using the methods and materials as described below.

Physical Limnology

Fifteen sample sites were chosen on the East Pond in three transects as well as at the valve. Ten sampling points were chosen on the West Pond in two transects including the valve that connects to the Jamaica Bay. A Geographic Positioning System (GPS) was utilized to establish geographic coordinates for all selected sampling sites. These sites were also marked visually so that subsequent sampling at these sites could be done with an additional degree of certainty. In order to understand the hydrology of the system and to estimate mixing characteristics of the ponds, bathymetric contours of the two ponds were developed. Following well-established mapping techniques, a gridded overlay was used with United States Department of Interior's Geological Survey Maps (Far Rockaway and Jamaica Quadrangles) to determine the area of each pond. A sonographic depth meter, depth/fish finder, and a measuring stick were used for this purpose. Depths were recorded at 40 sites on the East Pond and 28 sites on the West Pond in a single sampling session in May 1996. Using data directly from the GPS system, SURFER^{TM} was used to develop contour and surface maps, and to calculate surface areas and estimate volumes. Source of freshwater in these ponds is not documented but is most likely due to runoffs, continuous infiltration from existing leaky water mains in the area, and from the groundwater. Based on meteorological data for the JBWR, precipitation is a major source of freshwater to the ponds.

Chemical Limnology: Analysis of Pond Water Quality Parameters

All sampling and analysis followed standard QA/QC protocols as well as standard and established methods.[7–10] Mixing in the water column was noted by visual observations in both of the relatively shallow ponds, suggesting that water column samples at mid-depth would be adequate. Sediment and water column samples were collected using a van Dorn sampler and analyzed according to various techniques listed below. A Horiba U-10 Water Quality Meter was used for field measurements of conductivity, salinity, temperature, turbidity, pH, and dissolved oxygen. Total dissolved solids (TDS) was measured in the field using a Solomat Water Quality Meter. Microbiological water quality and sediment oxygen demand were determined in the lab. Copper and lead were determined by atomic absorption spectrophotometry. An Orion Meter was used to conduct ammonia and nitrate analyses using ion selective electrodes. Several samples were frozen upon return to the lab over the course of the project. These samples were then thawed and diluted to 100 mL at a 3:1 dilution ratio of deionized water to sample before they were analyzed for nitrate and ammonia.

Biological Limnology

Based on discussions with Wildlife Refuge Personnel, it is believed that fresh water fish were introduced into these ponds by some of the local residents. There is also a possibility that some fish may have entered through existing tide gates or outlet pipes. Each sampling day, field notes were taken to document the various fish and wildlife present in the East and West Ponds. Fish nets were stretched across the East Pond in September 1996 to add to the list of fish populations recorded during routine sampling. Sediment samples were brought back to the laboratory and benthic organisms were also identified over the course of the project.

Assuming minimal spatial variation, random samples were taken from at least two sites on each pond within the photic zone. Once volumes within 1 L were filtered, chlorophyll pigments were extracted from the phytoplankton and algae remaining on the membrane filter at the addition of 90% alkalized acetone. Samples were analyzed on a Genesys 5 UV-Vis Spectrophotometer at varying wavelengths after 24 h.[11] In this study, no corrections were made for chlorophyll degradation products such as phaeophytin-a, but corrections for turbidity were made. Lind's integral treatment was used to calculate the photosynthetic productivity of the ponds' algal mass.[12]

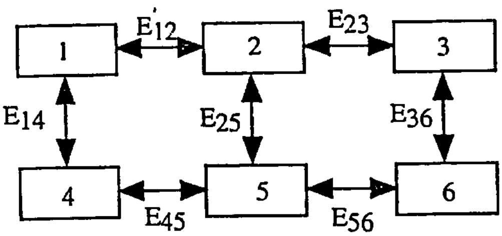
RESULTS AND DISCUSSION

Based on a survey of existing literature and reports, it was determined that a total of five investigations of the East/West Ponds of the JBWR were conducted between 1975 and 1997 (including the present study). Review of these data indicated that the 1979, 1994, and the current study focused on some of the same water quality and limnological studies.[12,13] Coliforms, heavy metals, N and P samples were collected and analyzed every two weeks. Coliform and protozoa data from the 1976 and 1982 studies were limited to the West Pond, but are nevertheless of value to understanding the long-term trends. A drawback when comparing data from all these studies is the difference in methodology and sampling strategy. These differences invariably contribute to uncertainties in data evaluation, but in the absence of other data, these are the "best" available estimates.

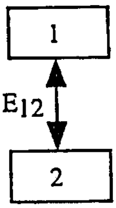
Physical Limnology

The bathymetric contours were identified for each of the ponds, using the procedure outlined earlier. The volume (EP: 439.344 m^3; WP: 168.915 m^3), area (EP: 441.275 m^2; WP: 162.575 m^2), and average depth (EP: 0.995 m; WP: 1.04 m) of each pond were calculated. While previous studies relied on one or two sampling locations per pond, 28–40 sampling locations were included in this study. Figure 1 shows the schematic model of the East Pond and West Pond. Although the average depth of both ponds is comparable, sections of the East Pond are deeper than the West Pond. The East Pond is approximately 2200 m long and about 200 m wide (average width). The West Pond has an irregular box-shape with slightly larger length compared to its width. The East Pond was therefore modeled as a six-segmented system while the West Pond was modeled as a two-segmented system.

The climate in the Jamaica Bay area is generally representative of the humid continental type, which prevails, in the northern part of the United States. The bay area is affected by its close proximity to the Atlantic Ocean. The maritime effect on the ocean tends to moderate the temperature in the Jamaica Bay to approximately 73°F in the summer (June through August) and 33°F in the winter (December through January). In the Jamaica Bay area, the precipitation is moderate and



East Pond Model



West Pond Model

Figure 1. Layout of East and West Ponds in Jamaica Bay wildlife refuge.

evenly distributed throughout the year. Monthly precipitation normally results in a monthly water equivalent ranging from 2.7 to 4.3 inches of precipitation and provides an annual average water equivalent of approximately 40–41 inches. Most of the rainfall from June through September comes from thunderstorm activity and is, therefore, usually of short duration but relatively intense. Winds are generated out of the north-northwest during the fall and spring and tend to be out of the south during the summer. The mean wind speed from data area weather station is approximately 12 miles per hour.

Pond Water Quality

Temperature was monitored over the course of June to November 1996 and March through September of 1997. In general, the data reflect that these seasons were not atypical. The minimum water temperature in the East Pond was 4.7°C and a maximum of 29.3°C was recorded in August 1996. The average temperature in the East Pond was 20.8°C. The minimum water temperature in the West Pond was 5.2°C. The maximum recorded temperature in the West Pond was 29.0°C and the average temperature over the period of study was 22.4°C. There was essentially no difference in water temperature from the sediment to the water surface in either pond. While a clear turnover that is generally expected with a change of seasons was not observed, a turnover was observed based on other data such as DO data. The most likely cause for such a phenomenon is the relatively shallow depth of both ponds and the extent of mixing due to wind action.

Conductivity and salinity of the East and West Ponds exhibited predictably identical trends. Salinity ranged from 1.89 parts per thousand (ppt) to 7.4 ppt with an average of 2.9 ppt in the East Pond. For the smaller and shallower West Pond, the salinity ranged from 3.6 ppt to 5.2 ppt with an average of 4.3 ppt. While there was a notable difference in the salinity at the valve point in each pond compared to the other sampling locations in each pond, there was little variation for the rest of the pond. This suggests that there is some leakage from the Jamaica Bay into the ponds but due to the "well-mixed" conditions in the ponds (particularly the West Pond), the salinity is essentially constant within each pond.

pH and DO followed similar trends. This is likely tied to the trends in primary production in the ponds. The pH of the ponds ranged between 7.70 and 9.25 for the East Pond with an average of 8.48. pH in the West Pond ranged from 7.74 to 9.08 with an average of 8.44. Dissolved oxygen data within the sample years were found to be within reasonable seasonal fluctuations, indicating adequate circulation within each pond.[14] DO levels never dropped to less than 2.57 mg/L in the West Pond or 5.68 mg/L in the East Pond over the period of this study (Figs. 2 and 3). The average DO values were 8.26 mg/L for the East Pond and 8.42 mg/L for the West Pond. As compared to data from 1994, the DO levels were generally in the same range except that the low DO level in the 1994 study was lower than in this study. The results of this were reflected in the fact that no fish kills were observed in the ponds during the period of this study, although fish kills were observed on the Jamaica Bay side, adjacent to each pond. Following the 1996–97 winter period, a peak in DO was observed illustrating the vernal turnover. Algal concentrations also increased during this period.

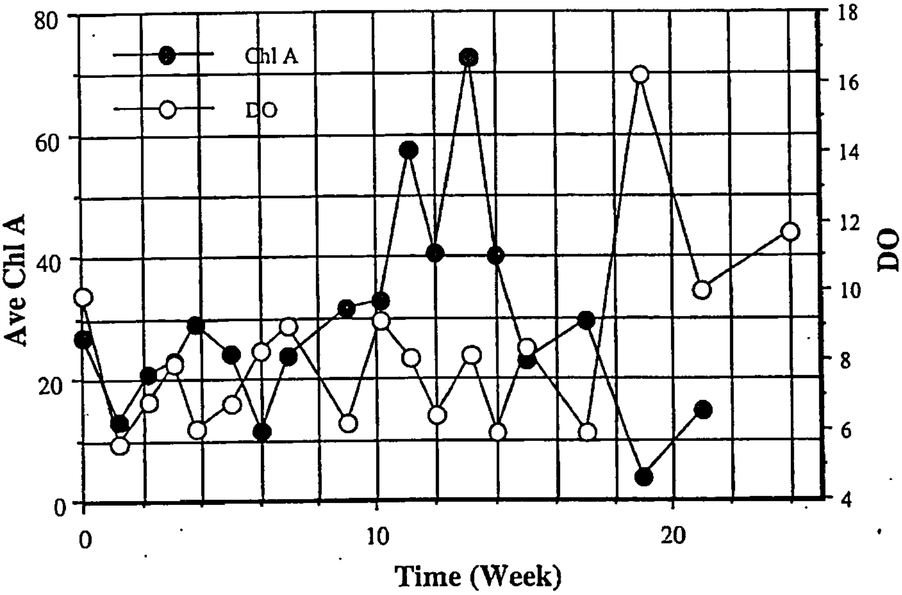


Figure 2. Chlorophyll and DO variation in the East Pond.

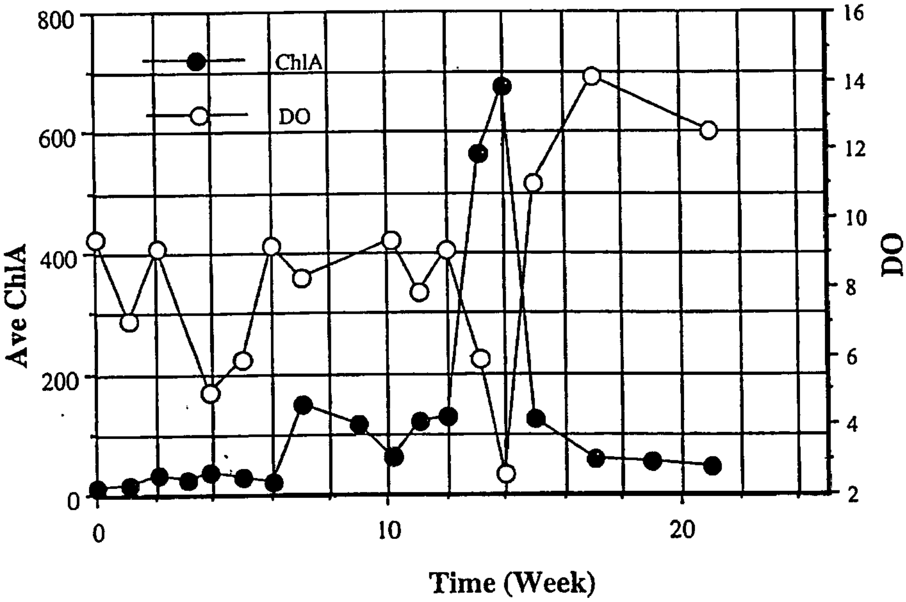


Figure 3. Chlorophyll and DO variation in the West Pond.

Based on previous data and discussion with park officials, copper and lead were identified as potential problem metals. In this study, data from field sampling showed that the speciation of these metals into the water column was not significant at most times. Experiments conducted in the laboratory with sediment from the East and West Ponds showed that the levels of copper and lead in the water column under both aerobic and anaerobic conditions were not significant and sometimes were below the detection level. Similar results were obtained in experiments to determine the effect of pH on heavy metal speciation for a range of pH from 5.0 to 9.5 under aerobic conditions.

Inventory of Fish and Invertebrates

A baseline inventory of fish, plankton, birds, and macrophytes was conducted as part of this study. Data and maintenance plans from previous studies were also considered in the preparation of this baseline inventory.[13,15] It should be noted that the project emphasized the abiotic characterization of the East and West Ponds, yet a synoptic observation of the biotic components of these human-made pond systems is provided here. Identification of various species was based on the available information at the JBWR and the literature.[16–19] *Cyprindotidae* (Killifish) and *Atherinidae* (Silverside) were observed in a fish inventory attempted in September 1996 using fish nets stretched across the East Pond. The following species of birds was recorded: *Recurvirostra* (Avocet), *Larus fuscus* (Blackbacked Gull), *Ardea* (Heron), *Toxostoma rufum* (Brown Thrasher), *Branta canadensis* (Canadian Goose), *Phalacrocorax* (Cormorant), *Egretta* (Snowy Egret), *Larus argentatus* (Herring Gull), *Branta canadensis minima* (Cackling Goose), *Anas patyrhynchos* (Mallard Duck), *Anser caerulescens* (Snow Goose), *Dendroica petechia* (Yellow Warbler). *Chlorophyta*, *Cyanophyta*, *Spartina alterniflora*, and *Spartina patens* were among the flora observed. A number of benthic organisms were observed during the period of this study. Historically, anoxic conditions resulting from algal blooms have led to wholesale die-off of benthic invertebrates. In this study, such drastic events were not observed following periods of algal blooms. Invertebrates observed in sampling of the water column and sediment included: *Amoeba*, *Copeopod*, *Daphnia*, *Ostracod*, *Stentor*, and *Vorticella*.

Mathematical Modeling

In order to better understand the interaction between chemical, biological, and physical processes in the East and West Ponds, and evaluate alternative management strategies, a chemodynamics-based mathematical model can prove very valuable. Several investigations and models exist in the literature which incorporate one or more of these processes.[20–26] A main objective of the mathematical modeling effort was to determine the response of the ponds (in terms of DO, BOD, and NBOD) for a "no aeration" case vs. an "aeration" case, which is being considered by the GNRA management as an alternative to minimize fish kills. The ability of the ponds to recover from typical CBOD and NBOD loads was investigated, particularly in terms of water column DO.

Hydrological flows and inputs were estimated based on average rainfall data for the New York area, using meteorological databases available in the literature.[27] Total surface runoff was estimated based on the land area presumably draining into the ponds and the Jamaica Bay, which surrounds these ponds. In estimating the

Table 1. Nutrient and BOD loading to the East and West Pond.

Inputs	Symbol	East pond	West pond	Units
Input phosphorus	$W_{PO}(t)$	3.80×10^5	1.04×10^5	$\frac{\text{mg P}}{\text{day}}$
Input nitrogenous BOD	$W_N(t)$	5.66×10^5	4.18×10^5	$\frac{\text{mg NBOD}}{\text{day}}$
Input soluble BOD	$W_{BOD}(t)$	1.32×10^6	9.73×10^4	$\frac{\text{mg BOD}_u}{\text{day}}$
Input DO (only when ponds are aerated)	$W_{DO}(t)$	0 to Varies	0 to Varies	$\frac{\text{mg}}{\text{day}}$

fraction of the surface runoff draining into both ponds, soil characteristics of the area, and the extent of land perimeter in contact with the Jamaica Bay. The total flow into each pond was assumed to be proportional to the surface area of the ponds. Nitrogen and phosphorus loading in surface runoff was estimated using data for northeast United States available in the literature.[25] A BOD loading to the ponds was assumed based on the surface runoff into the ponds and assuming an average BOD of such runoff in urban areas.[25,28] The data on phosphorus, nitrogen, and BOD loading are summarized in Table 1.

A dynamic ecosystem model was developed for the East and West Ponds with a focus on dissolved oxygen concentration in the pond. The model is presented in Fig. 4 showing some key factors and interactions for a control volume element of the water column in the East and West Ponds. As shown in Fig. 4, the model for each pond included various processes and species that were considered key to the fate of DO in the system. Variables used in the mathematical model are listed in Table 2. There are nine state variables in each compartment of the lake model. Nitrate and ammonium uptake by all organisms was assumed to be proportional to their fractional concentration, although it is recognized that ammonium uptake is generally preferred due to its higher energy content. Phytoplankton respiration, photosynthesis, phytoplankton grazing by zooplankton and fish, as well as zooplankton grazing by fish was included in the model. Decay (or death) rates of each species were also included in the model. A function for biochemical oxygen demand (BOD) loading into the ponds was also developed to reflect the reality that some BOD may be carbonaceous and some due to nitrogenous inputs such as ammonia and reduced nitrogen species. Both carbonaceous BOD (CBOD) and nitrogenous BOD (NBOD) were linked with the mass balance for dissolved oxygen. Deposition of decaying organic matter to the sediment (sedimentation) was modeled using first-order kinetics. Pathways for decaying matter to be deposited into the sediment were also included in the model.

The West Pond was modeled as a bi-layered system with internal mixing within each layer and dispersive flux transport between the top and bottom layers.

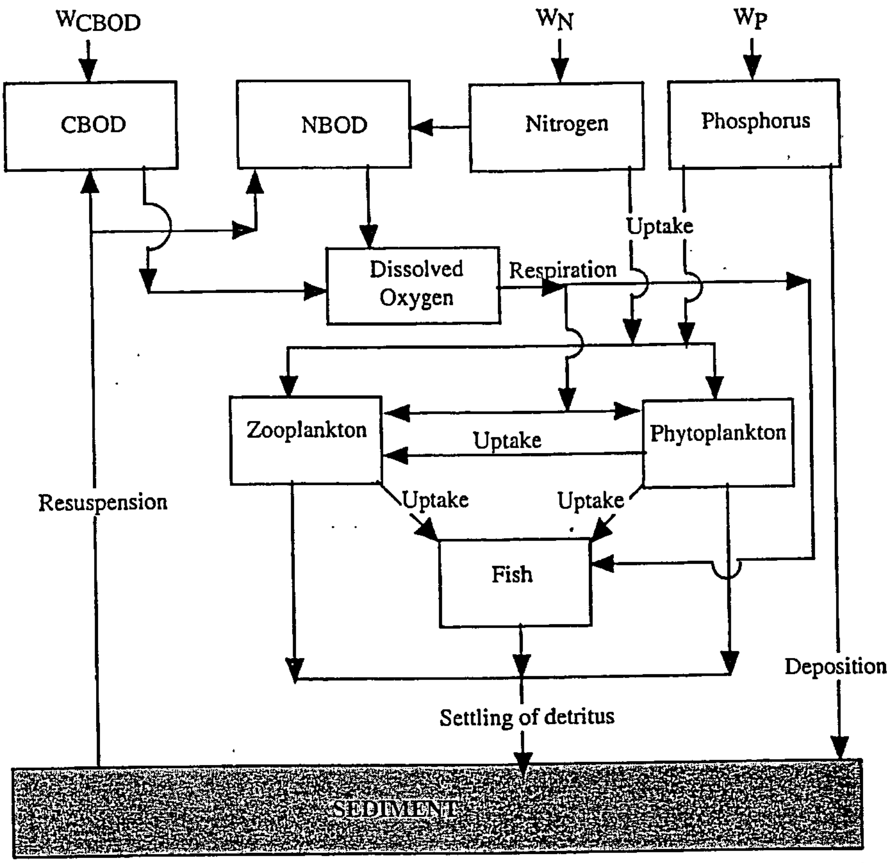


Figure 4. Model showing processes and interactions within an element.

Table 2. State variables used in the mathematical model.

Variable	East pond model notation	West pond model notation	Units
Time	t	t	days
Phytoplankton	C_1	C_1	$\frac{\text{mg dry wt}}{\text{L}}$
Zooplankton	C_2	C_2	$\frac{\text{mg dry wt}}{\text{L}}$
Fish biomass	C_3	C_3	$\frac{\text{mg dry wt}}{\text{L}}$
Biochemical oxygen demand	C_4 to C_9	C_4 and C_5	$\frac{\text{mg}}{\text{L}}$
Nitrogenous BOD	C_{10} to C_{15}	C_6 and C_7	$\frac{\text{mg}}{\text{L}}$
Dissolved oxygen	C_{16} to C_{21}	C_8 and C_9	$\frac{\text{mg}}{\text{L}}$
Phosphorus	C_{22} to C_{28}	C_{10} and C_{11}	$\frac{\text{mg}}{\text{L}}$

The shape, depth, variation, and apparent mixing characteristics of the West Pond suggested that a bi-layered model would be sufficient. The shape, depth variation and apparent mixing characteristics for the East Pond suggested that a more segmented model would be appropriate. The East Pond was modeled as a six-section compartmentalized pond (three horizontal segments) with three upper compartments and three lower compartments. For both ponds, the lower depth was assumed to be 0.25 m from the sediment and the remaining depth was attributed to the top layer or compartment. Individual compartment volumes were determined from the data obtained in this study by dividing the total volume of each pond by the number of compartments used to model it.

Table 3 is a summary of the parameters, variables, and rate constants used in the model. A typical matrix of differential equations for the two-compartment West Pond model is shown in Table 4. Due to repetitiveness and length, equations for the East Pond (a six-compartment model) have not been shown here and are available elsewhere.[12] The system of coupled ordinary differential equations was solved, using a fourth-order Runge-Kutta method. Most kinetic processes were either assumed to be first-order or second-order, based on data from a wide range of literature.[25,29] A linear kinetic model was used for hydrolysis and decay of all organisms. Nonlinear second-order kinetic expressions were used for consumption of phytoplankton by zooplankton, and of zooplankton by fish.[25] The general expression for mass balance of each state variable depends on advection, dispersion, and the rate of utilization, transformation, and consumption.

In order to determine the model's sensitivity to input parameters, the model was run at various BOD loading rates, sediment oxygen demand rates, phosphorus loading rates and nitrogen loading rates (data not shown). As expected, the sediment oxygen demand had a major impact on the dissolved oxygen in either pond. BOD loading due to surface water runoff also had an impact on DO in each lake as they approached steady state. For the range of phosphorus and nitrogen loading considered, the dissolved oxygen in the system was not as severely impacted. While it is generally recognized that phosphorus loading is a critical parameter in evaluating eutrophication of freshwater systems, the magnitude of BOD loading was found to have a larger impact on the dissolved oxygen levels in the ponds.

The primary focus of these models was to evaluate how oxygen concentration in the ponds changed as a function of time, particularly over a period of three to four months in the summer and early fall period. Data from this study and kinetic parameters from literature were used together to test a range of conditions that may occur. The mathematical models for each pond were solved numerically, under a wide range of initial conditions. The models are designed to permit a user to change the number of segments, change the pond parameters, or change kinetic data to allow evaluation of scenarios in the future. During the process of developing the model, it became apparent that there is an additional need for data on seasonal variations in nitrogen, phosphorus, and BOD loading, as well as more specific information on the nutrient loading into these ponds by migratory birds. As this data becomes available, the models developed for each pond in this study can be modified accordingly.

The models developed above for the East and West Ponds were each run for the following cases: (i) no aeration; (ii) no aeration with resuspension; (iii) resuspension

Table 3. Parameters and variables used in the model.

Variable	Definition	Range		Values used	Units
		Min	Max		
B	**Phytoplankton concentration**			varies	mg/L
μ_B	phytoplankton growth rate	0.50	3.00	2	day^{-1}
v_B	phytoplankton settling velocity	0.10	2.00	0.125	
g_{BZ}	phytoplankton uptake by zooplankton	$1.25*\mu Z$	$2*\mu Z$	$1.5*\mu Z$	day^{-1}
g_{BF}	rate of phytoplankton uptake by fish	0.00015		0.0015	day^{-1}
m_B	phytoplankton mortality rate	1.5	2.5	varies	day^{-1}
Z	**Zooplankton concentration**			varies	mg/L
μ_Z	zooplankton growth rate	0.15	0.25	0.21	day^{-1}
v_Z	zooplankton settling velocity	—	—	0	day^{-1}
g_{ZF}	rate of zooplankton uptake by fish	0.10		0.0001	day^{-1}
m_Z	zooplankton mortality rate	0.15	2.75	varies	day^{-1}
F	**Fish concentration**			varies	mg/L
μ_F	fish growth rate			0.0025	day^{-1}
m_F	fish mortality rate	0.001	0.005	varies	day^{-1}
$\mathbf{L_{oc}}$	**CBOD concentration**			varies	mg/L
R_c	resuspension rate			0.1	day^{-1}
v_c	settling rate of CBOD			0.1	day^{-1}
K_c	CBOD decay rate			0.2	day^{-1}
Lon	**NBOD concentration**			varies	mg/L
v_n	settling rate of NBOD			0.1	day^{-1}
K_n	NBOD decay rate	0.14	0.31	0.02	day^{-1}
DO	**Dissolved oxygen concentration**			varies	mg/L
W_a	oxygen input into system	0.00		varies	mg/day
	(oxygen input is only for cases when oxygen is supplied by aerators)				
K_L	surface reaeration constant	2.00	2.00	2.0	day^{-1}
DO_{sat}	DO saturation concentration			10	mg/L
PO	**Phosphorus concentration**			varies	mg/L
k_{sp}	settling rate constant for phosphate			0.1	day^{-1}
P	photosynthetic O_2 production rate			1.5	day^{-1}
R_B	respiration rate	0.05	0.50	0.1	day^{-1}
R_Z	zooplankton respiration rate	0.02	0.11	0.08	day^{-1}
R_F	fish respiration rate			varies (0.1 to 1.0)	day^{-1}
K_B	phytoplankton decay rate	0.02	0.10	0.02	day^{-1}
K_Z	zooplankton decay rate			0.01	day^{-1}
K_d	fish decay rate			0.31	day^{-1}
H_{avg}	average depth of pond (east)			0.97	m
	average depth of pond (west)			1.02	m
$E_{i,j}$	Bulk dispersion coefficient between pond compartments			Varies	$m^3\,day^{-1}$

Table 4. Matrix of differential equations for the West Pond.

$$\frac{dC_1}{dt} = \left\{\mu_B - \frac{v_B}{H_{avg}}\right\}\left\{C_1 f(C_1)\right\} - \left[-0.58[C_8(0.75) + C_9(0.25)]^{0.5} + 3.22\right]C_1 - \left[g_{BZ}C_2 + g_{BF}C_3\right]$$

$$\frac{dC_2}{dt} = \left\{\mu_Z - \left[0.03[C_8(0.75) + C_9(0.25)\right]^{0.5} + 0.28] - \frac{v_Z}{H_{avg}}\right\}C_2 - [g_{ZF}C_3]$$

$$\frac{dC_3}{dt} = \left\{\mu_F - [-0.00129[C_8(0.75) + C_9(0.25)]^{0.5} + 0.0051]\right\}C_3$$

$$\frac{dC_4}{dt} = \left\{R_{e1} - \frac{v_C}{H_1}\right\}\{C_4\} + E_{1,2}[C_5 - C_4] - K_C C_4 + \frac{W_{BODsc1}}{V_1}$$

$$\frac{dC_5}{dt} = \left\{R_{e5} - \frac{v_C}{H_2}\right\}\{C_5\} + E_{1,2}[C_4 - C_5] - K_C C_5 + \frac{W_{BODsc2}}{V_2}$$

$$\frac{dC_6}{dt} = \left\{R_{e1} - \frac{v_n}{H_1}\right\}\{C_6\} + E_{1,2}[C_7 - C_6] - K_n C_6 + \frac{W_{BODsn1}}{V_1}$$

$$\frac{dC_7}{dt} = \left\{R_{e5} - \frac{v_n}{H_2}\right\}\{C_7\} + E_{1,2}[C_6 - C_7] - K_n C_7 + \frac{W_{BODsn2}}{V_2}$$

$$\frac{dC_8}{dt} = \left\{\frac{w_{a1}}{V_1} + \frac{K_L}{H_1}[\mathrm{DO}_{sat} - C_8] - \{C_1 f(C_1)[a_1\mu_B - a_2P]\right\} - [R_B C_1 + R_F C_3 + R_Z C_2] - [K_n C_6 + K_C C_4 + K_d C_3 + K_Z C_2 + K_B C_1] + E_{1,2}[C_9 - C_8]$$

$$\frac{dC_9}{dt} = \left\{\frac{W_{a2}}{V_2} - \frac{0.12(C_9)^{0.3}}{H_2}\right\} - \{C_1 f(C_1)[a_1\mu_B - a_2P]\} - [R_B C_1 + R_F C_3 + R_Z C_2] - [K_n C_6\,\phi(C_6) + K_C C_5 + K_d C_3 + K_Z C_2 + K_B C_1] + E_{1,2}[C_8 - C_9]$$

$$\frac{dC_{10}}{dt} = \left\{\frac{W_{PO1}}{V_1}\right\} - [0.01][\mu_B][C_1] - [0.01][\mu_Z][C_2] + E_{1,2}[C_{11} - C_{10}] - k_{sp}C_{10}$$

$$\frac{dC_{11}}{dt} = \left\{\frac{W_{PO2}}{V_2}\right\} - [0.01][\mu_B][C_1] - [0.01][\mu_Z][C_2] + E_{1,2}[C_{10} - C_{11}] - k_{sp}C_{11}$$

W_{BODsni} is the NBOD loading in mass per day into segment "i"
W_{BODsei} is the BOD loading in mass per day into segment "i"
V_1 and V_2 are the volumes of the two compartments for the west pond model
$E_{1,2}$ = Bulk dispersion coefficient/Volume of compartment in day^{-1} between the two compartments for the west pond model
Phosphorus is assumed to constitute 1% of any organism.
Nitrogen is assumed to constitute 5% of any organism.

and aeration. When the initial DO concentration was set to 6.0 mg/L, the ponds recovered rapidly.[12] Results from all "no aeration" modeling runs indicated that the concentration of oxygen in the West Pond increased briefly and reached quasi-steady state conditions over a 4-month period. Initial conditions impact the system to some extent, and the DO in the West Pond recovered to levels of over 5.0 mg/L in all three cases.

For the West Pond, results from a modeling run (with resuspension) with an initial DO of 2.0 mg/L in both compartments (DO1 and DO2) of the water column are shown in Fig. 5 with DO levels recovering to over 6.0 mg/L in both compartments. The predicted concentrations of nitrogen, phosphorus, and BOD loading are shown in Fig. 6. The model indicated that NBOD, potentially from surface runoff and migratory bird populations, was absorbed by the pond and the long-term nitrogen levels in the pond in both compartments were under 3.0 mg/L. Average measured NBOD (due to ammonia) was 8.51 mg/L in the 1994 study and 7.50 mg/L in the 1996–97 study. Average measured nitrate concentration in the West Pond was 5.91 mg/L. The model predicted that phosphorus levels in the upper compartment will reach a steady-state concentration of under 1.0 mg/L and the concentration in the bottom segment will approach zero. Measured values of phosphorus, in the 1994 study, range from 0 mg/L to 3.2 mg/L, with an average value of 1.57 mg/L. Field sampling in June-July 1996 and June-July 1997 showed that chlorophyll production increased and turbidity correspondingly varied between 19.5 NTU to 222.4 NTU. The increase in primary productivity measured as chlorophyll *a* production was higher in the West Pond compared to the East Pond. The relatively high surface:volume ratio of the West Pond may have resulted in a larger fraction of the influent phosphorus to be absorbed by the phytoplankton, as also suggested by chlorophyll data in Fig. 3.

Results from an identical model run (initial DO of 2.0 mg/L, with resuspension) for the East Pond are shown in Fig. 7. The model predicted that DO levels in the East Pond will recover to around 5.0 mg/L in the bottom three compartments and to

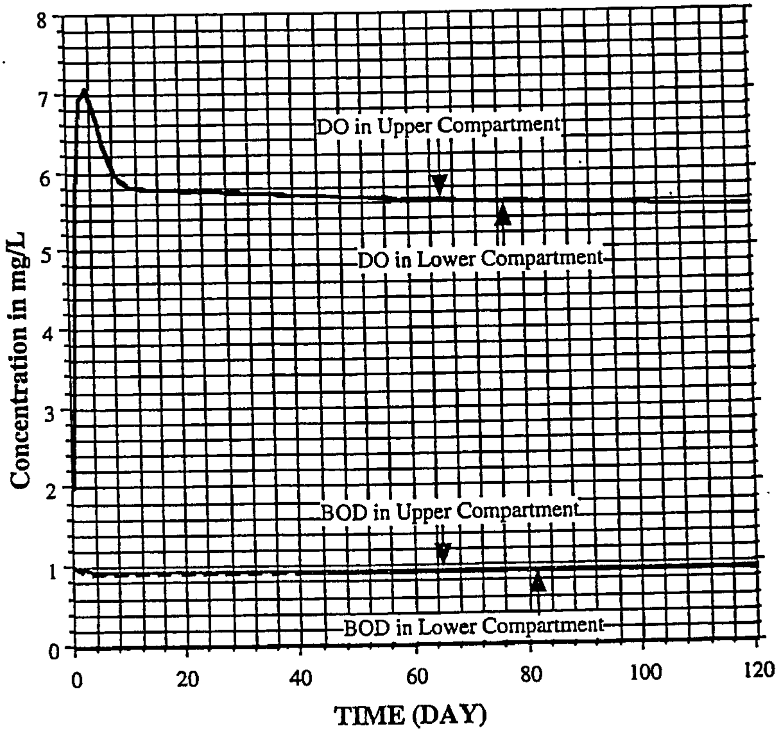


Figure 5. Predicted DO and BOD response in West Pond in the absence of aeration.

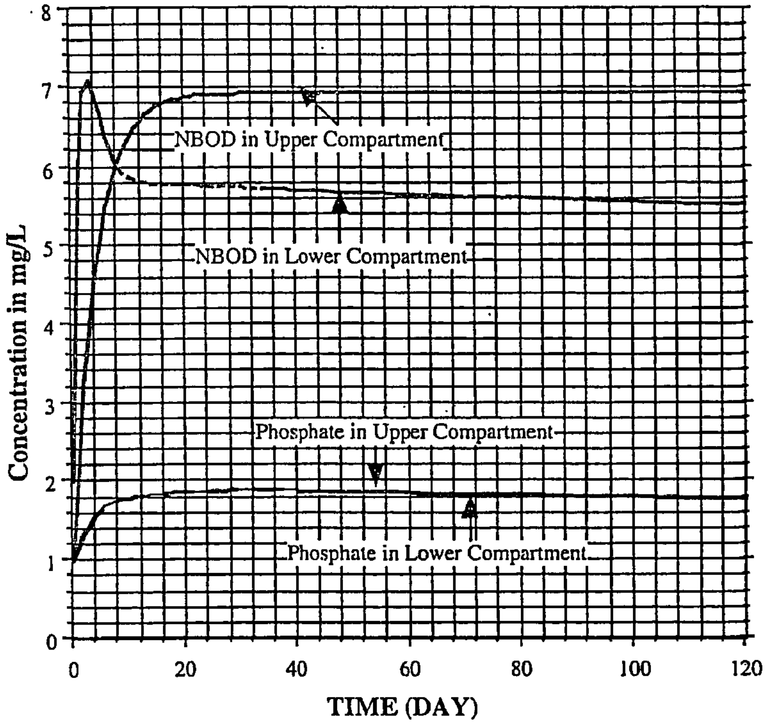


Figure 6. Predicted NBOD response and phosphate in West Pond in the absence of aeration.

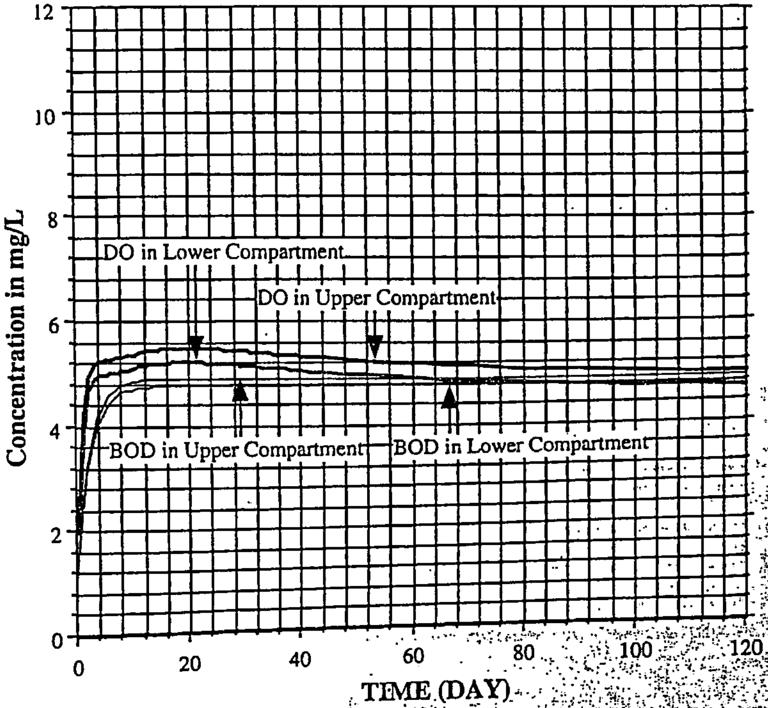


Figure 7. Predicted DO and BOD response in East Pond in the absence of aeration.

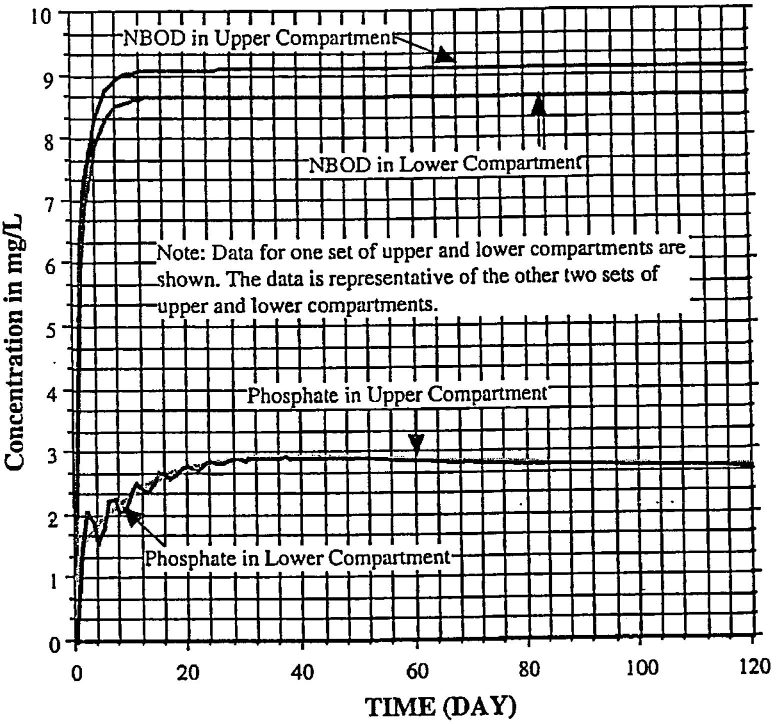


Figure 8. Predicted NBOD response and phosphate in East Pond in the absence of aeration.

5.5 mg/L in the top three compartments. NBOD concentrations were predicted to be between 12 and 14 in all six compartments. Concentrations in only one set of top-and-bottom compartments of the total six compartments are shown in Fig. 8 for purposes of clarity. Average measured ammonia concentration in the East Pond ranged from 0.01 to 1.7 mM with an average of 0.23 mM (3.9 mg/L). Average measured NBOD (due to ammonia) in the 1994 study was 3.73 mg/L and 12.51 mg/L in the 1996–97 study. Average measured nitrate concentration in the East Pond was 3.63 mg/L. Phosphorus levels predicted by the model suggest that concentrations in all six compartments (only two of which are shown in Fig. 8) will approach 4.2 mg/L in 4 months. Measured values of phosphorus, in the 1994 study, range from 0 mg/L to 4.47 mg/L, with an average value of 2.01 mg/L. This higher predicted and measured average phosphorus concentration in the pond water column may potentially be due to a higher mass of phosphorus input into the pond and a lower surface:volume ratio of the East Pond, compared to the West Pond. As a consequence, it is likely that a lower fraction of phosphorus was absorbed by the phyto- and zoo-plankton, which is also indicated by chlorophyll data (Fig. 2). Field sampling in June-July 1996 and June-July 1997 showed that chlorophyll production increased in the East Pond and turbidity correspondingly varied between 12 NTU and 111.3 NTU. As noted earlier, these increases were lower compared to the West Pond.

When the nutrient, turbidity, and DO data are considered together with measured chlorophyll *a* data, it is evident that the West Pond behaves differently compared to the East Pond, with higher assimilation of ammonia. It was observed that peak chlorophyll *a* concentrations corresponded with peak NH_3 concentrations. Following this period where peak concentrations were observed, the DO levels rebounded rapidly, classically illustrating an autumnal turnover.

Models for the East Pond and West Pond were also run for case (iii), incorporating DO input due to mechanical aeration and a higher rate of resuspension. For a minimal level (e.g. due to wind and wave effects) of resuspension (Table 2), the model suggested that DO levels in either pond would increase to over 8.0 mg/L eventually. If the extent of resuspension is increased (twice the rate in Table 2), thereby increasing the contribution to DO depletion, the levels of DO in both ponds dropped to under 2.0 mg/L. This is obviously an undesirable condition, from a management standpoint. A major unknown is the extent of resuspension due to a mechanical aeration device in either pond. The extent of resuspension would depend on the type of aeration system selected. However, given the relatively shallow average depth of either pond (around 1 m), it is quite likely that the extent of sediment resuspension due to any aeration system will be significantly above the levels caused by wind and wave effects in these ponds.

The modeling results are partially supported by the field data available for the East and West Ponds. Throughout the period of this study, the measured DO concentrations in both ponds indicated that acute hypoxic conditions did not occur. This is likely in part because the management practices of removing bird carcasses and clean up of occasional fish kills was presumably effective. Nitrogen (either due to runoff or due to bird populations) was also found to be effectively absorbed by the pond ecosystems for the range of conditions tested in the modeling effort, with no deleterious effects on dissolved oxygen in either pond. While these results are indicative that the field, lab, and modeling results compare favorably, additional quantitative long-term field data is needed to help further refine and validate the model.

SUMMARY AND CONCLUSIONS

Characterization of the East and West Ponds was conducted as part of this study. A mathematical model for nitrogen, phosphorus, and dissolved oxygen was developed for the East and West Ponds. A two-compartment segmented model was constructed for the West Pond and a six-compartment model was constructed for the West Pond. Data from this study and typical data from the literature were used to analyze the effect of nutrient inputs on the East and West Pond DO levels.

A goal of this study was to evaluate if there was a need for aeration systems to counter the problem of low DO levels which was observed periodically over the years. Results from the modeling studies indicated that dissolved oxygen levels recovered to over 5 mg/L in all long-term (> 4 months) predictive models. Given the results from modeling studies and field data from 1994 and the current study, installing an aeration system in the ponds to supply oxygen does not appear to be necessary. It appears that both ponds have the capacity to recover from BOD loading, due to nutrient loading from the bird population and surface runoff in the area. Field observations show that hypoxia (DO < 1.5 mg/L) and a fish kill incident was observed in a 1994 study but not in this study, indicating that the current management practices of removing bird carcasses and clean up of occasional fish kills was fairly effective.

The mathematical model predicted that the NBOD concentration in the East Pond would range from 12.0 to 14.0 mg/L while the average measured NBOD concentration was 3.63 mg/L in 1994 and 12.51 mg/L in the 1996–97 study. The model predicted that the phosphorus concentration in the East Pond would approach 4.2 mg/L in a 4-month period, while an average concentration of 2.1 mg/L was measured in a 1994 study. The mathematical model predicted the NBOD concentration in the West Pond to be around 3.0 mg/L while the average measured concentration of NBOD (due to ammonia) averaged 8.3 mg/L in 1997, and averaged 4.6 mg/L in 1994. The under-prediction by the model is most likely because of a more variable loading process in 1997, but the predicted value is closer to the 1994 data. The model predicted that the phosphorus concentration in the West Pond would be under 1.0 mg/L in a 4-month period, while an average concentration of 1.57 mg/L was measured in a 1994 study.

In comparing model predictions and field data, some consideration must be given to the range of the measured NBOD and phosphorus data, as well as other uncertainties such as predicting nutrient loading and kinetic rate constants assumed in the model. Chlorophyll data indicated that the variation in the West Pond was higher than in the East Pond over the entire period of study. Algal blooms and mats were observed in the summer of 1996 and 1997 but no impact on fish populations was observed. In summary, the mathematical model developed in this study showed that the effects of BOD, nitrogen, and phosphorus due to surface runoff and migratory birds were not as detrimental to water quality and aquatic life in either the East Pond or the West Pond.

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