Chapter 23

Application of WASP5E to Model Phosphorus Removal Dynamics in a Stormwater Wetland

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Water pollution abatement has received considerable attention from the research community over the recent years. Treatment of urban stormwater runoff has likewise been the focus of sizeable amounts of research. Phosphorous is a key indicator parameter for eutrophication problems and was therefore the parameter of focus in this research. Urban activities create sources of phosphate such as fertilizers, animal waste, detergents, etc. Phosphate loads in urban runoff vary greatly due to variations in rainfall characteristics, watershed features and urban activities (EPA, 1993). Reported ranges of total phosphate loads vary from 0.2 to 2.0 kg/ha for residential areas, and from 0.9 to 6.0 kg/ha for industrial areas (Novotny and Olem, 1994). Constructed wetlands have been widely promoted for urban stormwater management because of their inherent capacity for water storage and water quality improvement.

The Ontario Land Use Planning Act (1990) defines "wetlands" as: "lands that are seasonally or permanently covered by shallow water, as well as lands where the water table is close to or at the surface. In either case the presence of abundant water has caused the formation of hydric soils and has favoured the dominance of either hydrophytic plants or water tolerant plants"

This research, conducted at the School of Engineering, University of Guelph, studied the feasibility of modeling phosphorus assimilative capacity by stormwater wetlands in cold climates. The over-riding aim of this research was

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the application of computer simulation in evaluating water quality improvement efficiency of constructed wetlands in an effort to enhance their proficiency and promote their utilization.

For this research, a vast amount of background data relating to urban stormwater, wetlands and modeling was collected and examined. Previous studies and field data were reviewed to find useful and adequate data sets for modeling purposes. Due to the lack of data from a constructed wetland system, a data set for the Hidden Valley wetland, a natural stormwater wetland (*Typha* marsh), was chosen and adopted to test the selected water quality models.

A number of water quality models were scrutinized to establish their adequacy for modeling phosphorus dynamics in wetland systems. The US EPA's WASP5 simulation program and the vegetation growth/phosphorus uptake model ECOL1 were selected. The linked phosphorus cycle kinetics of WASP5 to ECOL1 developed here is called WASP5E. The two primary objectives of the study were to assemble into a computer simulation process the main components of phosphorous dynamics in stormwater wetlands and to test the utility of the process in simulating those phosphorous dynamics.

Phosphorus dynamics in wetlands systems have been widely described and analyzed in literature. Phosphorus wetland processes are schematically illustrated in Figure 23.1. The dynamics of phosphorus removal in wetlands is an interaction of mechanisms such as sedimentation, chemical precipitation and incorporation into biomass, plants and algae. For a description of P cycle in wetland systems, refer to Tchobanoglous and Schroeder (1987), Vymazal (1995), Kadlec and Knight (1996), Strecker *et al.* (1992), Shaver (1995), Kadlec and Kadlec (1978), Bayley (1985), Kadlec (1987), Reddy and DeBusk (1987), Good and Patrick (1987), Hossner and Baker (1988), and Davis *et al.* (1978).

23.1 Models Description

This section presents a description of the two computer models used in this research, WASP5 and ECOL1. The main focus of this study is on the model algorithms related to the phosphorus cycle dynamics. Algorithms of each model affecting the phosphorus dynamics will also be addressed.

23.1.1 WASP5

WASP5 is a dynamic water quality simulation program. Conventional pollutants in a body of water such as nutrients, are simulated in this program by the sub-model EUTRO5. The model network represented in WASP5, is a set of segments that together represent the physical configuration of the water body. The network water column segments can be of two types: (i) surface water

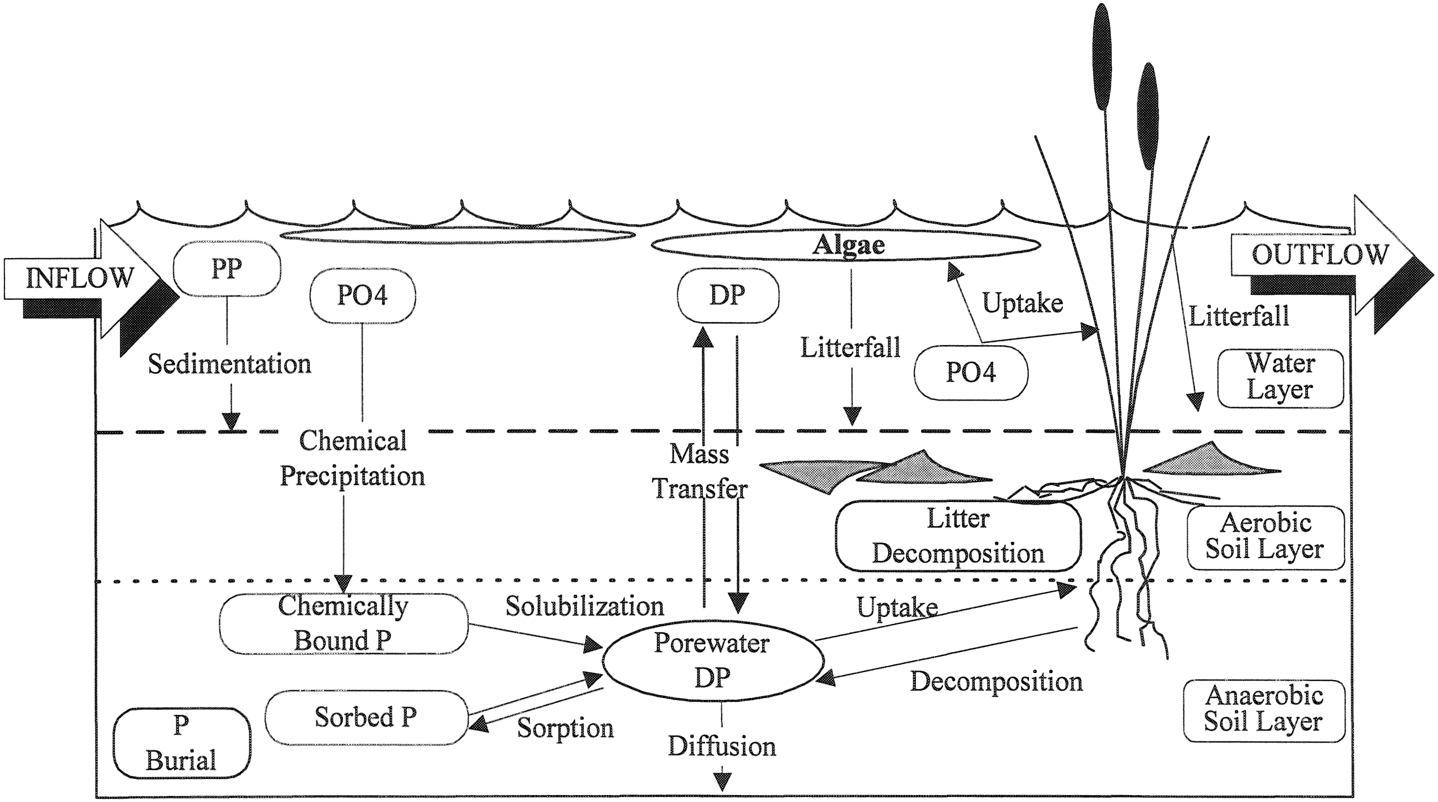

Figure 23.1 The wetland phosphorus cycle.

(epilimnion); and (ii) subsurface (hypolimnion). Along with water column segments, benthic segments can be included. These can represent: (i) upper benthic segments; and (ii) lower benthic segments.

All information presented in this section was taken from the WASP5 Part A: Model Documentation (Ambrose et al. (1993a); refer to this manual for more details). The mass balance equation employed in EUTRO5 accounts for all the material entering and leaving through direct and diffuse loading, advective and dispersive transport, and physical, chemical, and biological transformation. The mass balance incorporates the x, y and z coordinates.

Transport processes of water quality constituents included in WASP5 simulation are advective flow and dispersive mixing in the water column, movement of pore water in the sediment bed, transport of particulate pollutants, and evaporation and precipitation processes. The transport of particulate pollutants includes settling, resuspension, scouring and sedimentation of solids. By this transport in EUTRO5, inorganic, phytoplankton, and organic phosphorus, sorbed onto solid particles, are transported between the water column and the sediment bed.

Within the phosphorus transformation processes, three phosphorus variables are modeled in WASP5: phytoplankton, organic and inorganic (orthophosphate) phosphorus. Organic and inorganic phosphorus are divided into particulate and dissolved concentrations, based on designated variable dissolved fractions for each. Figure 23.2 illustrates the state variables and interactions involved in the phosphorus cycle simulated by EUTRO5, where PO_4 represents orthophosphate and OP relates to organic phosphorus. During simulation, PO_4 is taken up by phytoplankton for growth, and returned from the phytoplankton biomass to both dissolved and particulate organic and dissolved inorganic phosphorus through endogenous respiration and mortality. A portion of the OP is converted to PO_4 through mineralization or bacterial decomposition. The phosphorus cycle rate equations are presented below with a brief description of the variable.

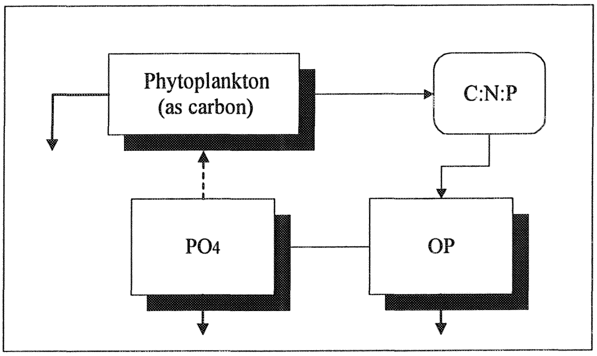

Figure 23.2 EUTRO5 phosphorus variables interactions.

Phytoplankton Phosphorus Rate Equation: The change of phosphorus as phytoplankton biomass with time is represented in WASP5 (Ambrose and Martin, 1993a):

$$\frac{\partial(C_4 a_{pc})}{\partial t} = \underset{\underline{growth}}{G_{p1} a_{pc} C_4} - \underset{\underline{death}}{D_{p1} a_{pc} C_4} - \underset{\underline{settling}}{\frac{V_{S4}}{D} a_{pc} C_4} \tag{23.1}$$

where:

C_4 = phytoplankton concentration, (mg L^{-1});
G_{pl} = specific growth rate, (day^{-1});
D_{pl} = biomass reduction rate, (day^{-1});
V_{S4} = phytoplankton settling velocity, (m day^{-1});
a_{pc} = phosphorus to carbon ratio, (mg P mg^{-1} C); and
D = depth of the waste column or model segment, (m).

Phytoplankton biomass is represented by an aggregated variable, chlorophyll *a*, which is characteristic of all phytoplankton. For internal computational purposes, EUTRO5 uses phytoplankton carbon as a measure of algal biomass using a carbon to chlorophyll *a* ratio. The growth rate (G_{p1}) is specified by a fixed maximum value which is a function of temperature, light limitation and phosphorus limitation. The light limitation factor takes into account the seasonal depth and turbidity light attenuation and photo-inhibition effects on phytoplankton population growth. WASP5 offers a choice of two similar light modeling formulations. For this study the formulation developed by DiToro given in the WASP manual (Ambrose and Martin, 1993a) was chosen; it averages conditions over a given depth and over a fixed interval of time. WASP models the phytoplankton reduction term (D_{p1}) as a function of respiration, death from parasitization and herbivorous zooplankton grazing. If the respiration rate of the phytoplankton as a whole is greater than the growth rate, there is a net loss of phytoplankton biomass.

Organic Phosphorus Kinetics. The kinetic rate of change of organic phosphorus in the water column and the benthic-water column exchange in the system are given by Equations 23.2a and 23.2b, respectively:

$$\frac{\partial C_8}{\partial t} = \underset{\underline{death}}{D_{p1} a_{pc} f_{op} C_4} - \underset{\underline{mineralization}}{k_{83}\, \theta_{83}^{T-20} \left(\frac{C_4}{K_{mpc}+C_4}\right) C_8} - \underset{\underline{settling}}{\frac{V_{S3}(1-f_{D8})}{D} C_8} \tag{23.2a}$$

$$\frac{\partial C_8}{\partial t} = \underbrace{k_{pzd}\,\theta_{pzd}^{T-20}\,a_{pc}\,f_{op}\,C_4}_{algal\ decomposition} - \underbrace{k_{opd}\,\theta_{opd}^{T-20}\,f_{D8}\,C_8}_{mineralization} \tag{23.2b}$$

where:

C_8 = organic phosphorus concentration, (mg L^{-1});
f_{op} = fraction of dead and respired phytoplankton recycled to the organic P pool;
K_{83} = dissolved organic phosphorus mineralization at 20° C; (day^{-1});
θ_{83} = temperature coefficient;
K_{mPc} = half saturation constant for phytoplankton limitation of P cycle, (mg C L^{-1});
f_{D8} = fraction of dissolved organic P;
V_{S3} = organic matter settling velocity, (m day^{-1});
k_{pzd} = anaerobic algal decomposition rate, (day^{-1});
θ_{pzd} = temperature coefficient;
k_{opd} = organic P decomposition rate, (day^{-1});
θ_{opd} = temperature coefficient; and

other variables as already defined.

Inorganic Phosphorus Kinetics. Finally, the inorganic phosphorus kinetic rate of change in the water column and the benthic-water column exchange in the system are given by Equations 23.3a and 23.3b, respectively:

$$\frac{\partial C_3}{\partial t} = \underbrace{D_{p1}a_{pc}\left(1-f_{op}\right)C_4}_{death} + \underbrace{k_{83}\theta_{83}^{T-20}\left(\frac{C_4}{K_{mpc}+C_4}\right)C_8}_{mineralization} - \underbrace{G_{p1}a_{pc}C_4}_{growth}$$

$$- \underbrace{\frac{V_{S5}\left(1-f_{D3}\right)}{D}C_3}_{settling} \tag{23.3a}$$

$$\frac{\partial C_3}{\partial t} = \underbrace{k_{pzd}\,\theta_{pzd}^{T-20}\,a_{pc}(1-f_{op})\,C_4}_{algal\ decomposition} + \underbrace{k_{opd}\,\theta_{opd}^{T-20}\,f_{D8}\,C_8}_{mineralization} \tag{23.3b}$$

where:

C_3 = inorganic phosphate concentration, (mg L^{-1});
V_{S5} = inorganic sediment settling velocity, (m day^{-1});
f_{D3} = fraction of dissolved inorganic P in the water column;

and other variables as defined above.

23.1.2 ECOL1

ECOL1 is a dynamic aquatic plant growth/nutrient uptake simulation model. It incorporates biomass yields and water quality concentration in the water body. This model contains two subroutines: ECOL that contains the primary algorithms to determine growth, respiration and death/washout for the plants; and ASSIM, which simulates the short term exchange rates of oxygen, phosphorus and nitrogen between the biomass compartment and the water column phase. All information was taken from the Aquatic Plant model -Derivation and Application manual (Walker *et al.*, 1982; refer to this manual for ECOL1 details).

Net production of biomass simulated by the ECOL subroutine is determined by subtracting biomass respiration and washout from biomass productivity. Productivity is the amount of new biomass produced, determined by an adjusted growth rate. The optimal vegetation growth rate is adjusted for temperature, solar radiation and nutrient present in the system. A light-temperature limited growth rate (THP) is determined for vegetation from a light-limited growth factor (RADC) and a temperature-limited growth rate (THCP). The amount of P available for plant uptake is calculated from the incoming P concentration (PSUPLY). The total demand of P (TOTP) in the system is calculated in ECOL by:

$$TOTP = THP * PASS * BIOMASS * AREA * ReqFac \qquad (23.4)$$

where:

THP = light-temperature limited growth rate; (h^{-1});
$PASS$ = phosphorus assimilation ratio by vegetation, (g P g^{-1} biomass);
$BIOMASS$ = density of vegetation, (g m^{-2});
$AREA$ = surface area of the segment, (m^2); and
$ReqFac$ = efficiency factor for nutrient utilization for vegetation.

By this method, the instantaneous phosphorus demand at each time step is calculated and is subjected to an efficiency factor. This factor, based on vegetation physical or biological conditions, and environmental condition (i.e. temperature), is greater than one and is adjusted during model calibration. PASS is a stoichiometric ratio of P uptake related to vegetation synthesized and submitted in the input file. Upon determination of phosphorus system demand, a P availability factor (PFAC) is determined by dividing the PSUPLY by the TOTP by vegetation. The estimated PFAC represents the nutrient limitation on growth and determines whether growth of new biomass can proceed. Biomass produced each time step is calculated by ECOL1 by:

$$PRODC = THP * BIOMASS * PFAC * NFAC * TS * INHIBT \qquad (23.5)$$

where:

$PFAC$ = phosphorus availability;
$NFAC$ = nitrogen availability;
TS = time step, (hr); and
$INHIBT$ = plant growth inhibition coefficient.

ECOL algorithms account for P luxury storage by the vegetation pool. If demand of P exceeds supply, the vegetation is able to draw upon stored supplies of P (STFAC) to meet the demand. The vegetation respiration rate (RESP) is based on the unit respiration rate at 20° C, corrected by the temperature correction factor (TFR). This rate is dependent upon the uptake rate of dissolved oxygen and is given by:

$$RESP = GR_{20} * BIOMASS * TFR * TS * \frac{O_2}{(O_2 + 1.5)} \qquad (23.6)$$

where:

GR_{20} = unit respiration rate at 20° C, (g g^{-1} h^{-1});
TFR = temperature correction factor;
O_2 = oxygen concentration (mg L^{-1}) ; and
other variables as above defined.

Vegetation death is calculated as vegetation productivity (PRODC) minus respiration (RESP). The last section of the ECOL subroutine calculates the total amount of phosphorus uptaken and released by vegetation (PUP and PREL, respectively) at each time step. The PUP is a function of the biomass present, the P availability (PFAC) and the vegetation P assimilation ratio (PASS). Phosphorus is released to the water as vegetation respires and dies. The PREL calculated in ECOL is a function of the vegetation respiration rate (RESP) and the PASS by vegetation. PUP and PREL are given as mass per area (g m^{-2}) unit.

The ASSIM subroutine calculates concentration of P in the system upon vegetation uptake and release at each time step. The program performs a mass balance procedure to account for the amount of P coming into the system (reach), the P concentration already in the system, and the amount of P taken up and released by vegetation. The computed output concentration is given as mg L^{-1}.

23.2 Description of the Study Area

The Hidden Valley wetland is an 18.4 ha natural cattail (*Typha glauca*) marsh located west of the Grand River in Kitchener, Ontario, adjacent to the south side of Highway 8 (see Figure 23.3) (Gehrels, 1988; and Limnoterra, 1988). The wetland occupies the central portion of a 100 ha drainage basin and has two major points of inflow and one of outflow. The main source of surface inflow is located at the western limit of the wetland area, draining 50 hectare of industrial/commercial parking areas developed west of Hidden Valley. The second point of inflow is a small natural watercourse located along the northern perimeter of the study, draining an 80 ha developed area containing unpaved land, roadways, and some housing. The outflow of the study area drains directly into the Grand River and is located at the southeastern corner of the wetland (Gehrels, 1988; Ecologistics, 1979; and Limnoterra, 1988).

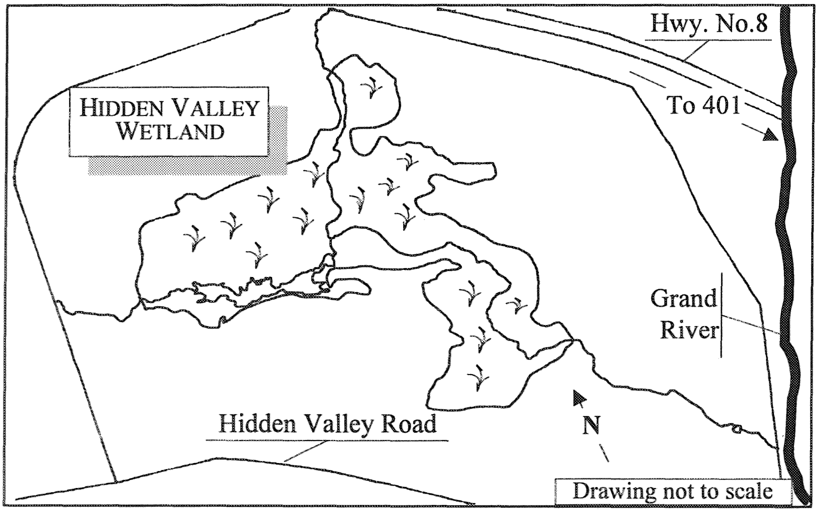

Figure 23.3 Hidden Valley location.

The Hidden Valley is located in an area with a mean annual length of growing season between 200-210 days, 'growing season' being defined as that period in an average year during which the mean daily temperature is equal or higher than 5.5° C (plant growth stops at lower temperatures) (Brown *et al.*, 1980). The climatological seasons for this area are: *Winter* (December - February) is cold (mean temperature of -6.1 °C), *Spring* (March - May) presents a noticeable warming trend (mean temperature of 5.5 °C), *Summer* (June - August) is warm (mean temperature of 18.7 °C), and *Fall* (September - November) is characterized by a marked decrease in temperature (mean temperature of 8.7 °C). Monthly mean precipitation during these seasons is not very different, with winter showing the lowest mean precipitation (60 mm) and summer the highest (81 mm) (Environment Canada, and Gehrels, 1988).

Hydrology and water quality data available for the Hidden Valley wetland used for calibration and validation (later discussed) were obtained from a study performed by Gehrels and Mulamoottil at the University of Waterloo, Waterloo, Ontario. These data were collected from June 1986 until July 1987 (Gehrels, 1988). Inputs to the hydrologic cycle wetland budget measured by Gehrels are precipitation, stream inflow, and groundwater inflow. The outputs are evapotranspiration, surface outflow and groundwater outflow. Reported flowrates of surface water entering the wetland through the main western drain range from 0.01 $m^3 s^{-1}$ to 2.16 $m^3 s^{-1}$, with an average non-storm flow of 0.04 $m^3 s^{-1}$; the northern inflow presented flowrates ranging from 0.01 $m^3 s^{-1}$ to 0.67 $m^3 s^{-1}$, with and average non-storm flow of 0.015 $m^3 s^{-1}$. Reported flowrates of surface water discharging from the wetland ranged from 0.00 to 0.18 $m^3 s^{-1}$, and an average non-storm flow of 0.004 $m^3 s^{-1}$.

Water quality data available for the Hidden Valley wetland include total and reactive phosphate (ortho phosphate), pH and chlorides. For simulation purposes, adequate organic phosphorus load estimates were determined by subtracting measured ortho-phosphates from measured total phosphorus. During summer, 10.0 kg of total phosphate and 2.0 kg of ortho-phosphate were calculated to enter the wetland through the northern drainage, and 12 kg of total phosphorus and 2 kg of ortho-phosphate were reported to enter through the western drainage. Reported surface outflow from the wetland showed ortho-phosphate and total phosphate exports increasing from the spring to summer and reaching a peak in the fall. The discharge of ortho-phosphate doubled in the fall.

For simulation purposes, estimates of water quality data and biological and physical features of the Hidden Valley wetland that are directly or indirectly involved in phosphorus dynamics were established. These parameters included nitrogen-to-phosphorus ratio, phytoplankton (represented as chlorophyll-*a* concentration) and vegetation biomass, and temperature in the water column.

23.3 Modeling Methodology

23.3.1 Model Integration

Model integration comprised linkage of vegetation phosphorus kinetics routines in ECOL1 and phosphorus cycle kinetics in WASP5. The procedure is illustrated in Figure 23.4, and called WASP5E herein.

WASP5E assigns the fraction of incoming ortho-phosphate available for vegetation and phytoplankton (represented by x in Figure 23.4) assimilation. This fraction is calculated as a function of PO_4 assimilation capacity and maximum growth rate for each component, and the ratio of vegetation/phytoplankton biomass present in the wetland (Equation 23.7). Environmental conditions represented by season may influence these factors, therefore, *x* was calculated on a seasonal basis.

$$x = \frac{\text{PASS}}{a_{pc}} \times \frac{Gp_{\text{veg}}}{Gp_{\text{phy}}} \times \frac{\text{Biomass}_{\text{veg}}}{\text{Biomass}_{\text{phy}}} \qquad (23.7)$$

where:

Gp_{veg} and Gp_{phy} = vegetation and phytoplankton growth rate, (day $^{-1}$);
$Biomass_{veg}$ and $Biomass_{phy}$ = vegetation and phytoplankton biomass, (g m^{-2});
a_{pc} = phosphorus to carbon ratio (mg/mg); and
other variables as defined above.

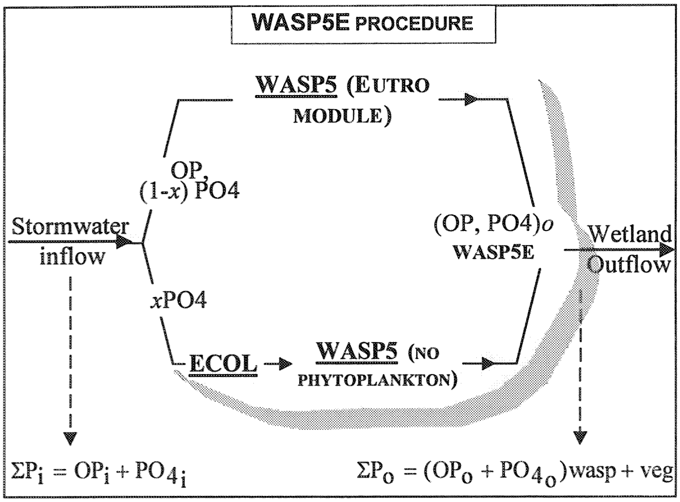

Figure 23.4 Representation of the computer modeling WASP5E procedure; *x* = fraction of ortho-phosphate assigned to vegetation, OP = organic phosphorus and PO_4 = ortho-phosphate.

In the WASP5E modeling, phosphorus cycle dynamics are simulated by WASP5 which involves organic phosphorus, ortho-phosphate and phytoplankton phosphorus cycle dynamic simulations on a half hour time step. On the other hand, ECOL1 simulates biomass yields and P concentration in the water body on a 2 hour time step. Phosphorus released by vegetation is given in ECOL1 algorithms as total phosphate. Therefore, reported values of the fraction of vegetation phosphorus recycled through respiration and mortality to the organic phosphorus pool and to the ortho-phosphate pool in wetland systems were applied to obtain computed ortho-phosphate and organic phosphorus concentration released by vegetation to the water column. The fraction of vegetation phosphorus recycled to the organic phosphorus has been reported to vary between 0.25 and 0.75 (Ambrose and Martin, 1993a; Mendelsohn and Rines, 1985; Vymazal, 1995). Dead vegetation matter and ortho-phosphate remaining in the system after net uptake by vegetation is loaded into WASP5. The linkage of ECOL1 followed by WASP5 with the omission of phytoplankton algorithms in the system performs this process, allowing benthic P dynamic simulation.

Mass of PO_4 and organic phosphorus (OP) resulting from each model procedure are combined within the WASP5E system to give the total computed outflow concentration (OP_0 and PO_{40}) after a given period of time (e.g. 2 hours). The general mass balance equation derived for WASP5E system is given by Equation 23.8. This mass balance is performed separately for organic phosphorus and inorganic phosphorus. Residential mass change within the system is represented by ΔMass/Δt in Equation 23.8. The mass inputs ($Mass_{in}$) and outputs ($Mass_{out}$) to and from the wetland, and the mass generated ($Mass_{gen}$) in the system are presented in Table 23.1 for organic phosphorus and ortho-phosphate respectively. The WASP5E water balance is given by Equation 23.9.

$$\frac{\Delta Mass}{\Delta t} = Mass_{in} - Mass_{out} \pm Mass_{gen} \quad (23.8)$$

$$\frac{\Delta V}{\Delta t} = P + SW_i + GW_i - E - SW_o - GW_o \quad (23.9)$$

where:

P = precipitation (L^3/T);
E = evapotranspiration (L^3/T);
$SW_{i,o}$ = surface water flow (input, output) (L^3/T);
$GW_{i,o}$ = groundwater flow (input, output) (L^3/T); and
ΔV = change in volume storage (L^3).

As part of each computer modeling phase described above, the following sequence of tasks was carried out: study area discretization, parameter selection, sensitivity analysis and model calibration and validation.

23.3.2 Study Area Discretization

The study area was considered as a single "block" system. Thus the system is assumed to be completely mixed, where the concentration of a constituent within the wetland and that exiting the wetland are equal. This assumption has been discussed as applicable for wetland systems with short hydraulic residence time and small length to width ratios (Dortch and Gerald, not published). Our

Table 23.1 WASP5E mass balance components.

Notation	Description	*G
Ortho - phosphate mass balance terms		
MPO$_4$in		
·MPO$_4$sw	stormwater discharge (north and west drainage)	
·MPO$_4$np	surface water non-point source runoff	
MPO$_4$out		
·MPO$_4$wout	surface water wetland outflow	
·MPO$_4$gw	groundwater discharge	
MPO$_4$gen		
·MPO$_4$phy-up	phytoplankton uptake	-
·MPO$_4$phy-rel	phytoplankton release	+
·MPO$_4$op-min	organic phosphorus mineralization	+
·MPO$_4$sed	ortho-phosphate settling	-
·MPO$_4$veg-up	vegetation uptake	-
·MPO$_4$veg-rel	vegetation release	+
Organic phosphorus mass balance terms		
MOPin		
·MOPsw	stormwater discharge (north and west drainage)	
·MOPnp	surface water non-point source runoff	
MOPout		
·MOPwout	surface water wetland outflow	
·MOPgw	groundwater discharge	
MOPgen		
·MOPphy-rel	phytoplankton release	+
·MOPop-min	organic phosphorus mineralization	-
·MOPsed	ortho-phosphate settling	-
·MOPveg-rel	vegetation release	+

* Generation: + = source of mass; - = sink of mass.

wetland has L:W ≈ 1.5. Other considerations must also be taken into account on this assumption, such as, wind stress, and water column depth. Within the system, three layers were distinguished, together representing the physical configuration of the system. The top layer, the "surface water layer", represents the shallow water column in the wetland. The other two layers represent the sediment within the wetland. The "upper benthic layer" is made up of the organic matter (peat) layer within the sediment, and the "lower benthic layer" consisted of silt sandy soils underlying the peat layer in the sediment. The initial volume of the wetland layers was calculated for the beginning of the simulated year. Initial volumes were estimated by average depth, length and width of the system layers (Novotny and Olem, 1994). The water depth was calculated, as suggested by Duever (1988) and Tchobanoglous (1987), by correlating major vegetation types with water depths, and depth of the sediment layers was obtained from a soils map of the area. Typical cattail systems water depth reported in literature range from 0.3 to 0.6 m (Tchobanoglous, 1987).

23.3.3 Parameter Selection

WASP5 Parametrization: The parameters involved in WASP5 simulation were divided into: 1. transport coefficients; and 2. phosphorous cycle kinetics constants.

Exchange and transport of constituents between the system segments and outside the system were estimated for simulation purposes. Advective exchange occurs due to the bulk motions of the flowing water, while nonadvective exchange occurs mainly due to mechanical mixing during fluid advection along with molecular diffusion. Available data for surface and groundwater flow, as measured by Gehrels, were used to calculate advective flows and dispersive coefficients within the study area. Seasonal average net groundwater flow varied from 0.005 to 0.011, where negative values indicate a net recharge flow to the groundwater. Dispersion values obtained in this analysis are within the range reported in literature, ranging between 10^{-8} to 10^{-10} m^2 s^{-1} for silty sand soils (diameter of 0.004 to 0.05 mm) (Bouwer, 1978; and Dortch and Gerald, not published). This range was considered for sensitivity analysis.

The transport of phosphorus sorbed to suspended solids, which undergoes sedimentation, was also addressed. Settling velocities were set within the range of Stokes' velocities corresponding to the suspended particles size distribution. Stokes' velocities for organic, inorganic and phytoplankton matter given by Mendelsohn and Rines (1985) were utilized in this study. Mendelsohn and Rines (1985) modeled the phosphorus cycle in a lake system applying the phosphorus kinetics equations from WASP program. Stokes' velocities for these three parameters given in their study range from 0.05 to 0.5 m d^{-1}.

The selection of phosphorus cycle kinetic constants was divided into three components of the phosphorus cycle as represented in WASP5: organic phosphorus, inorganic (orthophosphate) phosphorus and phytoplankton phosphorus kinetics. The expected values for the coefficients and parameters involved in phosphorus cycle kinetics are tabulated in Table 23.2, with a brief description of the variables. These values were mostly obtained from literature (otherwise indicated). It must be kept in mind that the model is capable of simulating more

Table 23.2 Phosphorus cycle kinetics: expected value of parameters.

Notation	Description	Expected value	Units
Phytoplankton Net Growth Terms			
Exogenous Variable			
f	Fraction of day that is daylight [1, 2]	0.5	- -
Z	Zooplankton population	0	mg C L^{-1}
Rate Constants			
k_{1c}	Phytoplankton max. growth rate [1, 2, 3]	2.0	day^{-1}
θ_{1c}	Temperature coefficient [1, 2]	1.068	- -
K_c	Phytoplankton self-light attenuation [1, 2]	0.017	m^2 mg^{-1}Chla
θ_c	Carbon - Chlorophyll *a* ratio [1, 2]	35	- -
I_s	Saturation light intensity [1, 2]	300	ly day^{-1}
K_{mP}	Half - saturation cnt for phosphorus [1,2]	0.001	mg P L^{-1}
k_{1R}	Endogenous respiration at 20° C [1, 2]	0.125	day^{-1}
θ_{1R}	Temperature coefficient [1, 2]	1.045	- -
V_{S4}	Phytoplankton settling velocity [1, 2]	0.1	m day^{-1}
k_{1d}	Phytoplankton death rate [1, 2]	0.02	day^{-1}
Phosphorus Reaction Terms			
a_{pc}	Phosphorus to carbon ratio [1, 2, 3, 4]	0.025	mgPmg^{-1}C
k_{83}	Dissolved organic P mineralization at 20° C [1, 2]	0.22	day^{-1}
θ_{83}	Temperature coefficient [1]	1.08	- -
k_{mPC}	Half saturation constant for phytoplankton limitation of P recycle	0.001	mg C L^{-1}
f_{op}	Fraction of dead phytoplankton recycled to the organic P pool [1, 2]	0.5	- -
f_{d3}	Fraction dissolved inorganic P in the water column [1, 2]	0.8	- -
V_{S3}	Organic matter settling velocity [2,]	0.32	m day^{-1}
V_{S5}	Inorganic matter settling velocity [2,]	0.32	m day^{-1}
Benthic Phosphorus Reaction Coefficients			
k_{pzd}	Anaerobic algal decomposition rate [1]	0.02	day^{-1}
k_{opd}	Organic P decomposition rate [1]	0.0004	day^{-1}
θ_{opd}	Temperature coefficient [1]	1.08	- -
f_{D3j}	Fraction inorganic P dissolved in benthic layer [1]	0.045	- -

[1] Ambrose and Martin, 1993a; [2] Mendelsohn and Rines, 1985; [3] Vymazal, 1995; and [4] Tchobanoglous, 1987.

variables than there are data available to support. During parameter selection, lack of data necessary to support some variables required the use of common literature values. With more time, these could be more fully characterized.

ECOL1 Parametrization: The parameter values involved in phosphorus dynamics within the ECOL1 vegetation pool were compiled from literature. These parameters represent vegetation growth and death kinetics in the system. Parameters that involved dynamics of *Typha spp.* (cattails) in freshwater systems are present in Table 23.3.

Table 23.3 Vegetation kinetics ECOL1 parameters.

Notation	Term	Base	Range	Units
Cgr20	Unit respiration rate at 20 °C [1, 2]	0.0027	0.0015-0.0045	$g\ O_2\ g^{-1}\ h^{-1}$
ReqFac	Efficiency factor for nutrient utilization [2]	2.25	1.2-3.5	---
K_{max}	Optimum growth rate for cattails [1, 2, 3, 4]	0.10	0.06-0.24	$g\ g^{-1}\ h^{-1}$
Ic	Light model constant [1, 2]	0.75	0.50-1.0	$ly\ min^{-1}$
Pass	Assimilation ratio for P for cattails [1, 3, 4]	0.0015	0.001-0.0025	$g\ g^{-1}$
Nass	Assimilation ratio for N for cattails [1, 2, 3]	0.02	0.015-0.04	$g\ g^{-1}$
$P_{in}p$	Initial P conc. in plants [1, 3]	0.0004	0.0004-0.004	$g\ g^{-1}$

[1] Vymazal, 1995; [2] Walker *et al.*, 1982; [3] Reddy and DeBusk, 1987; and [4] Brix, 1994.

23.3.4 Sensitivity Analysis

Sensitivity analysis was performed for both computer models, focusing intensively on the summer months (June, July and August), since they present the highest fluctuations in phosphorous concentration and flowrates in the wetland's inflow and outflow. After a series of runs, it was possible to gain a sense of the model sensitivity for some parameters. No attempt is made here to present the comprehensive results for each parameter analysed; parameters that yield highest sensitivity for each model simulation are presented.

During the analysis, the parameters were changed one-by-one using the lowest and highest value from each parameter value range, and the percent change in computed output was recorded. On the graphical representation (below), the middle point represents simulation of the system using expected values. The % change in computed output was related to the change in input parameter, where the computed output obtained using expected value parameters correspond to 0.0 % change in computed output.

Parameters analyzed for sensitivity for WASP5 simulation were the advective flows, nonadvective flows, sediment transport parameters, and the phosphorus cycle kinetics constants (see Tables 23.2 and 23.4). These parameters were altered one by one to determine their effect on both orthophosphate and organic phosphorus computed average concentration in the water column over summer.

Table 23.4 Phosphorus cycle kinetics: range of rate parameters tested for sensitivity.

Notation	Description	Expected value	Range	Units
Phytoplankton Net Growth Terms				
Rate Constants				
k_{1c}	Phytop. max growth rate [1, 2, 3]	2.0	1.0 - 4.0	day^{-1}
θ_c	Carbon - Chlorophyll *a* ratio [1, 2]	35	25 - 35	- -
k_{1R}	Endogenous resp. at 20°C[1, 2]	0.125	0.05-0.13	day^{-1}
V_{S4}	Phytoplankton settling vel. [1, 2]	0.1	0.05 - 0.5	m day^{-1}
k_{1d}	Phytoplankton death rate [1, 2]	0.02	0.02 - 0.6	day^{-1}
Phosphorus Reaction Terms				
k_{83}	Dissolved organic phosphorus mineralization at 20° C [1, 2]	0.22	0.22-0.44	day^{-1}
f_{op}	Fraction of dead phytoplankton recycled to the organic P pool [1, 2]	0.5	0.25-0.75	- -
f_{d3}	Fraction dissolved inorganic P in the water column [1, 2]	0.8	0.7-0.85	- -
V_{S3}	Organic matter settling vel. [2]	0.32	0.25-0.5	m day^{-1}
V_{S5}	Inorganic matter settling vel. [2]	0.32	0.25-0.5	m day^{-1}
Benthic Phosphorus Reaction Coefficients				
f_{D3j}	Fraction inorganic P dissolved in benthic layer [1]	0.045	0.001-0.045	- -

[1] Ambrose and Martin, 1993a; [2] Mendelsohn and Rines, 1985; and [3] Vymazal, 1995.

Figure 23.5 presents relative sensitivity for computed average PO_4 concentration for summer months. From this analysis, computed orthophosphate outflow concentration was observed to be most sensitive to organic and inorganic matter settling velocity (V_{S3} and V_{S5}), to dissolved organic phosphorus mineralization (K_{83}) and to the fraction of dissolved inorganic phosphorus in the water column (Fd_3). Similarly, this analysis revealed that the computed organic phosphorus concentration is most sensitive to settling velocity (V_{S3}) and to the dissolved organic phosphorus mineralization parameter (K_{83}).

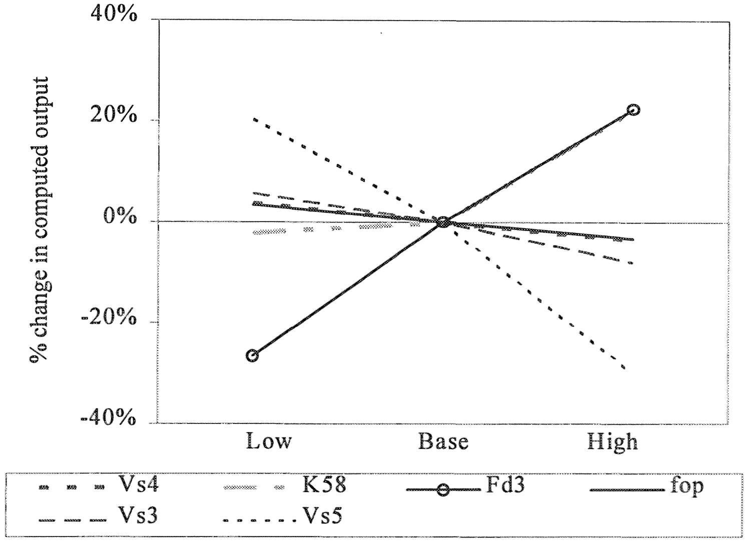

Figure 23.5 Relative sensitivity of computed output for WASP5 for orthophosphate input parameters.

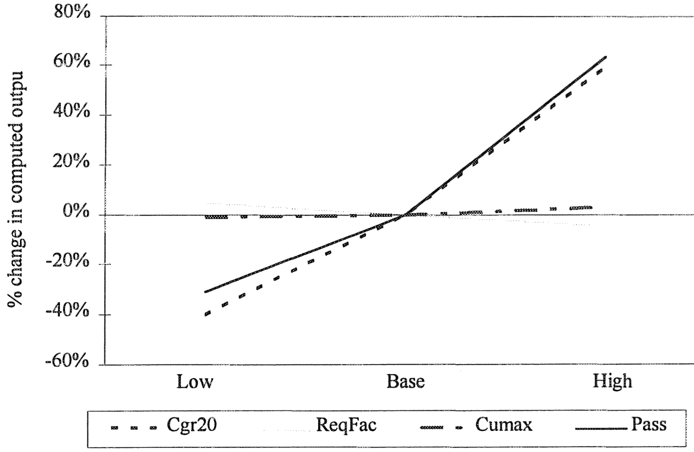

Figure 23.6 Relative sensitivity of computed output for ECOLI for phosphate uptake by vegetation input parameters.

Sensitivity analysis for ECOL1 was performed to determine the effect of vegetation kinetics parameters on the computed average phosphate release and uptake by vegetation. In addition, the analysis was performed for the computed average phosphorus concentration in the water column. Figure 23.6 illustrates the relative sensitivity for the computed average phosphorus uptaken by vegetation. These analyses revealed a high degree of sensitivity of the computed output for kinetics parameters such as the vegetation unit respiration rate (Cgr20), the factor for nutrient utilization (ReqFac), and the cattails phosphorus assimilation ratio (PASS). The phosphate uptaken by vegetation was also found to be sensitive to the optimum growth rate of cattails (K_{max}).

23.4 WASP5E Application to the Hidden Valley Wetland

The summer and fall hydrologic and water quality data set was used to calibrate the various coefficients and parameters described above for phosphorus cycle kinetics, as it represents the time of the year with the highest hydrologic and phosphorus loads. The key calibration parameters and coefficients were the ones identified previously from sensitivity analysis that yield the highest impact on the model response. The range of values for parameters and coefficients used for WASP5E calibration were identical to those used for sensitivity analysis. The values for parameters and coefficients adjusted by WASP5E calibration are presented in Table 23.5. Other parameters and coefficients were kept at the expected value as presented in Tables 23.2 and 23.3. Ortho-phosphate and organic phosphorus are the only water quality variables available for the Hidden Valley wetland to which the model can be calibrated. Hence, this limits the reliability of the calibration for any particular model parameter.

Table 23.5 Phosphorus cycle kinetics: parameter values adjusted from calibration.

Not.	Description	Adjusted values	Units
WASP5 Parameters			
V_{S4}	Phytoplankton settling velocity	0.13	m day^{-1}
k_{83}	Dissolved organic phosphorus mineralization at 20° C	0.35	day^{-1}
f_{op}	Fraction of dead and respired phytoplankton recycled to the organic phosphorus pool	0.40	- -
f_{d3}	Fraction dissolved inorganic P in the water column	0.70	- -
V_{S3}	Organic matter settling velocity	0.25	m day^{-1}
V_{S5}	Inorganic matter settling velocity	0.25	m day^{-1}
Vegetation kinetics ECOL1 parameters			
Cgr20	Unit respiration rate at 20 °C	0.0015	gO_2 g^{-1} h^{-1}
ReqFac	Efficiency factor for nutrient utilization	1.2 - 3.5	---
K_{max}	Optimum growth rate for cattails	0.24	g g^{-1} h^{-1}
Ic	Light model constant	0.50	ly min^{-1}
Pass	Assimilation ratio for P for cattails	0.001-0.0025	g g^{-1}

In ECOL1, the phosphorus assimilation capacity ratio (PASS), reflects the stoichiometry of phosphorus composition on the vegetation population which determines the relation between phosphorus uptake/mass of vegetation synthesized. The value for this parameter varies due to the varying cellular content of phosphorus which is, in turn, a function of the external nutrient concentrations and the past history of the vegetation population. The use of a constant ratio in the simulation by ECOL1, is therefore questionable. For this reason, we considered it appropriate for the Hidden Valley simulation to calibrate this ratio by season within the given range (0.001 to 0.0025 g g^{-1}).

Comparison of observed and simulated ortho-phosphate and organic phosphorus concentrations for the calibration period is presented in Figure 23.7. Adjusted calibrated parameters were used to simulate organic and ortho-phosphate concentration during winter and spring (1986/1987). Comparison of observed and simulated PO_4 and OP concentrations for this period is presented in Figure 23.8. In Figures 23.7 and 23.8, the observed instantaneous concentration data are presented with their corresponding estimated errors, 30% error for outflow organic phosphorus and 25% error for outflow ortho-phosphate. A plot of the continuous results based on a 2 hour time step and the instantaneous observed concentrations for the entire year is presented in Figure 23.9. Correspondent parameters were adjusted seasonally.

Several approaches to statistically evaluate the goodness of fit between computed and observed data have been widely discussed (James, 1994). For this research, the standard error of estimate (SEE) and the relative error (RE) were calculated for WASP5E seasonal and entire year performance. As a representative statistic to measure the accuracy of fit between WASP5E computed data and the observed data, the SEE was calculated by Equation 23.10 (James, 1994):

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}\left(C_M - C_D\right)^2}{n-2}} \qquad (23.10)$$

where:

C_M = the model computed value;
C_D = the measured value (observed data); and
n = the number of points compared.

The relative error statistic provides a measurement of model performance that is comparable among different variables because they are normalized to the value of each variable. The mean relative error was calculated using Equation 23.11 (Mendelsohn and Rines, 1985):

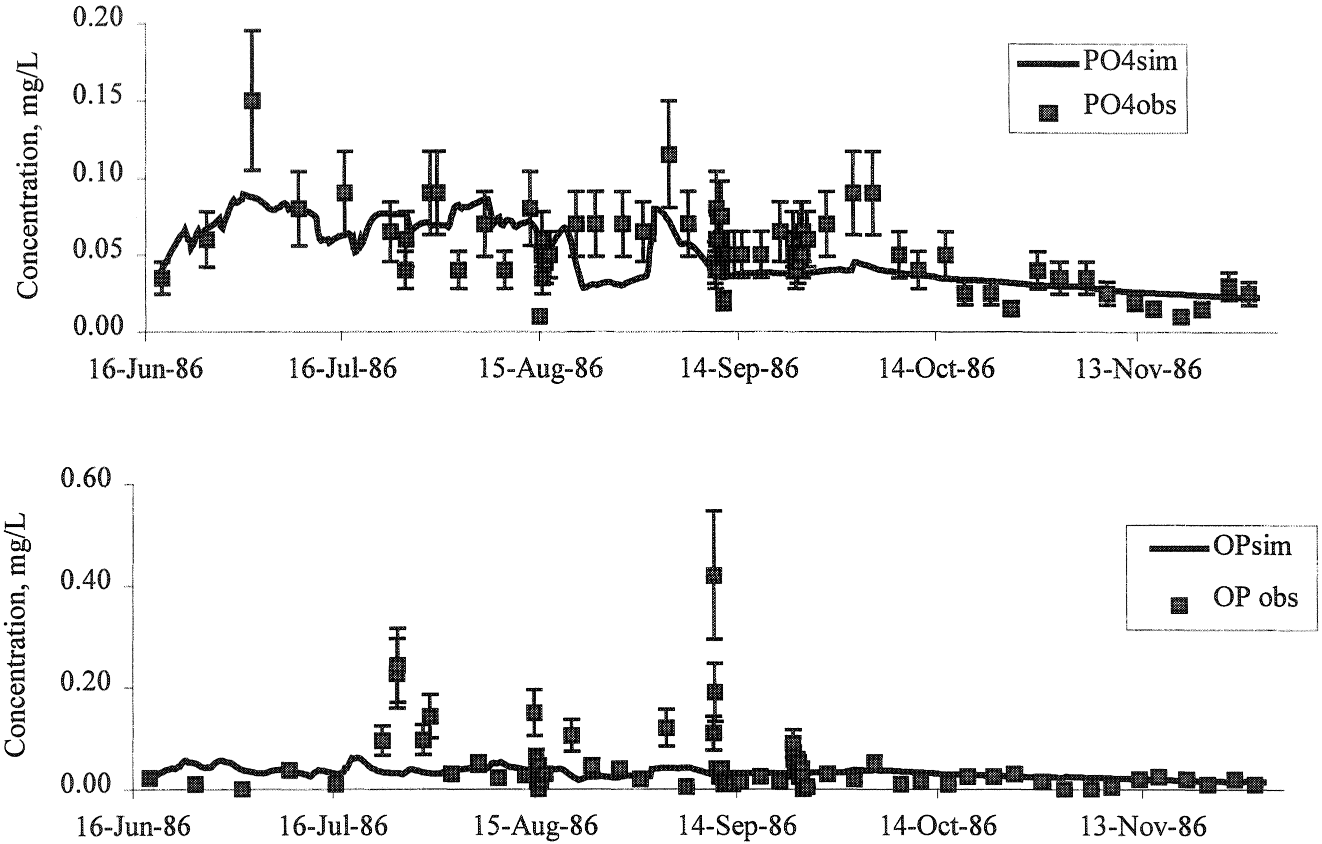

Figure 23.7 Observed and simulated ortho-phosphate (above) and organic phosphorus (below) concentration for summer and fall 1986.

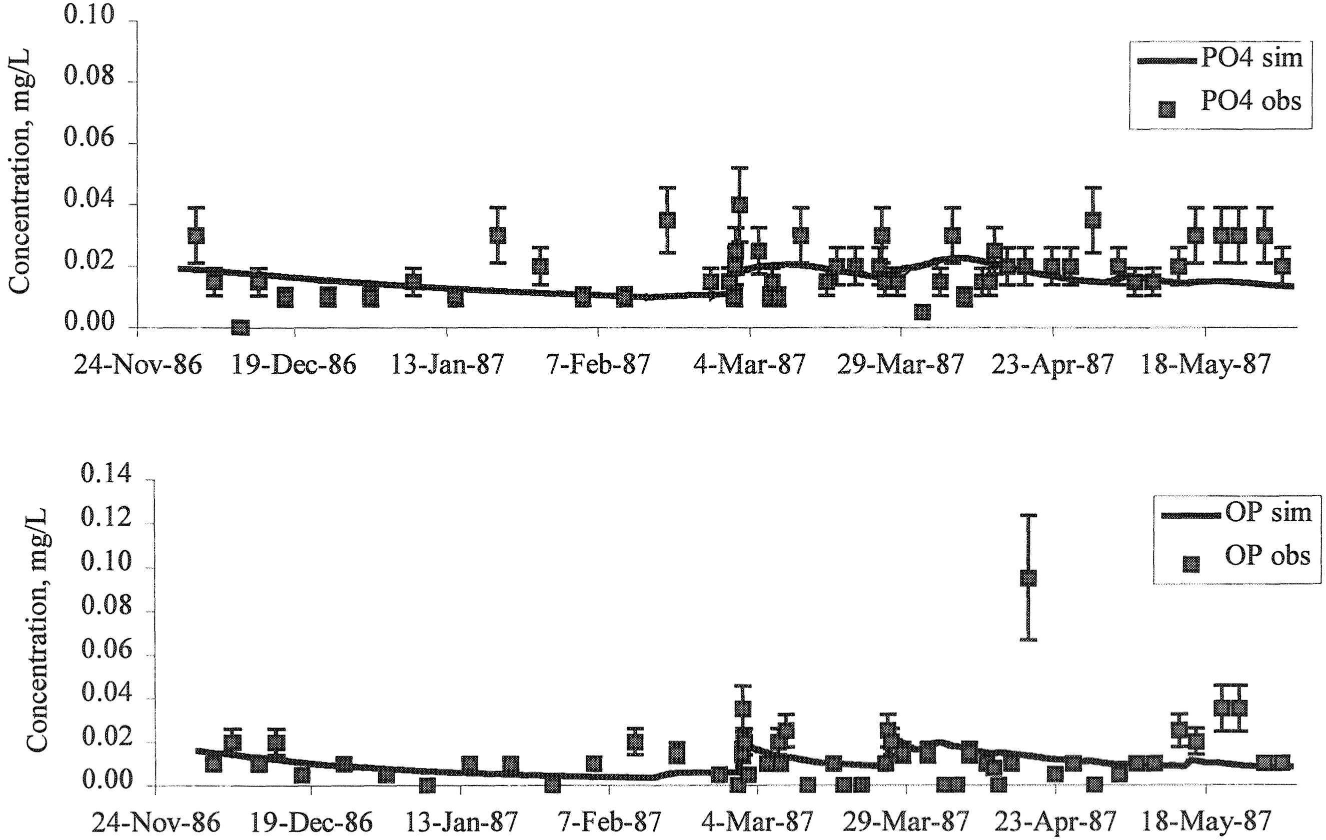

Figure 23.8 Observed and simulated ortho-phosphate (above) and organic phosphorus (below) concentration for winter and spring (1986-1987).

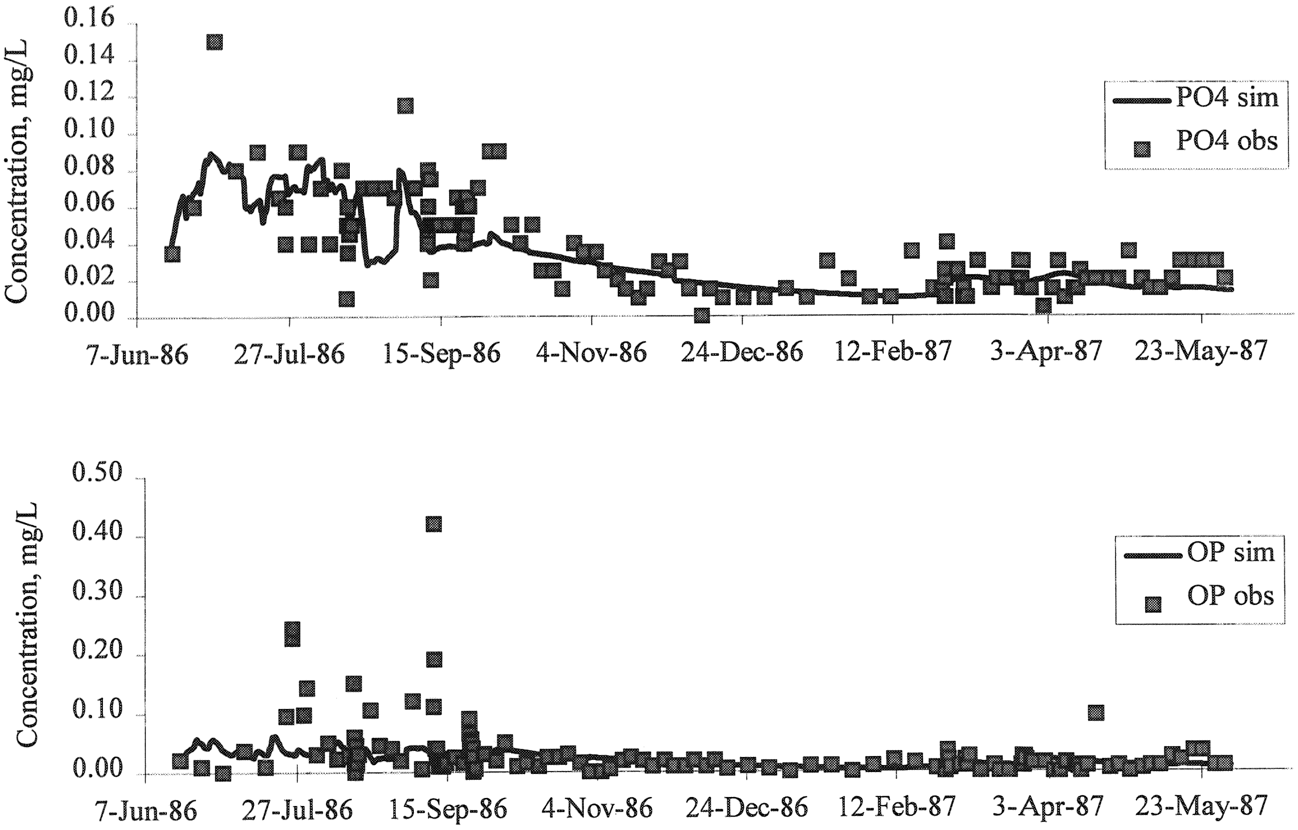

Figure 23.9 Continuous ortho-phosphate (above) and organic phosphorus (below) WASPE5 simulation from June 1986 to June 1987.

$$RE = \frac{\left|\overline{C_D} - \overline{C_M}\right|}{\overline{C_D}} \qquad (23.11)$$

where:

$\overline{C_D}$ = the mean measured value; and

$\overline{C_M}$ = the mean computed value.

Table 23.6 presents a statistical evaluation determined from the WASP5E simulation, based on a 2 hour time step, by season and for the entire year.

Table 23.6 Summary of statistics analysis for WASP5E simulation results.

Season	Ortho-phosphate		Organic phosphorus	
	SEE (mg L^{-1})	RE %	SEE (mg L^{-1})	RE %
Summer	0.026	4.1	0.071	45.6
Fall	0.021	26.9	0.037	15.5
Winter	0.011	11.7	0.007	14.8
Spring	0.010	10.9	0.017	10.9
Year	0.018	15.9	0.040	27.2

23.5 Discussion

WASP5E links the phosphorus dynamics processes simulated by WASP5 to the vegetation growth/phosphorus uptake module called ECOL1. Through this linkage WASP5E assigns the fraction of incoming ortho-phosphate available for vegetation and phytoplankton assimilation. It has been widely discussed that phosphorus uptaken by vegetation occurs primarily through the roots from the sediments. The ECOL1 model overlooks this phenomena since it only simulates P dynamics in the water column but excludes simulation dynamics of P in the pore water in the sediment. The model performs the simulation of ortho-phosphate taken up by vegetation by assigning an efficiency factor for phosphorus utilization by vegetation. This factor is specified in the input file and although its interpretation is not clearly defined in the ECOL1 manual, in the current study, adjustment of this factor was the mechanism employed to account for the P that, if simulated, would go to sedimentation and could be present in the sediment layer in a form available for vegetation uptake. It was recognized that this approach may be somewhat coarse but it was considered that due to restrictions such as lack of phosphorus concentration data for sediments, other feasible approaches may not have been any better.

In addition, algorithms of phosphorus dynamics in ECOL1 alone exclude full consideration of vegetation phosphorus sedimentation and organic matter decomposition in the sediment. The linkage of ECOL1 followed by WASP5 with the omission of phytoplankton algorithms in the system (see Figure 23.4), partially addresses this problem by loading dead organic matter from ECOL1 vegetation to the WASP5 benthic segment, allowing P dynamics in sediment and organic matter decomposition to be simulated.

The results from WASP5E simulation were verified against standard material balance equations (for water and PO_4 and OP). This mass balance verification was within 5% for organic phosphorus and ortho-phosphates and within 9% for water. This affirms that the WASP5 procedure computes the P balance with 5 to 9% error for this dataset.

An understanding and measurement of the rate of processes involved in phosphorus dynamics simulation in a wetland system is a key factor to select an appropriate simulation time step. The ECOL1 model used a 2 hour time step for phosphorus vegetation simulation. This time step was chosen to capture the short term variation of key environmental conditions for this process such as solar radiation and temperature profiles through a typical day. For the WASP5 simulation, a 0.5 hour time step was applied by the model itself, based on the rate of processes involved in phosphorus dynamics accounted for in WASP5. The rate of these processes tends to vary within the same system, where they are affected by different environmental or physical factors, such as surface water velocity and hydraulic retention time, thus complicating the task of estimating an appropriate time step. Time steps are constrained within a specific range to maintain stability and minimize numerical dispersion, or solution inaccuracies. The 0.5 hr. results were then averaged to yield a 2 hr step consistent with ECOL1. Given the relatively slow response of the wetland to changing flow, radiation and chemical conditions, it is believed that the 2 hour time step is adequate to capture P dynamics in wetlands of this type.

The relative error calculated for seasonal simulation (Table 23.6) revealed that WASP5E accurately simulates organic phosphorus and ortho-phosphate outflow during winter and spring, at a relative error of 15% or less. During summer, the model simulation yielded a significantly higher relative error for organic phosphorus simulation, whereas for inorganic phosphorus WASP5E yielded a much lower relative error (4%). During fall, the organic phosphorus simulation resulted in a low relative error while for ortho-phosphate a higher relative error was observed.

Although the effects are not clearly defined, it has been generally reported (Vymazal, 1995) that exceedingly high or low temperatures affect the normal performance of wetland processes. Vegetation and biological processes can be highly restricted under these conditions. The WASP5E simulation during summer and fall (when average temperature are higher than 10°C) may have been restricted by the way in which WASP5E integrated models handle fluctuating temperatures. The kinetic rate parameters, such as unit respiration rate for vegetation (Cgr20 of ECOL1), are typically set for standard conditions (e.g. 20°C). The temperature correction relation employed in ECOL1 may oversimplify the actual relationship.

The Hidden Valley wetland was characterized during summer mainly by wet periods, high temperatures, low flow rate at the outlet of the wetland with sporadic peaks and low concentrations of organic phosphorus and ortho-phosphate entering the wetland through the surface water. This combination of hydrologic factors and physical factors may have created critical conditions for removal mechanisms of phosphorus, such as quick release of phosphorus by vegetation under high temperature and low flows, or concentration of phosphorus under high evapotranspiration periods and subsequent washout by continuous rainfall events. These processes were reflected in sudden high levels of organic phosphorus and ortho-phosphate observed at the outflow of the wetland.

During the fall, a new set of environmental characteristics were observed. Conditions that may have affected the efficiency of wetland vegetation for ortho-phosphate uptake, potential death and washout of vegetation over high outflows, as well as possible release of phosphorus from sediments, are: high precipitation, decrease in temperature, increase in outflow rates and higher concentration of phosphorus entering the wetland via surface water.

During the winter and spring, the Hidden Valley wetland exhibits hydrodynamic and physical characteristics that are quite different. In winter the temperature and precipitation is low and the inflow concentrations and outflow rates are significantly reduced. The wetland vegetation effects are essentially absent during this season. These conditions may cause relatively low process rates in the wetland, reflected by low constant outflow concentrations discharging from the wetland. Spring presented a relative warming trend, consistent with increasing precipitation and outflow rates. Concentrations at the outflow begin to vary, best described by relatively consistent low organic phosphorus and ortho-phosphate concentrations.

The ortho-phosphate simulation performed by WASP5E yields a slight underestimation at high observed concentrations and an overestimation at low observed concentrations. For organic phosphorus the computed underestimation occurred at higher observed concentrations, which occur in summer and fall.

23.6 Sources of Error

The main modeling phases are listed in Table 23.7

Natural variability in the real ecosystem. The variability of the processes begins with the variability and frequency of stormwater introducing phosphorus into the wetland.

Table 23.7 WASP5E simulation performance evaluation.

Natural variability in the real system error.
Observation and sampling error of observed inputs and outputs.
Algorithms structure of the model system and model aggregation.
Area discretization - start-up error.
Input datafile / parameter selection error.
Parameter optimization.

Observation and sampling error of observed input and output. Errors in data observation are mainly related to field instrumentation, whereas the error related to sampling may be associated with the timing and location of the field equipment (James, 1994 and Gehrels, 1988). In estimating the error, the limited frequency of sampling and the lack of samples duplicates were a critical factor, and sometimes its effect is underestimated. The reported estimated errors of the observed data could represent a conservative error estimation, and higher relative error could be expected.

Algorithm structure of the model system and model aggregation. This error addresses algorithms absent from the model structure. This will require future investigation, but includes:

1. WASP5 does not modify the benthic P mineralization rates or the P dissolved fraction as a function of DO or other chemistry. Anaerobic /aerobic conditions in the water-sediment interface may promote exchange of phosphorus between this interface. It has been suggested (Gehrels, 1988; and Sloey *et al.*, 1978), that if the dissolved oxygen drops below 2 mg L^{-1}, phosphorus can be released from the sediment to the interstitial water and subsequently to the water column. The omission of this algorithm within the model could cause underestimation, especially in summer and fall, of organic phosphorus and ortho-phosphate outflow levels.
2. Linkage of a hydrodynamic model which properly simulates flow routing in the system to WASP5 may result in a substantial enhancement of the simulation. Factors to consider include cross-section, profile and overbank geometry. The integration of a hydrodynamic model could potentially provide information on wetted perimeter which will allow exposed sediment areas to be calculated. WASP5 assumes that its benthic segments are always under water, which excludes the simulation of areas that are temporarily exposed and therefore subjected to changes in redox conditions affecting movement of phosphorus accumulated in the

sediment. Under such conditions, decomposition rate as a function of wet and dry state would have to be defined.

3. In addition, tighter linkage between ECOL1 and EUTRO5 algorithms would have improved simulation of plant material depositing to benthic segments and undergoing mineralization.

Area discretization-"start-up error". Spatial discretization of the study area was restricted mainly by the limitation of the spatial distribution of the observed data (e.g. at the two inflows and the outflow of the wetland). The potential "start-up error" could be mainly attributed to calculation of initial volume of the system layers as well as initial concentration of organic and inorganic phosphate in each layer.

Input datafile-parameter selection error. Some of the most common errors in model simulation result from incorrect data specification in the input file and selection of input parameters.

Parameter optimization error. Parameter optimization plays a fundamental role in water quality simulation. In this process, the key is to calibrate the model appropriately, keeping the parameter values within their reasonable ranges and pay particular attention to parameters that were revealed as more crucial during the sensitivity analysis. As previously mentioned, the only observed variables to which the model can be calibrated were organic phosphorus and ortho-phosphorus. Lack of observed data on vegetation and phytoplankton biomass may have greatly limited the WASP5E calibration process.

23.7 Conclusions

The following conclusions were drawn:

1. WASP5E was successful in assembling into a computer procedure some of the main components of phosphorus dynamics that take place in a wetland system.
2. WASP5E seasonal simulation revealed simulation to a relative error of 15% or less of organic phosphorus and ortho-phosphate outflow during winter and spring.
3. WASP5E simulation for organic phosphorus and ortho-phosphate slightly underestimated outflow concentrations at high observed concentrations and a slight overestimation at low observed concentrations. This was clearly illustrated for summer and fall.
4. The temperature correction employed in ECOL1 may have oversimplified the actual relationship, thus disturbing WASP5E simulation performance particularly in summer simulations.
5. Benthal release of phosphorus from sediment caused by change in redox condition in the water-sediment interface and the litter

decomposition in the Hidden Valley wetland may have occurred during summer and fall 1986. These processes are not accounted for in the WASP5E algorithms, thus underestimating organic phosphorus and ortho-phosphate outflow levels.

6. Other wetland processes, such as filtration of particulates, is not included in WASP5E algorithms.
7. The wetland level of discretization applied in this study was adequate for calibration purposes and coarse management decisions. More detailed discretization could be desired for specific management practices, which in turn will require an extensive collection of chemical and hydrological data and thus increase the overall costs.
8. The simulation time step applied adequately captured phosphorus dynamics occurring in the wetlands.
9. WASP5E calibration processes were greatly dependent on observed data pertaining to vegetation and phytoplankton biomass for the Hidden Valley wetland, which were limited.
10. The integration of a hydrodynamic model could potentially provide more elaborate information on wetted perimeter which will permit the calculation of exposed sediment areas. In addition, the simulation of short circuiting flows, which scour the sediment and flush the vegetation, should also be considered in a hydrodynamics model.

Notation

a_{PC}	phosphorus to carbon ratio, (mg P mg^{-1} C);
AREA	surface area of the segment, (m^2);
BIOMASS	density of vegetation, (g m^{-2});
BIOW	washout factor;
C_3	inorganic phosphate concentration, (mg L^{-1});
C_4	phytoplankton concentration, (mg L^{-1});
C_8	organic phosphorus concentration, (mg L^{-1});
D	depth of the waste column or model segment, (m).
D_{pl}	biomass reduction rate, (day^{-1});
DV	change in volume storage (L^3 / T).
E	evapotranspiration (L^3 / T);
f_{D3}	fraction of dissolved inorganic P in the water column;
f_{D8}	fraction of dissolved organic P;
f_{op}	fraction of dead and respired phytoplankton recycled to the organic P pool;
G_{pl}	specific growth rate, (day^{-1});
GR_{20}	unit respiration rate at 20° C, (g g^{-1} h^{-1});
$GW_{i,o}$	groundwater flow (input, output) (L^3 / T); and

INHIBT	plant growth inhibition coefficient.
K_{83}	dissolved organic phosphorus mineralization at 20° C; (day^{-1});
K_{mPc}	half saturation constant for phytoplankton limitation of P cycle, (mg C L^{-1});
k_{opd}	organic P decomposition rate, (day^{-1});
k_{pzd}	anaerobic algal decomposition rate, (day^{-1});
NFAC	nitrogen availability;
O_2	oxygen concentration (mg L^{-1}) ;
P	precipitation (L^3 / T);
P_{ASS}	phosphorus assimilation ratio by vegetation, (g P g^{-1} biomass)
PFAC	phosphorus availability;
q_{pzd}	temperature coefficient;
q_{83}	temperature coefficient;
q_{opd}	temperature coefficient;
ReqFac	efficiency factor for nutrient utilization for vegetation.
STFAC	storage factor for P in plants;
$SW_{i,o}$	surface water flow (input, output) (L^3 / T);
TFR	temperature correction factor;
THP	temperature-adjusted growth rate; (h^{-1});
TS	time step, (hr); and
V_{S3}	organic matter settling velocity, (m day^{-1});
V_{S4}	phytoplankton settling velocity, (m day^{-1});
V_{S5}	inorganic sediment settling velocity, (m day^{-1});
WASH	total amount of biomass washout, (g biomass m^{-2} hr^{-1});

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