PHOSPHORUS REMOVAL BY URBAN RUNOFF DETENTION BASINS

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ABSTRACT

An empirical model previously developed for predicting phosphorus retention in reservoirs is tested against the urban lake/detention pond data set. Detention pond design criteria developed under the EPA's Nationwide Urban Runoff Program (NURP) are evaluated using the model. For summer precipitation and runoff quality typical of St. Paul, Minnesota, a basin designed according to NURP criteria is estimated to have a long-term-average phosphorus removal efficiency of 47-68 percent. For a given loading regime, phosphorus removal is shown to be more sensitive to pond depth than to surface area. Specific design features for enhancing phosphorus removal (deepening, promoting infiltration, promoting plug flow, and chemical treatment) are discussed. The methodology can be used to evaluate wet detention pond design criteria in other regions, with substitution of appropriate precipitation and runoff quality characteristics.

INTRODUCTION

Cause–effect relationships linking urban watershed development to lake and reservoir eutrophication are well established. Urban watersheds typically export 5 to 20 times as much phosphorus per unit area per year, as compared with undeveloped watersheds in a given region (Reckhow et al. 1980; Athayde et al. 1983; Dennis, 1985). Summaries of urban runoff data collected under the EPA's Nationwide Urban Runoff Program (NURP) indicate mean concentrations of 420 ppb total phosphorus and 150 ppb dissolved phosphorus (Athayde et al. 1983). In contrast, lakes with total phosphorus concentrations exceeding 20–30 ppb may experience nuisance algal growths (Vollenweider, 1976). NURP concluded that "lakes for which the contributions of urban runoff are significant in relation to other nonpoint sources (even in the absence of point source discharges) are indicated to be highly susceptible to eutrophication and that urban runoff controls may be warranted in such situations" (Athayde et al. 1983).

A relationship between urban land use and phosphorus export for watersheds in the Minneapolis/St. Paul area is shown in Figure 1 (Walker, 1985a). Increases in phosphorus export associated with urban watershed development primarily reflect increases in impervious area and surface runoff. Runoff tends to have much higher concentrations of total and dissolved phosphorus compared with base flows that are filtered through the soil column before reaching stream channels or lakes. Specific urban sources (lawn fertilizers, leaf fall, pets) and streambank erosion resulting from higher peak flows also contribute to urban phosphorus loadings.

Physical, economic, and institutional constraints make control of nonpoint phosphorus export from urban watersheds a difficult problem. While the concept of "source control" is attractive, the sources are generally too diverse to permit control of a major fraction of the total loading by targeting one or more specific components. Devices and management practices such as catch basins and street sweeping are generally ineffective at controlling the export of fine particulates and soluble nutrients which have the greatest potential for stimulating lake eutrophication. Performance monitoring conducted under NURP (Athayde et al. 1983; U.S. Environ. Prot. Agency, 1986) has shown that detention ponds, which intercept, store, and treat runoff before releasing it to receiving streams or lakes, can be designed to provide significant removals of many urban runoff pollutants, including phosphorus.

This paper compiles and analyzes data on phosphorus removal by runoff detention basins and urban lakes reported in the literature. It describes the basin design criteria for suspended solids removal developed under NURP. An empirical model for predicting phosphorus removal efficiency as a function of watershed characteristics, basin morphometry, and climatologic factors is described and tested. The model is employed to evaluate the NURP design criteria from a phosphorus removal perspective under Minnesota climatologic conditions. Specific design features which may enhance phosphorus removal are discussed.

NURP DESIGN CRITERIA FOR SUSPENDED SOLIDS REMOVAL

Athayde et al. (1983) concluded that wet detention basins, in which permanent water pools are maintained, are potentially effective for reducing loadings of suspended solids, heavy metals, and nutrients

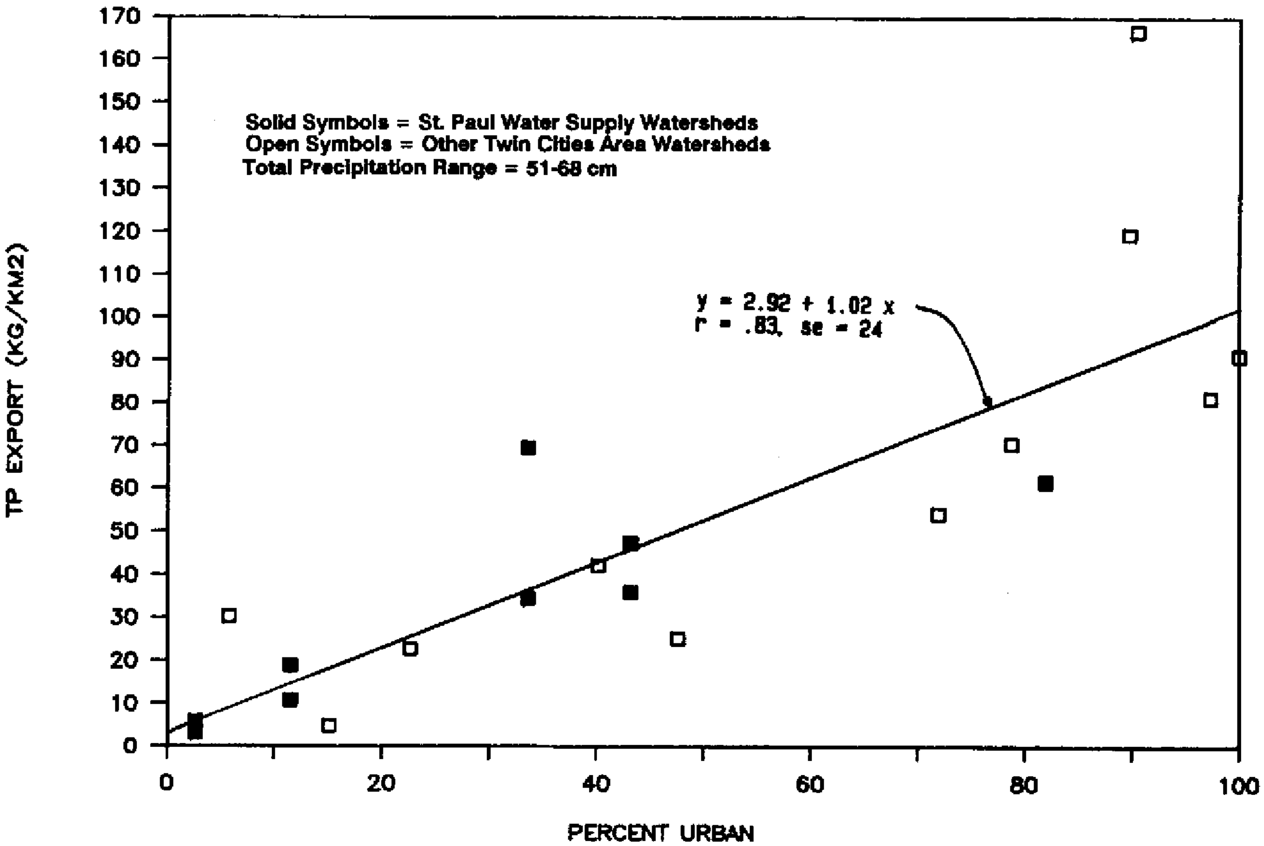

Figure 1.–Phosphorus export vs. urban land use for twin cities watersheds. Reference: Walker, 1985a.

from urban watersheds. Dry detention basins, which are used to control peak runoff but empty completely between storm events, have pollutant removal performance which ranges "from insignificant to quite poor". The presence of a permanent pool is important because it (1) permits "treatment" (sedimentation, adsorption, biological uptake) to occur during the relatively long times between storm events; (2) increases sedimentation efficiency and reduces bottom scouring potential by dissipating runoff energy; and (3) provides a habitat for algae and aquatic plants which can assist in the removal of soluble pollutants.

While some success with extended detention dry ponds (flood detention areas fitted with outlet control devices designed to store runoff for a day or so following events) has been reported for suspended solids and heavy metals, removals of soluble and total nutrients in such basins have been quite low (Randall,1982; Athayde et al. 1983).

Based upon analysis of data from wet detention basins monitored under NURP (Table 1), Driscoll (1983) has shown that average removal efficiency for suspended solids depends upon the following hydraulic and variables:

Q_m/A = mean surface overflow rate during storm periods (cm/hr)
= pond outflow / surface area

V_p/V_m = permanent pool volume / mean storm volume (dimensionless)

The first ratio determines potential removal during storm events for particles of a given settling velocity. Under ideal conditions for sedimentation, particles having settling velocities greater than Q_m/A would be removed; the remaining would either pass through the pond or remain suspended in the pond at the end of the event. The second ratio determines the pond's potential to store and subsequently remove materials during quiescent periods between storm events.

Using data from several NURP projects, Driscoll (1983) constructed a frequency distribution for particle settling velocities in typical urban runoff:

Percentile :	10	30	50	70	90
Velocity (cm/hr) :	.9	9	46	210	2000

Table 1.—Hydraulic characteristics and treatment effectiveness of NURP wet detention basins.

LOCATION	BASIN	BASIN/ WATERSHED AREA	MEAN DEPTH M	Q_m/A	V_p/V_m	PERCENT REMOVAL SS	TP	DP
Lansing, MI	Grace No.	.0001	0.8	270	.045	0	0	0
Lansing, MI	Grace So.	.0004	0.8	72	.17	32	12	23
Ann Arbor, MI	Pitt	.0009	1.5	57	.52	32	18	0
Ann Arbor, MI	Traver	.0031	1.3	9.1	1.16	5	34	56
Ann Arbor, MI	Swift Run	.0115	0.5	6.0	1.02	85	3	29
Long Island, NY	Unqua	.0184	1.0	2.4	3.07	60	45	
Washington, DC	Westleigh	.0285	0.6	1.5	5.31	81	54	71
Lansing, MI	Waverly Hills	.0171	1.4	2.7	7.57	91	79	70
Glen Ellyn, IL	Lake Ellyn	.0176	1.6	3.0	10.7	84	34	

Hydraulic Characteristics Relative to Mean Monitored Storm:

Q_m/A = Mean Surface Overflow Rate During Storm (cm/hr)
V_p/V_m = Basin Permanent Pool Volume/Mean Runoff Volume

SS = Total Suspended Solids
TP = Total Phosphorus
DP = Total Dissolved Phosphorus

Data Source: Driscoll (1983)

For a typical urban watershed in northern U.S. climate (runoff coefficient = .2, mean storm size = 1 cm, mean storm duration = 4 hours), the ratio of pond area to watershed area would have to exceed .001 to remove particles with settling velocities above the median value (46 cm/hr) during an average storm. To remove fine particles (say, 10th percentile or settling velocity = .9 cm/hr) during an average storm, the ratio of pond area to watershed area would have to exceed .12; the maximum ratio for basins listed in Table 1 is .029. Especially since storms with above average intensities have major influences on long-term average performance, it is unlikely that a typical basin design would remove significant quantities of fine particles during storm events.

Several investigators have shown that phosphorus tends to be concentrated in the fine particulate fractions of street dirt and urban runoff suspended solids (Sartor et al. 1974; Pitt, 1979; Ahern et al. 1980). To achieve significant removals of fine sediments and phosphorus, quiescent settling must be involved, i.e., the pond must be large enough to store runoff for treatment during the relatively long periods between storm events. With sufficient storage, mechanisms other than settling (biological uptake, adsorption) can also contribute to phosphorus removal. Under these conditions, overall performance would be more sensitive to volume ratio (V_pV_m) than to the overflow rate (Q_m/A).

For a given climatologic regime, the above hydraulic parameters and average removal efficiency can be related directly to basic design features such as mean depth and ratio of basin area to watershed area, as illustrated in Figure 2 (Athayde et al. 1983). The performance curves are based upon simulations which account for regional storm event distributions, settling under dynamic and quiescent conditions, and the distribution of particle settling velocities in urban runoff (Driscoll, 1983; U.S. Environ. Prot. Agency, 1986). Based upon NURP data and model predictions, effective control of suspended solids and associated pollutants can be achieved in basins with a mean depth of at least 1 meter and surface area greater than or equal to one percent of the watershed area, for a typical urban watershed with a runoff coefficient of 0.2.

Table 2 evaluates the hydraulic parameters of a detention basin designed according to NURP criteria and operating in the Minneapolis/St. Paul climate. The "relative volume" (V_{rel} =ratio of pond volume to impervious watershed area (cm)) is a useful summary statistic which normalizes pond size against the contributing watershed. As shown in Table 2, the pond performance indicators Q_m/A, V_p/V_m, and T, can be calculated from V_{rel} and regional precipitation characteristics. The mean hydraulic residence time (T, years) is defined as pool volume divided by the mean seasonal outflow. This hydraulic variable has been used in empirical models for predicting average sediment retention in reservoirs (Brune, 1953) and phosphorus retention in lakes and reservoirs (Vollenweider,1976; Canfield and Bachman,1981). A NURP pond operating in the Twin Cities summer climate would have a relative volume of 5 cm, a mean storm overflow rate of 4.5 cm/hr, a pond/mean-storm volume ratio of 5.3, and a mean hydraulic residence time of 16.4 days. Summer precipitation statistics have been used for the

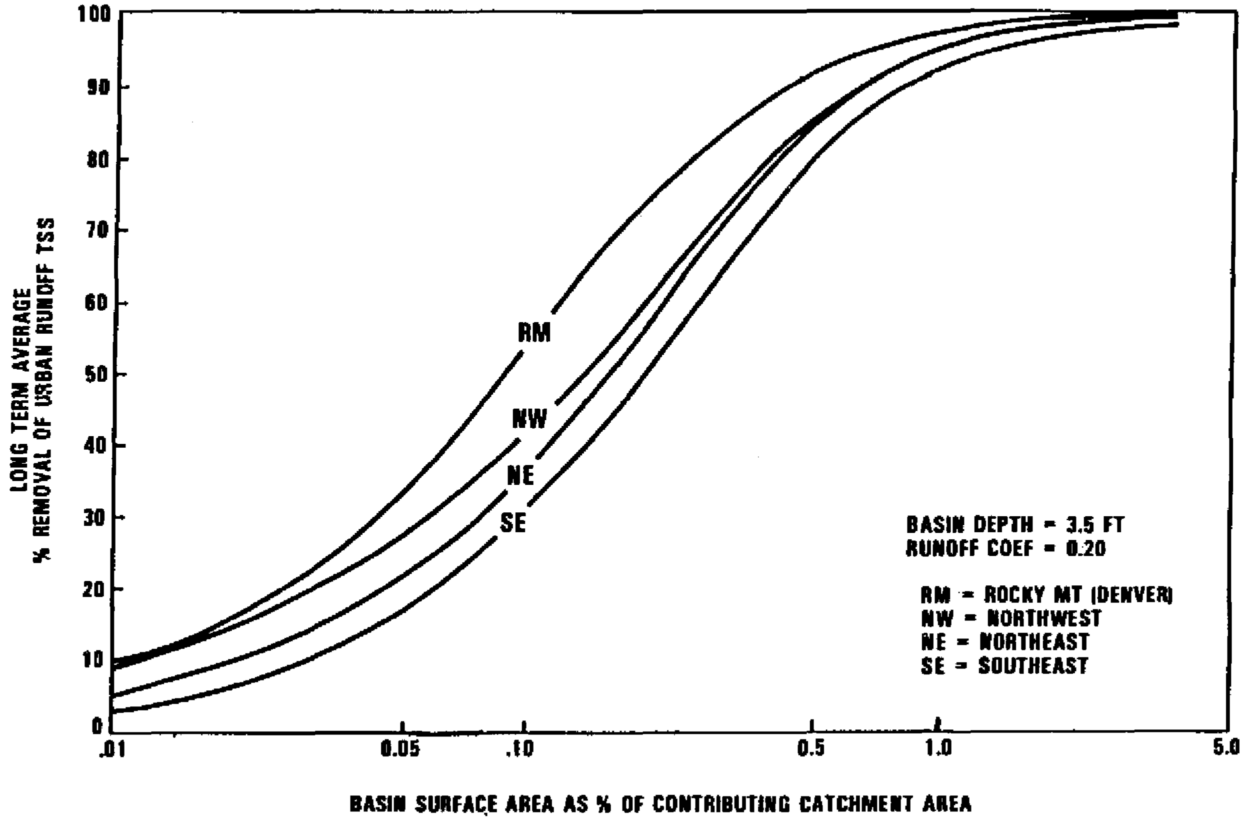

Figure 2.—Detention basin performance for suspended solids removal. Reference: Athayde et al., 1983.

evaluation because they incorporate the peak rainfall month for this region (June) and because monitoring data indicate that differences between urban and nonurban watersheds with respect to runoff and phosphorus export are most apparent during the summer months. Analogous statistics can be calculated for other regions, with appropriate adjustments in the precipitation statistics.

Driscoll (1983) predicted total phosphorus removal efficiency as a function of suspended solids removal efficiency and the fraction of inflow phosphorus in particulate form. This approach is deficient, however, in that it assumes that the dissolved fraction is inert and that particulate phosphorus is distributed uniformly among size fractions. Removal efficiency for dissolved phosphorus equals or exceeds that for total phosphorus in five out of the seven basins (with complete data in Table 1). The removal of dissolved phosphorus is especially important for controlling eutrophication because dissolved forms are the most readily available for algal uptake in downstream lakes. It is apparent that mechanisms other than particle settling (adsorption, precipitation, biological uptake) are partially responsible for phosphorus transformations and removal in these basins. It would be difficult to model all of these mechanisms explicitly.

With a pond volume exceeding five times the mean storm runoff volume, fluctuations in pond fine-particle concentrations associated with average events would tend to be relatively small. For the purposes of predicting long-term average removals of fine particles and phosphorus in a typical wet detention pond, it may not be necessary to consider temporal variability associated with individual storm events. A simpler, empirical approach that deals with annual or seasonal phosphorus loadings and mean hydraulic residence times is possible.

DATA BASE DEVELOPMENT

Pond performance and related data compiled from the literature are summarized in Table 3. The data set includes nine natural and artificial wet detention basins monitored under NURP (Driscoll, 1983). Data from urban lakes in Minnesota, Illinois, Washington, D.C., and Missouri are also included. Wetlands with permanent pools are represented in Minnesota and Florida. These consist of artificial detention ponds and wetlands in series. Hydraulic residence times

Table 2.—Detention pond design and performance variables.

POND AND WATERSHED CHARACTERISTICS:		NURP POND DESIGN CRITERIA
A_w	= watershed area (ha)	
r_c	= watershed runoff coefficient	= .2
A	= pond area (ha)	$\geqslant .01\ A_w$
Z	= pond mean depth (m)	$\geqslant 1$
PRECIPITATION CHARACTERISTICS:		**VALUES FOR MINNEAPOLIS/ST. PAUL JUNE—AUGUST**
P_m	= mean storm size (cm)	= .95
T_e	= mean time between event midpoints (hrs)	= 75
T_d	= mean storm duration (hrs)	= 4.2
P_t	= total seasonal precipitation (cm)	= 27.7
T_t	= length of season (years)	= .25
WATERSHED RUNOFF:		
V_m	= mean storm runoff volume (ha × cm)	$= A_w r_c P_m$
V_t	= total seasonal runoff volume (ha × cm)	$= A_w r_c P_t$
POND PERFORMANCE INDICATORS:		**VALUES FOR NURP POND IN TWIN CITIES CLIMATE**
V_{rel}	= pond relative volume (cm)	
	$= 100\ AZ/(A_w r_c)$	= 5.0 cm
Q_m/A	= surface overflow rate during mean storm (cm/hr)	
	$= V_m/(T_d A) = P_m Z/(V_{rel} T_d)$	= 4.5 cm/hr
V_p/V_m	= pond volume/mean runoff volume	
	$= 100\ AZ/(A_w r_c P_m) = V_{rel}/P_m$	= 5.3
T	= mean hydraulic residence time (years)	
	$= 100\ AZ/(V_t/T_t) = V_{rel} T_t/P_t$	= .045 years = 16.4 days

and removal efficiencies have been calculated from permanent pool volumes and total outflow over the entire monitoring period for each impoundment.

The data set represents a diverse collection of systems from different areas of the country. Common factors include the presence of a permanent pool and domination of inflows by urban (or, in two cases, agricultural) runoff. The data set is limited in the sense that different sampling intensities, durations, seasons, and data reduction techniques were employed by the various investigators.

In every case except two (Ann Arbor/Traver and Washington/Burke), the reported removal of suspended solids exceeds that of total phosphorus. This is consistent with the tendency for phosphorus to concentrate in the fine particulate fractions which are less readily removed via sedimentation. Some fraction of the total phosphorus in urban runoff is in a dissolved form (12 to 68 percent for systems in Table 3) and may be removed or transformed at rates which are slower than direct sedimentation. Driscoll (1983) attributed the low suspended solids removal efficiency at Traver (suspended solids removal 5 percent, total phosphorus removal 34 percent) to bank erosion at the outlet structure.

MODEL TESTING

A variety of empirical models have been developed for predicting phosphorus retention in lakes and reservoirs (Vollenweider,1976; Canfield and Bachman,1981). The model considered here (Table 4) is based upon data from 60 Corps of Engineer reservoirs (Walker,1985b) and has been tested against independent reservoir and lake data (Clasen and Bernhardt,1980). The sedimentation of phosphorus is represented as a second-order reaction, i.e., the rate of phosphorus removal per unit volume per unit time is proportional to the square of concentration. With a fixed second-order decay rate, K_2, of 0.1 m^3/mg-yr, the model explains 80 percent of the variance in Corps reservoir outflow concentrations. When the decay rate is related to surface overflow rate and inflow ortho-phosphorus/total phosphorus ratio using the empirically-derived equation in Table 4, the explained variance increases to 89 percent.

Table 3.—Summary of detention pond, wetland, and urban lake characteristics.

LOCATION	BASIN	BASIN/ WATERSHED AREA RATIO	MEAN DEPTH M	HYDRAULIC RESID. TIME YRS	INFLOW TP PPB	INFLOW DP TP	(C) REMOVALS (%) TP	(C) REMOVALS (%) DP	(C) REMOVALS (%) SS	PLOT SYMBOL	MONITORED STORMS
USEPA NURP Detention Basins (USEPA, 1982; Driscoll, 1983) (a)											
Lansing, MI	Grace No.	.0001	0.8	0.001	395	.12	0	0	0	o	18
Lansing, MI	Grace So.	.0004	0.8	0.003	435	.14	12	23	32	o	18
Ann Arbor, MI	Pitt	.0009	1.5	0.006	200	.20	18	0	32	o	6
Ann Arbor, MI	Traver	.0031	1.3	0.031	91	.36	34	56	5	o	5
Ann Arbor, MI	Swift Run	.0115	0.5	0.017	134	.29	3	29	85	o	5
Long Island, NY	Unqua	.0184	1.0	0.094	229		45		60	o	8
Washington, DC	Westleigh	.0285	0.6	0.091	398	.56	54	71	81	o	32
Lansing, MI	Waverly Hills	.0171	1.4	0.263	198	.22	79	70	91	o	29
Glen Ellyn, IL	Lake Ellyn	.0176	1.6	0.119	506	.19	34		84	o	23
Minnesota Wetlands (Brown, 1985) (b)											
Twin Cities, MN	Fish	.0221	1.2	0.100	307	.59	44	32	92	x	5
Twin Cities, MN	Spring	.0007	1.3	0.002	293	.68	0	0	0	x	5
Minnesota Wetland (Weidenbacher and Willenbring, 1984; Wilson, 1986)											
Roseville, MN	Josephine	0.619	1.2	0.124	416	.67	62	69	79	j	
Minnesota Urban Lakes (Erdmann et al., 1983)											
Minneapolis, MN	Harriet	.3080	8.8	23.529	1232		96			m	
Minneapolis, MN	Calhoun	.1326	9.8	7.407	700		89			m	
Minneapolis, MN	Isles	.1554	2.4	1.321	685		87			m	
Minneapolis, MN	Cedar	.1062	6.0	3.096	439		88			m	
Minneapolis, MN	Brownie	.0228	4.9	0.193	181		66			m	
Florida Detention Pond/Wetland (Martin and Smoot, 1986)											
Orlando, FL	Pond	.0047	1.9	0.020	181	.34	35	57	58	f	13
Orlando, FL	Wetland	.0177	0.2	0.007	118	.23	13	0	53	f	13
Orlando, FL	Pond + Wetl.	.0224	0.6	0.027	181	.34	43	52	80	f	13
Illinois Urban Lake (Hey, 1982)											
Glen Ellyn, IL	Lake Ellyn	.0161	1.6	0.076	441	.31	60	72	87	*	14
Washington Urban Runoff Detention Pond (Randall, 1982)											
Washington, DC	Burke	.1150	2.6	0.106	398	.51	59	56	37	b	29
Missouri Agricultural Flood Detention Reservoir (Schreiber et al., 1980)											
Columbia, MO	Callahan	.0056	2.0	0.029	1409	.07	74	43	88	+	3 yrs
Missouri Urban Lake (Oliver and Grigoropoulos, 1981)											
Rolla, MO	Frisco	.0512	1.0	0.077	309		65		88	z	25

(a) Mean Residence Times for NURP Detention Basins Calculated from Mean Storm Overflow Rates Reported by Driscoll (1983), Assuming Mean Storm Duration/Total Time Between Storms = . 05.
(b) Mass Balances on Minnesota Wetlands Reported for March–Mid May Only
(c) TP = Total Phosphorus, DP = Dissolved Phosphorus, SS = Total Suspended Solids

This formulation has been shown to be useful for predicting reservoir-to-reservoir variations in average pool and outflow phosphorus concentrations and for predicting spatial variations within reservoirs (Walker,1985b).

The empirical retention model is tested against the urban lake/detention pond data set in Figure 3. Data set ranges and performance statistics are summarized in Table 5. To permit inclusion of seven impoundments with missing data, inflow dissolved phosphorus is assumed to be 38 percent of inflow total phosphorus, based upon summaries of urban runoff data by Athayde et al.(1983), Driscoll (1983) and Ahern et al. (1980). To satisfy data requirements of the retention model (Table 4), inflow ortho phosphorus is assumed to be 79 percent of inflow total dissolved phosphorus in each case (Ahern et al. 1980; Bowman et al. 1979).

As shown in Figure 3, observed and predicted removals generally agree to within 15 percent, with one exception. Lake Ellyn, an Illinois urban lake monitored under NURP, occurs twice in the data set, once from the summary of NURP data reported by Driscoll (1983) (observed removal = 35 percent, predicted removal = 74 percent) and once from a report by Hey (1982), the project investigator (observed removal = 60 percent, predicted removal = 63 percent). Differences in data reduction procedures and/or averaging periods may account for the discrepancies between these two sources.

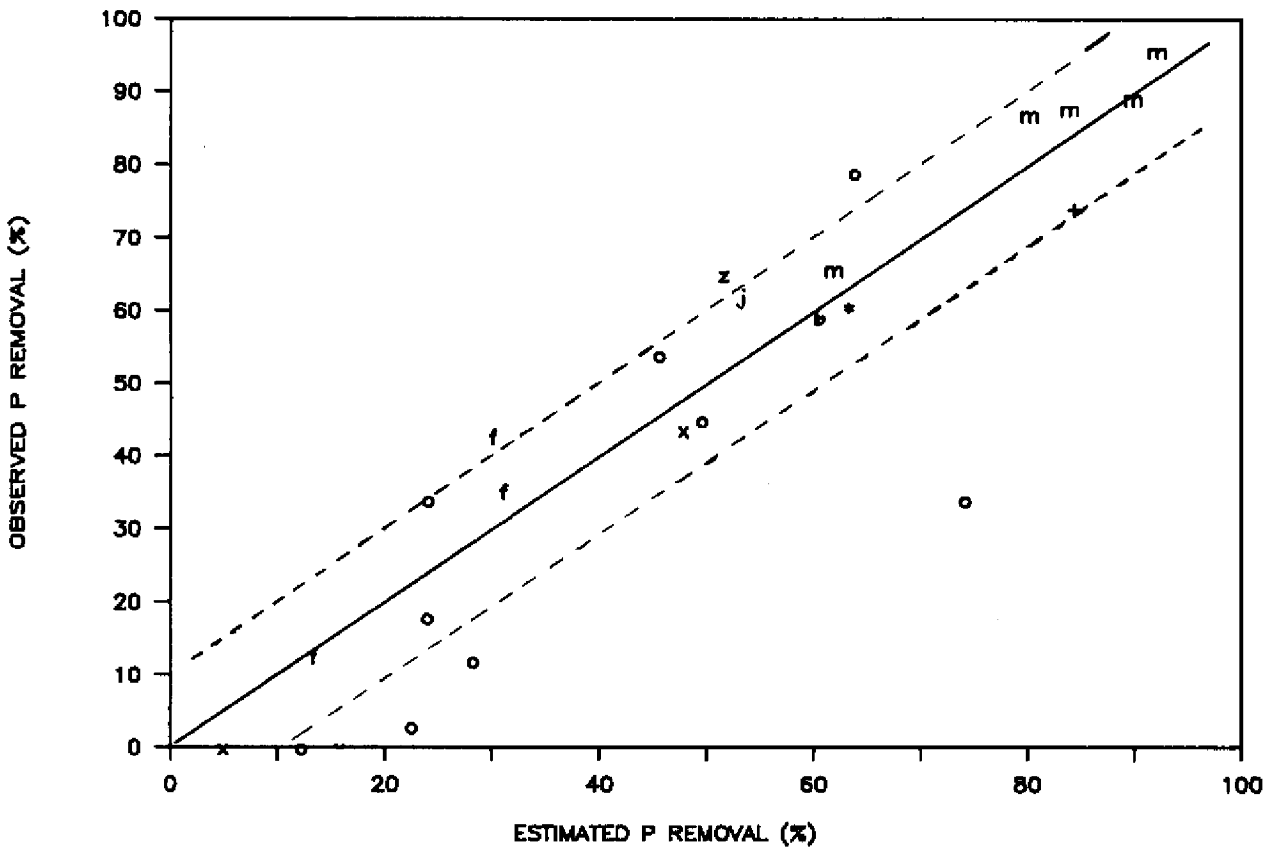

Figure 3.—Observed and predicted phosphorus removal efficiencies symbols defined in Table 3. Dashed lines indicate 10 percent error bounds.

Table 4.—Phosphorus retention model developed for Corps of Engineer reservoirs.

Symbol Definitions:

F_o	= inflow ortho P/total P ratio
T	= mean hydraulic residence time (years)
	= mean pool volume/mean outflow rate
Q_s	= mean surface overflow rate (m/yr)
	= mean outflow rate/mean surface area
P_i	= inflow total phosphorus concentration (mg/m^3)
	= total phosphorus loading/mean outflow rate

Second Order Decay Rate (m^3/mg-yr):

$K_2 = .056\, Q_s F_o^{-1}/(Q_s + 13.3)$

Dimensionless Reaction Rate:

$N_r = K_2 P_i T$

Retention Coefficient (Mixed System):

$R_p = 1 + [1 - (1 + 4N_r)^{.5}]/(2N_r)$

With the exception of the Minneapolis lakes, the mean depths and hydraulic residence times of the impoundments in this data set tend to be lower than those represented in the model development and testing data sets (Table 5). Model errors, as measured by mean squared errors in the logarithms of predicted outflow concentrations, are of similar magnitude (.017 for Corps Reservoirs, .034 for OECD Reservoirs and Shallow Lakes, .018 for the entire detention pond data set, and .012 for the detention pond data set excluding the outlier discussed above). Despite the heterogeneity of the detention pond data set, the empirical model derived from much larger and more consistent data bases appears to be useful for predicting average phosphorus removal efficiencies without detailed simulation of individual storm events.

MODEL APPLICATIONS

The empirical model tested above can be used to examine the relationship between basin morphometric features (area, depth) and phosphorus removal efficiency for a given watershed and climate. Such an application is demonstrated below for precipitation rates and urban runoff concentrations typical of the St. Paul area. The approach can be applied to other areas with substitution of appropriate regional parameters.

Model implementation requires specification of mean hydraulic residence time, surface overflow rate, inflow total phosphorus concentration, and inflow orthophosphorus/total phosphorus ratio. As shown in Table 2, relative volume is directly propor-

Table 5.—Data set and model performance statistics.

	MODEL DEVELOPMENT	MODEL TESTING	THIS STUDY
Data Set	a	b	c
Impoundments	60	20	24
-Data Set Characteristics			
Mean Depth (m)	1.5–58	5–20	.2–8.8
Residence Time (years)	.013–1.91	.3–1.6	.001–23.5
Inflow Total P (ppb)	14–1047	5–1000	91–1232
Inflow Ortho P/Total P	.06–.95	.13–.8	.06–.54
Model Performance Statistics*			
Predicted Variable: Annual Outflow Total Phosphorus Concentration			
N	60	20	24 (23)**
R^2	.887	.886	.780 (.850)
Mean Squared Error	.017	.034	.018 (.012)
Predicted Variable: Mean, Growing-Season, Mixed-Layer P Concentration			
N	40	19	
R^2	.923	.934	
Mean Squared Error	.013	.019	

*Model Performance Statistics Calculated on Log_{10} scales
**Excluding One Outliers (Lake Ellyn/Driscoll (1983))
Data Sets:
a U.S. Army Corps of Engineer Reservoirs, Walker (1985a)
b OECD Reservoir and Shallow Lakes Program (Clasen and Bernhardt, 1980)
c Urban Lakes and Detention Ponds, This Study, Table 3

tional to mean hydraulic residence time for a given season length and total precipitation. Mean surface overflow rate (mean depth/mean hydraulic residence time) can be calculated for a given relative volume and pond depth. Based upon review of regional urban runoff data, an inflow total phosphorus concentration of 650 ppb and inflow orthophosphorus/total phosphorus ratio of 0.3 have been assumed for the purposes of the following evaluations.

Using the above parameters, predicted total phosphorus removal percentages are plotted as a function of relative volume and mean depth in Figure 4. A basin designed according to NURP criteria (V_{rel} = 5 cm, Z = 1 m, Table 2) is estimated to have a phosphorus removal efficiency of 59 percent. The predicted performance is very sensitive to V_{rel} at values below 3 to 5 cm. At values above 5 cm, however, performance is relatively insensitive to volume and increasingly sensitive to mean depth.

An alternative way of expressing the performance curves is to plot percent removal against basin relative area (pond area/(watershed area X runoff coefficient)) for various mean depths (Fig. 5). This isolates effects of pond area and depth. Generally, depth sensitivity is maintained over a wide range of relative areas. In contrast, performance is relatively insensitive to area for relative areas above 3 percent. This suggests that deepening a pond is generally preferable to increasing its surface area for improving phosphorus retention.

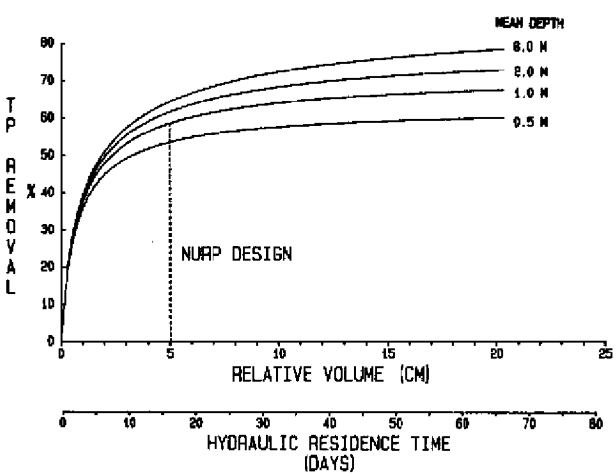

Figure 4.—Predicted phosphorus removal efficiency vs. relative volume (X axis = pond volume/(watershed area x runoff coefficient).

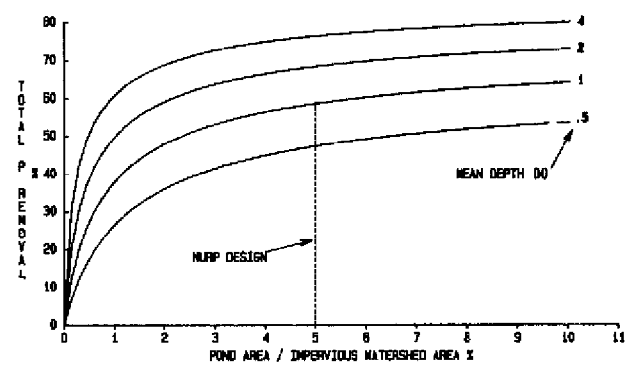

Figure 5.—Predicted phosphorus removal efficiency vs. Relative area (X axis = 100 percent x pond area/(watershed area x runoff coefficient).

The flatness of the performance curves suggests that the NURP design is relatively robust and cost-effective for phosphorus removal. When land values are not considered, pond volume is the best predictor of capital cost (Schueler, 1986). When land values are considered, however, costs may be more directly related to area, depending upon local conditions. In order to increase removal efficiency from 59 to 75 percent, (a 40 percent reduction in the residual loading) the pond volume would have to be increased by a factor of 4 (from V_{rel} = 5 to 20 cm). This could be achieved, for example, by increasing the mean depth from 1 to 3 meters and increasing the relative area from 5 to 6.6 percent.

Figure 6 illustrates the sensitivity of model predictions to twofold variations in each input parameter for a basin designed according to NURP criteria. Removal rates are most sensitive to inflow phosphorus concentration, inflow ortho phosphorus/total phosphorus ratio, and the effective second-order decay coefficient (predicted removal range = 47 to 68 percent). A first-order error analysis indicates that the effects of model error can be approximately represented by twofold variations in the effective decay coefficient for estimation of 90 percent confidence ranges (Walker, 1985b). Thus, when potential model error is considered, the predicted performance of a NURP basin would range from 47 to 68 percent. Compilation and analysis of regional runoff data can help to reduce uncertainty associated with estimates of P_i and F_o.

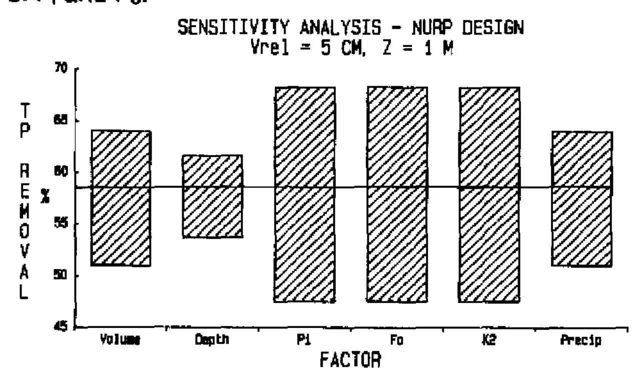

Figure 6.—**Sensitivity of model predictions to input factors effects of 2-fold variations in each input factor on predicted phosphorus removal efficiency are shown. Base values are 5 cm for relative volume, 1 m for depth, 650 ppb for pi, .3 for Fo, and 27 cm for precipitation. For example, the depth bar shows the predicted performance range for a depth range of 0.5 to 2 meters with other input factors held fixed.**

Sensitivities to volume and precipitation rate range from 51 to 64 percent. The responses to twofold variations in precipitation approximately reflect the expected performance range under different seasonal hydrologic conditions. Based upon analysis of 20 years of precipitation data from the Minneapolis/St. Paul airport, seasonal (in this example, June–August) precipitation averages 28 cm and ranges from 13 to 43 cm. The relative insensitivity of performance to variations in precipitation rate and mean hydraulic residence time reflects that fact that the NURP design criterion occurs on a relatively flat portion of the volume performance curves in Figure 4.

DESIGN FEATURES TO IMPROVE PHOSPHORUS REMOVAL EFFICIENCY

Model applications indicate that the NURP design criterion corresponds to a 47 to 68 percent removal efficiency for total phosphorus under the average seasonal climatic conditions considered. As discussed above, urban watershed development typically results in a 5 to 20-fold increase in phosphorus export (Fig. 1). If a "zero-impact" situation is called for, removals 80 to 95 percent would be required. While the NURP design is apparently robust and cost-effective, it may not be sufficient to satisfy water quality management objectives in some watersheds.

Possibilities for modifying detention basin designs to promote phosphorus removal beyond the levels predicted above include

1. Deepening ponds beyond 1 meter
2. Designing to promote infiltration
3. Using ponds in series to promote plug flow
4. Applying chemicals to precipitate orthophosphorus

Performance sensitivity to these options is illustrated in Figure 7. Depending upon site-specific conditions, some or all of these options may be applicable.

The first option is to increase mean depth and relative volume. As discussed above, cost-effectiveness (mass of phosphorus removed per unit volume) decreases as the relative volume increases beyond 5 cm. Increases in volume may be accomplished via excavation, dredging, and/or increasing normal pool elevation. Generally, the latter would be most economical, but it may interfere with adjacent land uses or flood control objectives. As illustrated in Figure 7, increasing the mean depth from 1 to 4 meters (at a fixed relative area of 5 percent) increases the removal efficiency from 59 to 76 percent. An additional doubling of depth to 8 meters increases efficiency by another 6 percent. Increasing depth to the point where thermal stratification would develop is not recommended because of the potential development of anaerobic conditions and subsequent release of dissolved phosphorus from bottom sediments.

The performance calculations assume that a water balance is maintained in the pond and that all

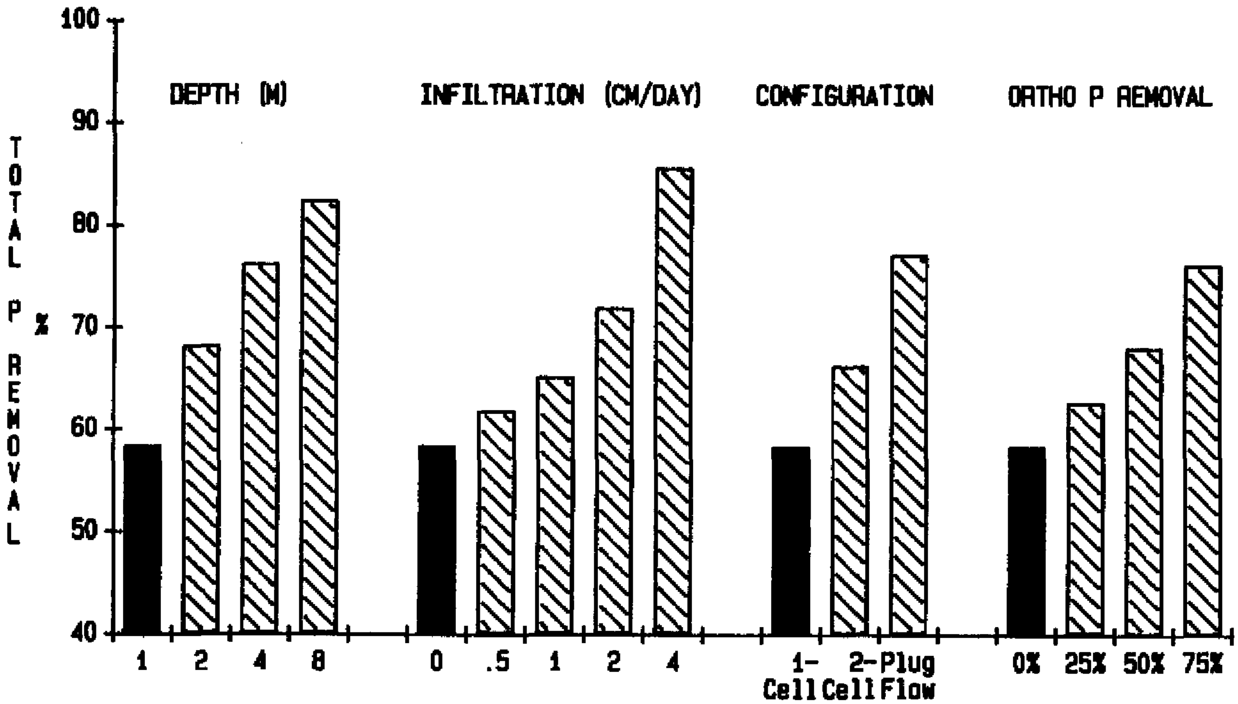

Figure 7.—Alternative methods for increasing phosphorus removal efficiency (solid bar = predicted performance of NURP basin design; hatched bar = predicted performance of modified design).

discharge is through a surface outlet. Overall phosphorus removal may be enhanced by promoting infiltration to groundwaters, which would tend to remove significant quantities of dissolved and suspended phosphorus via adsorption and filtration. Feasibility depends strongly upon soil characteristics and groundwater regimes. Self-sealing of pond bottoms with organic material and clays may limit long-term performance. During extended dry periods, loss of permanent pool volume may pose aesthetic problems. Design of outlets and topography to promote overflow of the pond onto adjacent pervious soils during storm events and subsequent infiltration may be feasible and effective in some situations.

Approximate perspectives on the potential effects of infiltration on removal efficiency are shown in Figure 7. The magnitude of the pond overflow rate in relation to the infiltration rate through the pond bottom determines potential benefits. Effects on removal efficiency have been estimated according to the following equation derived from a mass balance:

$$1-R_{pi} = (1-R_p)(1-i/q_s) \qquad (1)$$

where,

R_{pi} = retention coefficient, adjusted for infiltration

R_p = retention coefficient without infiltration

q_s = pond surface overflow rate (cm/day)

i = infiltration rate (cm/day)

This assumes that percolated water no longer contributes to downstream loading. McGauhey (1968) reports "equilibrium infiltration rates" (after extended periods of permanent flooding) for sands and loams in the range of 1.5 to 37 cm/day. The NURP design in this climate corresponds to a surface overflow rate of 22 m/yr or 6 cm/day. As illustrated in Figure 7, increasing the infiltration rate from 0 to 4 cm/day increases removal efficiency from 59 to 86 percent. Promoting infiltration may be a viable option in areas with permeable soils.

The solution to the phosphorus retention model (Table 4) assumes completely mixed conditions. Separation of the detention pond into two or more distinct cells would promote plug-flow conditions and increase removal efficiency for suspended solids and phosphorus. The importance of designing sedimentation basins to promote plug-flow behavior is well established in the sanitary engineering field (Fair et al. 1968). Oberts (1983) has suggested that staged designs for runoff treatment (sedimentation basins followed by natural or artificial wetland basins) may be beneficial in providing a range of conditions and habitats for various removal mechanisms to operate and in protecting wetlands from sediment accumulation. Two-cell configurations have also been suggested to facilitate pond maintenance (Driscoll, 1986). Urban trash, coarse and medium suspended solids (representing most of the sediment mass) would tend to be deposited in the first pond. Dredging or other maintenance practices could be implemented in the first pond without disturbing established biological communities in the second. The second pond would also provide a buffer against water quality disturbances associated with maintenance of the first pond.

The model can be used to evaluate the potential benefits of multicell designs with respect to phosphorus removal. The second-order sedimentation model has been shown to apply to simulations of spatial variations in several lakes and reservoirs, when advection and dispersion processes are represented (Walker, 1985b). The solution for the retention coefficient under plug-flow conditions is given by:

$$R_p = N_r/(1 + N_r) \quad (2)$$

where N_r is defined in Table 4. Figure 6 compares the predicted performance of a NURP basin in each of three configurations (completely mixed, two-cell, plug flow). The two-cell case is based upon simulation of two, completely-mixed basins in series, each with a relative volume of 2.5 cm. Generally, some elevation drop would be required between the first and second cells to prevent back-mixing. Performance of the basin increases from 59 to 83 percent as the configuration changes from mixed to plug-flow conditions. The potential increase in performance is substantial enough to seriously consider two-cell or multicell designs.

The addition of chemicals to promote precipitation of orthophosphorus is another method to improve performance. Ahern et al. (1980) used laboratory settling column tests to estimate the annual phosphorus removal efficiency of a sedimentation basin in an urban Wisconsin watershed. It was projected that seasonal addition of alum would increase annual removal efficiency from 62 to 76 percent. Applying ferric chloride or alum to the inflows of drinking water reservoirs in Europe has been shown to be effective at reducing reservoir algal growths (Bernhardt, 1980; Bannink et al. 1978; Hayes et al. 1984). The feasibility of applying this technique to onsite and regional detention ponds in the watersheds of the St. Paul water supply lakes is currently under investigation (Walker, 1986). While chemical addition would involve additional cost and more intensive operation, the expense and effort may be justified in some situations, depending upon runoff chemistry, watershed conditions, and lake/reservoir management objectives.

Effects of chemical treatment to remove orthophosphorus can be estimated by adjusting the inflow orthophosphorus/total phosphorus ratio used to calculate the effective sedimentation rate (Table 4). As illustrated in Figure 6, chemical treatment to remove between 0 and 75 percent of the inflow orthophosphorus (without influencing inflow total phosphorus) would increase removal efficiency from 59 to 76 percent. Model projections are similar to those obtained by Ahern et al. (1980).

Other possibilities for improving performance include (1) promoting growth of specific types of aquatic vegetation which are adapted to phosphorus removal from the water column (versus bottom sediments) and (2) hydraulic design of outlet structures to provide temporary storage on top of the permanent pool (slow draining flood pool). The latter may increase detention time and removal efficiency for larger events, depending upon the extent of flood storage volume available, outlet design, hydrograph characteristics, and flood elevation constraints. It is not possible to evaluate these alternatives with a model of the type described above, however.

MAINTENANCE CONSIDERATIONS

The design criteria evaluated above refer to permanent pool volume and depth during the period of operation. Removal of sediment would be required at periodic intervals in order to maintain performance. Since dredging costs are typically three to five times dry excavation costs per unit volume (Schueler, 1986), it may make sense to oversize a pond initially to insure performance over a specified design period. Experience with detention ponds in the Washington, D.C. area and in Canada indicates volume losses on the order of .5–1 percent per year (Scheuler, 1986; Chambers and Tottle, 1980). Monitoring data on suspended solids export from stabilized urban watersheds can be used to project sediment accumulation rates for detention ponds in a particular region. Since potential sedimentation rates during construction periods are much greater and more difficult to predict, the initial pond volume criteria should apply to pond conditions at the end of the construction period when watershed vegetation has been re-established. The sizing of ponds is only one design aspect; other practical considerations regarding design and operation are discussed in a publication by the Washington Area Council Governments (1986).

Multiple-use potentials of detention ponds should be considered in their design and maintenance. Based upon a survey of 360 Maryland residents, the public considers wet detention ponds to be important resources with respect to wildlife attraction, landscaping, aesthetics, recreation, and property values (Metropolitan Washington Council Governments, 1983). These values, combined with potential pollutant removal effectiveness, suggest that urban ponds have important places in lake and watershed management.

CONCLUSIONS

1. An empirical model originally developed for predicting phosphorus retention in reservoirs has been shown to be useful for predicting phosphorus retention in urban lakes and wet detention basins.

2. Detention pond sizing criteria for suspended solids removal developed under the EPA's Nationwide Urban Runoff Program can be most effectively expressed in terms of relative volume (pond volume/impervious watershed area > 5 cm) and mean depth (> 1 meter). For a given climate, relative volume is directly linked to important predictors of pond performance, including mean hydraulic residence time and pond/mean storm volume ratio.

3. For conditions typical of the St. Paul area, ponds designed according to NURP criteria are estimated to have mean hydraulic residence times of 16 days and total phosphorus removal efficiencies of 47 to 68 percent. The design appears to be reasonably robust (insensitive to key design parameters). With appropriate adjustments in precipitation statistics and runoff water quality conditions, the methodology can be applied to predict pond performance in other regions.

4. Possibilities for improving performance include: (1) increasing mean depth; (2) promoting infiltration; (3) promoting plug flow conditions; (4) chemical treatment to remove orthophosphorus; (5) encouraging growth of certain types of aquatic plants; and (6) design of outlet structure to provide extended detention of large runoff events. These may be useful and appropriate, depending upon the desired level of control and other site-specific conditions.

5. Allocating additional pool volume to allow for sediment accumulation over a design lifetime is suggested as a means of improving treatment longevity and reducing long-term maintenance requirements.

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