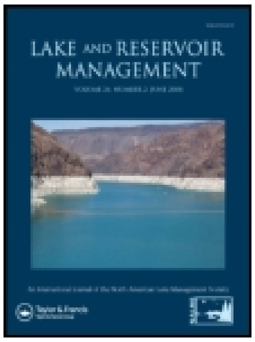

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Calibration of Phosphorus Export Coefficients for Total Maximum Daily Loads of Massachusetts Lakes

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ABSTRACT

Mattson, M. D. and R. A. Isaac. 1999. Calibration of phosphorus export coefficients for total maximum daily loads of Massachusetts lakes. Lake and Reserv. Manage. 15(3):209-219.

In an effort to develop Total Maximum Daily Loads of total phosphorus for hundreds of Massachusetts lakes we reanalyzed the land use export coefficients of previously published diagnostic/feasibility studies. Typically, literature values for phosphorus loading per unit area of land use overestimate total phosphorus loading to Massachusetts lakes. We used a stagewise regression technique to screen a variety of models and to select export coefficients that were reasonable, based on the literature, and which offered a good fit to the data. The final model was verified by predicting phosphorus loadings to an independent set of Massachusetts lakes with an average error of 36 percent. The process has been automated with the use of the Arcview Geographic Information System computer system and digital maps of land use. With additional data, the model can also be used to predict lake total phosphorus concentrations under a variety of proposed land use management plans.

Key Words: phosphorus, models, land use, GIS, TMDL, lake management, stagewise regression.

Section 303(d) of the Federal Clean Water Act, 40 CFR 130.7 requires each state to (1) identify waters (the 303d list) for which normally required effluent limitations are not stringent enough to attain water quality standards, and (2) to establish Total Maximum Daily Loads (TMDLs) for such waters for the pollutant of concern. The TMDL establishes the allowable pollutant loading from all contributing sources at a level necessary to attain the applicable water quality standards. The TMDLs must account for seasonal variability and include a margin of safety (MOS) that accounts for uncertainty of how pollutant loadings may impact the receiving water's quality. After public comment and final approval by the EPA, the TMDLs will be used in the development of watershed management plans and to set appropriate permits for wastewater and other discharges, if any.

The most recent 303d list for Massachusetts includes 561 freshwater lakes that fail to meet the Commonwealth's Surface Water Quality Standards (314 CMR 4.00). Of these, 469 are listed for nuisance aquatic plants of which about 90 percent are macrophyte problems and 10 percent are algal problems. Violations of water quality standards caused by non-native macrophyte species are not listed unless the nuisance condition is related to nutrient enrichment. A total of 58 additional lakes are listed specifically for nutrients and/or other nutrient-related water quality problems such as low dissolved oxygen or turbidity associated with algal blooms, bringing the total number of potential nutrient TMDL reports to 527. Even in the most common situation, where reductions in nutrient loading are not expected to control the rooted aquatic macrophytes (which obtain most of their nutrients from the sediments), nutrient controls may be considered a necessary management objective to protect water quality. Reductions in nutrient loading are expected to reduce the biomass of algae and nonrooted macrophytes, reduce future symptoms of eutrophication, and reduce the possibility of nuisance algal blooms. Such blooms may occur following routine management of macrophytes, which can lead to release of nutrients and enhanced availability of light.

The first step in nutrient management is to calculate the current nutrient load for the lake. Although direct measurement of nutrient loadings is preferred, the large number of lakes requiring nutrient TMDLs and the short time schedule allowed by the EPA make it necessary to develop a modeling approach to estimate current loadings. For most lakes, the modeling efforts will target phosphorus for TMDL controls. In most freshwater systems phosphorus is the limiting nutrient, is the easiest to control and such control does not favor the nitrogen-fixing nuisance blue-green cyanobacteria. This paper describes the methods used in model development, calibration and validation for total phosphorus (TP) loading to lakes and reservoirs in Massachusetts.

Review of Past Studies

Previous attempts to model phosphorus loadings to Massachusetts lakes are reported in various diagnostic/feasibility (D/F) studies, most of which were funded by the Massachusetts and/or EPA Clean Lakes Program. As reviewed by Mattson et al. (1998), some of these studies used the mass balance method of multiplying water flow times nutrient concentration to estimate loadings while others used the simpler land use area times an export coefficient to estimate loading; sixteen of the studies used both methods. The studies which used the land use approach typically used the median or in some cases, mean, phosphorus export coefficients reported for each land use type in Reckhow et al. (1980) as the 'most likely' estimate of the nutrient loading rate. The median phosphorus export coefficients used in the 16 D/F studies were 0.2 $kg \cdot ha^{-1} \cdot yr^{-1}$ for forest, 0.7 $kg \cdot ha^{-1} \cdot yr^{-1}$ for residential and 1.91 $kg \cdot ha^{-1} \cdot yr^{-1}$ for urban areas variously listed as high density residential, commercial and industrial (the actual land uses in each study were often divided into more subcategories). This method assumes phosphorus loading from each identified land use type is proportional to the area of the land use within the watershed of the lake. Thus, multiplying the land use areas (in hectares) by their respective coefficients and adding the result to any other sources (e.g., septic system inputs or atmospheric inputs) will be a good estimate of the total yearly external loading of phosphorus to the lake. Internal loading (recycling) either was assumed to be negligible, or was estimated either from literature values or from phosphorus increases in the hypolimnion. A report by Mattson et al. (1998) suggests that the use of Reckhow et al. (1980) phosphorus export coefficients by these studies typically overestimates total measured inputs as shown in Fig. 1. The best fit line ($r^2 = 0.76$) has a slope of 0.48, indicating an average twofold overestimate by the standard land use coefficient method as compared to the measured mass balance method. For 15 of the 16 studies, the land use loading estimate was greater than the measured phosphorus loading (Fig. 1). Removing internal recycling inputs from the measured inputs would make the fit even worse.

There may be several possible reasons why the loading coefficients from the literature do not agree with the measured inputs to these lakes. It is possible that the measured phosphorus loadings are biased low, due to inadequate stormwater sampling in many of the D/F studies. If this bias were significant, then we would expect to see a significant underestimate of lake total phosphorus concentrations, but this is not the case as shown in Fig. 2 (see discussion below). It is unlikely that the land use data itself is biased in any significant way and the only remaining likely factor to account for the difference between the two methods is bias choosing the appropriate land use export coefficients themselves.

As noted above, most D/F studies simply used the median or mean loading coefficient reported by Reckhow et al. (1980), however, it is possible that phosphorus export is relatively low in Massachusetts compared to the nationwide studies reported in Reckhow et al. (1980). One possibility is that Massachusetts soils are relatively low in phosphorus, as indicated by a map of soil phosphorus in the United States (PPI, 1994). Although no data was shown for Massachusetts, neighboring states of Vermont and New York showed few or moderate numbers of high phosphorus soil tests while other parts of the country, specifically the Mid-Atlantic States, Florida, the Upper Mid-West and the Northwest States all show a high frequency of elevated soil phosphorus (PPI, 1994). States in these latter high phosphorus regions were frequently cited in Reckhow et al. (1980) report, while studies from Massachusetts were not explicitly cited. Thus, a hectare of a given type of land use may export less phosphorus in Massachusetts as compared to other parts of the country. This is further supported by

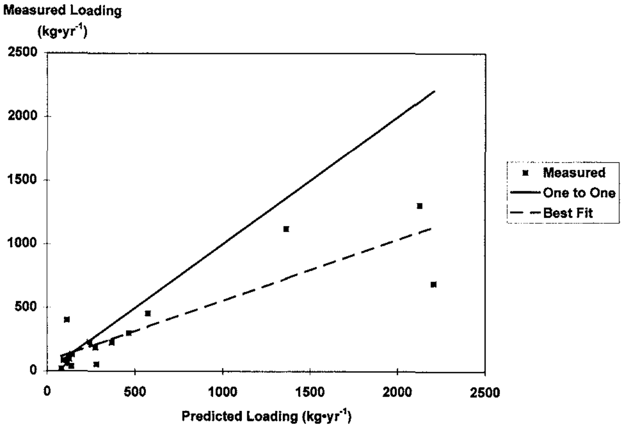

Figure 1.–Land use Estimated Loading vs. Measured Total Internal and External Loading. Data from 16 D/F studies reviewed by Mattson et al. (1998).

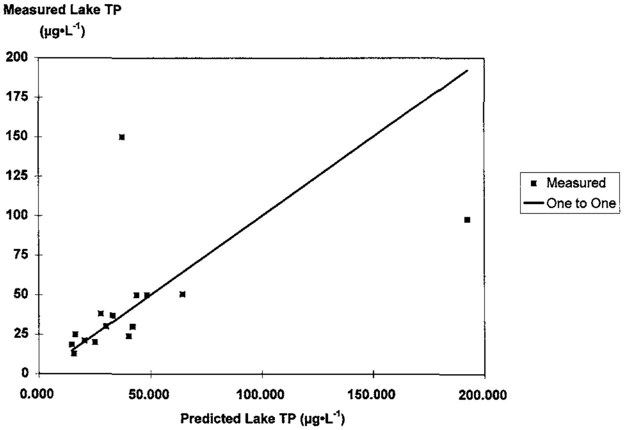

Figure 2. –**Measured vs. predicted total phosphorus concentrations. Predictions based on measured phosphorus loadings from 16 D/F studies and Reckhow's (1979) equation.**

the map of phosphorus export provided in a study of phosphorus export of streams in the United States (Smith et al., 1997), which shows Massachusetts typically has low phosphorus export.

Another possibility is that the simple land use export method does not account for interactions between land uses. For example, phosphorus exported from a high source area (e.g., agriculture) may be subsequently removed from the water as the water and nutrients pass through forests and wetlands and other nutrient uptake areas downstream of the source area, resulting in a lower overall export coefficient. A final possibility is that the studies on which the Reckhow et al. (1980) coefficients are based overestimated phosphorus export due to the difficulty in accurately measuring low levels of phosphorus in stream water.

In the D/F studies reviewed by Mattson et al. (1998) the measured phosphorus loadings gave better predictions of in-lake total phosphorus concentrations than the land use method when the simple Reckhow (1979) equation was applied to both. The measured loadings resulted in a good agreement between predicted and measured total phosphorus concentrations with roughly equal numbers of over predictions as under predictions (Fig. 2). The r^2 is only 0.25 ($\alpha<0.05$) but increases to 0.86 ($\alpha<0.001$) when one high outlier is removed. The land use based estimates of lake total phosphorus produced an r^2 of 0.47, but 12 of the 16 estimates were greater than expected as shown in Fig. 3. These two figures support the assumption that the measured phosphorus loading data are appropriate to use for calibration of the land use method, and that the resulting predicted loadings should be useful to estimate lake total phosphorus concentrations with the Reckhow (1979) equation.

We wished to develop a simple land use loading type model that could be easily applied to Massachusetts lakes where little or no measured phosphorus loading data was available. The model should be easily understood, with export coefficients within the range of values reported in Reckhow et al. (1980) and be a good unbiased estimator of external loading. We decided to 'calibrate' the simple land use export coefficient method against the measured loading rates reported by the 16 Massachusetts D/F studies. Our approach is to use multiple regression to suggest a range of possible models and coefficients, yet allow best professional judgment to guide in the final selection of the model. Regression techniques, similar to stagewise regression on residuals described by Draper and Smith (1966), are used to help choose coefficients, but no formal statistical tests are performed on the fitted regression. Instead, the final model is tested against an independent validation dataset to confirm the applicability and to estimate the accuracy of the model. As a final test, the predicted loadings will be applied to the Reckhow (1979) equation to predict average annual lake total phosphorus concentrations.

Development of the Model

The nonpoint source lake phosphorus loading model we developed in this paper, hereafter called NPSLAKE was loosely based on a similar approach developed at the University of Rhode Island (Kellogg et al., 1998) and on Arcview programs written by DEP staff. The NPSLAKE program was written to automatically integrate with existing Massachusetts Geographic Information System (GIS) land use data layers, allow input of watershed runoff in inches from Krug et al. (1990) and calculate loadings to lakes and to estimate lake total phosphorus concentrations based on the Reckhow (1979) equation. We

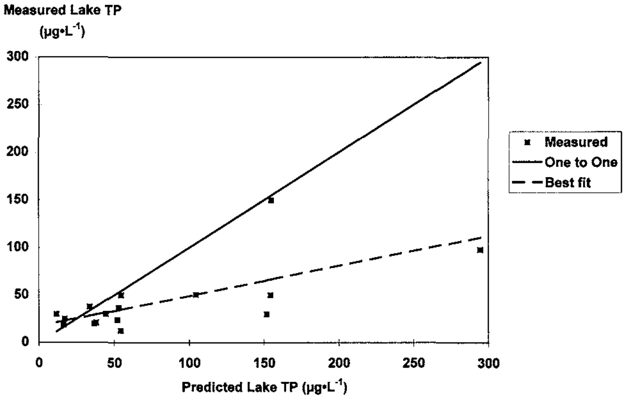

Figure 3. –**Measured vs. predicted total phosphorus concentrations. Predictions based on land use phosphorus export coefficients used in 16 D/F studies and Reckhow's (1979) equation.**

reevaluated the 16 Massachusetts Diagnostic Feasibility (D/F) studies as reviewed by Mattson et al. (1998). These D/F studies were on Massachusetts lakes with nuisance aquatic plant problems or other nutrient related problems, and which had both measured and land use estimated phosphorus loading data. An additional 11 Massachusetts D/F studies with a wide range of loadings and geographic distribution were used as a validation data set. Locations and summary information for both data sets are presented in Table 1.

To computerize the modeling effort, watershed boundaries were first digitized using the Arcview PC GIS system (ESRI, 1995). The land uses for the lakes were estimated based on the available GIS digital land use maps provided by the Massachusetts Executive Office of Environmental Affairs MassGIS office. An example of the land use for the watershed of Bare Hill Pond is shown in Fig. 4.

To simplify the modeling effort we combined the land use types into three major categories of similar

Table 1.–Characteristics of Lakes in the Study*. The estimated P loading is from the final model results.

Name of Lake, Town	Estimated P Loading	Lake Area	Mean Depth	Hydraulic Load	Measured TP conc.
Calibration Data Set	$kg \cdot yr^{-1}$	Ha	m	$m \cdot yr^{-1}$	$\mu g \cdot L^{-1}$
Bartlett Pond, Northborough	275	18	1.4	35	30
Browns Pond, Peabody	127	10.1	3.3	10.3	24
Buttonwood Pond, New Bedford	169	2.4	0.9	45	98
Chauncy Lake, Westborough	171	70.8	3.6	2.69	50
Dimmock Pond, Springfield	74	3.8	1.2	1.8	150
Forest Lake, Metheun	87	19.4	3.4	3.04	21
Forge Pond, Granby	780	30.3	3.4	46.41	50.5
Herring Pond, Eastham	23	17.7	6.2	2.23	12.7
Long Pond, Littleton	176	39.9	2.7	4.8	37
Mill Pond, West Newbury	132	6.5	1.2	31	30
Nashawannuck Pond, Easthampton	687	12.7	1.6	84.2	50
Prospect Lake, Egremont	98	22.3	1.7	12	18.5
Silver Lake, Wilmington	85	11.5	3.9	3.71	30
Stockbridge Bowl, Stockbridge	683	148	6.8	13.19	38
Walker Pond, Sturbridge	215	41.7	2.0	18.6	25
Waushakum Pond, Framingham/Ashland	260	33.2	4.8	9.17	20
Validation Data Set					
Prindle Pond, Charlton	38	30.3	1.4	2	32
Mansfield Lake, Great Barrington	35	10.7	2.1	3.4	75
Long Pond, Yarmouth	245	21.8	3.0	8.9	38
Lake Ellis, Athol	219	28	1.2	18.9	15
Ell Pond, Melrose	261	9.6	1.7	26.2	73
Jennings Pond, Natick	314	3.7	1.3	111.9	61
Bare Hill Pond, Harvard	273	126.8	3.0	4.8	44
North Pond, Hopkinton	364	93.2	2.4	8	14
Lake Shirley, Lunenburg	964	146.3	2.2	15.3	19
Horn Pond, Woburn	691	50.6	7.3	27.5	60
Lake Ripple, Grafton	1817	28	1.2	196.2	25

* References for the Diagnostic/Feasibility Studies of the lakes used in this analysis are available from the senior author upon request.

export: 1) Forest, 2) Rural, and 3) Urban. While such a classification is simple and convenient, errors may be introduced by lumping land uses with differing export coefficients, such as pasture (median of 0.81 $kg \cdot ha^{-1}yr^{-1}$) with row crops (median 2.24 $kg \cdot ha^{-1}yr^{-1}$) as listed in Reckhow et al. (1980). We included a separate variable to account for private septic system inputs of phosphorus. The corresponding MassGIS land use types (and code numbers) in each category were:

Forest: (3) Forest
Rural: (13) Low-density residential, lots > 1/2 acre, (1) Cropland, (2) Pasture, (6) Open Land, (7-9) Recreation, (17) Urban open land, (21) Woody perennial.
Urban: (10-12) Residential, lots< 1/2 acre, (15) Commercial, (16) Industrial, (18) Transportation, (19) Waste disposal, (5) Mining.

Atmospheric deposition of phosphorus directly to lakes is small and was not significant in the model regression, perhaps because lakes act as a sink rather than a source of nutrients, and so we decided to drop it from our phosphorus loading analysis. For similar reasons wetlands also were not used in the phosphorus loading analysis, following the rational used in previous studies (Rast and Lee, 1978).

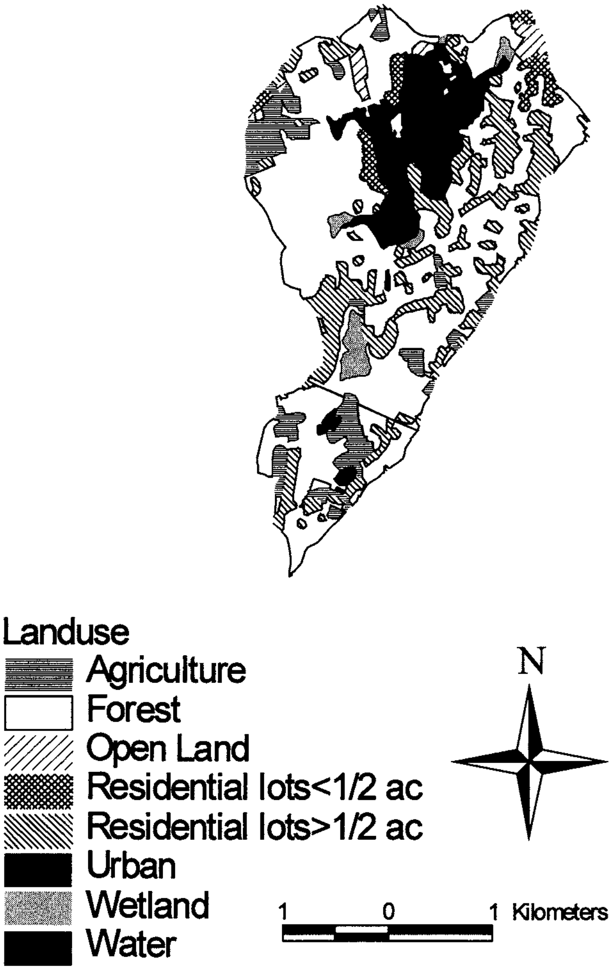

Figure 4. –Example of land use map for Bare Hill Pond, Harvard, Massachusetts.

The private septic system phosphorus inputs were estimated based on the assumptions typically used in the D/F studies, which closely followed the recommendations of Reckhow et al. (1980). Briefly, we assumed that homes in non-urban areas within 100 m of the lakeshore were the only source of septic system phosphorus inputs.

The regression models were of the form:

$$L_{ex} = a \cdot \text{house septics} + b \cdot \text{forest ha} + c \cdot \text{rural ha} + d \cdot \text{urban ha} \qquad (1)$$

where:

L_{ex} is the external total phosphorus loading in $kg \cdot yr^{-1}$
a is the septic export loading coefficient with units of $kg \cdot house^{-1} \cdot yr^{-1}$,
b, c, and d are export loading coefficients with units of $kg \cdot ha^{-1} \cdot yr^{-1}$.

From a preliminary regression analysis (not shown) it was apparent the model did not fit the data very well. After closer examination of the D/F reports it was found that many reports included large 'guestimates' of internal recycling of phosphorus from the sediments (or in some cases macrophytes) as part of the annual load. Since this internal recycling is not an annual external input to the lake system and it is difficult to predict from land use, it was decided to remove this factor from the measured loading data in all the D/F studies where it was listed, although it can be added as an optional input in the NPSLAKE model to predict in-lake TP concentrations. In addition, we removed indirect point source wastewater inputs from sewage treatment facilities for three ponds (392 $kg \cdot yr^{-1}$ from Forge, and 132 $kg \cdot yr^{-1}$ from both Bartlett Pond and Chauncy Lake, which is tributary to the former) based on discussions and data in BEC (1989) and W&H (1986). Thus, for model calibration and validation, measured inputs refer to external inputs of nonpoint sources. Wastewater inputs and other point sources were judged to be difficult to predict based on land use data and, thus, have to be estimated as an optional step, as for internal loading described above.

A full model multiple regression (which included an intercept term) was applied to the dataset of 16 D/F studies. The model explained a large portion of the variation (r^2=0.92, SE= 86 $kg \cdot yr^{-1}$), but some of the coefficients were not reasonable based on our understanding of the nature of nonpoint source pollution and the assumptions used in the approach. For example, the septic system variable was negative rather than positive and only the forest coefficient was significant at the 95 percent level. Note that the relatively high correlation (ranging in absolute magnitude from 0.16 to 0.94) between our independent variables in the calibration dataset may lead to unstable regression coefficients depending on which predictors are included in the model (Draper and Smith, 1966). In an effort to control the sign and relative magnitude of the coefficients, we decided to use a stagewise regression approach. It was decided to eliminate the intercept term since it was not significant and is typically not included in simple land use loading models where it is desired to have zero loading when all land use areas are zero. When this was done the coefficient for septics then increased to 0.5 $kg \cdot house^{-1} \cdot yr^{-1}$, which agreed with previous estimates in Massachusetts (e.g., LER, 1991) and thus the septic coefficient was fixed at this value. Note that the residuals may not sum to zero in our analysis because the intercept term is specifically omitted from the model (Draper and Smith, 1966).

We then used iterative regressions to fix the rural loading rate to 0.3 $kg \cdot ha^{-1} \cdot yr^{-1}$ based on a compromise between the best fit and our attempts to increase the coefficient to values closer to those typically reported in the literature for rural land use (e.g., 0.5 $kg \cdot ha^{-1} \cdot yr^{-1}$ as reported in Rast and Lee, 1978). After subtracting the loading associated with both septics and rural effects we then used a reduced model multiple regression on the remaining (residual) loading to reestimate the remaining two coefficients. The coefficients for our first calibration model were 0.5 $kg \cdot house^{-1} \cdot yr^{-1}$, 0.13 $kg \cdot ha^{-1} \cdot yr^{-1}$, 0.3 $kg \cdot ha^{-1} \cdot yr^{-1}$, and 1.0 $kg \cdot ha^{-1} \cdot yr^{-1}$ for septic, forest, rural and urban land uses, respectively. The model explained a large portion of the variation in loading (r^2=0.89) as shown in Fig. 5.

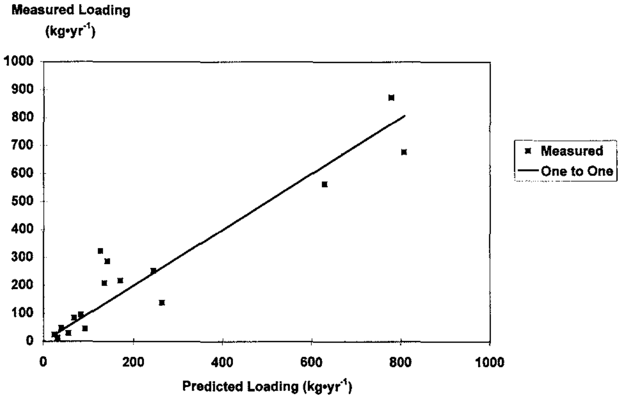

Figure 5.–Measured vs. predicted phosphorus loading from initial model. Predicted values from the initial linear model applied to calibration dataset.

When the model was applied to the validation dataset where three of the lakes exceeded the range of measured loadings of the calibration, a lack of fit became obvious and the model was rejected. Upon examination of raw data and residual plots (not shown), urban areas showed a distinct nonlinearity that suggested a transformation was needed. Praire and Kalff (1986) reported a similar nonlinearity between catchment size and phosphorus export where phosphorus export per unit area declines as catchment size (watershed area) increases. A square root transformation of urban areas resulted in a good fit to the data as well as simple units for the coefficient, since the square root of area is distance.

We set septics and rural coefficients, as before, to 0.5 $kg \cdot house^{-1} \cdot yr^{-1}$ and 0.3 $kg \cdot ha^{-1} \cdot yr^{-1}$, respectively, and used regression as before to reestimate the remaining terms. The final model was:

$$L_{ex} = 0.5 \cdot \text{house septics} + 0.13 \cdot \text{forest ha} + 0.3 \cdot \text{rural ha} + 14 \cdot (\text{urban ha})^{0.5} \qquad (2)$$

where:

L_{ex} is the external total phosphorus loading in $kg \cdot yr^{-1}$

0.5 is the septic export loading coefficient with units of $kg \cdot house^{-1} \cdot yr^{-1}$,

0.13 is the forest loading coefficient with units of $kg \cdot ha^{-1} \cdot yr^{-1}$,

0.3 is the rural loading coefficient with units of $kg \cdot ha^{-1} \cdot yr^{-1}$,

14 is the urban loading coefficient with units of $kg \cdot ha^{-0.5} \cdot yr^{-1}$

The transformed model gives higher predictions than the linear model for urban areas less than 196 hectares and lower predictions for urban areas greater than 196 hectares. The nontransformed coefficients are lower than the median estimates of Reckhow et al. (1980) and the D/F studies cited above, but are within reasonable limits reported by Reckhow et al. (1980). In addition, our results roughly agree with the EPA report on nutrient loading in the United States (Rast and Lee, 1978), in which reported: 0.1, 0.5 and 1.0 $kg \cdot ha^{-1} \cdot yr^{-1}$ for forest, agriculture+rural and urban phosphorus export, respectively.

As shown in Fig. 6, the final model still explained a large portion of the variation in loading of the calibration dataset (r^2=0.91) with some lack of fit at the lower end. The small dataset did not justify attempting further transformations to improve the fit. The average error (square root of mean square error) was 81 $kg \cdot yr^{-1}$. The validation set also fit very well to the final model (r^2= 0.89), even for those lakes with large watersheds and consequently large predicted loadings (Fig. 7). There was no obvious lack of fit in the final

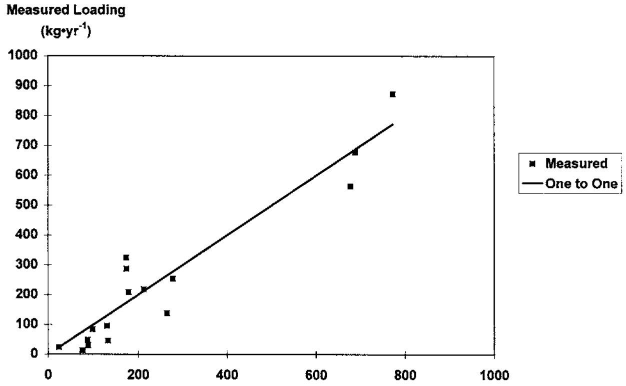

Figure 6.–Measured vs. predicted phosphorus loading from final calibration. Predicted values from the final, transformed model based on the calibration dataset.

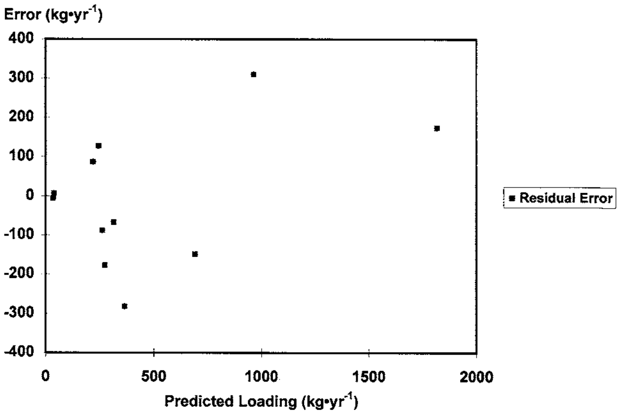

Figure 8.–Residuals vs. Predicted Loading. Residuals from final model based on validation dataset.

residual plot and most residual errors were less than 300 kg·yr^{-1} in magnitude (Fig. 8).

As a final test we compared the best fit regression line of measured vs. predicted loads and found an intercept of 78 (SE=68) and a slope of 0.85 (SE=0.099). Thus, the Reckhow et al. (1990) null hypothesis tests of best fit line of intercept equals zero and slope equals one are not rejected and the model passes the validation test. The 95% confidence limits are -78 and +228 for the intercept and 0.63 and 1.08 for the slope. The square root of the mean square error of the validation set predictions, not of the best fit line, is 172 kg·yr^{-1}, compared to the average measured loading of 480 kg·yr^{-1} for the validation set, or about a 36 percent error of average model estimates. This error is greater than twice the error in the calibration set and is probably a better estimate of expected accuracy. The relatively high error of the model may in part be due to the diverse bedrock geology found within Massachusetts which is related to surface water chemistry (Mattson et al., 1992; Griffith et al., 1994).

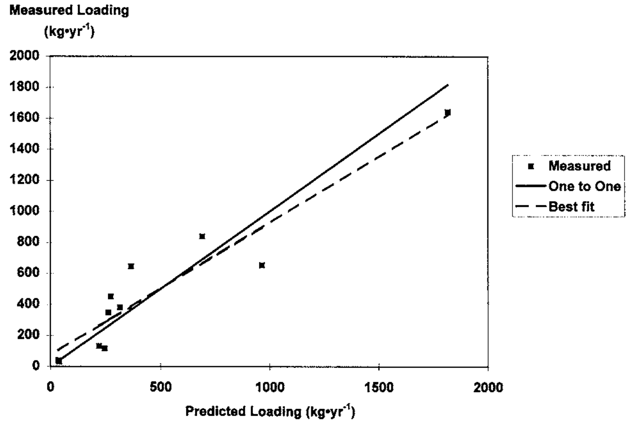

Figure 7.–Measured vs. predicted phosphorus loading for final Model validation. Predicted values from the final, transformed model applied to the validation dataset.

Although overall accuracy is on the order of ±36 percent for total external loading, the accuracy of loading attributed to any particular land use activity within a given watershed is probably somewhat worse. This is especially true for lakes with other unknown sources of phosphorus, such as inputs from waterfowl droppings, cranberry bog fertilizers and confined livestock or dairy operations where this model is likely to underestimate the loading of phosphorus to the lake. If best management practices are already in place in the watershed, then the model is likely to overestimate loading. Thus, caution should be used in interpretation of loads from particular land uses.

Application of the Model

The NPSLAKE model was designed to be run on the Arcview MassGIS extracted land use data table. The NPSLAKE model requires input for the number of homes with septic systems within 100 meters of the lake shore (counted and input by hand), the area of the lake (automatically computed if the lake is the largest body of water on the land use map), the amount of water runoff in inches for the area (read from a runoff map in Krug et al., 1990, but typically 24 inches for most of central Massachusetts), and any point sources and other external or internal sources of additional phosphorus to the lake. The model then estimates total phosphorus loading to the lake in kilograms per year. For comparison purposes, the model also performs similar calculations for nitrogen inputs and sediment loading, but these were based on published export coefficients (Reckhow et al., 1980;

EPA, 1983, respectively). By simply changing land use categories, the model can also be used to simulate the phosphorus loadings under fully forested or fully developed land use conditions.

The model uses total area of watershed, runoff converted to meters, and lake area in m^2 to calculate water loading to the lake and applies the Reckhow (1979) model to estimate average lake concentrations of total phosphorus by the equation:

$$\text{Lake TP} = L / (11.6 + 1.2 \cdot q_s) \qquad (3)$$

where

TP = lake phosphorus concentration in mg·L^{-1}
L = external and internal areal loading of phosphorus to lake in g·m^{-2} yr^{-1}
11.6 = constant for settling velocity of phosphorus in m·yr^{-1}
q_s = areal water loading to lake in m·yr^{-1}

This lake model was chosen because it was based on 47 north temperate lakes in North America, the input variables for the Massachusetts calibration lakes were similar to those on which the model was developed (see Table 1). One lake (Dimmock Pond) slightly exceeded the measured maximum total phosphorus range (150 μg·L^{-1} compared to 135 μg·L^{-1}) and one lake slightly exceeded the water loading range (196 m·yr^{-1} compared to 187 m·yr^{-1}), but all lakes fell within the range of phosphorus loadings reported in the Reckhow (1979) study. Two of the lakes may be considered seepage lakes (Dimmock Pond and Silver Lake), yet even these have some water flow in temporary inlets and outlets during storms and it is assumed that the areal loading rate q_s is appropriately estimated by runoff maps. The Reckhow equation predictions were consistently within the predictions made by other more complex models in several comparisons reported in various D/F studies. Most important perhaps, the model does not require the input of mean lake depth, which is not available for many of the lakes on the Massachusetts 303d list for which the model was intended.

We applied the external phosphorus loads estimated from the NPSLAKE model (excluding internal recycling) to the Reckhow (1979) equation and compared the resulting predictions of lake total phosphorus concentrations to measured concentrations. The results show a correlation of r^2=0.66 but the average error is 19 μg·L^{-1} (Fig. 9), or about the same magnitude as the average lake total phosphorus concentration in Massachusetts. The r^2 falls to 0.16, but is still significant at the 95 percent level even if the two highest points are removed. Estimates of internal recycling (sediment phosphorus inputs) are required to further improve the accuracy of the predictions.

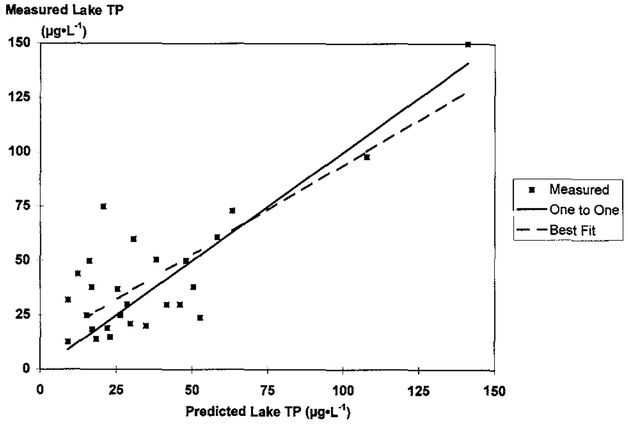

Figure 9.–Predicted vs. Measured Lake Total Phosphorus Concentrations. Predictions based on P loading from NPSLAKE modeled loading for both calibration and validation datasets and the Reckhow (1979) model.

Alternately, internal loading may be estimated based on the additional loading required to account for the difference between predicted and observed lake total phosphorus concentrations. For example, an internal load of approximately 680 kg·yr^{-1} would be needed to be added to the phosphorus load estimates for Bare Hill Pond in Table 2 in order to have the TP concentration predicted from Equation 3 match the observed concentration of 44 μg·L^{-1}

The NPSLAKE model was optimized to predict external phosphorus loads, not in-lake TP concentrations. If internal phosphorus loading estimates are available, the model predictions of in-lake TP should improve and the model could be used for predicting the magnitude of the trends in TP, trophic state and transparency that might be expected from a given reduction in phosphorus loading. The predicted TP concentrations can be used to calculate trophic state based on Carlson's Trophic State Index (TSI) (Carlson, 1977) which is an index typically ranging from 20 to 80 with each ten fold difference in TSI is equivalent to a one step increase in trophic level; e.g., mesotrophic to eutrophic, and represents a doubling of phosphorus and a doubling of algal biomass. The boundaries for classification are approximately: oligotrophic TSI <40, mesotrophic TSI 40-50 and eutrophic TSI > 50. The TSI can be calculated from:

$$\text{TSI} = 10(6-(\ln(48/\text{TP})/\ln(2))) \qquad (4)$$

where TP is in units of μg·L^{-1}

In addition, Secchi disk transparency can be related to TSI by rearrangement of Carlson's (1977) equation to yield:

$$\text{Secchi (m)} = \exp^{(\ln 2 \cdot (6-(\text{TSI}/10)))} \qquad (5)$$

This result can be compared to the state established

4-foot (1.2 meter) transparency standard for swimming beaches. Caution must be used with such predictions as they were developed for algal dominated lakes and the models may not apply well to macrophyte dominated lakes or lakes where phosphorus is not limiting. For example, in some lakes nuisance growth of macrophytes may suggest eutrophic conditions while the lake TP may be low enough to classify as mesotrophic because the macrophytes often use sediment phosphorus rather than lake phosphorus as the major nutrient source.

If the difference between the present TSI and the forested condition TSI is greater than or equal to 10 then we assume that cultural sources have doubled the watershed phosphorus loading. If the difference in TSI is less than ten then a management plan to protect water quality may still be warranted but a formal TMDL may not be required. An example of the NPSLAKE output is shown in Table 2.

Table 2.–NPSLAKE Model Results for Bare Hill Pond. Part a includes input data and related watershed information, part b shows land use loading results, and part c shows final lake predictions.

Part A. Input data:

Average Runoff = 61.0 cm·yr^{-1} (24.0 in·yr^{-1})
Lake area = 126.8 Ha. (313.1ac)
Homes with septic systems within 100m of lake.= 95.0
Other P inputs = 0.0 kg·yr^{-1}

Watershed information:
Watershed Area (including lake and wetlands)= 971.7 Ha (3.8 mi^2)
Average Annual Water Load = 5923451.0 m^3·yr^{-1} (6.7 cfs)
Areal water loading to lake: q_s = 4.7 m·yr^{-1}.

Part B. Estimate of annual Nonpoint Source Pollution Loads by land use:

Land use	Area Ha (%)	P Load kg·yr^{-1} (%)	N Load kg·yr^{-1}	TSS Load kg·yr^{-1}
Forest category				
Forest:	524.1 (53.9)	68.1 (25.0)	1310.2	12577.4
Rural category				
Agriculture:	77.2 (7.9)	23.2 (8.5)	762.7	27821.2
Open land:	18.0 (1.8)	5.4 (2.0)	93.4	3985.2
Residential Low:	171.7 (17.7)	51.5 (18.9)	944.4	66623.1
Urban category				
Residential High:	27.7 (2.9)	70.2 (25.7)	152.4	12913.0
Comm - Ind:	2.8 (0.3)	7.1 (2.6)	28.0	108.7
Other Land uses				
Water:	130.6 (13.4)	0.0 (0.0)	0.0	0.0
Wetlands:	19.6 (2.0)	0.0 (0.0)	0.0	1038.7
Subtotal	971.7	225.5	3412.4	126680.7
Other P inputs:	NA	0.0 (0.0)		
95.0 Septics:	NA	47.5 (17.4)		
Total	971.7 (100.0)	273.0(100)	3412.4	126680.7

Part C. Summary of Lake Total Phosphorus Modeling Results

Areal P loading L= 0.2 g·m^{-2}·yr^{-1}.
Reckhow (1979) model predicts lake TP = $L/(11.6+1.2q_s)$'1000 = 12.5 μg·L^{-1}
Predicted transparency = 3.8 meters.
If all land were forested, P export would be 106.8 kg·yr^{-1}
And the forested condition lake TP would be 4.9 ppb.
Thus anthropogenic inputs increase lake TP by 155.7 percent.
The Trophic State Index has increased from 27.1 to 40.6
The Lake is predicted to be mesotrophic and culturally eutrophied.

This NPSLAKE output table can then be used as the starting point to estimate current loadings from each of the sources: forest, rural, and urban land use, local septic system inputs, and any point sources identified. The target can be set either by a simple percentage reduction or by modeling an acceptable lake TP concentration and recalculating the reduced loading required to achieve it. For example, if algae are the primary cause of violations of water quality standards then Reckhow's (1979) model can be used to estimate what loading would be required to reduce lake TP (and hence decrease TSI and increase transparency) to meet water quality standards and the swimming standard of 4 foot visibility. An equitable target loading allocation is then chosen based on modeling, best professional judgement and the available control methods.

It is important to stress that the predictions may not be accurate in any given lake. They do, however, provide the lake managers with a reasonable expectation of a typical lake response. A margin of safety can be explicitly added to the calculations. Once the final TMDL is determined, the loading must be partitioned to wasteloads from point sources, to the various nonpoint sources and to the margin of safety if explicitly included. If rooted macrophytes, particularly invasive, nonnative macrophytes are the primary cause of violation of water quality standards then other direct controls (e.g., Mattson et al., 1998) on the macrophytes should be carefully considered.

Summary

A phosphorus loading model based on land use was developed by quasi-stagewise multiple regression techniques in order to limit coefficients to within reasonable bounds. The model was validated by an independent data set and found to be accurate within about 36 percent with a root mean square error of 172 $kg \cdot yr^{-1}$. Despite the uncertainties associated with predictions, the model can still serve as a useful starting point for estimating loadings to lakes and for simulating how loading allocations can be adjusted to meet target conditions. The model is relatively quick to run and the results can be further tested by using the estimated loadings along with water loading in a model such as Reckhow (1979) and comparing the estimated total lake phosphorus concentrations to actual concentrations in the lake. Large differences between predicted and observed lake TP suggest a reevaluation of loading calculations to the lake is required.

As in any environmental model, it should be considered a simple tool to be used, along with other local information and best professional judgment to devise a reasonable management plan and should not be considered an equal substitute for data collected in the field. Given the uncertainties associated with predicted loadings from any given land use however, it is probably best to use the overall loadings as a guide and to simply propose percentage reductions in total loading and to incorporate those point and nonpoint source control measures that can achieve those percentage reductions.

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