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Phosphorus loads to surface waters:
A simple model to account for spatial pattern of land use

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ABSTRACT

Surface waters are sensitive to disturbances in their watersheds, especially those disturbances that lead to increased sediment erosion and nutrient transport. Land use planning to sustain surface water quality for most watersheds should account for effects of both agriculture and urbanization on nutrient transport. We developed a simple model to predict nonpoint-source phosphorus (P) loading to surface waters using land use, topography and stream networks from geographic information system (GIS) databases commonly available to natural resource managers and researchers. We estimated areas of the watershed that strongly contribute to P loading by simulating overland flow, and modeled annual P loading by fitting three parameters to stream monitoring data. We calibrated the model using P loading data from two years of contrasting annual precipitation from Lake Mendota, WI, a typical eutrophic northern temperate lake whose watershed is dominated by agriculture and urban lands. Land use scenarios were developed to predict annual P loading from pre-settlement and future land use. At the annual scale, as much as half of the Lake Mendota watershed did not contribute significantly to P loading. The greatest contribution to loading comes from a riparian corridor that varies in width from 0.1 km to about 6 km surrounding surface waters that feed into Lake Mendota. The apparent width of this corridor varies directly with precipitation. We estimate that loading from pre-settlement land use was one sixth of the loading from present land use. The future scenario, representing an 80% increase in existing urban land (from 9 to 16% of total watershed area, which would take 30 years to achieve at current land use trends) caused only modest increases in annual P loading, but could have significant effects on water quality. If the watershed was converted to 100% urban land, P loading to the lake would double and potential effects on water quality would be severe. Changes in P loading respond most strongly to land use changes that included conversions of undisturbed vegetated lands to either urban or agricultural land uses, especially in riparian areas. Variability in total annual rainfall leads to variability in the riparian area that affects loading. This uncertainty has implications for policies intended to control nonpoint nutrient inputs.

KEYWORDS: phosphorus loading, land use, water quality modeling, Lake Mendota, nonpoint source, watershed, riparian, export coefficients

KEY PHRASES: impact of land use on phosphorus loading, effect of agriculture versus urban land uses, phosphorus export coefficients, non-point source pollution/run-off, impact of riparian areas on nutrient transport

INTRODUCTION

At the landscape scale, lakes are open systems, strongly linked to their surrounding watersheds through the transport of materials carried by surface runoff from land to water. The rate of transport of sediments and nutrients has increased in many watersheds due to human induced disturbances such as agriculture, urban development, mining and forestry practices. These fluxes have contributed to the cultural eutrophication of surface waters, generally as a direct result of increased loading of phosphorus (P), the nutrient most commonly limiting freshwater primary production (Schindler 1977). Nonpoint P loading represents a serious threat to water quality due to current land use practices and continuing and rapid land use changes in many parts of the world (National Research Council 1992, Duda 1993).

The impact of watershed characteristics on surface water quality depends on regional geology, soil P content and erodibility (Hobbie and Likens 1973, Dillon and Kirchner 1975), topography and land use (Omernik 1976, Osborne and Wiley 1988, Hunsaker et al. 1992), and precipitation (Sharpley et al. 1981). Negative effects of land use activities often increase with land disturbance, soil erosion, and proportion of impervious surfaces (Arnell 1982, Byron and Goldman 1989). However, at the scale of watersheds or landscapes, relationships between land use and water quality are more difficult to discern. Although the proportional areas of different land use types in a watershed explain some of the variance in water quality parameters, much remains unexplained (Reckhow et al. 1980, Osborne and Wiley 1988, Hunsaker et al. 1992). Among the poorly understood factors is the transition from agricultural to urban land.

Phosphorus Loading Models

Early models examining the impact of land use on surface water quality at the watershed scale were based on equations such as (Reckhow et al. 1980):

$$L = \sum_{i=1}^{m} c_i \; A_i \qquad (1)$$

where L is total P loading (kg P/yr), m is number of land use types, c_i is the P export coefficient for land use i (kg P ha^{-1} yr^{-1}) and A_i is area of land use i (ha). Export coefficients (c_i) are estimated by monitoring runoff from plots or watersheds of the appropriate land use and dividing by the area drained. Much work in the 1970's involved efforts to derive and compile nutrient export coefficients for different land uses (Dillon and Kirchner 1975, Rast and Lee 1978, Reckhow et al. 1980, Clesceri et al. 1986). Equation 1 assumes that total export increases linearly with total watershed area. However, Prairie and Kalff (1986) showed that nutrient export in agricultural watersheds does not increase linearly with watershed area. Hydrologists have known for some time that the sediment delivery ratio (sediment delivery : gross sediment erosion) decreases with watershed area (Walling 1983). Since most P from land reaches surface waters attached to sediment particles, sediment delivery must be accounted for when considering land use effects on water quality (Novotny and Chesters 1989). Nutrients are deposited or transformed as they are transported from source areas to streams and lakes, and this attenuation increases as watershed size increases. Attenuation may be watershed specific depending on topography, soil type, and weather. Consequently, choosing relevant export coefficients is difficult and many factors must be considered to reduce uncertainty (Reckhow et al. 1980). In fact, the use of export coefficients for predicting present or future water quality with changing land use is recognized by many to be a highly subjective effort (Beaulac and Reckhow 1982, Frink 1991). Despite the uncertainties associated with export coefficients, they are intuitively simple and easy to apply. As a result, they have been incorporated into many water quality models to calculate and express nutrient export from land to water (Reckhow and Simpson 1980, Reckhow and Chapra 1983).

At the opposite end of the complexity spectrum, detailed mechanistic analyses begin with hydrologic models that predict surface and sometimes subsurface flow. These models range from data-intensive distributed parameter models, to physically based hydrologic models (Grayson et al. 1992, DeVantier and Feldman 1993). While they break down the complex processes to elemental components that appear to be tractable at small enough spatial scales, these models are hard to apply because data are almost always lacking and difficult to obtain, and the models are often restricted to small watersheds or subwatersheds (DeVantier and Feldman 1993). Some of these models have large numbers of free parameters so it is easy to obtain a good fit to calibration data but, because the models are overparameterized, prediction errors may be large and interpretation of results is difficult (Grayson et al. 1992).

Overview of an Alternative Approach

We suggest a modeling approach that accounts for flow distance, unlike export coefficients, but does so by fitting only one additional parameter, unlike the parameter-rich mechanistic models:

$$L = \sum_{i=1}^{m} \sum_{p=1}^{n} f_i \; A_{p,i} \; T_i^p \qquad (2)$$

where L is total phosphorus loading (kg P/yr), m is the total number of land use types, n is the total number of pixels (equal sized grid-cells) in the contributing area, p is the distance of each pixel to water in the path of surface overland flow (in number of pixels), f_i is the P flux coefficient for land use i (kg P ha^{-1} yr^{-1}), $A_{p,i}$ is the area of land use i, distance p from open water (ha), and T is the transmission coefficient ($0 < T < 1$, dimensionless) which represents the proportion of P that is transported to the next pixel in the path of surface overland flow. The additional parameter not found in export coefficient models, T, accounts for the amount of P that is attenuated between pixels; and p, the distance of each land use from water along the flow path, determines how much P eventually reaches surface water. The transmission coefficient itself could take various forms. We chose this particular function to simulate attenuation of P as it travels in a path from source areas to surface waters. This model assumes that a fixed proportion of P is attenuated for every pixel of travel, in contrast to traditional export coefficients which assume that 100% of P eroding from a land parcel will reach surface water. Export coefficients and P flux coefficients have the same units (kg P ha^{-1} yr^{-1}), but they differ in that flux coefficients represent P production and transport to the **next pixel** along the flow path rather than the production and transport that reaches surface waters. P flux coefficients and traditional export coefficients should have the same value when applied to a given area of riparian or urban land where we assume all P is transported to surface waters.

Compared to agricultural lands, urban lands attenuate sediment-bound nutrients much less since water flow in urban areas is efficiently channelled to surface waters through storm sewers. To model this difference, we let $T = 1$ for all urban lands regardless of distance to water. P flowing over agricultural land, wetlands and forests is assumed to attenuate P, so T is allowed to vary between 0 and 1. While there may be sediment sinks in urban areas in the form of open space, pervious areas and detention basins, on average, attenuation is much less than for rural and naturally vegetated areas.

Like other P loading models, equation 2 assumes that within a given watershed, land use, topography, and total runoff are the major determinants of P flux. The model applies to P transport in overland flow. While some P is transported in groundwater, this flux can be small compared to surface flow, especially in agricultural (Peterjohn and Correll 1984) and urban areas. Total phosphorus is transported to surface waters predominantly in sediment-bound form. We would not recommend equation 2 for nitrogen loading, since transport in dissolved fractions and especially through groundwater is very important (Peterjohn and Correll 1984).

Input data for the model are spatially referenced databases of watershed land use, topography and hydrography; and calibration data are total annual P loadings to the lake from all subwatersheds for at least one year. The watershed may be broken down into any number of equal-sized grid-cells to use this model, although parameters and uncertainties depend on grid-cell size (Vieux and Needham 1993). The approach we propose attempts to take advantage of both the spatial data structure of Geographic Information Systems (GIS) and the intuitively simple export coefficient concept. We applied the model using pre-existing GIS databases readily available for public use (U.S. Geologic Survey (USGS), provider: Wisconsin Department of Natural Resources (WDNR) Geographic Services Section). Alternate sources of input data include satellite images, aerial photography, or topographic maps. We test the approach using watershed and loading data for the Lake Mendota watershed, a typical north temperate culturally eutrophic lake in southern Wisconsin, USA. Parameters were estimated for the Lake Mendota watershed to use to compare P loading under pre-settlement, current, and projected future land use.

METHODS

Study Site

Lake Mendota, the uppermost lake in the Yahara River chain of lakes (Kitchell 1992), is a large (4000 ha), eutrophic lake located in South Central Wisconsin (43° 6'N, 89° 24'W) near Madison in Dane County. This rich agricultural region has well drained silt loam soils in the uplands, and poorly drained silts with organic material underlain by alluvial deposits in the lowlands (Cline 1965). During the study years approximately 86% of the land was agricultural, 9% urban, 4% wetlands, and 1% forest (see Fig. 5). Five major streams and 2 main storm sewers drain the watershed (Fig. 1). The Yahara River subwatershed is 96% agricultural with low relief. Before entering the lake, the river is joined by Token Creek, a stream of higher baseflow than Yahara River (Lathrop 1992), with a subwatershed of similar land use as the Yahara River. Pheasant Branch Creek enters from the west and drains a steeper terrain than any of the other subwatersheds. The two storm sewers, Spring Harbor and Willow Creek, drain urban areas in the southwestern portion of the watershed and flow directly into the lake.

Prior to European settlement (1830's), the watershed vegetation was dominated by oak savannah and prairie (Curtis 1959). By approximately 1870, the current proportion of agricultural land had been achieved in Dane County (Lathrop 1992). This conversion left a marked effect on water quality, and culturally eutrophied Lake Mendota (Kitchell and Sanford 1992). Currently, land in the watershed is being converted from agricultural to urban uses, especially around the Madison metropolitan area and surrounding smaller communities (Dane County Regional Planning Commission 1992).

Watershed Data

Land use/cover, hydrography and watershed boundary data were obtained from the WDNR Geographic Information System Database (copyrighted, WDNR Geographic Services Section, Madison, WI). The land use/cover data were derived from 1:250K GIRAS data (USGS) by the WDNR Geographic Services Section. For our purposes, we combined 24 surface feature categories of land use/cover into 6 classes: (1) Agriculture (row and non-row crops, pastures and feedlots); (2) Urban (residential, commercial and services, industrial, mixed urban or built-up land, transitional areas, and industrial and commercial complexes); (3) Road (highway, communications and utilities); (4) Forest (all forest types); (5) Wetland (forested and non-forested wetlands); and (6) Lake (small lakes and ponds excluding Lake Mendota). The original source of the hydrography data was 1:100K DLG data (USGS). We converted the data from vector to raster format at 100 m x 100 m pixel size to match the topographic data. Since this resolution is coarse relative to many streams and rivers, we only considered the presence/absence of any stream for each pixel. Because we did not model instream attenuation of nutrients, we assumed that if surface runoff (of P) reached a stream, all of the P was transported to the monitoring station. The digital elevation model

(DEM) dataset was created by converting USGS 1-Degree DEM to raster format with elevations resampled at 100 m intervals (Lynn Usery, University of Wisconsin Geography Department, Madison, WI). The issue of pixel size was most critical for the DEM data since these data were used to predict overland flow, therefore we obtained data at the finest resolution available to us, and converted all other files to this grid size. Nevertheless, the DEM data had a distinct "stair-step" appearance. Therefore, we smoothed the data by interpolating between elevations. The algorithm first searched for the occurrence of groups of pixels with similar elevation and then computed the quadratic interpolation based on the elevations of the end points (outside the flat region) and the middle point in the flat area. For example, a series of pixels with the following elevations:

9 1 1 1 9

would be transformed into:

9 4 1 4 9.

The values outside the range and the median point do not change values. We used the interpolation algorithm on the rows and columns separately in all 4 directions and averaged the results pixel by pixel.

Contributing Area

The contributing area is defined as the area of the watershed that has the potential to contribute to P loading based on overland water flow, which we assumed followed the path of steepest descent. To estimate this area we created raster files of the distance of each pixel to the nearest stream in the water flow path. If a given pixel was lower or equal in elevation to all of its neighbors, then it was assumed not to contribute to surface runoff. Water flow paths were estimated using a hexagonal grid in which each pixel has two neighbors above it, two below, and one on either side. Hexagons approximate distance more accurately than a four-neighbor scheme by allowing measurement in 6 directions instead of 4. To convert the 100 m x 100 m DEM data to a hexagonal format, we shifted every other row by one half of a pixel. This maintained all of the four directional differences while making half of the diagonals a distance one and the other half a distance two. Thus, on average, diagonal movement had distance 1.5 instead of the 2.0 for a four-neighbor "city block" scheme.

Within the contributing area, we define the effective land area as the area that actually contributes to runoff (and P loading) based on total annual runoff. By definition, the effective land area will always be either equal to or less than the contributing area. Variability in effective land area for a single watershed is climate-driven. The contributing area, on the other hand, should not change from year to year.

Coefficients

Phosphorus inputs and discharge of the 5 major streams and 2 storm sewers draining into Lake Mendota watershed were monitored in 1976 and 1977 (Lathrop 1979). Water samples for total P were collected during both runoff events and baseflow conditions. Annual P loadings were calculated by direct integration using P concentration data and continuous stream discharge data for 1976 and 1977. The two years contrasted in weather conditions: 1976 had high precipitation during the spring months followed by a summer drought, and 1977 had average spring precipitation with high summer rainfall (Lathrop 1979). Total runoff for 1976 was much higher than in 1977. Based on an 18-year time series of annual stream discharge for the Pheasant Branch Creek subwatershed, runoff was above average in 1976 (less than one standard deviation above the mean) and below average in 1977 (one standard deviation below the mean) (USGS Water Resources Data, Wisconsin). This contrast allowed us to assess the impact of total annual runoff on model parameters.

Three parameters (*T* for all non-urban lands and P flux coefficients for agricultural and urban lands) were estimated by minimizing the root mean squared errors (RMSE) between predicted and observed data. Three different sets of model parameters (P flux coefficients and *T*) were estimated: for 1976, 1977, and both years combined. Parameters were estimated using a simple neural network, called a linear perceptron (Hertz et al. 1991). We placed upper and lower bounds on estimated P flux coefficients using literature export coefficients (0.0 to 5.4 for agricultural lands and 0.2 to 6.0 for urban lands) (Reckhow et al. 1980). However, for reported calibrations, the bounds were never reached.

Forest and wetlands combined represented less than 5% of the total watershed area in the baseline land use, and we assumed their relative contribution of P to be small compared to urban and agricultural land. Therefore, we set their P flux coefficients to export coefficients from the literature for forest (0.10 kg P ha^{-1} $yr^{-1)}$) (Reckhow et al. 1980) and to our best approximation based on soil and geology of the region for wetlands (0.05 kg P ha^{-1} yr^{-1}).

To obtain average P export coefficients for the subwatersheds as they are commonly defined in the literature, we divided the annual total P loads from each monitoring station by the respective subwatershed areas for both 1976 and 1977. We also compiled a set of traditional export coefficients from the literature that best represent the low, high, and 'most likely' value for both urban and agricultural land in the Lake Mendota region. The criteria that we used to choose these values were based on region, soil type, and crop or urban type (Reckhow et al. 1980, Frink 1991). In addition, when possible, we chose coefficients derived from small field studies so they would be more comparable to P flux coefficients. The 'most likely' export coefficient for agriculture was estimated by calculating a weighted average of export coefficients using the proportional area of crop types found in Dane County: 41% pasture land, 35% corn, and 24% oats and hay (Lathrop 1992).

Phosphorus Loading Scenarios

We estimated P loading to Lake Mendota using three different land use scenarios: baseline, presettlement, and +80% urban (see Fig. 5A,B and C). Baseline refers to the land use in 1976-77. The presettlement scenario was simulated by converting all urban and agricultural pixels of the baseline land use map to natural vegetation. We used 0.3 kg P ha^{-1} yr^{-1} as a P flux coefficient for natural vegetation obtained by averaging results from two studies for native prairies in Wisconsin and Minnesota respectively (Wojner 1977, Timmons and Holt 1977).

The urbanization scenario represents a realistic future land use configuration that is projected to increase existing urban lands by 80% in Dane County in approximately 30 years (Dane County Regional Planning Commission 1992). We converted pixels to urban land use in areas where urban growth is expected to occur: the cities of Madison and Middleton around the southwestern shores of Lake Mendota, and the smaller communities throughout the watershed. However, since the Lake Mendota watershed is predominantly agricultural, the percentage of urban land in the entire watershed only increased from 9% to 16%. Almost all of the land use change in the urbanization scenario involved converting previously agricultural land to urban land, much of which was already in the contributing area of the watershed.

To predict P loading for each scenario, model runs were performed using each of the three sets of model parameters: 1976, 1977, and both years combined. Since the two years represent a wide range of total annual precipitation, they should bracket the average condition.

Jackknife estimates of parameter variance

To examine the uncertainty in the model parameters, we estimated parameter values using jackknifed data sets where one subwatershed was left out at a time (Sokal and Rohlf 1981). Agriculture and urban P flux coefficients were recalculated for each iteration, while the transmission coefficient from the complete data set was used.

RESULTS

Phosphorus export coefficients calculated for the Lake Mendota subwatersheds show a distinct trend of decreasing P export per area with increasing subwatershed total area, as well as large year to year variation in P export (Fig. 2). However, differences in land use between subwatersheds confounds this trend. Land use in the two smallest subwatersheds, Willow Creek and Spring Harbor storm sewers is dominated by urban lands (81% and 67% respectively), compared to the other subwatersheds where urban lands only comprise from 2-6% of the total area. Our modeling effort was, in part, an attempt to account for the combined effects of area and land use.

The transmission coefficient (T) that minimized the squared errors between predicted and observed values was 0.97 for 1976, 0.93 for both years, and 0.0002 for 1977 (Fig. 3).

Although the slopes of the lines are quite flat around the minima, the values for 1976 and for both years combined are clearly not close to 0, and the value for 1977 is clearly not close to 1, suggesting real differences between the two years. Model predictions were, on average, within 16% of the observed values in 1976, and within 9% in 1977 (Fig. 4). Total P loading was more than twice as high in 1976 than in 1977, and variation between subwatersheds was large during the high runoff year.

The difference between high and low runoff years on the effective land area (the area that contributes to loading based on runoff for a given year) is shown in Fig. 5 D-I. During low runoff years, only areas adjacent to surface waters and urban areas (both represented by white areas) contribute significantly to loading. The largest contrast is between the urbanized scenario and all others where the total area that contributes all of its P increases (Fig. 6F,I). Even in relatively dry years (1977), urban areas will contribute to loading, whereas in agricultural or vegetated areas, much of the P produced in the contributing area is attenuated before reaching water. Differences between high and low runoff years are large and more pronounced than the differences between scenarios.

The transmission coefficient determines the effective land area, ie. that amount of the contributing area that significantly contributes to loading in a given year. As *T* decreases, the effective land area decreases, so areas farther from streams will not contribute P (Table 1). In the low runoff year, only 30% of the contributing area transports a significant amount of P to surface waters, but during a high runoff year, 87% of the land that can contribute to loading does. This contrast is important since land use within the effective land area may be quite different from land within the entire watershed (Fig. 6). For the baseline scenario, the proportion of urban land in the total watershed is 9%. However, the proportion of urban land in the effective land area is 16% during 1976, the high runoff year, and even higher (53%) during 1977, the low runoff year (Figure 6B). These trends are amplified in the urbanization scenario (Fig. 6C). The difference in the effective land areas between high and low runoff years in the pre-settlement scenario is less important (Fig. 6A).

The P flux coefficients from the model can be compared to P export coefficients from other studies. The literature P export coefficients for agriculture and urban lands in Fig. 7 represent the likely range for the Lake Mendota watershed based on soil type, land use practices, and weather conditions. P flux parameters for agriculture and urban lands estimated from the model are within the range of plausible P export coefficients from the literature. The range for urban coefficients are narrower for both the model flux coefficients and the literature values. Also, the 'most likely' literature values and average values from the model run are very similar. The model suggests that on a per hectare basis, agricultural P flux is larger than urban P flux in the Lake Mendota watershed.

The range of P loading predicted from the model is much lower than the range of loading obtained from using values of P export coefficients from the literature (Fig. 8). Consequently, it is easier to discern differences in loading between land use scenarios and years from model output than from literature coefficients. The most striking result is the 6 fold increase in loading that occurred from pre-settlement to baseline land use for all three runoff conditions. This increase in loading is due to the disturbance of vegetated land by both agriculture and urbanization. The urbanization scenario led to a modest increase in annual P loading in the high runoff year, and a larger increase in the low runoff year.

However, the area of urban lands only increased from 9% to 16% of the total watershed area (Fig. 6B,C). When the entire watershed is converted to urban lands, P loading to the lake doubles (see Table 2).

We examined how in-lake processes may respond to predicted changes in P loading using an empirical model that predicts in-lake spring total P (TP) from annual P loading, lake mean depth, flushing rate and P retention (Dillon and Rigler 1974) (Table 2). We then converted spring TP to average summer blue-green algal biovolume using a regression equation calculated from a 15 year time series (Lathrop and Carpenter 1992) (Table 2). Average pre-settlement spring TP concentrations are about five times lower than the concentrations from the average baseline condition. Although only minor increases in spring TP (2%) occur from an 80% increase in existing urban land use during the high runoff year, larger increases in spring TP occur during the low runoff year (30%). Similarly, blue-green algal biovolume is zero in the pre-settlement scenario except for very small amounts under high runoff conditions. For the baseline land use, blue-green biovolumes are variable and dependent on loading.

DISCUSSION

Our model examines the relationship between land use, topography, annual precipitation and annual P loading to surface waters. This relationship could be examined at scales ranging from that of the field plot operating in hours to days, to the regional scale over decades and thousands of kilometers. We chose a scale relevant to the management of entire watersheds to sustain water quality of lakes, estuaries and rivers. We also took advantage of pre-existing GIS databases commonly available to researchers and managers

(USGS). These data proved to be adequate to address the questions that we have here and our results suggest that much can be explored further with these types of data.

P flux coefficients vs. P export coefficients

The P flux coefficients (f_i) can be viewed as P export coefficients (c_i) that are unbiased by the size of the watershed. The P flux coefficients represent the amount of P that is transported 100 m downhill from one land unit to the next. They should be similar to P export coefficients that are calculated from single plot studies. The range of agricultural coefficients that we chose from the literature based on the soil and crop types in the Lake Mendota watershed is comparable to those estimated by the model (Fig. 7). The variability in published coefficients is due in part to different weather and precipitation conditions. The 'most likely' value from the literature is slightly lower than the average value estimated by the model, perhaps because it includes values for pasture land (which make up 41% of the total agricultural land area in Dane County). Reported coefficients for pasture are usually lower than those for other land uses because they are estimated from larger watershed studies where nutrient attenuation can be large.

Since urban lands were not subject to attenuation of P flow in our model, P flux coefficients and P export coefficients are directly comparable. The 'most likely' value that we obtained from the literature for this watershed was close to the average values estimated from the model. This similarity corroborates our assumption that little attenuation of nutrients occurs from urban lands. In addition, the range of urban values for model and literature coefficients were both narrower than for agricultural land, perhaps due to the fact that urban lands are subject to less variability caused by precipitation since they are subject to less attenuation.

For all calibration runs of the model, agricultural flux coefficients are generally greater than urban flux coefficients. This result contrasts with most studies that present both agriculture and urban export coefficients (Rast and Lee 1978). These studies have generally not estimated the attenuation of P flow with distance from surface waters. Neglect of attenuation could lead to large errors in loading estimates, especially when comparing effects of different land uses, and may explain part of the enormous variance in agricultural export coefficients in the literature.

Contributing Area

We assumed that location of land uses was important, and attempted to estimate which parts of the watershed contribute most strongly to loading based on topography and distance to water. Since P is carried to surface waters primarily by runoff, we simulated overland flow across the entire watershed by the path of steepest descent. We assume that this procedure will provide a rough measure of the potential source loading areas at the annual scale. At finer spatial and temporal scales, it may be necessary to include factors such as antecedent soil conditions, rain intensity and duration, and groundwater recharge (Black 1991). About half of the Lake Mendota watershed could potentially contribute to surface loading. This low percentage was due to the flatness of much of the watershed, and also the low stream density especially in the Yahara subwatershed (see Fig. 1). Refinements of these estimates may be possible as digital elevation and loading data become available at finer resolutions (DeVantier and Feldman 1993).

We analyzed an isolated intense storm event on 23-24 February of 1977 to assess the rain-to-runoff relationship in this watershed. At the time, the ground was frozen with little snow cover, so much of the rain should have been converted to surface runoff. We calculated the volume of rain that fell on each subwatershed, and determined the volume of runoff (excluding baseflow) that resulted from this storm event. The runoff volumes above baseflow at the two largest and predominantly agricultural subwatersheds, Yahara and Sixmile Creek, were 14.1% and 21.7%, respectively, of the total volume of water that fell on each subwatershed as rain. In the two smaller subwatersheds (Spring Harbor and Willow Creek), which are dominated by urban lands, flow volume above baseflow was 54.1% and 47.8% of the total rain volume. These relative runoff volumes also support the fact that large agricultural watersheds (Yahara River and Sixmile Creek) are more likely to attenuate nutrients than urbanized watersheds (Spring Harbor and Willow Creek).

P export coefficients estimated for the subwatersheds also corroborate the estimates of contributing area. When the total export of P at the annual scale from each subwatershed is divided by its area (size range of 10 - 180 km^2), there is a clear relationship to the size of the watershed, with the two largest (and flattest) subwatersheds, Yahara and Sixmile Creek, showing substantially lower export per area than the other subwatersheds (Fig. 2). This trend suggests that there are large portions of the Yahara and Sixmile Creek subwatersheds, which together make up 51% of the total watershed area, that do not contribute to runoff. This relationship is confounded by the effects of land use however, since the two smallest subwatersheds are dominated by urban land uses. Nevertheless, the trend is still evident for the remaining subwatersheds, and these combined effects of land use and watershed size emphasize the need to address both issues when assessing the impacts of land on water quality.

Watershed hydrologists have shown that the actual area of land that contributes to storm runoff, and thus sediment transport, can be relatively small and dynamic (Walling 1983, Hibbert and Troendle 1988, Eshleman et al. 1993). This has been referred to in the literature as the "variable source area concept" (Troendle 1985, Black 1991) and has usually been applied at the event scale for relatively small watersheds. Others have suggested, however, that this concept be applied to large watersheds to explain other processes such as nutrient cycling (Naiman et al. 1992). Our results suggest that it is appropriate to examine nonpoint source P loading in a similar context.

In our model, the transmission coefficient is linked to the width of this contributing area. Since T attempts to account for the attenuation of sediment-bound nutrients from source areas to watershed outlets, it is similar to the sediment delivery ratio (Walling 1983). The wide range of T estimated by the model suggests strong weather effects on this function, which seems reasonable considering the wide range of sediment delivery ratios that have been found in previous studies. Piest et al. (1975) have shown sediment delivery ratios to vary from 1% to 520% for individual storm events for a single watershed measured over 10 years, and from 1% to 72% for annual estimates. It is not unreasonable to expect similar variability for T.

Riparian areas

The attenuation of sediment and nutrients by runoff is influenced not only by distance to water, but also by topography, riparian land use, disturbance and the presence of impervious surfaces (Lowrance et al. 1984, Peterjohn and Correll 1984, Hibbert and

Troendle 1988, Byron and Goldman 1989). Studies addressing the importance of riparian land use versus land use in the entire watershed have been equivocal (Omernik et al. 1981, Osborne and Wiley 1988, Levine and Jones 1990, Hunsaker et al. 1992). Some have found that including riparian terms does not improve regressions of water chemistry parameters against land use indices (Omernik et al. 1981). Others have found that regressions improved when riparian land was considered, or weighted more heavily than other lands (Osborne and Wiley 1988, Levine and Jones 1990). These apparently conflicting results may be due to the fact that a wide range of watershed sizes and perhaps topographies were used in the different studies. The relationship between land use and water quality in watersheds of 25 - 55 km^2 (Omernik et al. 1981) may differ from those of watersheds as large as 1,300 km^2 (Osborne and Wiley 1988). Larger watersheds may have areas that are more distant from surface waters, or have much lower stream densities. In the Lake Mendota watershed, land use of the effective land area can be quite different from land use in the watershed as a whole (Fig. 6). This contrast was especially evident in the low runoff year when only areas immediately adjacent to water and urban areas contributed to P loading, representing only 17 % of the total watershed area (compared to 50 % during the high runoff year) (Fig. 5). The area of the watershed that contributes most of the loading is dynamic in width and strongly dependent on weather.

The importance of riparian areas in trapping sediment-bound nutrients has been shown in both modeling and field studies (Schlosser and Karr 1981, Lowrance et al. 1984, Peterjohn and Correll 1984, Cooper and Bottcher 1993). Correll et al. (1992) found that hardwood forests next to agricultural land removed 80% of TP in overland flow. Hill (1981) found a negative correlation between TP load and proportion of forested land. Our model was not intended to estimate effects of riparian forest. However, the model's sensitivity to land use location suggests that riparian land use is important, and that undisturbed or continuously vegetated riparian regions could significantly mitigate P loading.

Annual Phosphorus Loading

Phosphorus loads from land increase with increasing disturbance, soil erosion, fertilizer applications, and proportion of impervious surfaces (Arnell 1982, Byron and Goldman 1989). The dominant land uses in the Lake Mendota watershed, agriculture and urban land, increase some or all of these factors. The change in land use from pre-settlement to baseline conditions increased P loading by about 6 times (Fig. 8). This model result is corroborated by paleolimnological evidence from Lake Mendota (Kitchell and Sanford 1992). The sediment record shows an abrupt and massive increase in secondary production of zooplankton, and large changes in sedimentary pigments in the lake in the early to mid-1800's, a time when the watershed was undergoing the almost complete transition from prairie and oak savannah to agriculture (Hurley et al. 1992, Kitchell and Sanford 1992). Zooplankton biomass, and presumably production, has been shown to increase as lakes are enriched with P (Hanson and Peters 1984, Pace 1986).

We were surprised by the modest response of total annual P loading to an 80% increase in urban land use (Fig. 8). This result can be understood as follows. First, although the existing urban area of the baseline condition increased by 80% in the urbanization scenario, urban land still only made up 16% of the total watershed area. Thus, the agricultural areas still exerted the strongest influence on total loading. Second, although the P flux coefficient for urban areas is generally lower than for agriculture in our model, all urban areas contribute to loading regardless of location in the watershed. This is not the case for agriculture, where P originating in non-riparian areas is attenuated before reaching surface waters. These two factors offset one another, so that although urban production of P per area is less than for agricultural lands, none of it is attenuated, resulting in little net change in total annual P loading. In addition, much of the agricultural land that was converted to urban use was already in the 'contributing area'. Larger effects may occur when previously non-contributing land is urbanized. Nevertheless, at the annual scale, there should be little net change in steady-state P loading to surface waters after some agricultural lands are converted to urban.

These results suggest that the sequence in which land use changes occur is important. Transitions from natural vegetation to land disturbed by either agriculture or urbanization have the strongest effects on total loading, especially when the changes occur in either large proportions of the watershed or affect riparian areas. Similar conclusions were reached in a study of land use changes within the 'Critical Area' of the Chesapeake Bay watershed of Maryland (land within 305 m of the landward boundary of tidal wetlands) (Houlahan et al. 1992).

Although we have not modeled the transient effects of converting land types from one to another (e.g. construction site erosion), we could estimate what these may be at the annual scale. Based on a sediment loss from construction sites of 227,300 kg ha^{-1} yr^{-1} (Dane County Regional Planning Commission, pers. comm.), and a sediment P concentration of 20 mg P kg^{-1} sediment (Sharpley et al. 1985), we estimate the loss of P from construction sites to be approximately 4.5 kg P ha^{-1} yr^{-1}. At the rate of development that the Lake Mendota watershed has undergone in the last several decades, this results in an export of P from construction sites of about 600 kg P/yr. This loading will probably occur in brief, intense events that could be locally significant in space and time. Our model is not scaled appropriately to deal with such events.

At the watershed scale, both agriculture and urban land uses appear to strongly determine total P loading. Consider a scenario in which 86% of the pre-settlement watershed is converted to urban rather than agricultural use. Total annual P loading from the completely urban watershed would be 71,620 kg/yr compared to 33,530 kg/yr for the baseline scenario where agriculture comprises 86% of the total area (using parameters from the average runoff condition) (Table 1). Since transmission coefficients for non-riparian agricultural lands are always lower than for urban land (where T = 1), the larger amount of P that is "produced" on agricultural land is attenuated, leading to lower overall contribution of P from agriculture than from urban lands. This effect should increase as the size of the watershed increases.

An important driver of P loading that is often ignored is climatic variability (Correll et al. 1992). We found a much larger difference in P loading between the high and low runoff years than between the baseline and urbanization scenarios (Fig. 8). This finding is consistent with studies showing large year to year variation in runoff and loading due to weather differences (Menzel et al. 1978, Correll et al. 1992). Agricultural lands are very sensitive to the timing and magnitude of rainfall in determining runoff and loading (Sharpley et al. 1981, Sharpley and Smith 1990, Vaithiyanathan and Correll 1992). In urban lands, this rainfall-loading relationship is decoupled since there is little attenuation of P flow. This decoupling may explain why the difference between high and low rainfall years is smaller in urbanized watersheds (urbanization scenario) than in less urbanized watersheds (baseline condition) (Fig. 8).

While agriculture and urban areas may be quantitatively similar in the magnitude of P loading, they are qualitatively different in their linkage to surface waters and response to precipitation. Urban areas are often located adjacent to streams or lakes, and are tightly linked to those waters through storm sewers. Some of these differences may be important at shorter temporal and spatial scales (e.g. storm events) not addressed here. Our calibration may underestimate the impact of changes in P loading since it uses annual means instead of event-based loading values. Also, we were not able to incorporate transitory effects of land use changes, such as construction site erosion, that may have large impacts on water quality over brief periods. Finally, our model only examines total P. Differences in the forms of P that are transported from urban and agricultural lands could be significant for water quality. Urban lands export a larger fraction of dissolved P compared to agricultural lands, where the majority of nutrients are transported in particulate form (Frink 1991). Dissolved nutrients will be readily available for algal uptake, unlike particulate nutrients that may sink out of the water column (Browman et al. 1979, Sonzogni et al. 1982).

Implications for Lake Water Quality

In many culturally eutrophic lakes, loading from non-point sources represents the major external source of nutrients which support high levels of primary production. This primary production is most commonly dominated by blue-green algae which are usually P limited and can form noxious blooms (Trimbee and Prepas 1987, Paerl 1988, Lathrop and Carpenter 1992). Long-term monitoring of Lake Mendota has shown great variability in water clarity, a result of variable densities of bloom-forming nuisance blue-green algae (Lathrop and Carpenter 1992). Nuisance levels of blue-green algae are caused by the interaction of (1) events that cannot be predicted or controlled, such as storms causing runoff and lake mixing; and (2) events that are partially controllable, such as fish populations leading to presence or absence of large zooplankton, and land-use policies that affect external nutrient loading (Paerl 1988, Carpenter 1992, Lathrop and Carpenter 1992, Rudstam et al. 1993). Years with unusually low runoff and P loading have unusually high water clarity, especially if herbivorous zooplankton are also abundant (Lathrop 1992). The management goal for sustaining water quality is to reduce blue-green algae blooms, and reducing external P load is one obvious approach to do this.

Blue-green algal biovolumes $> 2\ \mu L/L$ are considered to represent poor water quality and bloom conditions (Lathrop and Carpenter 1992). The blue-green algae biovolumes predicted from the baseline land use scenario (Table 1) represents the water quality of Lake Mendota of the past several decades, where blue-green algal biovolumes and formations of blooms are highly variable between years (Lathrop and Carpenter 1992). In contrast, in the +80% urbanization scenario during low, average and high runoff conditions, blue-green algal biovolumes are always $>2\ \mu L/L$. This effect is amplified when the entire watershed is urbanized, in which case summer average blue-green algal biovolumes are well above those levels for all other scenarios regardless of runoff conditions. With an increasing proportion of urban lands, P loading will become both less variable in time and consistently higher than for the same amount of naturally vegetated or agricultural land. As a result, the probability of blue-green algal blooms should increase.

Management and Policy Applications

The watershed is the appropriate scale for management of land resources that impact water quality. Piecemeal decisionmaking at local or small scales is known to be risky since contributions from any given hectare of land are minor (Sidle and Sharpley 1991). Results from the model run of different land use scenarios show that the effect of seemingly large changes in land use on total annual loading can be difficult to detect. This idea is similar to that proposed by some for the effective management of wetlands, where it is necessary to examine wetlands' cumulative impacts on water quality as components of landscapes (Preston and Bedford 1988, Johnston et al. 1990). Not only is the total area of wetlands important, but their location in relation to overland flow and receiving waterbodies is critical for both wetland functioning and water quality.

Failure to consider the spatial distribution of land uses and climatic variability in nutrient loading may contribute to failures of management plans to improve water quality in many lakes (Persson et al. 1983, Johengen et al. 1989, Meals 1993). Land use and its spatial pattern are critical to evaluate nonpoint sources of nutrients. While many studies show that riparian areas strongly impact P loading, our results indicate that the critical width of the riparian region is dynamic and closely linked to total precipitation. Policies directed at the control of nonpoint source nutrients recognize that critical areas near surface water should reduce total nutrient loading (e.g. Maryland's Critical Areas Act, Houlahan et al. 1992). However, the greatest uncertainties may lie in the definition of the "critical" width of this riparian zone, and the recognition that it may vary from year to year.

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Table 1. The cumulative effective land area (presented as the percent of the total contributing area) at given distances from surface waters for four values of the transmission coefficient (T).

	T:	1.00	0.97	0.93	0.0002
	Runoff Year:	-	(High)	(Avg)	(Low)
Distance					
0 - 100 m		29.9 %	29.9 %	29.9 %	29.9 %
0 - 200 m		40.4	40.1	39.7	29.9
0 - 1000 m		84.7	78.3	71.1	29.9
0 - 2000 m		96.3	85.8	75.2	29.9
0 - 5800 m		100.0	87.3	75.7	29.9

Table 2. Total loading, spring total phosphorus (TP), and average blue-green algae (BGA) biovolume during summer months for four land use scenarios during low, average, and high runoff conditions. Note that BGA biovolume does not include other algal taxa.

Scenario:	Loading (kg/yr)	Spring TP [a] (mg P/L)	BGA Biovolume [b] (μL/L)
Pre-settlement			
Low	1352	0.004	0.00
Avg	5778	0.019	0.00
High	6958	0.023	0.15
Baseline			
Low	20200	0.066	1.67
Avg	33530	0.097	2.77
High	39660	0.129	3.90
+80% Urban			
Low	26710	0.087	2.41
Avg	34789	0.108	3.16
High	40380	0.131	3.97
All Urban			
Low	99450	0.323	10.78
Avg	71620	0.233	7.59

High	46550	0.151	4.68

[a] Based on model to predict spring total phosphorus from loading (Dillon and Rigler 1974)

[b] Obtained from regression equation based on 15 years of blue-green summer averages and spring total phosphorus in Lake Mendota from 1976-1990 (R^2 = 0.31, P = 0.032) (Lathrop and Carpenter 1992)

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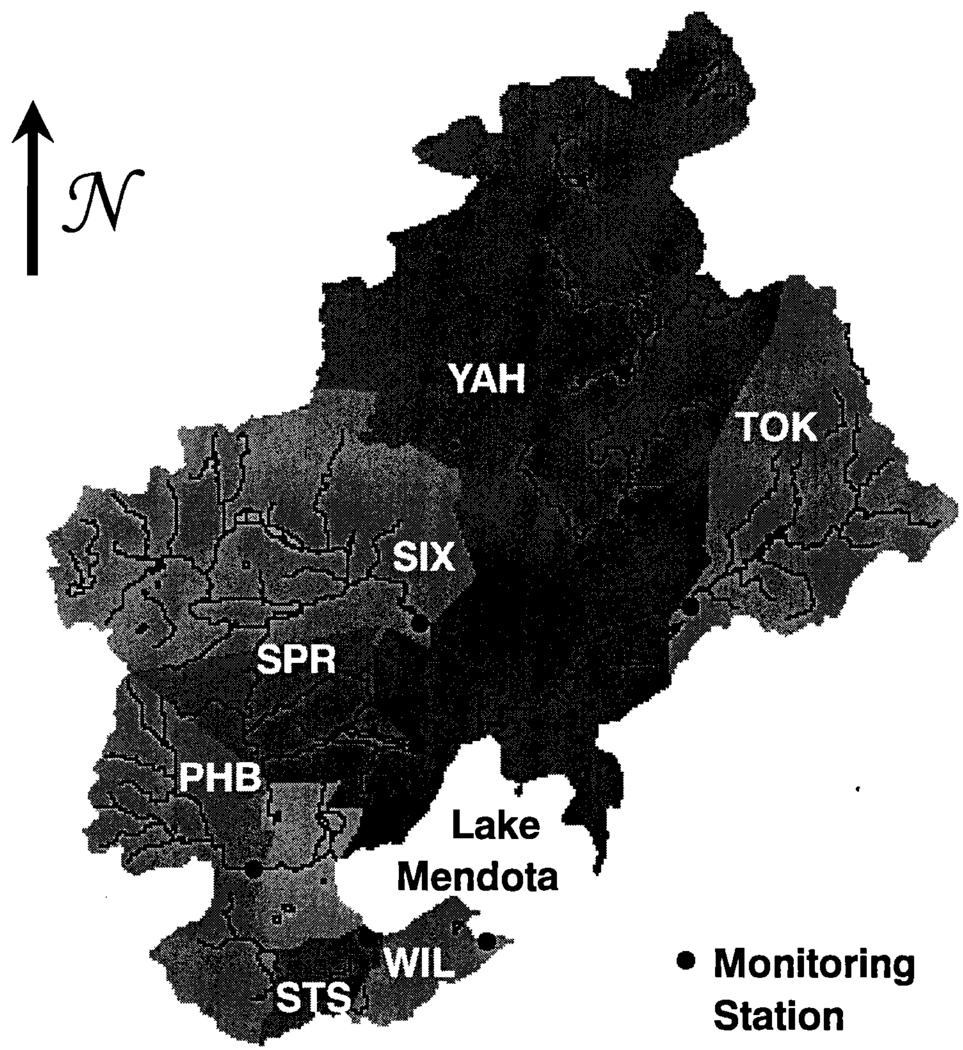
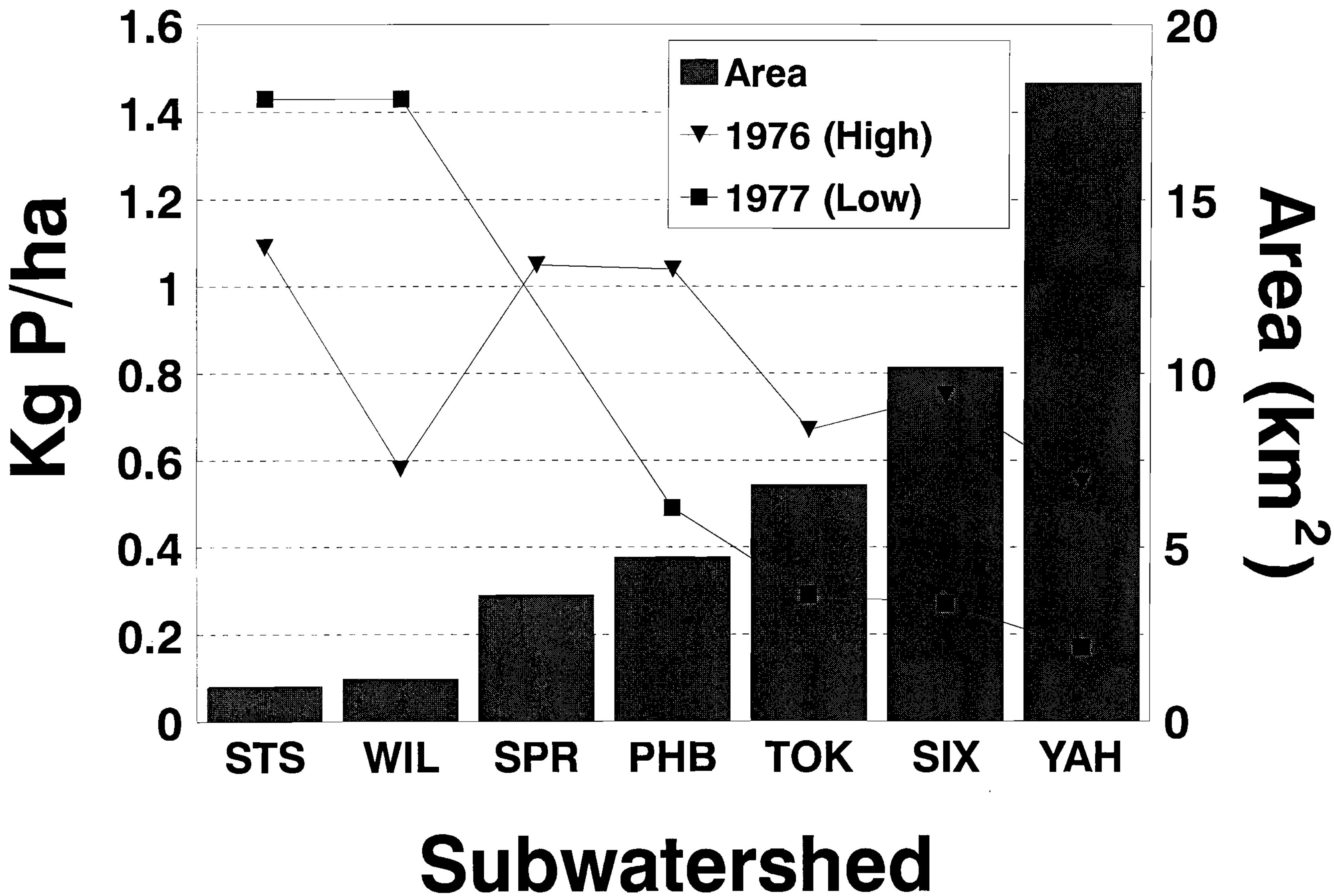
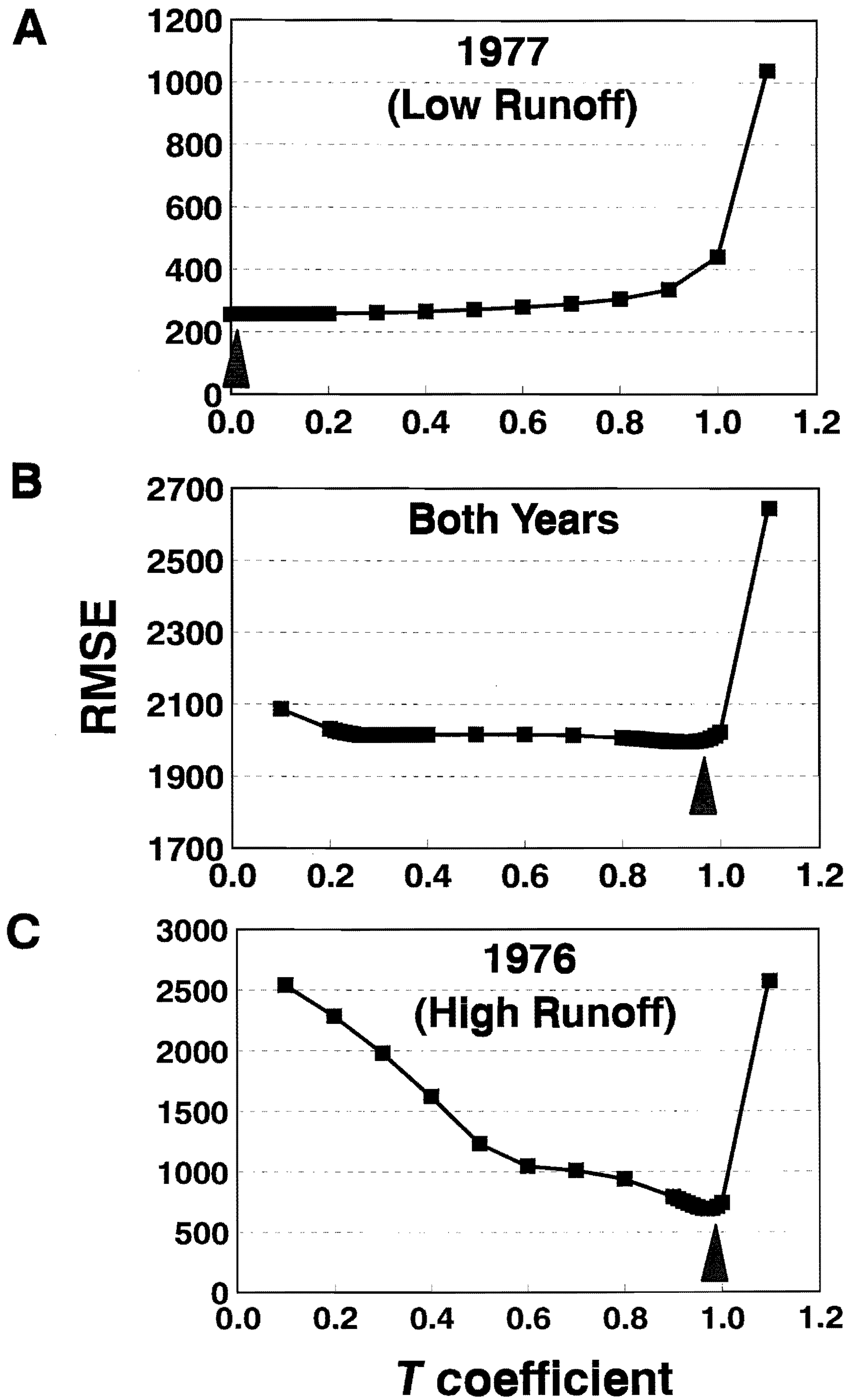
(area) and in the effective land area for the three model runs representing low, average, and high runoff conditions for the pre-settlement (A), baseline (B), and urbanization (C) scenarios.

Fig. 7. The P flux coefficients (kg P/ha) estimated from the model for the three model runs representing the low, average, and high runoff conditions; open circles represent jackknifed parameter estimates (see text); and the low (filled circle), most likely (filled square), and high (filled circle) values for P export coefficients from the literature for agriculture and urban land uses.

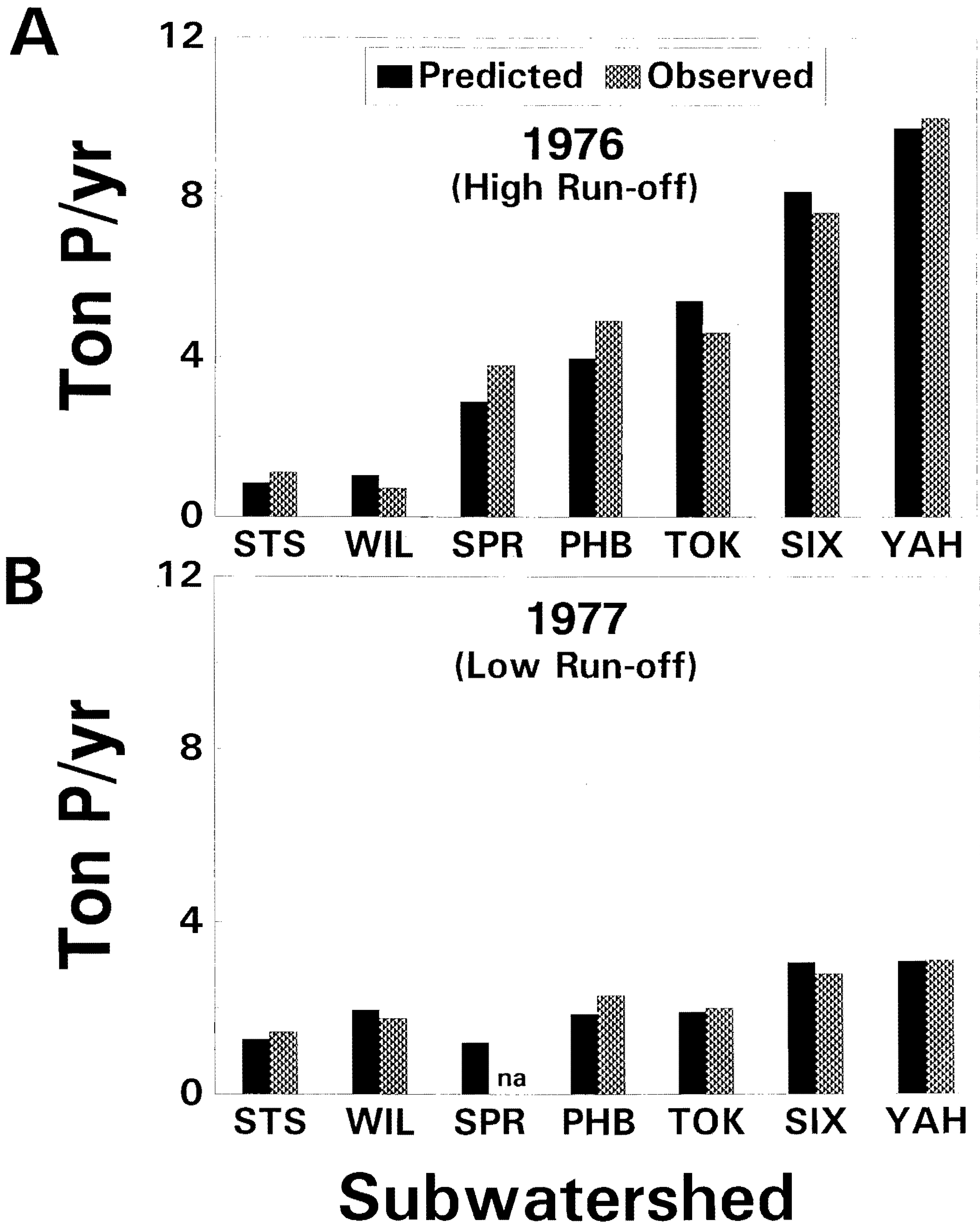
Fig. 8. Total P loading (metric tonnes P/yr) predicted for the pre-settlement, baseline, and + 80% urbanization scenarios from the three model runs representing the low, average, and high runoff conditions; and estimates of P loading using low, most likely, and high P export coefficients from the literature and the total watershed area to predict loading.

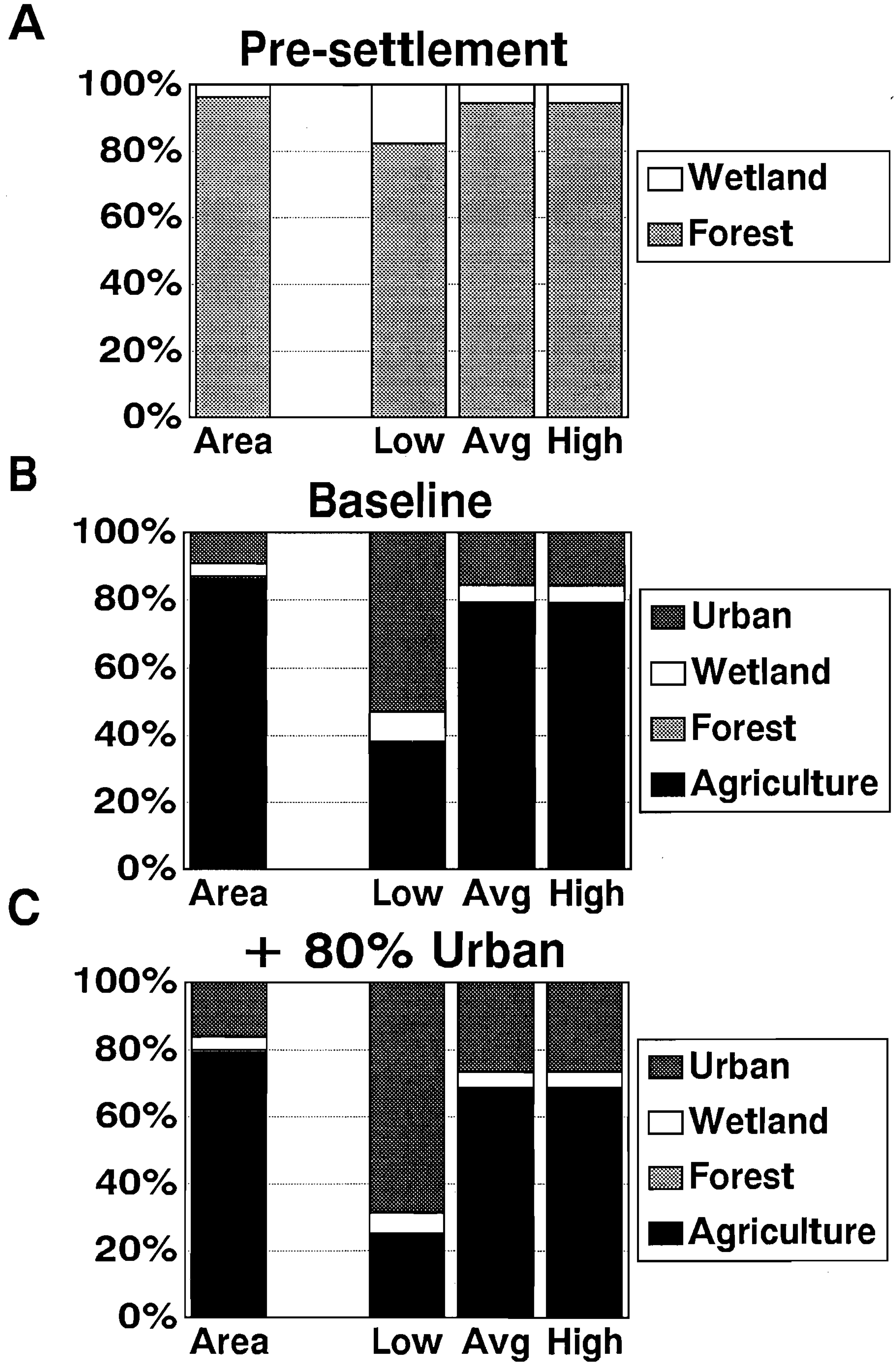

N
YAH
TOK
SIX
SPR
PHB
Lake
Mendota
WIL
STS
Monitoring
Station


Kg P/ha
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Area
1976 (High)
1977 (Low)
20
15
10
5
0
Area (km 2)
STS
WIL
SPR
PHB
TOK
SIX
YAH
Subwatershed

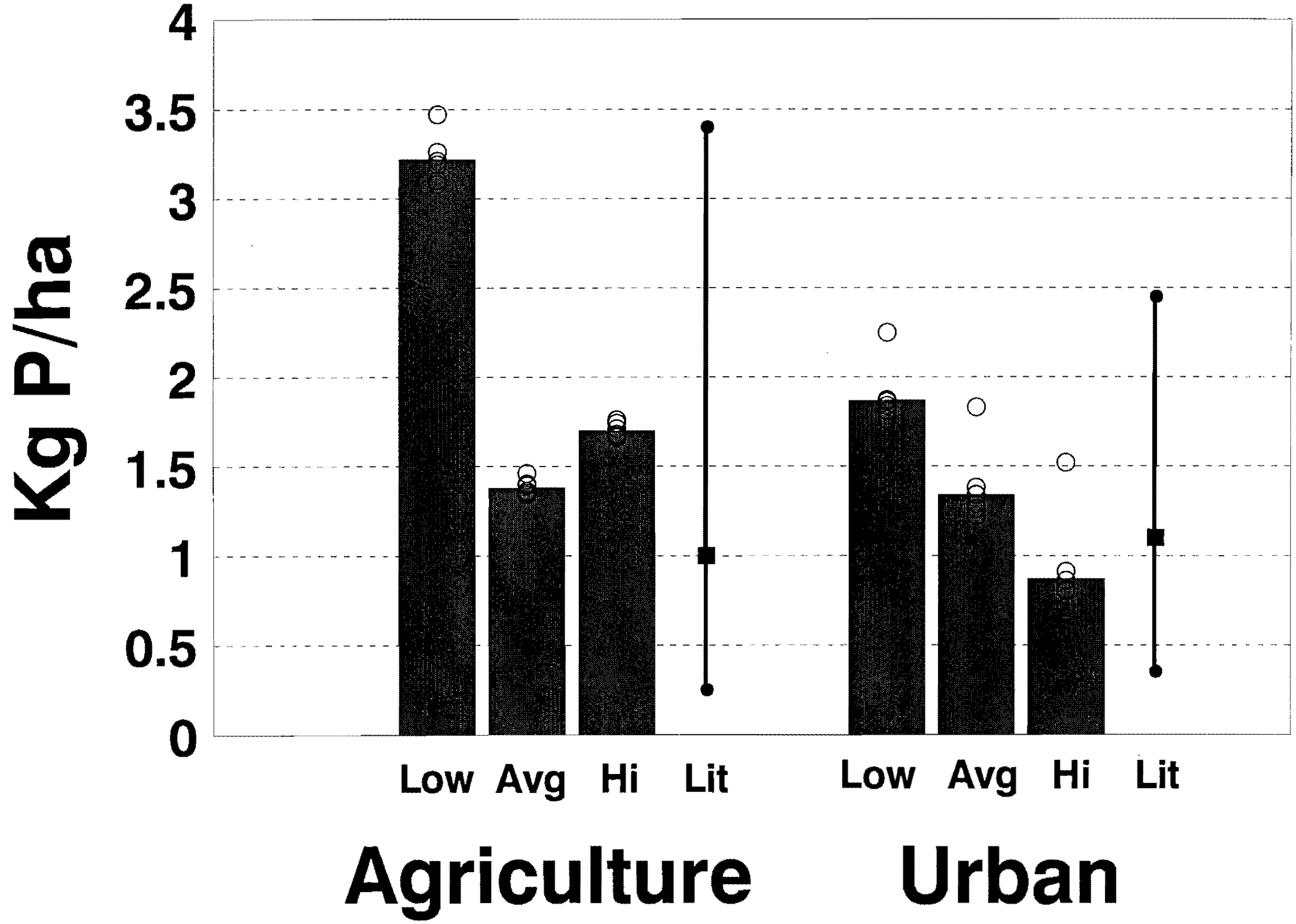


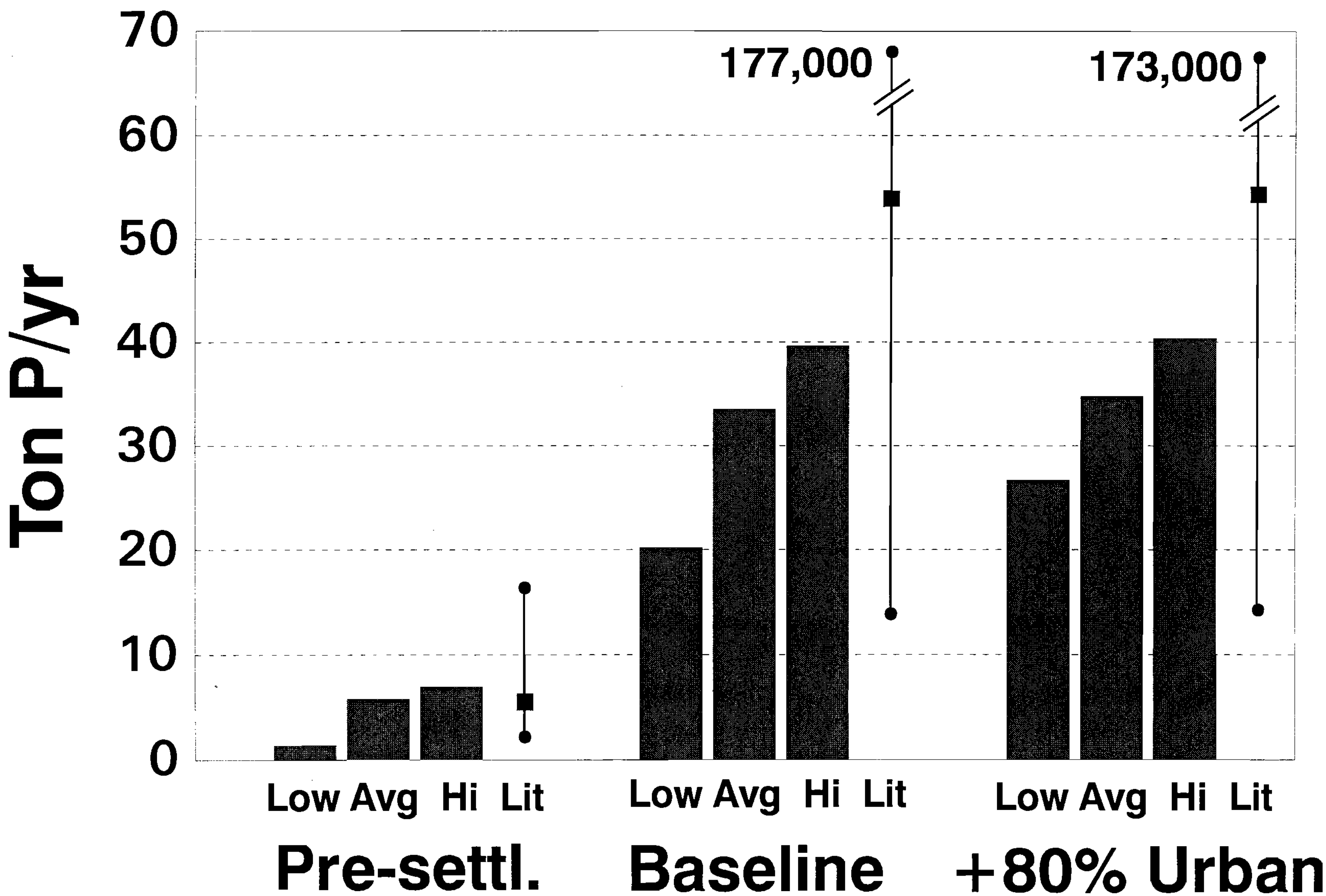
A
1977
(Low Runoff)
B
Both Years
C
1976
(High Runoff)
RMSE
T coefficient


A
B
Ton P/yr
Predicted
Observed
1976
(High Run-off)
1977
(Low Run-off)
0
4
8
12
STS
WIL
SPR
PHB
TOK
SIX
YAH
na
Subwatershed



A
Pre-settlement
100%
80%
60%
40%
20%
0%
Area
Low
Avg
High
Wetland
Forest
B
Baseline
100%
80%
60%
40%
20%
0%
Area
Low
Avg
High
Urban
Wetland
Forest
Agriculture
C
+ 80% Urban
100%
80%
60%
40%
20%
0%
Area
Low
Avg
High
Urban
Wetland
Forest
Agriculture


Kg P/ha
4
3.5
3
2.5
2
1.5
1
0.5
0
Low Avg Hi Lit
Low Avg Hi Lit
Agriculture
Urban



Ton P/yr
70
60
50
40
30
20
10
0
177,000
173,000
Low Avg Hi Lit
Low Avg Hi Lit
Low Avg Hi Lit
Pre-settl.
Baseline
+80% Urban