Estimates of diffuse phosphorus sources in surface waters of the United States using a spatially referenced watershed model

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Abstract The statistical watershed model SPARROW (SPAtially Referenced Regression On Watershed attributes) was used to estimate the sources and transport of total phosphorus (TP) in surface waters of the United States. We calibrated the model using stream measurements of TP from 336 watersheds of mixed land use and spatial data on topography, soils, stream hydrography, and land use (agriculture, forest, shrub/grass, urban). The model explained 87% of the spatial variability in log transformed stream TP flux (kg yr^{-1}). Predictions of stream yield (kg ha^{-1} yr^{-1}) were typically within 45% of the observed values at the monitoring sites. The model identified appreciable effects of soils, streams, and reservoirs on TP transport. The estimated aquatic rates of phosphorus removal declined with increasing stream size and rates of water flushing in reservoirs (i.e. areal hydraulic loads). A phosphorus budget for the 2.9 million km^2 Mississippi River Basin provides a detailed accounting of TP delivery to streams, the removal of TP in surface waters, and the stream export of TP from major interior watersheds for sources associated with each land-use type.

Keywords Nutrients; phosphorus; reservoirs; surface water; watershed model

Water Science and Technology **Vol 49 No 3 pp 1–10** © US Government 2004

Introduction

As progress has been made in the control of municipal and industrial effluents over the past several decades in developed countries of the world, attention has increasingly focused on diffuse pollutant sources (Carpenter *et al.*, 1998). Diffuse sources have been recognized as major contributors to nutrient pollution in many inland and coastal waters in the United States and Europe (Carpenter *et al.*, 1998; Behrendt, 1993). This has expanded the need for information on the relative importance of specific diffuse sources, especially in large watersheds of mixed land use, to guide regulatory policy and nutrient management efforts. Watershed models have frequently relied on land-use based "export coefficients" to estimate nutrient sources and transport in large watersheds (Beaulac and Reckhow, 1982), but these methods have proved to be unreliable because literature estimates of nutrient export (kg ha^{-1} yr^{-1}) are highly variable, reflecting local differences in climatic conditions, nutrient supply, and biogeochemical processing of nutrients in soils and streams (Beaulac and Reckhow, 1982; Prairie and Kalff, 1986; Frink, 1991). Moreover, literature coefficients often describe nutrient export from small catchments, and provide little information about how the rates of nutrient supply and attenuation change during transport through the streams and reservoirs of large watersheds. This has complicated efforts to accurately estimate nutrient delivery from specific sources to downstream water bodies such as reservoirs and estuaries where eutrophication is of concern (Diaz and Rosenberg, 1995).

Recent applications of the statistical watershed model SPARROW (SPAtially Referenced Regression On Watershed attributes; Smith *et al.*, 1997) in the United States and New Zealand have advanced understanding of nutrient transport over large spatial scales (Smith *et al.*, 1997; Preston and Brakebill, 1999; Alexander *et al.*, 2000, 2001, 2002a, 2002b). SPARROW is a statistically calibrated regression model with mechanistic components (e.g. surface-water flow paths, first-order loss functions) and mass-balance constraints. The model estimates empirically the rates of nutrient delivery from point and

diffuse sources to streams, lakes, and watershed outlets. The spatial referencing of stream monitoring stations, nutrient sources, and the climatic and hydrogeologic properties of catchments to stream networks explicitly separates landscape and surface-water features in the model. This allows nutrient supply and attenuation to be tracked during water transport through streams and reservoirs, and accounts for nonlinear interactions between nutrient sources and watershed properties during transport.

Past versions of the model have successfully used measures of the intensity of agricultural activities (e.g. fertilizer, livestock wastes) and wastewater effluent to model nitrogen and phosphorus transport in streams (e.g. Smith *et al.*, 1997; Alexander *et al.*, 2000, 2001; Preston and Brakebill, 1999). In the analysis presented here, we use the SPARROW model with detailed land-use data, recently made available at the 30-m scale for the United States, to estimate the transport and contributions of major diffuse phosphorus sources in US surface waters. A land-use based SPARROW model provides an alternative to the use of export coefficients, and illustrates the value of using generally available stream monitoring and land-use data to obtain empirical estimates of diffuse nutrient sources and transport in streams and reservoirs. Land-use based versions of the SPARROW model have been previously developed for selected watersheds in the United States and New Zealand (Alexander *et al.*, 2002a; McMahon *et al.*, 2003).

Data and model description

The SPARROW regression model of total phosphorus (TP) flux in streams (kg yr^{-1}; see model structure in Figure 1) was calibrated using 336 stations in the US Geological Survey's (USGS) national stream monitoring program (see Figure 2; Alexander *et al.*, 1998). Information on this program, including sampling and laboratory methods, is given in Alexander *et al.* (1998). Selected attributes of the stations and watersheds are given in Table 1. Mean-annual estimates of TP flux, the response variable in SPARROW, were estimated at each monitoring site for a 1992 base year using conventional load estimation techniques (Cohn *et al.*, 1989; see also Smith *et al.*, 1997). The selected monitoring stations satisfied minimum data requirements (>30 TP values; >10 years of daily flows) and had a standard error of the mean flux of less than 20%. Surface-water flow paths are defined for approximately 62,000 stream reaches using a 1:500,000-scale river network for the United States for which water flow, water time of travel, reservoir/lake storage properties (~2,300 waterbodies), and watershed boundaries (based on 1-km digital elevation models) are available (Nolan *et al.*, 2002). The Anderson level II land-use classification of the reach catchments was developed from the NLCD 92 (1992 National Land Cover Data; Vogelmann, 2001) 30-m resolution Landsat 5 Thematic Mapper (TM) satellite data. Soils characteristics are from STATSGO (Wolock, 1997).

The model structure (Figure 1) and supporting equations are described in detail in Smith *et al.* (1997) and Alexander *et al.* (2002a). In-stream mean-annual TP flux (TP_i) at the downstream end of a given monitored reach i is expressed as the sum of all monitored and unmonitored sources of phosphorus in the set of upstream reaches denoted by $J(i)$. The defined set of upstream reaches for the given reach i accounts for nested watersheds in the monitoring network by excluding reaches at or above an upstream monitoring station and including as a source to basin i all monitored loads at stations adjoining nested basin i. An estimable expression for TP_i is written as

$$TP_i = \left\{ \sum_{n=1}^{N} \sum_{j \in J(i)} S_{n,j} \beta_n \exp(-\alpha' Z_j) \prod_m \exp(-k_m^s T_{i,j,m}) \prod_l \frac{1}{1 + (k^r q_{i,j,l}^{-1})} \right\} \varepsilon_i \qquad (1)$$

where $S_{n,j}$ is phosphorus mass from land-use source n in the drainage of reach j; β_n is a land-use-specific coefficient; $\exp(-\alpha' Z_j)$ is a factor affecting the proportion of available

phosphorus mass delivered to reach j as a function of land-to-water delivery coefficients (defined by vector α) and associated landscape properties (e.g. soil permeability), Z_j (expressed as a deviation from mean levels), in the drainage to reach j; $\exp(k^s_m T_{i,j,m})$ is the proportion of phosphorus mass in reach j transported to downstream reach i as a function of a first-order loss process in streams defined by the water time of travel (T) and an estimated loss rate (k^s_m) for reaches in each streamflow class m; $1/(1+(k^r q^{-1}_{i,j,l}))$ is the proportion of phosphorus mass in reach j transported to downstream reach i as a function of a first-order loss process in lakes and reservoirs (e.g. Kelly *et al*., 1987) defined by an estimated net settling velocity coefficient (k^r) and the areal hydraulic load (q: ratio of outflow discharge to water-surface area) for l reservoirs located between reaches i and j; and ε_i is a multiplicative error term assumed to be independent and identically distributed across independent sub-basins in the intervening drainage between stream monitoring sites. The reciprocal of the land-to-water delivery factor, Z_j^{-1}, was applied for drainage density where a positive relation to stream flux was expected. Coefficient estimation was performed on the log transforms of the summed quantities in Eq. (1) using non-linear least-squares estimation (Smith *et al*., 1997).

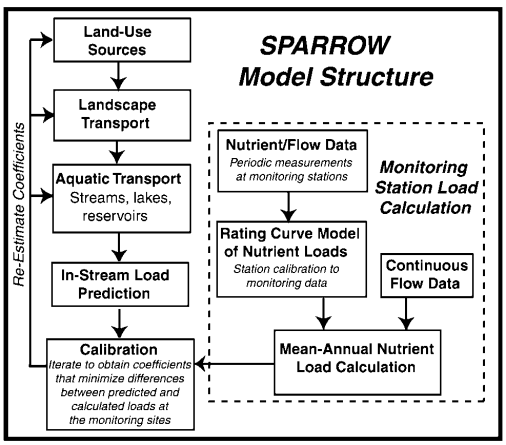

Figure 1 SPARROW land-use based nutrient model structure. Modified from Alexander *et al*. (2002a)

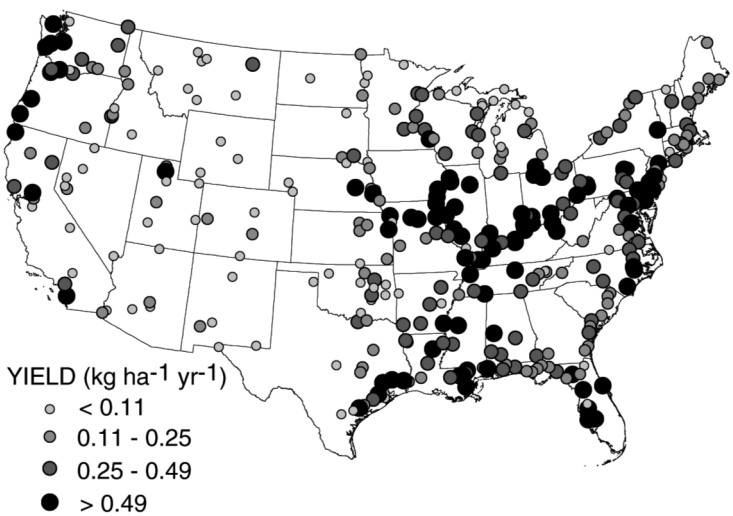

Figure 2 Mean-annual estimates of total phosphorus yield at 336 USGS stream monitoring sites in the United States

Table 1 Selected water-quality and watershed characteristics for the 336 stream monitoring sites

Station Metric	Minimum	25th	Median	75th	Maximum
Total phosphorus					
Flux (metric tons yr^{-1})	0.32	75.8	312	912	124,860
Concentration (mg l^{-1})	0.01	0.06	0.10	0.18	0.98
Yield (kg ha yr^{-1})	0.001	0.12	0.25	0.49	7.2
Number of observations	30	96	130	157	2,399
Streamflow (m^3 s^{-1})	0.59	28.2	79.8	261	18,204
Runoff (cm yr^{-1})	2	14	32	47	205
Drainage area (km^2)	84	3,527	13,655	41,570	2,919,670

Model calibration

Values of mean-annual TP flux (kg yr^{-1}; Table 1), the SPARROW response variable, span about five orders of magnitude at the monitoring stations. Corresponding TP yields are shown in Figure 2, and range from 0.09 to 722 kg km^{-2} yr^{-1} with station yields differing by about a factor of five over the interquartile range (Table 1). The highest TP yields occur in the northern central portion of the US where the predominant sources are agricultural, consisting primarily of corn and soybean row crops. High yields are also evident along the heavily populated eastern coastal areas and in many southern agricultural watersheds draining to the Gulf of Mexico. Relatively low TP yields are found in the arid western regions of the US, which are dominated by shrub and grass lands.

The SPARROW TP model explains 87% of the spatial variability in the log-transformed values of mean-annual TP flux at the monitoring stations. Model predictions of TP yield are typically within –31 to 46% (interquartile range; median = 4.2%) of the calculated TP yields. The root mean square error of ±74% gives an estimate of the mean error expected for a reach-level prediction. The regression residuals were evaluated for normality and constant variance and were found to provide acceptable adherence to these model assumptions. Moderate under-predictions occurred for stations in the far western portion of the Pacific Northwest, where extreme runoff conditions exist (>100 cm yr^{-1}), and in the agricultural mid-continent region of the US. A regional coefficient was successfully estimated in the final model (Table 2) to correct for under-predictions in the mid-continent region.

The estimated model parameters appear in Table 2. We estimated phosphorus source contributions for four land-use classes, including cultivated, urban, forest, and shrub/grasslands. Cultivated lands were separated into three classes: row crops, small grains/fallow land, and pastureland. Pasturelands include areas with grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops. The urban source coefficient reflects TP contributions from both point and diffuse sources in urban land areas. The land-use coefficients (β) in Table 2 describe the yield of phosphorus delivered to waterbodies for mean levels of the land-to-water delivery factors (α). With the exception of small grains/fallow land and shrub/grasslands, all land-use coefficients were statistically significant ($p<0.02$). A mean coefficient of 1.23 kg ha^{-1} yr^{-1} was estimated for row crops in regional watersheds of the mid-continent areas of the Mississippi River Basin. This regional row-crop coefficient was estimated to correct under-predictions of TP flux in these areas in initial models; the coefficient may reflect higher corn and cotton fertilizer application rates in these regions (ERS, 1994) and additional P contributions from soils in areas of the Lower Mississippi Basin (Coupe, 2002). TP flux in streams was negatively related to the permeability of soils indicating that higher TP flux occurs in watersheds with lower soil permeability. This is consistent with previous USA SPARROW models (Smith *et al.*, 1997), and potentially reflects higher phosphorus delivery to streams via surface runoff and tile drainage in areas of low soil permeability. Drainage density was positively

Table 2 SPARROW spatial regression model coefficients for total phosphorus [Mississippi regional watersheds include the Ohio, Tennessee, and the Upper and Lower central valleys of the Basin. *Q* is the mean-annual streamflow of each reach.]

Model parameters	Coefficient units	Estimated coefficient	Standard error	Statistical significance (p)
Phosphorus source (β), [delivery to streams for mean land-to-water loss]				
Cultivated land				
Row crops	kg ha^{-1} yr^{-1}	0.33	0.14	0.0190
Row crops (*Mississippi Basin regional watersheds*)	kg ha^{-1} yr^{-1}	1.23	0.38	0.0007
Small grains, fallow	kg ha^{-1} yr^{-1}	0.08	0.14	0.5656
Pasture	kg ha^{-1} yr^{-1}	1.20	0.27	<0.0001
Urban land	kg ha^{-1} yr^{-1}	3.63	0.75	<0.0001
Forest land	kg ha^{-1} yr^{-1}	0.19	0.03	<0.0001
Shrub and grasslands	kg ha^{-1} yr^{-1}	0.06	0.04	0.1391
Land-to-water loss coefficient, α				
Soil permeability	hr. cm^{-1}	0.0427	0.0204	0.0374
Drainage density	km^{-1}	0.0103	0.0107	0.3361
In-stream loss rate, k^s				
k_1 ($Q < 2.8$ m^3 s^{-1})	day^{-1}	0.195	0.091	0.0322
k_2 (2.8 m^3 s^{-1} < Q < 14.2 m^3 s^{-1})	day^{-1}	0.068	0.041	0.1023
k_3 ($Q > 14.2$ m^3 s^{-1})	day^{-1}	0.012	0.023	0.6140
Reservoir loss rate, k^r	m year^{-1}	14.3	3.7	0.0001
Model r-squared		0.87		

related to TP flux in streams. The in-stream loss rate coefficients (k^s) quantify the first-order rate of in-stream phosphorus loss per unit of water travel time (for example, $k_2 = 6.8\%$ removal of phosphorus per day of water travel time). The rate of TP loss declines with increasing channel size from 0.195 per day of water travel time in small channels to 0.012 per day in large channels. These rates are appreciably lower than estimated by a previous SPARROW TP model for the USA (Smith *et al.*, 1997), but are consistent with the previously observed inverse relation with channel size. This inverse relation is consistent with theories about the physical and biological mechanisms explaining nutrient removal in streams (Stream Solute Workshop, 1990). The contact and exchange of stream waters with the benthic sediments, light penetration, and algal activity are generally expected to decline with increasing stream depth, leading to decreases in the rates of phosphorus loss from biological uptake and sedimentation (Peterson *et al.*, 2001). The estimated TP settling velocity for lakes and reservoirs (k^r) of 14.3 m yr^{-1} describes a mean-annual net rate of phosphorus removal; this rate falls within the range of 5 to 20 m yr^{-1}, which is typically observed in North American and European lakes (Chapra, 1997). Model estimates of the fraction of TP inputs that are removed in reservoirs decline with increasing rates of water flushing (i.e. areal hydraulic load) of reservoirs.

Model predictions

SPARROW predictions of TP flux and yield and their source shares associated with each of the land-use classes were generated for the approximately 62,000 stream reaches in the United States.

Limited confirmation of the SPARROW estimates of TP yield (kg ha^{-1} yr^{-1}) was obtained for specific land uses (Figure 3) through comparisons with TP yield rates reported in the literature for North American watersheds with relatively uniform land cover (Beaulac and Reckhow, 1982; Frink, 1991). SPARROW TP yield predictions were selected for hydrologically independent watersheds with relatively uniform land use (i.e. more than 90% of the TP yield is from a single land use). Watersheds ranged from 1 to 9,500 km^2

(interquartile range = 30–200 km^2); these watersheds are typically larger than those reported in the literature and reflect the effects of cumulative TP losses with increasing watershed size. In general, the range of TP yields reported in the literature is large, reflecting local variations in natural and cultural factors, but median yields from major land types are typically less than about 2 kg ha^{-1} yr^{-1} (Beaulac and Reckhow, 1982). SPARROW cropland yields (interquartile range = 0.3 to 1.2 kg ha^{-1} yr^{-1}; median = 1.1 kg ha^{-1} yr^{-1}; watersheds consisting predominantly of row crops, small grains, and fallow lands) are generally less than the median of literature yields for row crops and mixed agriculture (1.6 kg ha^{-1} yr^{-1}). The SPARROW yields for pasture and urban lands are similar to the median of literature TP yields. Reported literature TP yields for forested watersheds are typically less than 0.5 kg ha^{-1} yr^{-1}, which is similar to those estimated by SPARROW.

The relative contributions of land uses to the phosphorus loads at the 336 monitoring sites are shown in Figure 4. Model predictions of the TP sources in streams are compared with the percentage of the total drainage area in each land-use class. Diffuse sources account for more than 85% of the phosphorus contributions in a majority of these streams given that urban sources, which include municipal and industrial point sources, are typically less than 15%. A disproportionately larger fraction of the stream TP flux originates from pasture and urban lands in relation to the area of the watersheds in these specific land uses. This result stems from the relatively high yield rates estimated for these land types. For example, the percentage of the stream flux originating from pasturelands is about three times the fraction of the drainage areas in pastureland. By contrast, many of the watersheds have more than 40% of their drainage area in forest (and large fractions of shrub/grass in the western US); however, the percentage of the TP flux originating from these land types is typically less than 20%, or less than half of their percentage share of drainage area. Cropland typically represents less than about 20% of the drainage area of a majority of the monitored watersheds. The percentage contributions from cropland to TP flux at the sites are estimated to be about the same magnitude as the fraction of the drainage areas in cropland. Although this result is consistent with the estimated yields in the model, somewhat higher percentage contributions from cropland might be generally expected in view of the higher TP yields reported in the literature for cropland-dominated watersheds as compared to those reported for other land uses (Figure 3). This result may be potentially explained, in part, by inaccurate NLCD classifications of row crops as pastureland in some US regions and will require additional evaluation.

A phosphorus budget (Table 3) was developed for the Mississippi River Basin and four

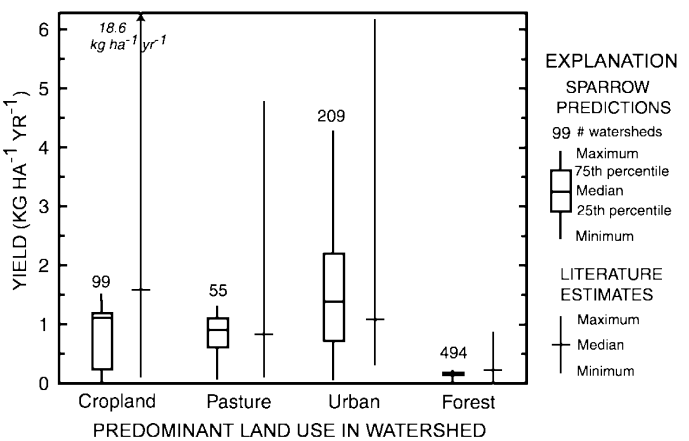

Figure 3 SPARROW and literature estimates of total phosphorus yield by land-use type. Literature rates for cropland reflect an average of the rates for watersheds with mixed agriculture and row crops

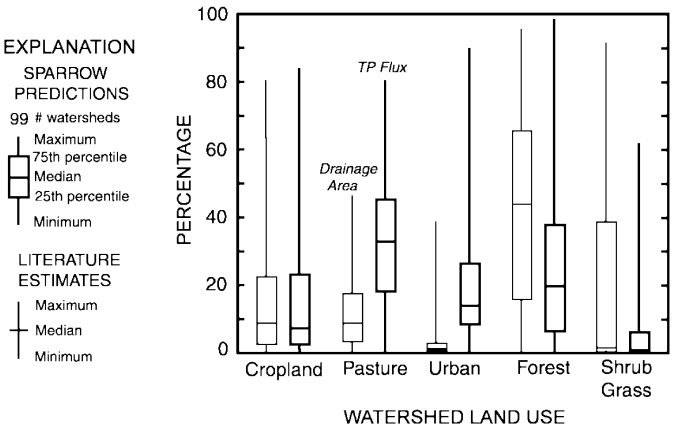

Figure 4 Percentage of monitoring station drainage area in a specified land use and the percentage land-use contributions to total phosphorus (TP) flux at the 336 stream monitoring stations

major interior watersheds (Figure 5) to illustrate the use of the model for estimating phosphorus transport to streams (i.e. "landscape yield") and watershed outlets ("watershed yield") for individual sources. In-stream and reservoir losses of TP account for differences between these two yield rates. Most of the phosphorus exported from the Mississippi River to the Gulf of Mexico originates predominantly from agricultural sources (77%) with cropland representing nearly 60% of this share. Urban sources (14%) represent the next largest source. Most of the TP exported to the Gulf from the Mississippi River originates in the Upper Mississippi and Ohio/Tennessee basins (72%) where both agricultural and urban sources are large (Table 3). These basins also have smaller TP losses (29 to 39%) in streams and reservoirs than occur in either the Missouri or the Lower Mississippi/Arkansas Basins. Negligible quantities of TP originate in the Missouri Basin where sources are generally small because of the predominant low TP yielding shrub and grasslands and the removal of large quantities of TP in reservoirs and streams. The areal hydraulic loads of Missouri reservoirs are considerably lower (about 1/5th) than those in the Upper Mississippi and Ohio/Tennessee basins. Thus, the fractions of TP removed in reservoirs of the Missouri Basin are higher by a factor of two or more. Streams of the arid Missouri Basin have much longer water travel times, which also accounts for higher phosphorus losses in this basin.

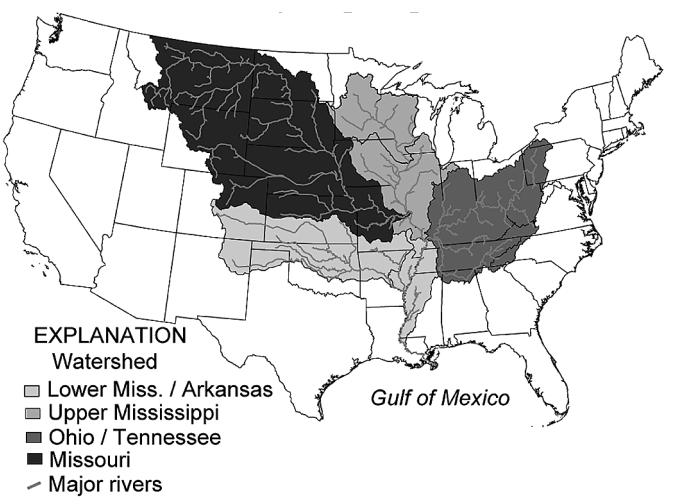

Figure 5 Mississippi River Basin and interior watersheds

Table 3 Total phosphorus (TP) budget for the Mississippi River Basin and four major interior watersheds

Watershed	Drainage area (km^2)	Land use[#] (% of drainage area)						Landscape yield[*] ($kg\ ha^{-1}\ yr^{-1}$)	Aquatic TP loss[+] (%)	Watershed yield ($kg\ ha^{-1}\ yr^{-1}$)	Sources of watershed yield (% of watershed yield)				
		C	P	U	F	SG	O				C	P	U	F	SG
Mississippi	2,919,600	28	13	2	22	30	5	0.42	47	0.22	44	33	14	9	1
Upper Miss.	446,700	48	18	3	20	2	9	1.06	39	0.65	62	23	12	3	<1
Ohio/TN	524,000	19	19	3	55	<1	4	0.80	28	0.58	37	34	16	14	<1
Missouri	1,307,200	28	9	1	9	51	2	0.27	64	0.10	24	54	13	5	3
Lower Miss.[@]	641,700	21	13	3	23	31	9	0.40	70	0.12	38	30	14	15	3

[#] Land-use classes are "C" (total cropland consisting of row crops, small grains, and fallow land), "P" (pasture), "U" (urban), "F" (forest), "SG" (shrub, grasslands), and "O" (other includes water, wetlands, and barren lands)

[*] Yield reflecting the delivery of phosphorus to streams and reservoirs from all sources

[+] Phosphorus removed in streams and reservoirs as a percentage of the quantities of phosphorus delivered to water bodies from all sources

[@] Estimates are computed as differences in drainage area and source fluxes near the outlet of the Lower Mississippi/Arkansas Basin (Belle Chasse, Louisiana) and the sum of those at the outlets of the Upper Mississippi, Ohio, and Missouri Basins. These calculations assume that phosphorus diversions to the Atchafalaya River Basin are identical to that known for streamflow (22 per cent). The Atchafalaya River serves as an alternate flowpath to the Gulf of Mexico accounting for a total of 30 per cent of the total flow of the two rivers

We compared the SPARROW predictions with those of a previous regression model (Goolsby *et al.*, 1999) that used aggregate measures of fertilizer, manure, and point sources in 42 monitored watersheds in the Mississippi Basin. The SPARROW model predicted moderately larger agricultural contributions (77% vs. 48%). SPARROW predicted that urban sources contribute 14% of the TP flux compared with the previous model estimates of 10% from municipal and industrial point sources. The earlier model (Goolsby *et al.*, 1999) attributed 42% of the phosphorus delivered to the Gulf of Mexico to unspecified phosphorus inputs that are correlated with water runoff.

Conclusions

SPARROW provides a watershed modeling technique for empirically estimating the rates of nutrient supply and loss during transport in surface waters. The land-use based application to TP measurements in streams demonstrates the utility of the model for quantifying natural and cultural diffuse sources, including phosphorus originating from agricultural, urban, and forested lands. The model identified appreciable effects of soils, streams, and reservoirs on phosphorus transport. The wide range of phosphorus losses in streams and reservoirs of the Mississippi River Basin (i.e. 28 to 70% of the external TP inputs to waterbodies) reflects regional differences in the physical and hydrologic properties of streams and reservoirs that affect biological processing of phosphorus and sedimentation. In general, lower rates of phosphorus removal were observed in deeper stream channels and more rapidly flushed lakes and reservoirs. The relatively conservative behavior of phosphorus in medium to large rivers (>14.2 $m^3 s^{-1}$) suggests that, in the absence of reservoirs, phosphorus is potentially transported over thousands of kilometres in rivers such as the Mississippi, similar to that observed for nitrogen in a previous study (Alexander *et al.*, 2000). The use of spatially referenced watershed properties in SPARROW provides a useful technique for obtaining spatially consistent estimates of nutrient transport over large spatial scales. Evidence of the nonlinear transport of phosphorus, including nonlinear interactions between loss processes and phosphorus sources related to both their location and magnitude, suggest that export coefficients from small catchments cannot be reliably extrapolated to large watersheds without accounting for these interactions.

The detection of regional differences in TP yields for row crops (i.e. Mississippi River Basin) suggests that the use of intensive measures of agriculture, such as those included in previous SPARROW models, are likely to better account for regional and local differences in fertilizer application rates and animal stocking densities. The use of intensive measures as predictors in the model may also reveal the cause of the relatively low row crop coefficient (0.33 kg km^{-2} yr^{-1}) for areas outside of the Mississippi Basin. Because row crops account for a relatively small fraction of the land area in most of the calibration watersheds (i.e. <20%), the model may have difficulty distinguishing one basin from another in the absence of more direct measures of phosphorus inputs from fertilizers. The use of additional monitoring stations in small, homogeneous watersheds may assist in estimating phosphorus yields from row crop agriculture, and help to improve the accuracy of future nutrient models. In addition, the effects of possible inaccuracies in the NLCD land-use classification of row crops and pasturelands on the model predictions will also need to be investigated. The inclusion of intensive measures of municipal and industrial point sources (e.g. sewered population, wastewater loads) may also assist in obtaining more specific estimates of urban point and diffuse sources.

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