A LANDSCAPE SCALE EVALUATION OF PHOSPHORUS RETENTION IN WETLANDS OF THE LAPLATTE RIVER BASIN, VERMONT, USA

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ABSTRACT

We used a landscape scale approach to examine phosphorus retention in wetlands of the LaPlatte River basin (13,723 ha), Vermont. Total phosphorus (TP) export from 15 study catchments (149-1,396 ha) was measured on 18 dates, representing a range in seasons and hydrologic conditions. Multiple regression models were developed to relate TP export to 14 possible explanatory variables based on land cover/use, quantified using a geographic information system. Most wetland variables had significant ($p < 0.10$) negative relationships with TP export on at least 1 date. These relationships were strongest on 2 spring snowmelt events, when 31% of the annual TP export from the LaPlatte River basin occurred. Overall, the percentage of nonagricultural poorly and very poorly drained soils was the best representation of phosphorus sinks in the study catchments. Identifying lands with poorly drained soils and no known sources of phosphorus may be a more functional and simpler method of delineating P sinks in the landscape than identifying wetlands using jurisdictional definitions.

1. INTRODUCTION

Phosphorus (P) cycling in wetlands has received much attention in recent years because P is the nutrient most commonly associated with cultural eutrophication, and because of the general notion that wetlands can improve water quality. The ability of wetlands to reduce P transport from source areas to receiving waters has been demonstrated; wetlands have been used to reduce P transport from point sources and

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wastewater treatment systems (e.g., Boyt et al., 1977; Fetter et al., 1978; Tilton and Kadlec, 1979; Begg et al., 2001), and, more recently, from nonpoint sources of P (e.g., Mitsch and Reeder, 1992; Chambers et al., 1993, Weller et al. 1996; Uusi-Kamppa et al. 2000; Kao and Wu, 2001). Nutrient budget studies of individual wetlands suggest that a wetland's ability to retain P varies with season, hydrology, and wetland type (e.g., Klopatek, 1975; Lee et al.; 1975; Peverly, 1982; Gehrels and Mulamoottil, 1989; Mitsch and Gosselink, 1993; Kadlec and Reddy, 2001; Sanchez-Carrillo and Alvarez-Cobelas, 2001). In addition, prolonged or exceedingly high inputs of P to wetlands may cause P binding sites to become saturated, reducing the wetland's ability to retain P (Howard-Williams, 1985; Drizo et al., 2002). Because of the variability in P retention in wetlands (e.g., Bridgham et al., 2001), extrapolation of results from studies of specific wetlands to wide geographic regions may be inappropriate.

Wetland functions are commonly studied intensively at the scale of an individual wetland. Public policies and strategies for P management and wetland conservation, however, are usually developed on a regional basis. Thus, managers require tools to evaluate wetland function at this broader scale. Methods have been developed to evaluate wetland functions based on visual characteristics and limited field measurements (e.g., Adamus, 1983; Adamus et al., 1987; Amman and Stone, 1991). Efforts are also underway to develop regional classification systems based on wetland functions and values (e.g., Brinson, 1993). Existing functional evaluation methods relating nutrient retention and wetland characteristics, however, are often based on limited scientific evidence. Techniques are needed for collecting empirical data on P retention in wetlands at a landscape scale to refine regional functional evaluation methods (Weller et al., 1996).

The majority of catchment P studies has focused on identifying areas of high P export. Regression analysis is often used to establish relationships between catchment P export and the area of land use and land cover types (e.g., Omernik, 1976; Devito et al., 2000). Predictive equations have been developed and applied regionally. This information is used to prioritize areas for nonpoint source P management (Tim et al. 1992; Wickham et al. 2000). However, reliable coefficients for wetlands or other areas of P storage are not generally available, despite their potential influence on P export from catchments (Meade, 1982). Literature values for predicting P retention by the diversity of wetland types in a catchment are generally unavailable.

Multiple linear regression (MLR) analysis and a geographic information system (GIS) has been used to explore the collective function of wetlands at a landscape scale (Eckhardt and Moore, 1990; Johnston et al., 1990); generally finding some significant relationship between wetlands and nutrients in surface waters. An investigation of wetlands in the Lake Champlain basin, Vermont suggests that riparian wetlands are more important than other wetland types for reducing catchment P export (Weller et al., 1996). Because of the variability in wetland function across wetland types and physiographic regions, landscape scale evaluations of the collective function of wetlands within relatively homogeneous regions are needed to inform local planners when making regulatory decisions and prioritizing wetlands for conservation. Our study examined P retention in wetlands in an agricultural basin in northwestern Vermont to better understand the influence of different wetland types on P export during a range of seasons and hydrologic conditions.

2. METHODS

2.1 Study Area

Our study was conducted in the LaPlatte River basin, located 16 km south of Burlington, Vermont (Figure 1). The LaPlatte River originates in the foothills of the Green Mountains and flows northwesterly 24 km before emptying into Shelburne Bay, Lake Champlain. The 13,723-ha basin encompasses two physiographic regions, the Champlain Lowland and the foothills of the Green Mountains. The Champlain Lowland comprises approximately 80% of the basin and is dominated by limestone, dolomite, and shale bedrock overlain by post-glacial lacustrine deposits of sands, silts, and clays. Bedrock in the foothills of the Green Mountains, the eastern 20% of the basin, is primarily schist, gneiss, and phyllite. Glacial till occurs in smaller portions of the basin within both physiographic regions (U.S.D.A. Soil Conservation Service, 1989). Basin topography is dominated by the flat to gently sloping Champlain Lowland; elevation ranges from approximately 30 m above sea level at Shelburne Bay to 500 m in the foothills. The climate is cool and humid, with a mean annual precipitation of 84 cm, and a mean annual snowfall of 198 cm (National Oceanographic and Atmospheric Administration, 1995).

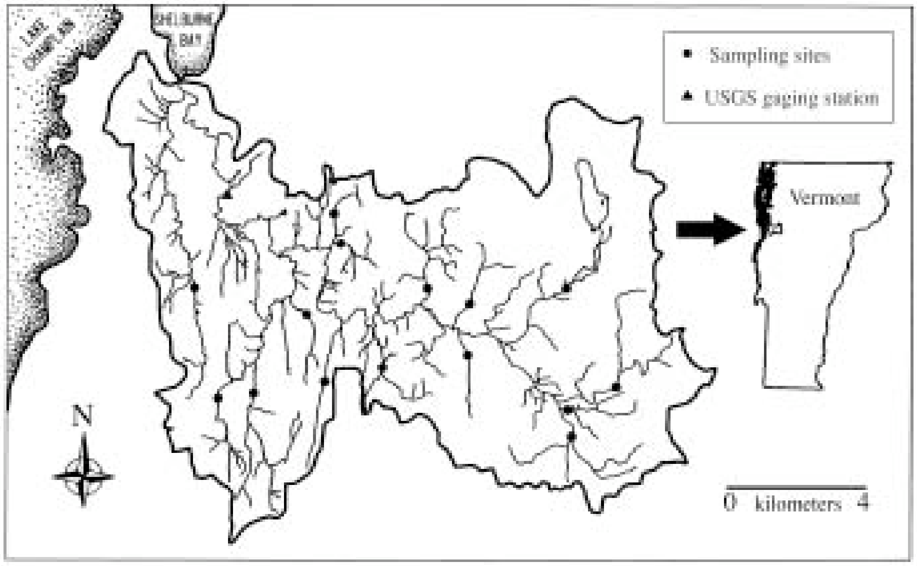

Figure 1. The stream network and sampling locations in the LaPlatte River Basin, Vermont.

Agriculture and forest characterize most of the LaPlatte River basin. Agricultural land predominates the Champlain Lowland and consists primarily of pasture and hay fields associated with the basin's 40 dairy farms (Meals, 1993). Hemlock-northern hardwood forests occupy most of the foothills of the Green Mountains and scattered patches throughout the Champlain Lowland. Urban land, primarily residential and recreational, comprises approximately 16% of the basin. Wetlands occupy approximately 7% of the basin and range in size from less than 1 to greater than 70 hectares. Wetlands are primarily associated with the riparian zone of the stream network; a small number occur in isolated depressions and on slopes within groundwater discharge zones.

We selected 15 relatively large catchments (149-1396 ha) within the LaPlatte River basin to evaluate the influence of wetlands on P export at the landscape scale. For measuring P export from each catchment, we selected individual stream reaches based on accessibility and the feasibility of measuring discharge (Figure 1). These stream reaches defined the outlet for each study catchment. All stream sampling sites were located upstream of town centers and known point source discharges of P, permitting the estimation of nonpoint source P export.

2.2 Spatial Analysis

The area of general land use and land cover types within each catchment was quantified from GIS coverages of catchment boundaries, land use, and wetlands using ARC/INFO (version 7.0.3, Environmental Systems Research Institute, Redlands, CA). Catchment boundaries were delineated on U.S.G.S. 7.5 minute topographic maps and verified in the field, particularly in areas of low relief. A GIS coverage was created by digitizing the catchment boundaries using ARC/INFO. This catchment boundary coverage was used to extract land use and land cover data for each study catchment. We used this data to develop explanatory variables for use in multiple regression analyses.

The base land use coverage selected for this study was developed from 1988 1:5000 panchromatic orthophotographs and updated with field surveys in 1990 as part of other studies. The overall accuracy of the linework was reported as +/- 25 m (Appleton, 1993). The land use coverage followed a classification system that was adapted for use in Vermont (Vermont Geographic Information System, 1992) from the Anderson land use and land cover system (Anderson et al., 1976).

We conducted further field surveys and orthophotograph analyses to provide a more accurate representation of the 1994-5 land use in the basin. Because the 1990 land use coverage provided no distinction among types of agricultural lands, the boundaries of all row cropland in the study area were mapped onto 1:5000 orthophotographs during summer field surveys in 1995, and digitized into the base coverage. In addition, a considerable amount of land classified as agricultural in the coverage was no longer in production; therefore, these areas were reclassified as transitional lands.

The documentation provided with the base land use coverage (Appleton, 1993) and preliminary field surveys in 1994 suggested that the coverage underestimated the area of wetland. A more recent coverage of wetlands in the entire LaPlatte River basin, prepared by Goldsmith (1994), was used to improve the base land use coverage. Goldsmith's wetland coverage was based on interpretation of National High Altitude Photograph (NHAP) color infrared imagery, enlarged to a scale of 1:20,000 from an original 1:58,000. Wetland boundaries were rectified using 1988 1:5000 orthophotographs. The incorporation of Goldsmith's wetland coverage into the base land use coverage increased the represented wetland area in the LaPlatte River basin from 367 ha to 1023 ha. This wetland coverage was overlayed onto the base coverage. Areas within study catchments coded as wetland on the base coverage and not coded as wetland on Goldsmith's coverage were checked in the field; all were determined to be wetland areas and were retained in the final coverage. The WET explanatory (or independent) variable (Table 1) includes these revisions in wetland area represented in the land use coverage.

Table 1. Description and codes for explanatory variables used in regression models. Explanatory variables are not completely independent and capture overlapping concepts, expecially with respect to wetland characteristics.

Explanatory Variables	Code
Land use and land cover	
Agriculture	AG
Row crops	CROP
Agricultural land excluding crops	NONCROP
Forest	FOREST
Single family residential and recreational	RESREC
Wetland	
Wetlands, lakes, and ponds	WET
Forested and scrub-shrub wetlands	WOODY
Emergent and open water wetlands	NONWOODY
Mixed emergent and scrub-shrub wetlands	PEM/SS
Nonagricultural wetlands, lakes, and ponds	NAWET
Lakes, temporarily flooded wetlands and seasonally flooded wetlands	RIVERINE
Lakes, ponds, and wetlands isolated or along first order streams	HEADWATER
Wetlands along second or third order streams	HIORDER
Poorly and very poorly drained soils excluding agriculture	HYDRIC

We categorized wetlands in various ways to better understand the role of different wetland types on catchment P export. Thus these predictor variable are not independent of each other, but attempt to capture different aspects of wetland characteristics. A commonly used classification of wetlands is by vegetation type (e.g, Cowardin et al., 1979). Therefore, we separated wetlands into three vegetation types, Woody, Nonwoody, and palustrine-emergent marsh/shrub-scrub PEM/SS (Table 1) and examined relationships between these wetland types and TP export.

Many wetlands in the LaPlatte River basin are used to graze livestock. Because livestock can contribute to high P export from catchments, wetlands used for pasture may act as P sources in the landscape, rather than P sinks. Therefore, we excluded the area of wetlands impacted by livestock from the total wetland area (WET), resulting in a new wetland variable, NAWET (Table 1).

P retention in wetlands may be related to periodic flooding regimes, depressions with distinct inflows and constricted outflows, diffuse channels, and dense vegetation. We identified wetlands with these characteristics from field surveys and used the area of these wetlands as a separate wetland variable. Because most of these wetlands were associated with stream channels, the variable was coded as RIVERINE (Table 1). Wetlands exluded from this category include wetlands located on slopes and wetlands with permanent standing water.

The overall influence of wetlands on catchment P export may be related to the spatial distribution of wetlands along the stream network. We distinguished among wetlands by their proximity to different stream orders. Wetlands without a connection to the perennial stream network or associated with first order streams were coded as HEADWATER (Table 1), and wetlands associated with second and third order streams were coded as HIORDER (Table 1).

Soil drainage data were used as an alternative to aerial photo-interpretation for inventorying wetlands in the study area. Most poorly and very poorly drained soils meet the hydric soils criteria in the Federal Manual for Identifying and Delineating Wetlands (Federal Interagency Committee for Wetland Delineation, 1989). The area of these drainage classes in each catchment was determined from an existing soils coverage of the LaPlatte River basin (U.S.D.A. Natural Resource Conservation Service, 1995). As with the NAWET variable, the area of agricultural land was excluded to eliminate agricultural sources of P. The resulting variable represented the area of nonagricultural poorly and very poorly drained soils, and was coded as HYDRIC (Table 1).

2.3 Water sampling and Chemical Analysis

Grab samples were collected at each sampling site (Figure 1) during 14 runoff events and 4 baseflow conditions from October 16, 1994 to October 15, 1995 (Figure 2). Sampling began the morning following major rain or snowmelt events and was completed within 10 hours. The tributaries were sampled in the approximate order of their position in the stream network: headwater sites were sampled first, followed by sites closer to the main stem of the LaPlatte River. The exact sampling order was varied on each date to reduce sampling bias. Water samples were packed in ice in the field and refrigerated at 4°C until analyzed.

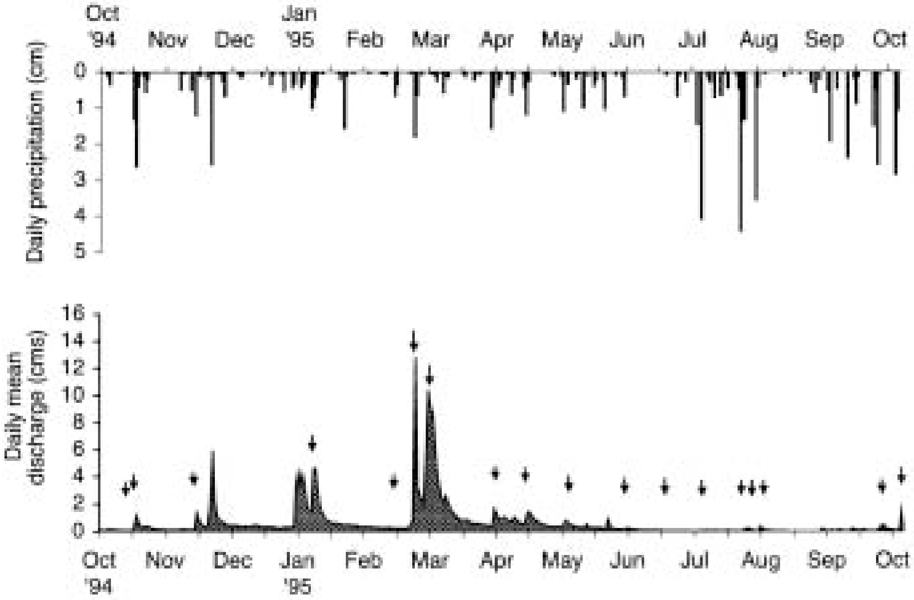

Figure 2. Daily precipitation in South Burlington, Vermont (10 km from the study area) and mean daily discharge of the LaPlatte River during the study period, October 16, 1994 to October 15, 1995. Arrows indicate stream sampling dates.

Samples were analyzed for concentrations of total P (TP) and soluble reactive P (SRP), a P fraction equal to orthophosphate (PO_4) plus a variable amount of labile organic P. TP was analyzed colorimetrically on a spectrophotometer using the molybdenum blue method following digestion in a sulfuric acid-persulfate solution (U.S. Environmental Protection Agency, 1983). SRP was measured on samples filtered using a

0.45 μm membrane filter via the molybdenum blue method within 48 hours of sample collection. The lower limit of detection for TP and SRP concentrations was 0.005 mg l^{-1}.

2.4 Streamflow and Phosphorus Export

We developed discharge rating curves using paired measurements of stage and flow for each sampling site over a range of hydrologic conditions. Stage was measured at each site from fixed points above or within the channel on each sampling date. Flow was measured on selected dates using a velocity-integrating flow meter according to the conventional mid-section method (Rantz, 1982). Where stream depths were too low to use the current meter (i.e., less than 4 cm), stream velocity was measured by timing floating objects over a known distance. At certain sites, low flow measurements were obtained by recording the time it took to fill a 4 l bucket below a culvert.

Discharge rating curves were developed for each sampling site according to Kennedy (1984). Exponential functions best described the flow vs. stage relationships at all sampling sites (range in $r^2 = 0.86$-0.99). Flow calculated from the rating functions using measured stage on each sampling date was multiplied by concentrations of TP and SRP to determine instantaneous exports from each study catchment. Where ice prevented accurate stage measurement or where extreme flow conditions altered the flow vs. stage relationship established in the rating curves, measured flow was used in the export calculation. TP and SRP exports were divided by the catchment area associated with each sampling site to normalize for catchment size in the statistical analyses.

Annual P export at the U.S.G.S. gaging station on the LaPlatte River main stem was estimated to compare the relative P loading during the events sampled. Total P concentration was determined for samples collected at the gaging station on each sampling date. P concentration data were also obtained from the Vermont Agency of Natural Resources (Smeltzer, 1996) for additional dates in the study year. The concentration data from both sources were used with corresponding mean daily discharge data provided by U.S.G.S. (Hammond et al., 1996) to estimate annual P export. The mean daily discharge on one date, March 8, 1996, was estimated by a hydrograph smoothing technique because of complications resulting from ice jamming at the gaging station. Annual P export was calculated according to a flow-stratified Beale Ratio Estimator method (BRE; Richards and Holloway, 1987; Preston et al., 1989). Daily P export on each sampling date was divided by the annual P export to determine the proportion of the annual P export on each date.

2.5 Data Analysis

We applied both simple and multiple linear regression analyses to explore relationships between P export and wetlands at the landscape scale. The dependent variable for all regressions was total P export (g ha^{-1} d^{-1}) and the explanatory variables were the 14 land use and land cover types, expressed as percentages of each catchment (Table 1). The number of explanatory variables in each regression model was limited to three to maintain adequate degrees of freedom. Relationships were evaluated by interpreting coefficients of determination (R_a^2), adjusted for the number of explanatory variables in the model, and p-values.

We used regression analysis in an exploratory manner to reduce the total number of explanatory variables to a reasonable subset for developing the final regression models. As an initial screening measure for selecting explanatory variables, we compared results of 2-variable models using TP export as the dependent variable and each land use and land cover type as the explanatory variable. For comparing wetland types, we developed separate models using 2 explanatory variables, the total agricultural variable and each wetland variable. Variables that explained a significant ($p < 0.10$) portion of TP export variance were selected for the final analyses. Multiple regression models using all combinations of the selected subset of explanatory variables were then evaluated to identify the combination that maximized the explained variance in TP export on each sample date.

Multicollinearity among explanatory variables can cause difficulties when interpreting regression coefficients and results of hypothesis tests. We avoided including variables expressing the same landscape characteristics in the same multiple regression models to reduce the effects of multicollinearity. In addition, we tested all combinations of explanatory variables for multicollinearity using the variance inflation factor (VIF, Neter et al., 1989). We excluded all combinations of explanatory variables having VIF values greater than 10 from the results presented.

We performed additional diagnostic tests on each regression model to determine if the assumptions necessary for conducting hypothesis tests and making inferences related to the slope coefficients were satisfied. We performed tests of normality (Shapiro-Wilks, $p < 0.05$) on the residuals and examined scatter plots of the residuals vs. predicted values. We applied a $\log_{10}$ transformation on the dependent variable, TP export, in some models to satisfy the constant variance assumption, thereby increasing our ability to interpret the models. The final regression models presented have both normally-distributed and homoscedastic residuals (Table 4). Given the exploratory nature of this work, no control for experiment-wise error was attempts.

3. RESULTS AND DISCUSSION

3.1 Land Use and Land Cover Data

Summary statistics calculated for each study catchment showed that most catchments were dominated by either agriculture or forest (Table 2). Forest land ranged from 3-77% of the study catchments, total agricultural land ranged from 5-75%, and residential and recreational lands ranged from 6-27%.

Wetlands represented smaller portions of the catchments than agriculture and forest (Table 2). Wetlands and surface waters (WET) ranged from 1-39% of the study catchments. Forested and scrub/shrub wetlands (WOODY) occupied less than 1% of most catchments, while NONWOODY and palustrine, emergent marsh/shrub-scrub (PEM/SS) wetlands were more evenly distributed. Approximately half of the catchments had a higher proportion of wetlands along second and third order streams (HIORDER) than along first order streams or in isolation from the stream network (HEADWATER). Most wetlands in the study catchments were associated with the stream network and had

Table 2. Land use and land cover percentages in 15 catchments of the LaPlatte River Basin. Catchment size is in hectares. Variable codes are described in Table 1.

ID	ha	AG	CROP	NON CROP	FOREST	RES REC	WET	WOODY	NON WOODY	PEM /SS	NA WET	RIV ERINE	HEAD WATER	HI ORDER	HYDRIC
1	1396	11.2	0.1	11.1	48.6	22.9	15.1	4.0	1.5	1.2	14.8	6.3	14.2	0.9	26.6
2	790	4.9	0.0	4.9	76.7	16.5	1.0	0.7	0.0	0.2	0.7	1.0	0.8	0.3	7.2
3	714	33.7	4.3	29.4	56.7	7.4	1.9	1.3	0.6	0.0	1.4	1.8	1.6	0.3	7.7
4	323	4.2	0.2	54.1	27.1	7.1	4.5	0.6	3.9	3.8	0.9	4.4	1.2	3.4	8.0
5	925	44.0	2.2	41.8	32.5	14.8	6.6	3.1	3.4	0.1	4.6	4.6	2.7	4.0	10.0
6	171	43.9	0.0	43.9	19.2	26.7	10.2	0.2	8.7	2.5	3.8	9.5	6.8	3.4	9.6
7	174	68.7	16.2	52.5	10.0	9.2	12.0	6.5	4.0	1.4	8.4	10.2	10.5	1.4	10.2
8	190	55.1	3.1	52.0	23.5	16.3	3.7	0.0	2.3	1.4	2.2	3.6	0.9	2.8	7.1
9	647	74.5	9.5	65.0	10.7	7.1	5.6	0.1	1.9	3.6	4.7	5.5	0.5	5.1	4.3
10	363	41.4	8.1	33.3	24.9	11.1	19.8	0.0	0.1	19.7	19.7	19.7	0.1	19.7	16.0
11	426	39.4	2.6	36.8	20.9	11.7	13.6	0.2	3.6	9.8	13.3	13.4	3.5	10.0	23.1
12	515	24.5	2.3	22.2	61.8	9.5	2.2	0.1	2.1	0.0	0.0	2.0	0.2	2.0	4.7
13	149	48.0	5.0	43.0	3.2	9.5	39.3	23.6	0.4	15.2	39.2	38.9	39.3	0.0	29.4
14	478	31.9	3.7	28.2	43.9	6.2	14.9	3.9	10.4	0.6	14.9	1.9	14.9	0.0	17.3
15	317	27.0	5.6	21.3	46.5	20.9	2.3	0.3	2.0	0.0	0.1	2.0	0.8	1.5	10.2

seasonal or temporary saturation water regimes (RIVERINE, 1-39%). The area of nonagricultural poorly and very poorly drained soils (HYDRIC) ranged from 4-29% of the catchments. Portions of this area included lands classified as residential, recreational, and forest lands in the base coverage.

3.2 Phosphorus Data

Stream P concentrations showed high spatial and temporal variability throughout the LaPlatte River basin during the study period. Total P (TP) concentrations ranged from 0.005 to 1.420 mg l^{-1} (Figure 3), while mean values at each site ranged from 0.020 to 0.550 mg l^{-1}. Most of the 223 observations of TP concentrations measured during the study period exceeded the 0.010 mg l^{-1} nutrient critera for rivers and stream (U.S. Environmental Protection Agency, 2001).

In general, high TP and SRP concentrations, and high SRP:TP ratios, were measured in streams draining agricultural catchments (e.g., Catchments 7, 8, and 9, Figure 3). Low SRP:TP ratios can be associated with agricultural catchments (Prairie and Kalff, 1986) due to the high particulate P often introduced where erosion potential of exposed soil particles is high. High SRP:TP ratios, however, have also been observed in heavily fertilized catchments. Exceptionally high TP concentrations were measured in a stream draining Catchment 15 (Figure 3a), which contained only 27% agricultural land. This stream received runoff from a ditch draining a concentrated livestock area. This livestock area acted as a point source of P because of the high concentrations (Figure 3a) produced from a relatively small area. Because this site was an easily identified outlier in preliminary regression models and repeatedly exerted a disproportionate influence on the calculation of regression equations, it was excluded from the results presented.

The lowest P concentrations were measured in streams draining catchments with high proportions of lakes and wetlands. The stream draining the catchment with the largest lake area (Catchment 1), had the lowest mean TP concentration for all dates sampled, 0.020 mg l^{-1}, and had the lowest variability in TP concentration throughout the study year (sd = 0.006, Figure 3a). This low variability reflects the moderating effect that lakes have on instream nutrient levels (Uttormark et al., 1974; Moustafa, 2000).

The temporal variability observed in instream P concentrations was partially related to the magnitude of streamflow. The highest TP concentrations and the highest TP exports (Figure 3) occurred on the highest flow event sampled, March 8, 1995 (Figure 2). Estimates of the total annual streamflow and P export at the U.S.G.S. gaging station (Figure 1) showed that approximately 10% of the total annual discharge and 31% of the total annual TP export (2405 kg) occurred on the two snowmelt dates sampled, March 8, 1995 and March 14, 1995. A similarly disproportionate export of P during high flow events was previously observed in the LaPlatte River by Meals (1985) and in other river systems (e.g., Johnson et al., 1976; Ellis et al., 1978; Monke et al., 1981; Lowrance et al., 1984; Paschal and Sherwood, 1987; Pionke et al., 1988; Longabucco and Rafferty, 1989).

Relationships between TP concentration and streamflow at each tributary were examined further using linear regression analysis. Regression models were developed using TP concentration (mg l^{-1}) as a dependent variable and measured streamflow (m^3 s^{-1}) as an explanatory variable. Only six models had significant positive linear relationships ($p < 0.10$) and each relationship was dominated by either one or two outlying data points. Log_{10} transformation of TP concentrations and discharge did little to improve the relationships.

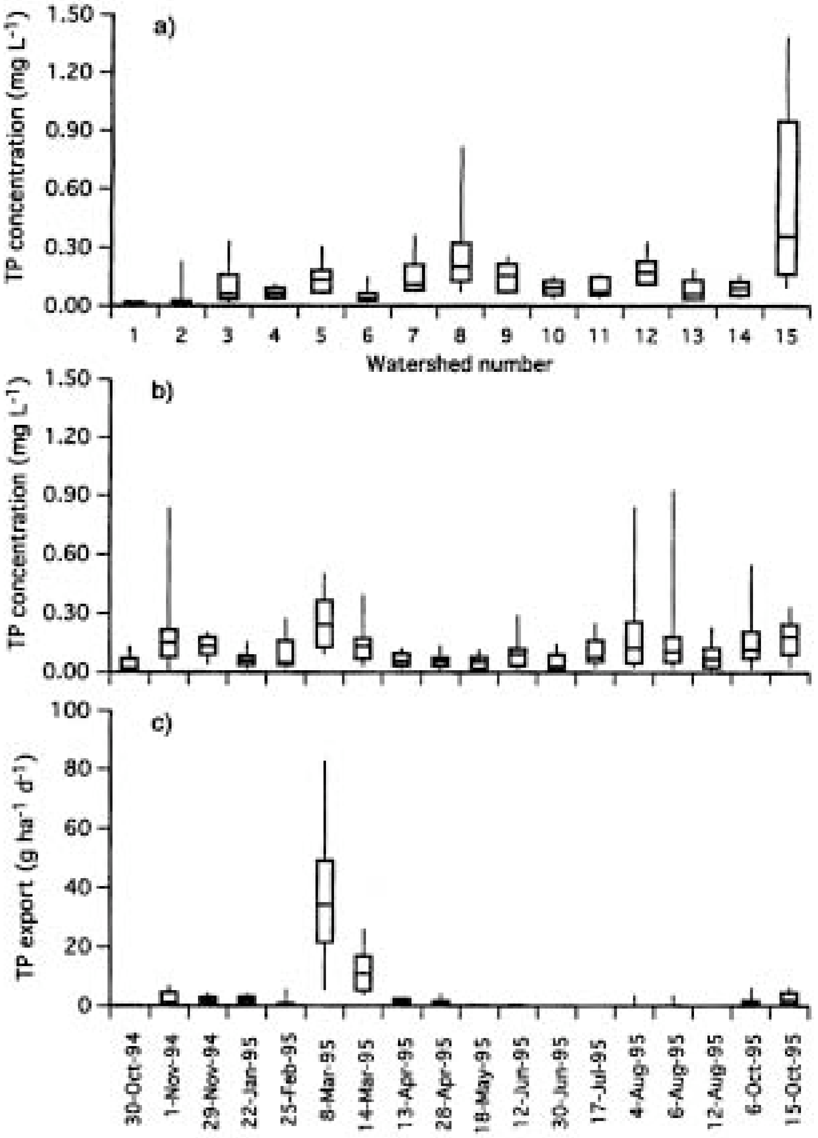

Figure 3. Spatial and temporal variability in total phosphorus (TP) data: a) TP concentrations at each catchment outlet for all dates sampled; b) TP concentrations on each smapling date for all catchments; c) TP export on each sampling date for all catchment outlets. Box diagram shows median value (center), upper and lower quartile (top and bottom of box), and high and low values (top and bottom of line).

The weak relationships observed between TP concentration and streamflow in some catchments are the result of variability in TP concentrations measured during spring and fall medium flow events and summer thunderstorm events (Figure 3a). For example, two spring rain events, April 13, 1995 and April 28, 1995, produced the two lowest mean TP concentrations for all sites (Figure 3a) despite the moderately high streamflow response (Figure 2). In addition, the intermittent flow following summer thunderstorms often produced exceptionally high TP concentrations during low discharge events (Figure 3b).

The high TP concentrations observed during many low streamflow events may be the result of a shift in flowpath dominance, from overland to subsurface flow. High concentrations of nutrients observed in stormflow following drought conditions by Mulholland et al. (1990) was attributed to leaching of vegetation in riparian zones, leaching of accumulated organic matter in drier portions of the channel, and hydrologic flushing of nutrients concentrated in soil water within the near-stream zone. Conversely, the low TP concentrations measured during the late spring rain events in our study may be the result of previous flushing of P in soil water during the snowmelt season. Thus, streamflow may be a poor predictor of P concentration when site- and season-specific conditions have a dominant effect on processes of instream P concentration.

3.3 Phosphorus Sources and Sinks in the Landscape

Results of the preliminary regression analyses examining relationships between TP export and agricultural, forest, and residential variables show that selecting a single variable for representing P source areas for the majority of dates sampled was not possible. Residential and forest variables were not significantly ($p < 0.10$) related to TP export on any date. Agricultural variables had significant positive relationships with TP export on many dates ($p < 0.10$), suggesting that these areas were sources of P. Different variables, however, had their strongest relationship with TP export on different dates. Therefore, all three agricultural variables, AG, CROP, and NONCROP, were selected for multiple regression analyses.

Results of preliminary multiple regressions using TP export, wetland and agricultural variables suggest that one wetland variable, HYDRIC, was a better representation of P sinks in the catchments than other wetland variables during a majority of the dates sampled. The variable, HYDRIC, had significant, negative relationships with TP export on 7 of the 18 dates sampled ($p < 0.10$, Table 3). These relationships were usually stronger than relationships between TP export and other wetland variables (Table 3). To examine the effect of changing the agricultural variable on the strengths of the relationships, three wetland variables, WET, NAWET, and HYDRIC, were selected for further analyses.

For our final analyses, we compared multiple regression models using all combinations of the three selected agricultural variables (AG, CROP, NONCROP) and the three selected wetland variables (WET, NAWET, HYDRIC) to maximize the explained variance in TP export on each sample date. Our results of the regression models with the highest, significant R_a^2 for each date ($p < 0.10$, Table 4) show significant relationships between TP export and agricultural and wetland categories on 8 sample dates, with R_a^2 ranging from 0.24 to 0.83. As with the preliminary regressions, models using HYDRIC as an explanatory variable have higher R_a^2 values and lower p-values than models using WET or NAWET. The consistency of this result adds further support to the idea that areas of nonagricultural poorly and very poorly drained soils were the best representation of P sinks in the study catchments of all wetland variables explored.

Table 3. Adjusted r^2 values for regression models of TP export vs. agricultural and wetland variables. Where there are no values the r^2 is less than 0.10. Each model contains the total agriculture (AG) variable and one wetland variable. The single variable model with AG predicting TP is included for comparison. Variable codes are described in Table 1.

DATE	AG	WET	WOODY	NON WOODY	PEM /SS	NA WET	RIV ERINE	HEAD WATER	HI ORDER	HYDRIC
11/01/94	0.07	0.24*	0.18		0.15	0.27*	0.18	0.15		0.30
11/29/94	0.32**	0.40	0.30	0.21	0.53**	0.44*	0.40	0.29	0.38	0.43
01/22/95	0.20	0.13	0.22		0.13	0.14	0.12	0.23	0.29	0.13
02/25/95					0.12					
03/08/95	0.34**	0.65***	0.49*	0.29	0.49*	0.64***	0.55**	0.54**	0.29	0.73**
03/14/95		0.18*			0.17*	0.17*				0.23*
04/13/95		0.15			0.22*	0.25*			0.15	0.25*
04/28/95				0.12						0.14*
05/18/95										
06/12/95										
08/04/95										
08/06/95										
08/12/95		0.11					0.16			
10/06/95										0.17*
10/15/95		0.13			0.14	014				0.21*

* p<0.10; ** p<0.05; *** p<0.01

The weaker relationships between TP export and the area of wetlands identified from aerial photo interpretation (WET) as compared to the area of wetlands delineated from soil drainage class (HYDRIC) may be explained by the difficulties in identifying wetlands from remotely sensed data. The color infrared imagery used to identify wetlands in the study catchments was taken in early spring prior to deciduous leaf production, facilitating the identification of surface waters and enhancing the ability to distinguish among vegetation types. Evergreen forested wetlands and temporarily flooded wetlands, however, are particularly difficult to identify (Federal Interagency Committee for Wetland Delineation, 1989). In addition, many poorly and very poorly drained areas cleared of characteristic wetland vegetation are not technically wetlands, according to some jurisdictional definitions of wetlands (e.g., Federal Interagency Committee for Wetland Delineation, 1989). Many of these areas were classified as residential and recreational lands in our land use coverage. Our results show that including forested, residential and recreational areas with poorly and very poorly drained soils in a wetland variable (i.e., HYDRIC) strengthened the negative relationship with TP export, suggesting that these areas function as P sinks in the study catchments.

Table 4. Coefficients in regression models of TP export vs. agricultural and hydric soil variables. Models are in the form: TP (g ha^{-1} d^{-1}) = $a + bX_1 + cX_2 + dX_3$, where X_i are the explanatory variables; both two and three variable models are shown. In some cases the dependent variable (TP) was transformed to $\log_{10} + 2$). r_a^2 is adjusted r-square.

						Coefficients (b, c, or d) in the model			
Date	n	trans	r^2	r_a^2	(a)	HYDRIC	AG	CROP	NONCROP
Spring									
03/08/95	14	No	0.87	0.83**	40.3**	-1.87**		2.30**	0.24
03/14/95	14	Yes	0.68	0.62**	3.24**	-0.03**		0.03#	
04/13/95	14	Yes	0.58	0.50**	2.11**	-0.03*			0.001
Fall									
11/01/94	14	Yes	0.72	0.64**	1.62**	-0.04*		-0.03	0.03**
11/29/94	14	No	0.52	0.43*	1.24**	-0.06	0.04*		
10/06/95	14	Yes	0.56	0.42*	1.74**	-0.05*		-0.06	0.02#
10/15/95	14	Yes	0.53	0.44*	2.01**	-0.04*			0.02#
Winter									
01/22/95	13	Yes	0.32	0.19	1.84**	-0.001			0.01#
02/25/95	14	Yes	0.35	0.24#	1.17*	-0.02	0.02#		

# $p<0.10$; * $p<0.05$; ** $p<0.01$

Similar landscape scale studies using regression analysis found significant relationships between nutrient concentration or export and catchment variables, including wetland types. Some of these have suggested that wetland position in the landscape influences the ability of a wetland to improve water quality (e.g., Whigham et al., 1988; Johnston et al., 1990; Detenbeck et al., 1993; Weller et al., 1996). Our results show that models using wetland variables expressing position in the landscape (HEADWATER, HIORDER) and measures of wetland vegetation type (WOODY, NONWOODY, PEM/SS) resulted in poor model fits. One exception to this pattern is the PEM/SS classification, which was negatively correlated to P export on four dates; the relationships, however, were relatively weak. For our study, distinguishing among wetland types for the purpose of classifying wetlands according to their ability to retain P was not possible. Measures of total wetland area (WET, NAWET, HYDRIC) were the most successful wetland variables for identifying P sinks in the landscape (Table 3). Therefore, our results suggest that all wetlands in the landscape, particularly defined by soil drainage class, are important for buffering the impact of P export from agricultural land to surface waters.

3.4 Seasonal patterns of phosphorus storage

A distinct seasonal pattern was observed in the ability of catchment variables to predict P export. R_a^2 values of the multiple regression models ranged from 0.24 to 0.83, with the highest values and the lowest p-values occurring in models representing spring snowmelt events (Table 4). This seasonal pattern may be explained by seasonal fluctuations in runoff producing areas and instream processes related to flow and biological activity.

Seasonal variability in runoff patterns can determine the contribution of various areas in a catchment to P export. During the highest streamflows in the early spring snowmelt period, much of the land surface area is saturated and may contribute overland flow and its associated P load. Many studies have suggested that this area expands and contracts throughout the year in relation to temperature, and precipitation intensity, duration, and frequency (e.g., Dunne and Black, 1970; Dunne et al., 1975; Bernier, 1985; O'Loughlin, 1986; Gburek, 1990; Eshleman et al., 1993; Montgomery and Dietrich, 1995, Kadlec and Reddy, 2001). Storm runoff during snowmelt conditions can increase the opportunity for land use practices and land cover types throughout a catchment to influence streamflow chemistry because of the relatively large runoff producing zones. Our relationships between TP export and land use and wetland variables that represented most of the area of the catchments were strongest during these saturated conditions (Table 4), suggesting that runoff producing zones were relatively large.

High flow events during snowmelt conditions may also create high opportunities for P retention in wetlands. Mitsch et al. (1979) found that 23% of the annual particulate P deposited in an alluvial swamp in southern Illinois occurred during a 5-day spring flood event, while Yarbro et al. (1984) found an increase in P retention in the Creeping Swamp in North Carolina as the area of inundation increased. Our study found strongest negative relationships between TP export and HYDRIC during the two spring snowmelt events sampled. Under snowmelt conditions, these hydric soils areas should produce saturation overland flow, according to the saturation overland flow models. It is likely, however, that erosion of P-laden sediments was restricted to steep saturated slopes and stream channels, and that areas with non-agricultural hydric soils acted more as sediment deposition areas, than as sediment source areas even during the highest flow events sampled.

Our relationships between TP export and agricultural and wetland variables were weakest during the summer and winter events. Precipitation during most summer events was greater than spring and fall events, however, streamflows were considerably lower. Nutrient budgets constructed for individual wetlands have suggested that wetlands are sinks for P predominantly during the lower flow growing season, and are sources for P during higher flow events in the fall and spring because of sediment scouring (Klopatek, 1975; Lee et al., 1975; Gehrels and Mulamoottil, 1989). On the whole, our results examining P retention in wetlands at a landscape scale did not follow this pattern. During the summer thunderstorm events pulses of P were most likely exported on relatively short time scales from areas near or within the stream channel, preventing the opportunity for P export from or retention in areas further from the channel. Simple generalizations of source and sink dynamics at the landscape scale under summer conditions may be precluded by site and season-specific conditions.

4. CONCLUSIONS

A landscape scale approach was used to identify catchment attributes that represent phosphorus sources and sinks in the landscape and to evaluate the collective function of these sources and sinks during a range in seasons and hydrologic conditions. Our results suggest that the best representation of P sinks in the landscape was the area of nonagricultural poorly and very poorly drained soils. This area had significant negative relationships with TP export in 6 of the 15 multiple regression models.

Soil drainage class was a more useful criterion for delineating P sinks in the study catchments than wetlands identified through color infrared photo interpretation. Wetlands identified from remotely sensed data may not adequately represent P sink areas because of the difficulties identifying evergreen forested and temporarily flooded wetlands, the inclusion of sloping wetlands, and the exclusion of low-lying areas devoid of wetland vegetation. Managers should consider that seasonally saturated areas lacking wetland vegetation may be important areas for P retention. While soil drainage class was useful for delineating the area of P sinks in this study, more research is needed to evaluate this relationship in other regions and, to develop functional evaluation methods with regional applicability that address other wetland functions and classification systems.

Results further suggest that wetlands function as P sinks during the highest P export season. The strongest negative relationships between wetlands and P export occurred during two spring snowmelt dates, when an estimated 31% of the annual TP export from the LaPlatte River occurred. Because runoff producing zones can be relatively large during the snowmelt season, land use in the entire catchment has a greater opportunity to influence streamflow chemistry than during lower flow seasons. Relationships between P export and both source (agricultural) and sink (wetland) variables were not significant on any summer date. Other processes, such as biological storage and release mechanisms operating throughout the catchment, or instream and near-stream P cycling may explain P export variation during the growing season.

Catchment modeling of P export used to identify sources and sinks of P and to predict reductions in P export following implementation of nutrient control measures should incorporate P sink variables to more accurately describe the relationship between P export and land use. Future landscape scale evaluations of P sources and sinks could also assist catchment managers by documenting more intensive temporal P export and storage patterns in small catchments within a season or during an event and by examining the influence of spatial patterns of P export and storage areas on P transport through the landscape.

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