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IMPORTANCE OF HYDRIC SOILS AND NEAR-LAKE AREAS AS PHOSPHORUS SOURCE AREAS IN THE LAKE CHAMPLAIN BASIN: EVIDENCE FROM A LANDSCAPE-LEVEL MODEL

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1. INTRODUCTION

The passage of the Clean Water Act in 1972 made maintaining and improving surface water quality a national goal. Much of the initial effort was levied against point sources of pollution (Puckett, 1995); however, controlling non-point pollution has become a priority as control of the remaining point source problems becomes increasingly less cost-effective. Non-point phosphorus (P) pollution, in particular, has received frequent public attention as it threatens many of our nation's streams and rivers. Eutrophication, typically caused by high P levels, has been identified as the number one water quality problem in many regions (NYC DEP, 1999; LCBP, 1994).

In light of the above, the identification of non-point sources is critical to minimizing phosphorus' impact on surface waters. Progress in this arena has been hindered by limited resources, as water quality assessment often requires continuous monitoring (Heidtke and Auer, 1993). To aid in the implementation of water quality programs, managers have turned to using a variety of models to both predict P levels (e.g., Auer et al., 1997) and to identify land areas most responsible for elevated P levels (e.g., Zollweg et al., 1995). The latter is an important management tool, as targeting source areas for clean up allows the implementation of cost-effective remedial strategies (Sharpley, 1995).

Within the literature, three general categories of non-point P models exist to predict P at varying spatial scales: complex mechanistic models (often developed for the plot or field scale), empirical models (used at any scale), and exploratory regression models (often employed at the landscape level). Mechanistic models such as Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980) and the

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Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al., 1982, 1985) incorporate both physical and chemical processes in order to predict nutrient and sediment loading. Some of these models can rely upon process-related equations that are uncertain and often inaccurate (Novotny and Chesters, 1989; Levine et al., 1993; Harris, 1998), do not utilize a resolution fine enough to capture the resolution of the parameters that drive the model (Baun, 1986), and are limited to use by large agencies or research groups that have the funds and computer technology to run them (Levine et al., 1993; Johnes and Hodgkinson, 1998).

Empirical models generally use a single equation to express the relationship between an easily measured parameter (i.e., land use) and non-point P. Export models (e.g., Johnes ,1996; Johnes and Hodgkinson, 1998; Heidtke and Auer, 1993) fall into this category. These models typically have low data requirements, can reflect a number of spatial scales, and serve to obtain a rough estimate of average long-term nutrient totals (Heidtke and Auer, 1993). Drawbacks include the inability to model episodic events and incorporate spatial and temporal information (Harris, 1998) and a lack of reliable export coefficients in the literature (Johnes and Hodgkinson, 1998; Levine et al., 1993).

Exploratory regression models are able to go beyond the single watershed scale. Model construction usually involves the application of spatial data to look for relationships between nutrient levels and various landscape parameters (e.g. Lamon, 1995; Robertson, 1997; Tufford et al., 1998). These models are an essential tool to study large-scale system behavior and provide the opportunity to integrate many types of data (e.g. SPARROW model used for the Chesapeake Bay and Gulf of Mexico, Smith et al., 1997, Alexander et al., 2000). A helpful feature of regression models is that they can combine spatial variations in landscape features such as geology, land use and biological communities (Johnes and Hodgkinson, 1998). In this way, they can predict overall patterns in dependent variables, permitting the identification of outlier watersheds.

The choice of model type and spatial scale is an important one, as it has bearing on the results generated. The processes affecting P transfer through the environment are different at varied spatial scales, causing wide variation in the results found in studies conducted at different scales (Wiley et al., 1997; Levin, 1992). Ultimately, researchers must consider the suitability of each spatial scale in solving the perceived problem. Recent discussion in the literature has stressed the importance of the integration of spatial scales in modeling, and ideas abound on the best way to do it (Wiley et al., 1997; Johnes and Hodgkinson, 1998; Levine et al., 1993).

An important first step in the integration of spatial scales is understanding which P transfer processes are most important at each scale. Within the Lake Champlain Basin, phosphorus research using mechanistic (Cassell et al., 1998) and empirical (Budd and Meals, 1994; Weller et al., 1996; Meals and Budd, 1998; Hegman et al., 1999) model has been conducted at a variety of scales. However, exploratory regression models at the whole basin scale are lacking. Landscape level studies of the basin are important because they can provide insight into the links between large scale compartments of the P cycle, which may not be apparent at a smaller scale.

For this study, a GIS database for the Vermont side of the Lake Champlain Basin was constructed to include a broad variety of landscape variables including land use, hydrology, geology, and location. Multiple regression was then used to explore those variables and their relationship to measured P levels in stream outlets in the studied portion of the Basin. The relationships that emerge, while only "correlations" and not proof of causation, can be used to infer P transfer processes that may be of use to watershed managers.

2. METHODS

2.1. Study Area

The Lake Champlain Basin stretches from the Adirondack Mountains of New York in the west, to the Green Mountains of Vermont in the east. Its northern border encompasses a small area of the plains of Quebec, Canada (Figure 1). The basin is 21,326 km^2, 56% of which lies in Vermont, 37% in New York, and 7% in Canada.

Phosphorus levels within Lake Champlain have been a recent topic of interest in all three regions. In 1993, a Water Quality Agreement between Vermont, New York and Quebec was signed, establishing in-lake P criteria. As a result of this agreement, a variety of research has been done on in-lake P levels (VT and NY DEC, 1997), the role of land use on P levels (Hegman and others 1999, Budd and Meals, 1993; Weller and others 1996), and the effect of different agricultural management practices on P levels (Clausen and Meals, 1989).

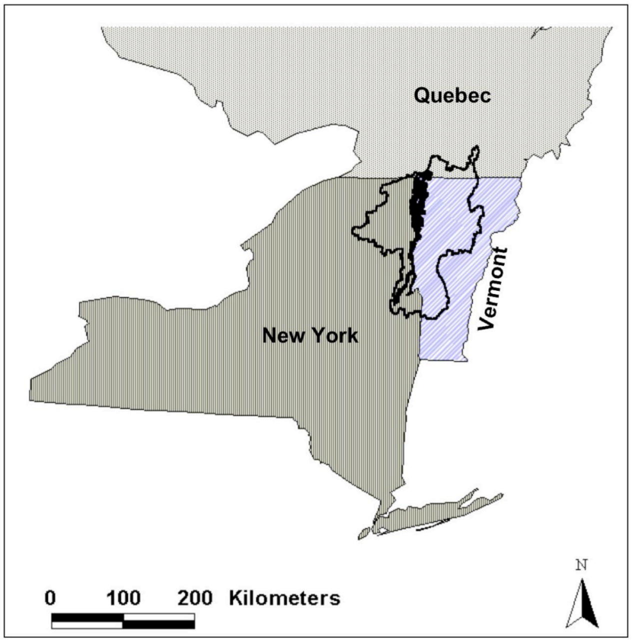

Figure 1. Location of the Lake Champlain Basin relative to Quebec, Canada; New York; and Vermont.

The broadest set of landscape data in Vermont are available for those 15 watersheds that drain into the lake from the Vermont side of the basin (Figure 2). Therefore, only those 15 watersheds were included in the study area. The land draining directly into the lake without an identifiable first order stream was not included in the study area, as no P data were available for it. The 15 study area watersheds, which range in size from 3,000 to 300,000 hectares, were hand digitized from 1:24,000 USGS topographical maps. The land use in the study area (1993 coverage) was 21% agriculture, 72% forest and 7% urban. The soils are glacial till in many areas, with large clay deposits near the lake.

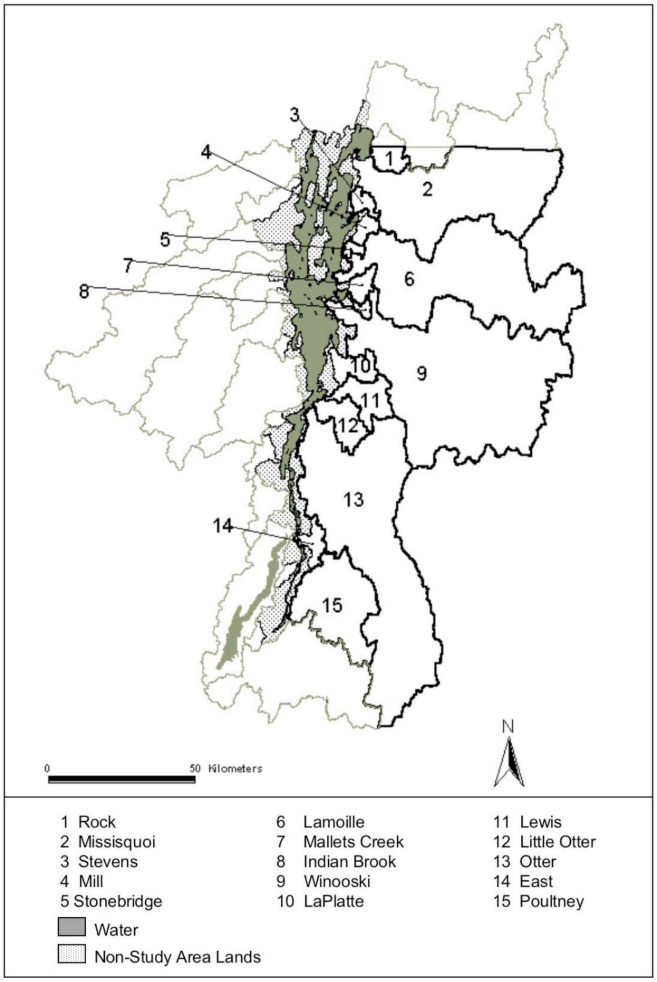

Figure 2. The 15 watersheds in the Lake Champlain Basin included in the study area.

2.2. Water Quality

Total Phosphorus (TP) concentration was measured at 15 stations during the period March 1990 to April 1992 by the Vermont and New York Departments of Environmental Conservation (VT DEC and NY DEC, 1997). Sample stations were located at the outlet of each of the 15 watersheds, upstream from any backwater influence from the lake. The number of samples taken at each site ranged from 103 to 82 in low, moderate and high flows, with 9%-35% representing high flows. TP samples were analyzed in VT DEC labs using EPA's Standard Method 4500-PF.

The plant operations records for all permitted municipal and industrial wastewater P discharges to surface waters were examined by the DEC, and from this an estimate was made of the point source P load to the lake. In this manner, P inputs to the lake could be partitioned between point and non-point sources.

The focus of this study was on both the non-point P concentrations in streams and rivers and the mass of non-point P export to Lake Champlain. For the purposes of this study, the P concentration used is a volume-weighted, concentration (mg P liter^{-1}) for a year period, while P export is an mass (kg P watershed^{-1} year^{-1}). According to Osborne and Wiley (1988) it is important to examine the impact of pollutants in terms of both concentration (as used in loading coefficients), and export (area-based export coefficients). In this study, the export regression models used independent variables based upon total watershed area (i.e., total hectares of agriculture in each watershed), while the concentration regression model used independent variables based upon percentage of watershed area (i.e., percent of the watershed that is agriculture). If study watersheds vary greatly in size, explained variation (r^2) in export models will then include a component of size because larger watersheds will export more P. Concentration models do not have this issue in interpretation of results.

Two of the 15 watersheds included in the study, the Rock and Missisquoi, crossed the boundary between the United States and Canada. Because of a lack of spatially explicit data for the Canadian portion of the basin at the time of this study, the P export for the Canadian portion of these two watersheds was reduced based upon a previous model constructed for the Lake Champlain Basin by Hegman et al. (1999). To reduce the P export, regionally derived land use export coefficients were applied to the area of agricultural, urban and forested land within the Canadian portions of the watersheds. The calculated P export was then subtracted from the original export given in the DEC report (VT DEC and NY DEC, 1997) to obtain an estimate of the P exported from Vermont lands. Note that only the P export measurements were adjusted; P concentration was not reduced for these two watersheds because concentration is not necessarily dependent on the size of the watershed.

2.3. GIS Data Layers

A variety of GIS coverages were used to quantify several aspects of landscape structure. The individual variables (Table 1) were placed into one of four datasets based upon whether they were related to land use, hydrology, geology, or location.

2.3.1. Land Use

Sixteen land use categories for the study area were obtained from classification of LANDSAT Thematic Mapper satellite data (VCGI, 1997A). Thirteen of the sixteen individual variables were used in analyses, as well as three aggregated variables (Table 1). A digital line graph coverage of major roads was obtained (VCGI, 1993) in order to estimate the density of paved roads in each watershed. Data on the number of farm animals in each watershed (Hegman et al., 1999) were also incorporated into analyses.

Table 1. Information on variables used in analyses. Variables shown are export model variables; variables used in the concentration models contain similar information, but are ratios of the variable to total watershed area (i.e., percentage rather than total square hectares of total agriculture). * indicates that totals include areas classified as wetland; wetland total includes agricultural areas classified as wetland.

Dataset	Indep. Variable	GIS Data Coverage Used	Coverage Source	Resolution
Borders		Lake and Watersheds	Hegman et al., 1999	1:24,000
Land Use	Barren Land	LANDSAT Land Use	VCGI, 1997A	1:250,000
	Total Agriculture*	"	"	"
	Brush	"	"	"
	Orchards	"	"	"
	Other Ag.	"	"	"
	Row Crops	"	"	"
	Hay / Pasture	"	"	"
	Total Forest*	"	"	"
	Decid. Forest	"	"	"
	Conifer. Forest	"	"	"
	Mixed Forest	"	"	"
	Total Urban*	"	"	"
	Residential	"	"	"
	Commercial	"	"	"
	Industrial	"	"	"
	Other Urban	"	"	"
	Roads	RDSCLx	VCGI, 1993	1:100,000
	Animal Units	VT & Quebec Animal Unit	Hegman et al., 1999	N/A
Hydrology	Surface Waters	National Hydrography dat.	USGS, 1999	1:100,000
	Total Wetland*	VSWInn; LANDSAT Land Use	VCGI, 1996; VGCI, 1997A	1:24,000; 1:250,000
	For. Wetland	"	"	"
	Non-for. Wetland	"	"	"
	Farmwater	Agricultural Streams	Seymour, 1998	1:5,000
	Avg. Precipitation	Precipitation Surface	created for this study	1:250,000
Geology	Clay	STATSGO	NRCS, 1994	1:250,000
	K-Factor > 3.0	"	"	"
	Hydric	"	"	"
	Slope > 25%	DEMnnnn	VCGI, 1997B	1:24,000
Locational	Riparian Agric.	National Hydrography dat.; LANDSAT Land Use	USGS, 1999; VCGI, 1997B	1:100,000; 1:250,000
	Riparian Forest	"	"	"
	Riparian Urban	"	"	
	Riparian Wetland	National Hydrography dat.; LANDSAT LU; VSWInn	USGS, 1999; VCGI 1997B; VCGI, 1996	1:100,000; 1:250,000; 1:24,000
	Riparian Clay	National Hydrography Dataset; STATSGO	USGS, 1999; NRCS, 1994	1:100,000; 1:250,000
	Riparian Hydric	"	"	"
	Near-lake Agriculture	Lake Champlain; LANDSAT Land Use	Hegman et al., 1999; VCGI, 1997B	1:24,000; 1:250,000
	Near-lake Forest	"	"	"
	Near-lake Urban	"	"	"
	Near-lake Wetland	Lake Champlain; VSWInn; LANDSAT Land Use	Hegman et al., 1999; VCGI, 1996	1:24,000; 1:24,000; 1:250,000
	Near-lake Hydric	Lake Champlain and Watersheds; STATSGO	Hegman and others, 1999; NRCS, 1994	1:24,000; 1:250,000

2.3.2. Hydrology

Digital hydrology data, including both streams and lakes, were obtained from the USGS (USGS, 1999) in order to quantify the amount of surface water in each watershed. Wetlands data were gained from two sources: the LANDSAT digital land use data described previously, and the Vermont Significant Wetlands Inventory (VSWI) (VCGI, 1996). Wetlands were classified as either forested or non-forested. The *Farmwater* variable was created from The Vermont Housing and Conservation Board's detailed coverage of streams, brooks and rivers that flow over agricultural lands within the Lake Champlain Basin (Seymour, 1998).

Precipitation data were obtained for 57 stations in and around the basin for the years 1951 - 1998 for the United States, and 1951 - 1991 for Canada (NCDC, various years; Environment Canada, 1994). These data were then averaged to create an annual value, and ArcView GIS 3.2 (ESRI, 1999) was used to create a precipitation surface for the entire basin following the geospatial interpolation methods of Hegman and others (1999).

2.3.3. Geology

Surficial geology data were obtained from the State Soil Geographic (STATSGO) database (NRCS, 1994), at a resolution of 1:250,000. The STATSGO database was used, in conjunction with its accompanying relational tables, to extract information on the presence or absence of hydric and clay soils. The structure of the STATSGO relational tables was such that a threshold had to be established in order to classify soils as hydric or clay. A soil polygon in the GIS soil coverage is predominately one soil type, but there can be upwards of 15 other types present. If a soil polygon consisted of greater than 10% hydric soils, it was classified as hydric in this study. Similarly, a threshold of 40% clay was established to categorize a soil polygon as clay for this study. Those soils, with a K-Factor greater than 3.0, represented by the variable *K-Factor > 3*, are considered highly erodible (Brady, 1990), and so were also included in the study. Defining these soil polygons using these % thresholds was done empirically, as the regressions were stronger than when a few different %'s were used. Testing of threshold %'s was not comprehensive.

A 7.5 minute Digital Elevation Model (DEM) (VCGI, 1997B) was used to extract information on slope within each of the watersheds. The variable *Slope* represents the amount of land in each watershed with greater than 25% slope.

2.3..4 Location

Two sets of locational variables were created, riparian variables and near-lake variables. The buffer utility included in ArcView 3.2 (ESRI, 1999) was used to extract land use, wetland and geology information from a 500 meter distance around all streams identified in the USGS digital stream water coverage (VCGI, 1997A). The resulting seven riparian variables (Table 1) were created in order to allow comparison of landscape variables within river corridors to data derived from the whole watershed (Osborne and Wiley, 1988; Johnson et al., 1997; Tufford et al., 1998).

The second set of locational variables, the near-lake variables, were also created with the ArcView buffer utility (Table 1). Information on land use, geology and wetlands was extracted from an empirically derived 5.6 km buffer zone around the lake's shoreline. The resulting five near-lake variables were included in the model building process to test the hypothesis that characteristics of land closer to the lake have a significant influence on P levels in the lake.

2.4. Statistical Methods

Statistical analyses were run using both P concentration (mg P l^{-1}) and P export (kg P $watershed^{-1}$ $year^{-1}$) as dependent variables. The distribution of all dependent and independent variables was assessed using visual observation of histograms as well as the Shapiro-Wilk statistic (SAS Institute, 1988). Most variables violated the assumption of normality, tending instead to be log-normally distributed. Therefore, all independent variables for the export model were transformed to log_{10} $(100 + x)$ prior to all analyses, while the independent variables for the concentration model were transformed to log_{10} $(0.5 + x)$. These transformations gave all variables a normal distribution. Dependent variables for the two models were only log-transformed.

Principal components analysis (PCA) on the covariance matrix was used to reduce the initial number of independent variables to a smaller set that still explained the majority of the dataset variation (Johnson and Gage, 1997). Separate PCA's were conducted for each model; one on each of the four datasets (land use, hydrology, geology, or location). For those principal components that explained greater than one percent of the total dataset variation, the relationships between the principal components and each variable, as well as between the individual variables, were examined using the correlation matrices. Variables were kept or discarded based upon two criteria: 1) variables could not be highly correlated within the dataset, and 2) variables kept must significantly correlate with at least one of the retained principal components. As this initial variable reduction procedure was not the final variable selection, variables were retained if there was any question of their contribution to the dataset.

Using the new, smaller set of variables, forward-selection linear regression models with an initial probability for entry of 0.25 were constructed with non-point P concentration (mg P l^{-1}) or export (kg P $watershed^{-1}$ $year^{-1}$) as the dependent variables. Variables significant at this level were then subjected to a more rigorous examination of their partial F-test, contribution to the model's r^2 and adjusted r^2, and minimization of the model's variance inflation factor, in order to identify that variable or combination of variables that best explain P export or concentration. Outliers were analyzed using the SAS system's PROC REG / INFLUENCE statistics (SAS Institute, 1988). The residuals of the final models were analyzed for normality and homogeneity of variance.

3. RESULTS

The principal components analysis reduced the number of independent variables from 39 to 10 in the export model datasets, and from 39 to 15 in the concentration model datasets. Many of the variables were highly inter-correlated, a common feature among landscape and other spatially distributed data (Johnson and Gage 1997), and so were deleted from consideration in the final model. In both models, a few highly correlated variables had similar, strong relationships with P. In the export model, *Total Agriculture*, *Row Crops* and *Hay/Pasture* had highly significant correlations ($r > 0.9$) with *P (kg* $watershed^{-1}$ $year^{-1}$*)*. These three independent variables are also highly inter-correlated, with $r > 0.95$. A similar situation occurred in the concentration model, with %*Other Agriculture*, %*Coniferous Forest* and %*Deciduous Forest* all having significant relationships with *P (mg* l^{-1}*)* ($r > 0.7$) as well as being inter-correlated ($r > 0.55$). In these cases, the variable that created the final model with the highest adjusted r^2 was kept, and all others deleted. Those variables kept for consideration in the final model are shown in Table 2.

Table 2. Final datasets used in the loading and export models. (Data were obtained from land cover information using ARC GIS.)

Export Model	Loading Model
Total Agriculture	%Total Agriculture
Other Ag/Mixed	%Orchards
Industrial	%Industrial
Other Urban	%Total Urban
Clay	%Clay
Hydric	%Hydric
Farmwater	%Farmwater
Total Wetland	%Total Wetland
Near-lake Agriculture	%Near-lake Agriculture
Near-lake Hydric	%Near-lake Hydric
Commercial	%K-factor > 3
	%slope
	%Brush
	%Surface Water
	%Total Forest
	%Barren

Forward selection linear regression using those export model variables shown in Table 2 as independent variables and *P (kg watershed*$^{-1}$ *year*$^{-1}$*)* as the dependent variable, showed that the combination of the variables *Hydric*, *Near-lake Agriculture* and *Near-lake Hydric* best explained P variation. The final export model, *P (kg watershed*$^{-1}$ *year*$^{-1}$*) = -1.568 + 1.042(Hydric) + 1.091(Near-lake Hydric) - 0.878(Near-lake Agriculture)*, is plotted in Figure 3a. The model has an adjusted r^2 of 0.93 and an F-value with Prob>F of 0.001. The coefficients for *Hydric*, *Near-lake Hydric*, and *Near-lake Agriculture* have a Prob>F of 0.001, 0.011, and 0.022, respectively.

Using the concentration model dataset (Table 2), forward selection regression showed that the combination of *%Total Agriculture*, *%Near-lake Agriculture* and *%Near-lake Hydric* best explained *P (mg l*$^{-1}$*)* variation. The final concentration model, *P (mg l*$^{-1}$*)* = -3.1 + 1.396(*%Total Agriculture) + 0.84(%Near-lake Hydric) – 1.04(%Near-lake Agriculture)* is plotted in Figure 4. The model has an adjusted r^2 of 0.686 and an F-value with Prob>F of 0.001. The coefficients for *%Total Agriculture*, *%Near-lake Hydric*, and *%Near-lake Agriculture* have a Prob>F of 0.001, 0.03, and 0.021, respectively. The residuals of both models show homogeneity of variance and are normally distributed.

4. DISCUSSION

4.1. Significance of Soil Property Parameters

The inclusion of the variable *Hydric* in the export model may denote the influence of soil properties on P transport. The variable *Hydric* represents the hectares of soil in each watershed that is predominately hydric in character, according to NRCS databases. These soils are either close enough to the groundwater table or have poor enough drainage to be seasonally wet. These properties have an effect on the way that both water and P are transmitted.

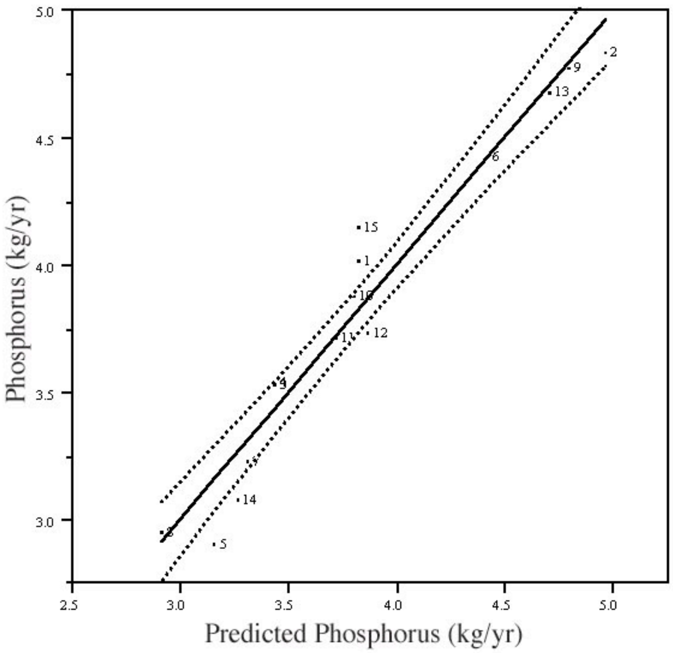

Figure 3. The final export regression model showing the regression line and the 95% confidence interval.

Proponents of the Variable Source Area (VSA) concept contend that soils located near surface waters produce most of the surface runoff in a watershed, and that the area of these contributing soils increases with rainfall intensity and duration (Pionke et al., 1990; Troendle, 1985; Gburek, 1990, Gburek and Sharpley, 1998). As the moisture content of these soils rises, the ability of water to percolate through the soil column decreases. As rains continue, the soil's infiltration capacity is exceeded and surface runoff occurs (Brady, 1990). Thus, as the soil in areas further away from the stream become saturated, they also begin to contribute to surface runoff, expanding the source area. This means that those soils in the watershed with greater infiltration capacities provide little surface runoff, with the processes of infiltration and groundwater recharge being dominant. As the soils classified as hydric in this study have properties that minimize their infiltration capacities, they may be an identifiable source of surface runoff in the basin. While all of the soils classified as hydric may not be located within a defined Variable Source Area, their ability to transmit surface runoff makes them a potential P source area.

Surface runoff has the energy to erode large amounts of soil and the capacity to carry particulates rich in P, making it an important mechanism in P transfer (Sharpley et al., 1994). Relying upon the premise of the VSA concept, if "contributing" soils are correctly classified, it should be possible to identify those areas of a watershed that are likely to be a large source of P to surfacee waters (Zollweg et al., 1995). A spatial overlap between high P-producing land uses and a high proportion of hydric soils should exist; however, for these source areas to exist. Analysis of the GIS database shows that an average of 82% of the study area's agriculture is located on areas classified here as hydric. As such, the significance of the variable *Hydric* may denote the importance of variable source area-related P transfer processes. The variables *Hydric* and *Total Agriculture* are unfortunately somewhat inter-correlated, making inferences about process more difficult.

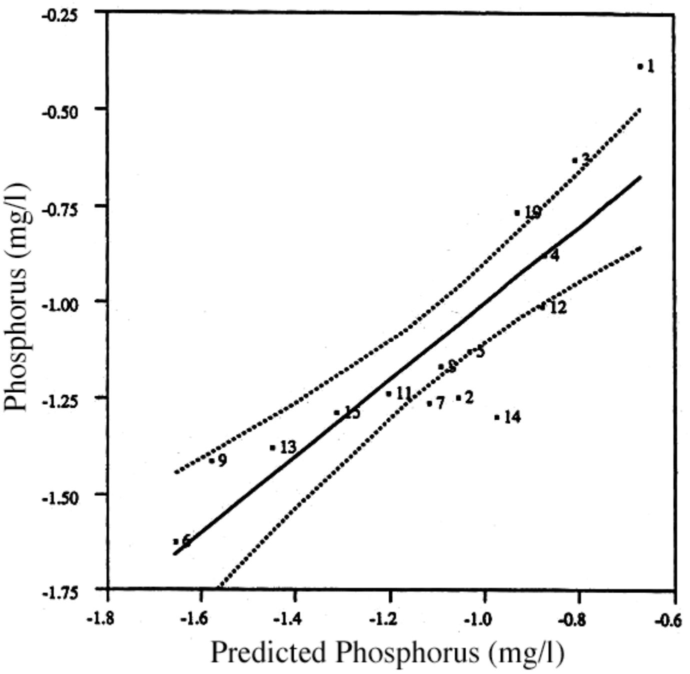

Figure 4. The final concentration regression model showing the regression line and the 95% confidence interval.

The other "geological" variable did not help explain the variation in either export or concentration models due to either a lack of relationship or the high inter-correlation between land use and geologic parameters, which is common in these types of studies (Richards et al., 1996; Beaulac and Reckhow, 1982; Hill, 1981). Many recent studies have found significant relationships between P and land use (Robertson, 1997;

Thierfelder, 1998; Tufford et al., 1998), which has reinforce the inclusion of only land use information in P models (Tufford et al., 1998; Driver and Troutman, 1989; Johnes and Heathwaite, 1997; Jordan et al., 1997; Meals and Budd, 1998; Hegman et al., 1999). However, this study, as well as other research that has found significant correlations between P and geology (Dillon and Kirchner, 1975; Robertson, 1997; Vaithiyanathan and Correll, 1992), suggests that focusing on the phosphorus-land use link may limit our future understanding of P dynamics in the landscape.

4.2. Significance of Locational Parameters

The addition of the near-lake variables into both the export and concentration models suggest that the location of landscape elements is important. One process-related mechanism that may explain the significance of these variables is in-stream nutrient retention. If in-stream retention is considerable, P entering a stream in the upland areas of a watershed would not subsequently reach the watershed outlet. Land near the lake may therefore have a larger influence on P levels in the lake than land in the watershed's headwaters (Thierfelder, 1998).

In-stream processes have the potential to influence the chemical and physical forms of P in a stream, which in turn affect how P is delivered downstream (Hill 1997; Meyer and Likens 1979; Minshall and others 1983). In a review of the transport mechanisms of P in streams and wetlands, Reddy and others (1999) cited many examples of studies in which streams retained significant amounts of P. A P transport model for the Lake Okeechobee Basin (Zhang and others 1996) found that, on average, one-third of the P reaching the stream would be assimilated upstream of the lake. House and Warwick (1998) concluded that both soluble dissolved P and total dissolved P levels decrease with distance downstream, probably due to uptake by sediments, macrophytes and benthic algae. These studies are in contrast to research that finds either no attenuation, or short-term attenuation followed by a large export (Hill, 1997; Wang et al., 1999; Meyer and Likens, 1979; Dorioz et al., 1989).

Given the variation in results of in-stream studies, a regional perspective provided by studies such as ours can be a source of information on the importance of this process. Isolated studies at a small scale are useful for exploring the mechanisms of in-stream retention and whether it is significant in specific stream environments. In order to view the management implications of significant in-stream nutrient retention however, a more regional perspective should be taken.

4.3. Negative Model Coefficients

Note that the coefficients on the variables *Near-lake Agriculture* and *%Near-lake Agriculture* are negative in both models. The negative coefficient, when taken literally, means that as the amount (or percentage) of agriculture in the near-shore zone increases, the P-export (or concentration) to the lake should decrease, a non-intuitive relationship. The possible source of this negative relationship becomes evident when the ratio of *Near-lake Hydric* : *Near-lake Agriculture* is examined. When the two variables are plotted separately against the ratio, it becomes clear that watersheds with a small amount of agriculture in the near-lake zone also have small amounts of hydric soil there. As the amount of agriculture increases, however, the relative amount of hydric soil in the near-lake zone decreases. As previously discussed, the relative amount of hydric soil versus agriculture in a watershed may have a large influence on P transfer, as agriculture on hydric soils may exports larger amounts of P than agriculture on non-hydric soils. The lower relative amount of near-lake hydric soil in watersheds with large amounts of near-lake agriculture would therefore mean lower overall P export. This relationship may account for the negative coefficient on the *Near-lake Agriculture* and *%Near-lake Agriculture* variables.

5. CONCLUSIONS

The results of this study exemplify the use of a landscape-level analysis to suggest P transfer processes are important at a large scale. It was conducted in order to develop landscape level research in the Lake Champlain Basin, as field scale studies, or even studies at the single watershed level, do not always allow us to identify the connections that exist among distinct P transfer processes (Schlosser and Karr, 1981). This study's use of a different research perspective illuminated two potentially important P transfer processes, hydric soil export and potential in-stream nutrient retention, that have been largely unexplored in the Lake Champlain region.

Landscape-level analyses have benefits that reach beyond their ease of use and simple data requirements. The information gained through this type of research raises questions about the assumptions we rely upon in modeling P in our landscape. The significance of both hydric soils and near-lake lands in this study point to complexities within the P transfer system that are not reflected in simply land use-based export coefficient modeling. Also beneficial is the landscape level model's focus on variability in P output between watersheds, making the recognition of outlier watersheds straightforward. If followed by a search for variables to bring in the outliers, such as the near-lake lands in this study, landscape level models can be useful in providing information that may point to why one watershed area produces more P than another. These important benefits help investigators identify new research questions, making the landscape level model a useful tool in setting research priorities for a region.

It is important to note that landscape scale models complement, but cannot replace the information gained from smaller scale studies. This study suggested the importance of both P source areas and in-stream nutrient retention. To substantiate this, a series of field experiments at a smaller scale should be conducted.

Identification of the landscape areas where P is exported or retained has important implications for both the scientific and management communities. Researchers can incorporate this knowledge into the development of spatially integrated models. These models can then be used by managers to narrow the scope of their remedial efforts by targeting discrete portions of the landscape, allowing for cost-effective management strategies. Incorporating various spatial scales into our research agendas results in a more complete understanding of the P transfer system, which in turn improves our decision-making abilities.

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