JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 37, NO. 6 AMERICAN WATER RESOURCES ASSOCIATION DECEMBER 2001

GIS-BASED HYDROLOGIC MODELING OF RIPARIAN AREAS: IMPLICATIONS FOR STREAM WATER QUALITY[1]

Matthew E. Baker, Michael J. Wiley, and Paul W. Seelbach[2]

ABSTRACT: Riparian buffers have potential for reducing excess nutrient levels in surface water. Spatial variation in riparian buffer effectiveness is well recognized, yet researchers and managers still lack effective general tools for understanding the relevance of different hydrologic settings. We present several terrain-based GIS models to predict spatial patterns of shallow, subsurface hydrologic flux and riparian hydrology. We then link predictions of riparian hydrology to patterns of nutrient export in order to demonstrate potential for augmenting the predictive power of land use/land cover (LU/LC) maps. Using predicted hydrology in addition to LU/LC, we observed increases in the explained variation of nutrient exports from 290 sites across Lower Michigan. The results suggest that our hydrologic predictions relate more strongly to patterns of nutrient export than the presence or absence of wetland vegetation, and that in fact the influence of vegetative structure largely depends on its hydrologic context. Such GIS models are useful and complimentary tools for exploring the role of hydrologic routing in riparian ecosystem function and stream water quality. Modeling efforts that take a similar GIS approach to material transport might be used to further explore the causal implications of riparian buffers in heterogeneous watersheds.

(KEY TERMS: aquatic ecosystems; GIS; ground water hydrology; modeling; watershed management; wetlands.)

INTRODUCTION

Human land use is a major factor influencing nonpoint sources of N and P in watersheds and the delivery of excess nutrients to surface waters (Correll, 1997; O'Neill *et al.*, 1997). At regional scales, many researchers have related patterns of watershed land use/land cover (LU/LC) to patterns of nutrient export in streams (Omernik *et al.*, 1981; Osborne and Wiley, 1988; Hunsaker and Levine, 1995; Tompkins *et al.*, 1997; Johnson *et al.*, 1997; Castillo *et al.*, 2000). Much of this work has incorporated mapped wetland vegetation to characterize riparian or catchment hydrology. Weller *et al.* (1996) used vegetative characterizations and spatial descriptions of wetlands to improve predictions of instream nutrient chemistry in western Vermont. Mixed-forested wetlands, the overall aerial extent of wetlands, and their proximity to streams greatly influenced multiple linear regressions (MLR) with P concentrations. Tompkins *et al.* (1997) related nutrient export to varying degrees and types of wetland cover in a mid-Michigan basin.

At local scales, a number of transect studies have shown that riparian forest "buffers" can be effective at removing excess nutrients from surface water and ground water (Peverly, 1982; Lowrance *et al.*, 1984; Peterjohn and Correll, 1984; Jacobs and Gilliam, 1985; Haycock and Pinay, 1993; Jordan *et al.*, 1993; Lowrance *et al.*, 1997). However, reviews of riparian nutrient dynamics make it clear that riparian areas exhibit a wide range of effects on stream water quality within and among regions (Cirmo and McDonnell, 1996; Hill, 1996; Correll, 1997). Even at very local scales, considerable spatial and temporal heterogeneity has been observed in rates of nutrient flux in riparian areas (Peverly, 1982; Elder, 1985; Pinay et al. 1989; Groffman *et al.*, 1992; Pinay *et al.*, 1992; Jordan *et al.*, 1993; Haycock and Pinay, 1993). Several studies examining the role of plants in N removal indicate that vegetation character (composition, structure, or successional stage) alters buffer effectiveness by affecting uptake rates or providing a source of C for soil denitrification (Correll *et al.*, 1992; Jordan *et al.*,

---

[1] Paper No. 01026 of the *Journal of the American Water Resources Association.* **Discussions are open until August 1, 2002.**

[2] Respectively, Doctoral Candidate and Associate Professor, School of Natural Resources and Environment, University of Michigan, G170 Dana Bldg., 430 East University, Ann Arbor, Michigan 48109-1115; and Research Biologist, Michigan Department of Natural Resources, Institute for Fisheries Research, 1109 North University Ave., 212 Museums Annex Bldg. 1084, Ann Arbor, Michigan 48109-1084 (E-Mail/ Baker: meb@umich.edu).

1993; Osborne and Kovacic, 1993; Pinay *et al.,* 1993). A number of investigators have suggested that the local hydrologic setting ultimately controls the extent to which riparian vegetation and soil denitrification can affect significant nutrient removal (Pinay and Decamps, 1988; Hill, 1990; Bohlke and Denver, 1995; Cirmo and McDonnell, 1996; Hill, 1996).

Sharpening predictions of surface and subsurface flow paths across broad heterogeneous landscapes is precisely the challenge facing ecologists seeking to understand both watershed and riparian nutrient dynamics (Osborne and Wiley, 1988; Phillips, 1989; Levine and Jones, 1990; O'Neill *et al.,* 1997; Weller *et al.,* 1998). The idea that variation in the hydrology of riparian areas is linked to variations in their ability to act as nutrient sinks is not new (Hynes, 1983; Elder, 1985; Howard-Williams, 1985; Pinay and Decamps, 1988; Cooper, 1990; Hill, 1990; Groffman *et al.,* 1992; Brinson, 1993a, 1993b; Bohlke and Denver, 1995). Since water is responsible for much of the material transport between riparian and other ecosystems, understanding riparian hydrology is both a logical and practical approach to understanding spatial variation in riparian buffer potential. Hydrologic transport of P is typically associated with the sediment in surface runoff, thus general watershed modeling concepts have been applied with some success (Phillips, 1989; Levine and Jones, 1990; Hunsaker and Levine, 1995; Soranno *et al.,* 1996). In contrast, ground water is considered an important vehicle for N transport from uplands to streams, but because N removal is accomplished via both root uptake and microbially mediated geochemical processes, its dynamics are somewhat more complex (Cirmo and McDonnell, 1996; Hill, 1996; Brunke and Gonser, 1997).

Accounting for ground water movement has been the focus of considerable work in hydrology (Freeze and Cherry, 1979). Common approaches include finite-difference, finite-element, or distributed ground water models using Darcy's Law (e.g., MODFLOW: McDonald and Harbaugh, 1988; Hill, 1992; Harbaugh and McDonald, 1996). Parameterization of such models can involve considerable investment in detailed local information (e.g., well pumping, well logs, piezometer/lysimeter studies). In the absence of detailed information or when working across broad spatial scales, hydrologists frequently rely upon preexisting data and proximal predictors. Increasingly, both researchers and natural resource managers require site-specific information over larger geographic areas (e.g., whole river basins, states, ecoregions). Understanding riparian contributions to the maintenance of stream water quality requires relative estimates of subsurface flux with respect to bodies of water, wetlands, and soils. Yet most ground water models have been concerned with the dynamics of specific supply aquifers, baseflow recession, individual wetlands and lakes, or contaminant plume tracking (Freeze and Cherry, 1979; Holtschlag and Crosky, 1984; Mandle and Westjohn, 1989; Molson and Frind, 1995; Christensen *et al.,* 1998; Martin and Frind, 1998). Ground water flux and recharge rates can be modeled at broader scales, but due to the lack of parameter input, the resulting information is frequently too coarse for use in riparian studies.

In analyses across very broad landscapes where computationally intensive distributed models are unwieldy and/or impractical, terrain-based hydrologic modeling represents an attractive alternative. Terrain-based hydrologic models such as TOPMODEL (Beven and Kirkby, 1979) utilize digital terrain and digital elevation data (DTMs and DEMs) to compute flow direction and accumulation across a landscape. Although they do not generate the detailed flux estimates of more intensive ground water models, terrain-based models have been used to estimate runoff, areas of soil saturation, and water tables in small catchments (e.g., O'Loughlin, 1981; Band, 1989; Band *et al.,* 1991; Quinn *et al.,* 1991; Grayson *et al.,* 1992; Wolock and Price, 1994).

Here we used GIS information derived from readily available digital maps and a novel approach to terrain-based ground water modeling to predict spatial patterns of hydrologic routing and riparian hydrology. We then used summaries of these predictions to predict patterns of nutrient export across broad, heterogeneous landscapes. Our objectives were to compare the relative utility of simple GIS-based models of riparian hydrology with LU/LC map classes and to illustrate the importance of incorporating explicit hydrologic information into landscape-scale nutrient export models.

MODELS AND METHODS

A Varied Landscape

The Lower Peninsula of Michigan provided an ideal natural laboratory for our study of variation in riparian hydrology. Michigan has a tremendous variety of local landscapes due to an exceptionally diverse array of glacial drift, pro-glacial deposits, and glacio-fluvial valleys (Farrand and Bell, 1982). A variable geology is complemented by ecologically relevant climatic gradients from north to south and east to west (Albert *et al.,* 1986). These features compliment a patchwork of LU/LC and result in a broad range of hydrologic conditions for our study.

MRI-DARCY Models

The Michigan Rivers Inventory (MRI; Seelbach and Wiley, 1997) ground water models, like other topographically based hydrologic models, used a DEM and other mapped information to estimate the spatial pattern of physical constraints on hydrologic flow paths. Instead of actual hydraulic heads or *in situ* conductivity measurements, the MRI ground water models relied upon a topographic approximation of head from a 1:24,000, 30-m DEM (1 m vertical resolution), and estimated hydrologic conductivity from a 1:250,000 surficial geology map in a GIS-application of Darcy's Law (MRI-DARCY; Baker *et al.,* 2001). Model estimates were interpreted as potential ground water flow velocities under the assumptions that topographic slopes are roughly proportional to ground water heads and that subsurface hydrologic conductivity is predictable from surficial deposits. Researchers and managers have used the models as a broad-scale (catchment, regional) and local-scale (~ 1 ha) quantitative index, as well as for qualitative visualization, of potential ground water deliveries across the Lower Peninsula. Various iterations of the MRI-DARCY model have been used successfully to predict stream baseflow yields, discharge accrual, water temperatures, fish community assemblages, and stream habitat conditions in Lower Michigan (Seelbach *et al.,* 1997; Wiley *et al.,* 1997; Wehrly *et al.,* 1998; Baker *et al.,* 2001; Seelbach *et al.,* 2001; Zorn *et al.,* 2002).

The MRI-DARCY model used a "moving landscape window" as its sampling template, incorporating a 4 km radial "snapshot" of the surrounding landscape in the generation of distinct delivery index values for every 30 x 30 m cell in a raster grid the size of Lower Michigan. The template consisted of 12 transects oriented 30 degrees apart (like the hands of a clock) for 4 km away from the centroid of a given focal grid cell (Figure 1A). Along each transect, elevation and hydrologic conductivity were sampled at 100-m intervals, and transect slope was multiplied by mean conductivity to determine a delivery estimate. As one proceeds away from the focal grid cell, transect profiles that increased in elevation were assumed to have the potential to contribute water to the focal cell (Figure 1B). Transect profiles that dropped below the elevation of the focal cell were assumed to have the potential to draw water away from the focal cell (Figure 1C). If a particular transect profile first rose above, then dropped below the elevation of the focal cell, the model assumed the potential for both contributions and withdrawals (Figure 1B). If a particular transect

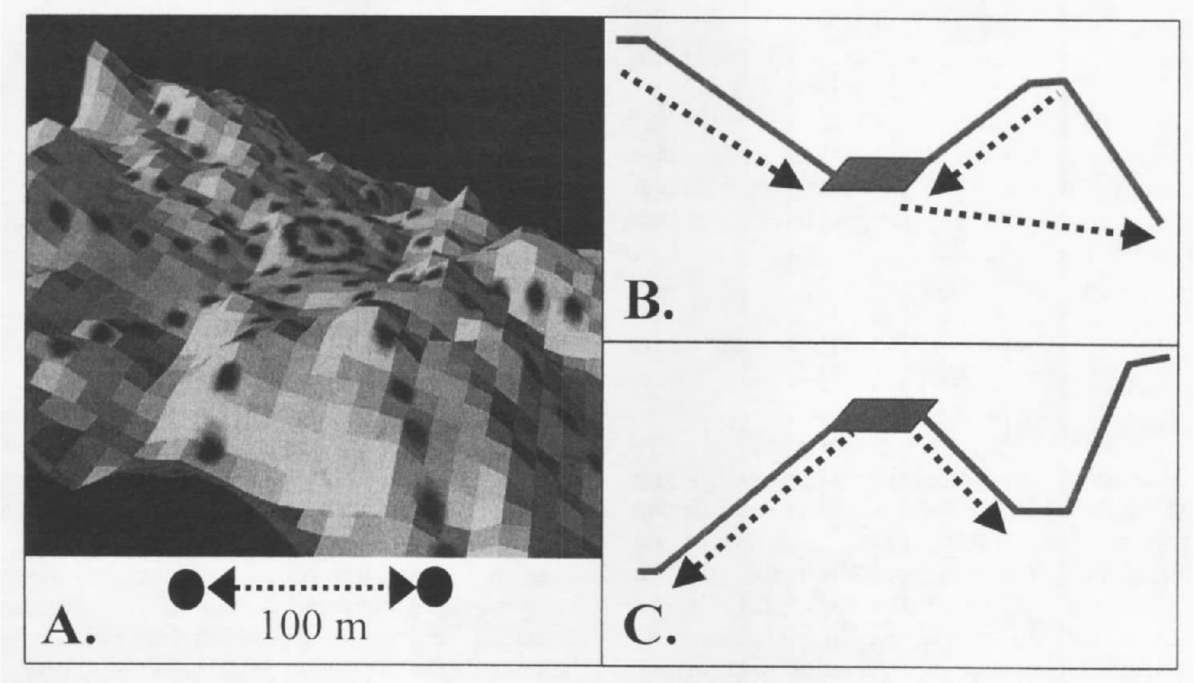

Figure 1. Diagram Showing the Transect Template Used to Combine Topographic and Geologic Information in the MRI-DARCY Models of Potential Ground Water Delivery (A), Transect Profiles Assumed to Contribute to the Focal Cell (B), and Transect Profiles Assumed to Withdraw From the Focal Cell (C). In 1A, black dots identify the location of template samples over a landscape grid depicting slope and aspect. White arrows indicate the direction and magnitude of transect contributions relative to the central, focal grid cell.

profile first dropped below, then rose above the elevation of the focal cell, the model assumed the resulting depression was a sink with the potential to withdraw from, but not to contribute to, the focal cell (Figure 1C). Unlike distributed hydrologic models that generate estimates via cell-to-cell flow, any of the 12 transects could contribute to or withdraw from a given focal cell from any distance along their length. Initially, only contributing transects were summed to determine potential delivery rate estimates for each grid cell (MRI-DARCYv3; Baker *et al.,* 2001). Another variation of the model consisted of summing all transects, regardless of their potential to contribute or withdraw, in an effort to estimate a two-dimensional mass-balance of ground water movement (MRI-DARCYIO; Baker *et al.,* 2001).

Hydrologic Classification

In order to evaluate the importance of spatial variation in hydrologic routing to streamside landscapes, we identified three general types of hydrologic regime: (1) perennially saturated, (2) seasonally inundated, and (3) dry or rarely inundated. Our rationale was that these broad categories were likely to provide useful information in predictive models of nutrient export. We used the MRI-DARCYIO to identify areas of "perennially saturated" soils having a positive flow accumulation (inflow [m/day^{-1}] – outflow [m/day^{-1}]) greater than one standard deviation (SD) above the mean for Lower Michigan. This particular cut-off value was identified after examining a number of examples of saturated wetlands from across the Lower Peninsula. Areas of positive flow accumulation less than this threshold were characterized as "unsaturated" and further subdivided into seasonally inundated and dryland categories.

"Seasonally inundated" riparian areas were identified using vertical proximity (< 1 m) to an interpolated phreatic surface. This interpolation assumed that any stream channel or lake is a representation of the water table surface. Our phreatic estimates were derived using MRI 1:100,000 hydrography maps and their DEM values as input for a surface interpolation operation in Arc/Info. The resulting estimate of the water table surface was subtracted from the DEM to generate a "depth to water table" map likely to be increasingly inaccurate with increasing distance from any water body. Our rationale was that root uptake and prolonged seasonal inundation of riparian soils was often dependent upon a shallow water table less than 1 m (the vertical resolution of our DEM) from the surface. "Dryland" areas were those with neither high rates of predicted ground water delivery (< 1 SD) nor close proximity to the water table (> 1 m). Such areas are not necessarily dry – they may include perched, run-off fed wetlands in addition to well-drained soils. Thus, the above classification thresholds are relatively arbitrary but we assumed the resulting groups would have fairly distinct average conditions. Application of these categories provided a context-dependent prediction of riparian hydrologic character across broad, heterogeneous landscapes.

Nutrient Export Analysis

Nutrient data for 290 sites across Lower Michigan were obtained from the MRI regional database (Figure 2). This data set included water quality samples collected by a combination of state, federal, and academic laboratories between 1975 and 1994, for which simultaneous stream discharge measurements were available. Proportional summaries of LU/LC classes and modeled hydrologic classes were generated using contiguous 500-m buffers of the river network upstream of each site. Although other GIS analyses have used narrower buffers (e.g., Osborne and Wiley, 1988; Hunsaker and Levine, 1995; Johnson *et al.,* 1997), we chose a wider 500-m buffer to accommodate the potential for variable source-area loading (e.g., Levine and Jones, 1990; Soranno *et al.,* 1996) and broad streamside wetlands observed in Lower Michigan (e.g., Tompkins *et al.,* 1997; Baker and Barnes, 1998; Crow *et al.,* 2000). LU/LC data were obtained from the Michigan Resource Information System (MIRIS; Michigan Department of Land and Mineral Services, Lansing) database based on 1978 aerial photography. Mapped resolution was approximately 1 ha, with a minimum lateral dimension of 61 m.

Our approach was to evaluate the effect of augmenting a standard "base nutrient export model" (hereafter "base model") with various combinations of variables that might be used to describe riparian conditions. We were primarily interested in the ability of our GIS-derived hydrologic classes to predict hydrologic function both with and without the vegetative structure or wetland information available from LU/LC maps. LU/LC class proportions were therefore aggregated in two ways so as to emphasize wetlands or vegetative structure: (1) agriculture, forest (coniferous, deciduous, and mixed), nonforest (range, barren), and wetland (forested and nonforested); (2) agriculture, forest (coniferous, deciduous, mixed, and forested wetland) and nonforest/herbaceous (barren, nonforested wetland, range). Urban and open water classes were summarized but not included in either analysis for reasons of parsimony. Because the purpose of these analyses was illustrative comparison rather than finding the best fitting MLR model, we utilized a standard set of independent variables in the various predictions of N and P concentrations and loads.

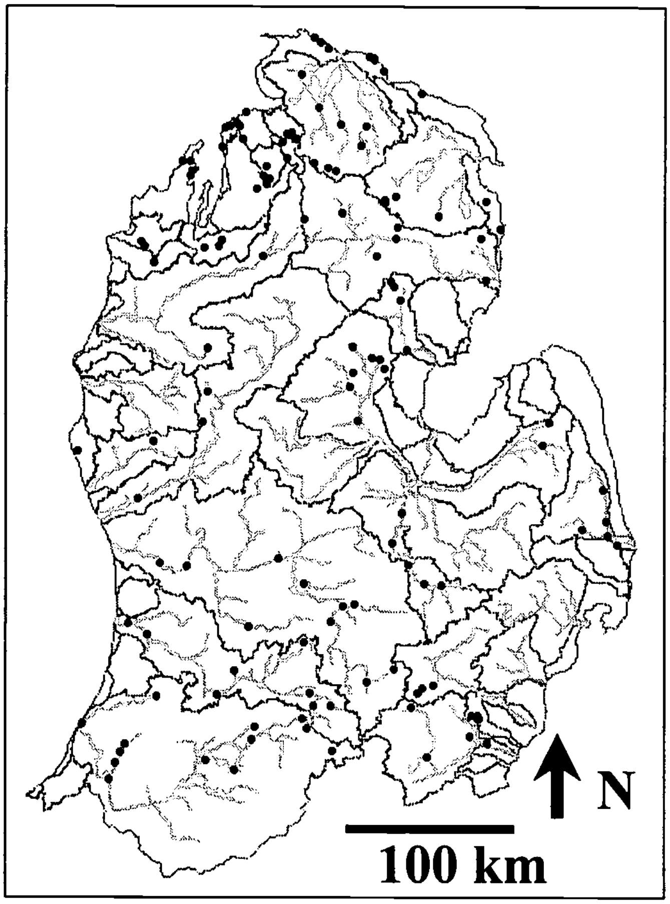

Figure 2. Map of Michigan Rivers Inventory Site Locations for Simultaneous Nutrient Concentration and Discharge Measurements Across the Major River Basins of Lower Michigan.

A conceptual diagram of our initial MLR model and the five augmented models used in the empirical/statistical comparison is presented in Figure 3. Our base model utilized drainage area and percent agriculture within a 500-m upstream network buffer as independent predictors of nutrient levels. The following model variations were compared using the r-squares and standard errors of the MLR estimates. A "mapped wetland" model, consistent with the idea that riparian wetlands can influence nutrient export, used LU/LC wetlands to augment the base model. In the "vegetation structure" model, wetlands were replaced with forest and non-forest/herbaceous cover classes to evaluate the effect of augmenting the base model with vegetation structure information. The "hydrologic class" model used GIS-derived hydrologic predictions instead of LU/LC information with the implicit hypothesis that terrain-based hydrologic inferences would better augment the base model than the information derived from LU/LC maps. However, because each of the above models used a different number of independent predictors, we included two additional models to evaluate the influence of differences in degrees of freedom. The "wetland hydrology" model uses the GIS-derived hydrologic classes to further characterize areas mapped as LU/LC wetlands, whereas the "vegetation hydrology" model uses the hydrologic classes to further characterize forested and herbaceous cover. In all models, dependent intercepts were forced through the origin because we assumed that nutrient levels at sites without any watershed or land cover source area were necessarily equal to zero.

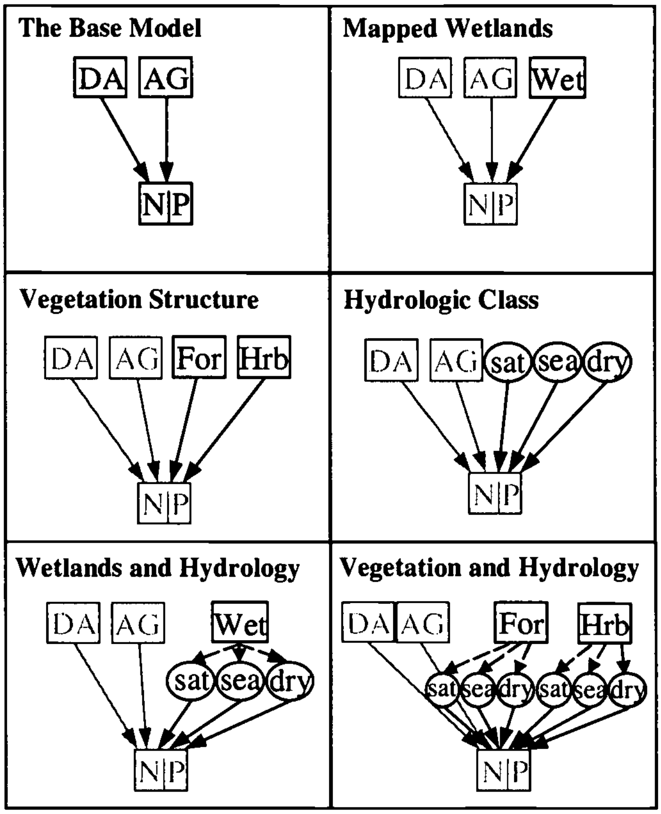

Figure 3. Diagrammatic Representation of Six Multiple Linear Regression Analyses Compared in the Case Study. Boxes indicate empirical variables, ovals indicate predicted hydrologic variables, solid arrows indicate implied effects of independent predictors on dependent variables, and dashed arrows indicate subdivision of empirical variables with predicted hydrologic classes. N | P = NO_2 + NO_3 or SRP, DA = Drainage Area, AG = Percent Agriculture, For = Percent Forest, Hrb = Percent Nonforested/Herbaceous, Wet = Percent Wetlands, sat = predicted saturated areas, seas = predicted seasonally inundated areas, dry = predicted dryland areas. Note that the base model shown in 3A, remains in gray in each of the remaining analyses.

RESULTS

Ground Water Models and Hydrologic Characterization

Predicted ground water delivery clearly varied across broad regions in the state as well as within specific local landscapes (Figure 4). At the scale of Lower Michigan, what we see is that many low-lying areas such as major river valleys are predicted to experience subsurface delivery, and that this is particularly true within the sand hills in northern Lower Michigan (Figure 4A). At the scale of a small valley segment, steep valley walls along meander bends are more likely to have seeps than more gently sloping valley walls, and sandy valley alluvium is predicted to conduct water more effectively than the till of adjacent moraines (Figure 4B). The MRI-DARCYIO model in Figure 4C illustrates the spatial variability in local "hotspots" of potential net ground water accumulation along the river valley bottom, as well as expanses of potential net ground water loss along the valley walls and into the upland. The white areas indicate adjacent uplands that have relatively steep subsurface gradients to the valley bottom. These locations have a proportionately high potential to deliver water and dissolved substances directly to the dark areas on the map simply because these areas are nearby, they are relatively conductive, and because they are situated above the darker areas. Across Lower Michigan, we

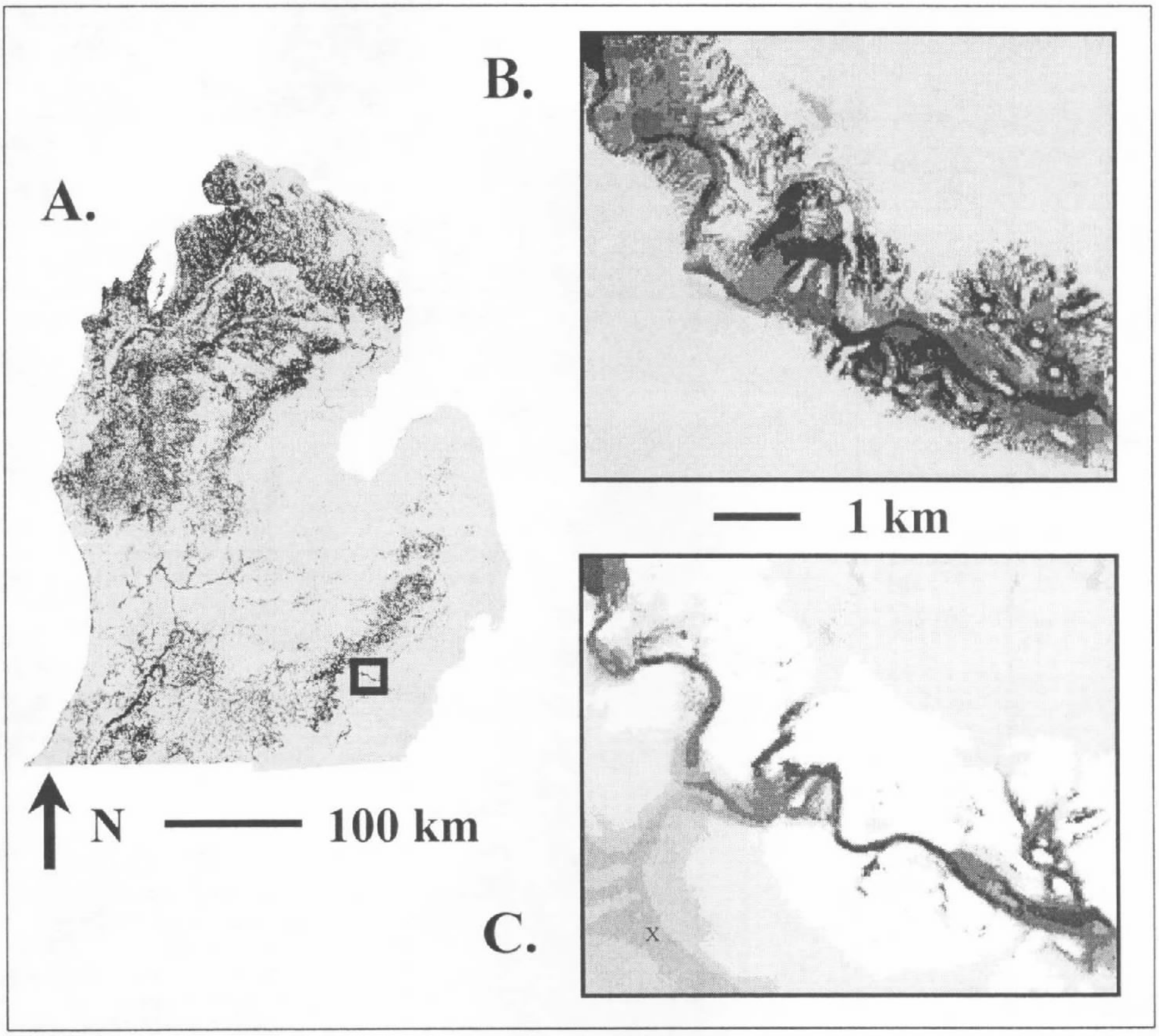

Figure 4. MRI-DARCY Model of Potential Ground Water Loading Across Lower Michigan (A), a Local River Valley Landscape Near Ann Arbor, Michigan (B), and the Same Landscape Viewed With the MRI-DARCY IO Model (C). Higher rates of potential flux or accumulation are shown in darker shade variations corresponding to 1/2 SD ($m \cdot day^{-1}$) relative to the mean for Lower Michigan. In the IO version, darker shades indicate higher net accumulation and lighter shades indicate net withdrawals. Values are relative to a net accumulation of zero as indicated by the shade marked with an X.

observed a variety of narrow to broad river valley bottoms with a range of predicted net groundwater accumulation estimates from 0 to >18 m/day^{-1} (> 3 SD). Concurrently, we observed adjacent landscapes with predicted ground water net loss estimates ranging from 0 to > 20 m/day^{-1} (> 3 SD). Broad and fine-scale variation in these predicted delivery patterns contributed to similar patterns of riparian hydrologic regime. Across Lower Michigan, we observed examples of valley bottoms occupied with uniform values of each of the three hydrologic categories, as well as examples of patchy combinations of classes as shown in Figure 5.

Nutrient Export Analyses

The MLR that comprised our base and augmented nutrient export models are compared in Figure 6. Predictions of NO_2+NO_3 export using drainage area and percent agriculture had higher squared-multiple-r values and lower standard errors than similar predictions of SRP export, and our base model accounted for a greater proportion of the observed variance in nutrient loads versus nutrient concentrations. Accordingly, it is worth noting that the increases in squared-multiple-r values and relative decreases in standard errors of the augmented models are smaller for NO_2+NO_3 than for SRP (Figures 6B and 6C). In our comparison of augmented nutrient export models, the mapped wetland model showed greater predictive power for SRP than the vegetation structure model despite differences in degrees of freedom, but this was not the case for NO_2+NO_3. In addition, for both NO_2+NO_3 and SRP, models using GIS-based hydrologic classes improved predictions of nutrient export relative to the base model more than models with either mapped wetlands or vegetation structure alone.

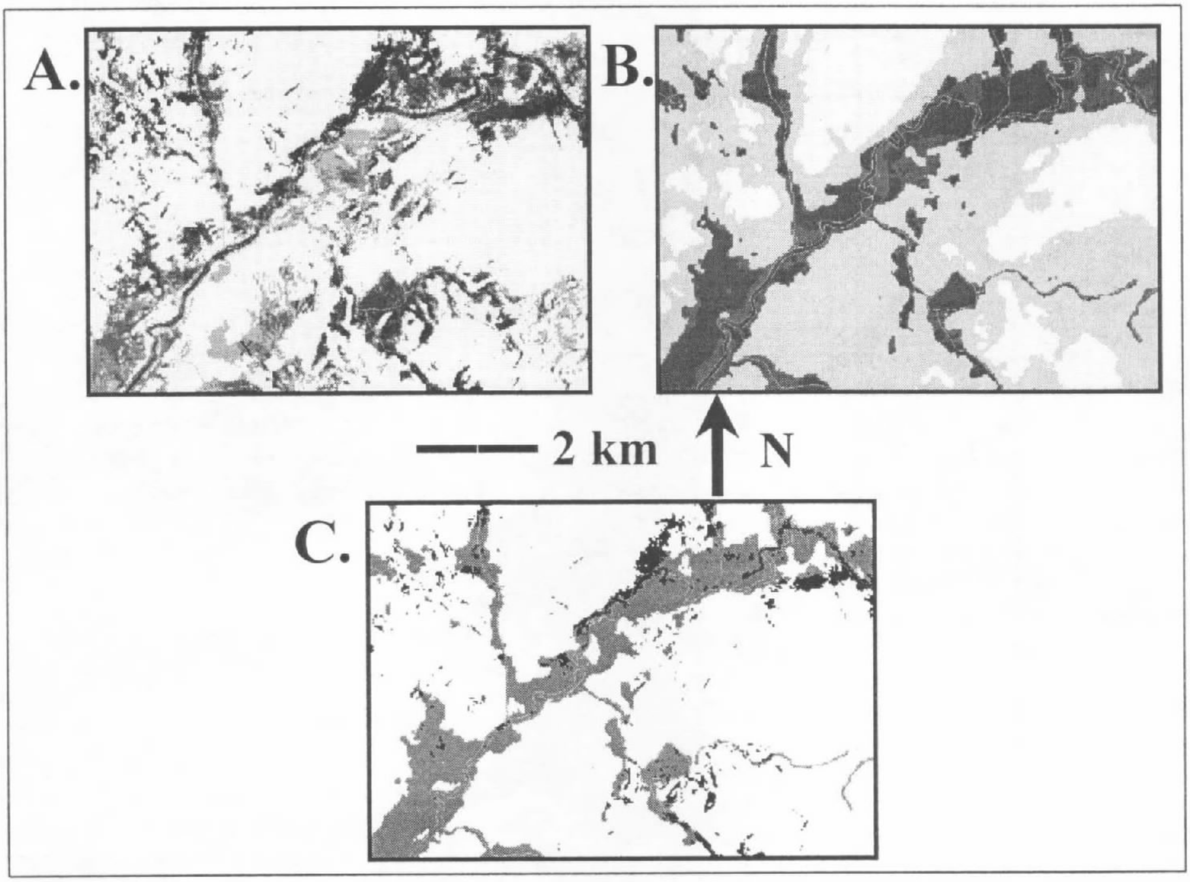

Figure 5. Maps of Potential Ground Water Loading (A) and Water Table Depth (B) Used to Estimate the Extent of Perennially Saturated and Seasonally Inundated Wetlands (C) in the Kalamazoo River Valley Near Augusta, Michigan. In 5A and 5C, black areas indicate high rates of ground water delivery (>1 SD m·day^{-1}) relative to the Lower Peninsula mean (X). In 5B and 5C, dark gray areas indicate seasonally inundated wetlands that are close (<1 m in elevation) to an estimated water table surface.

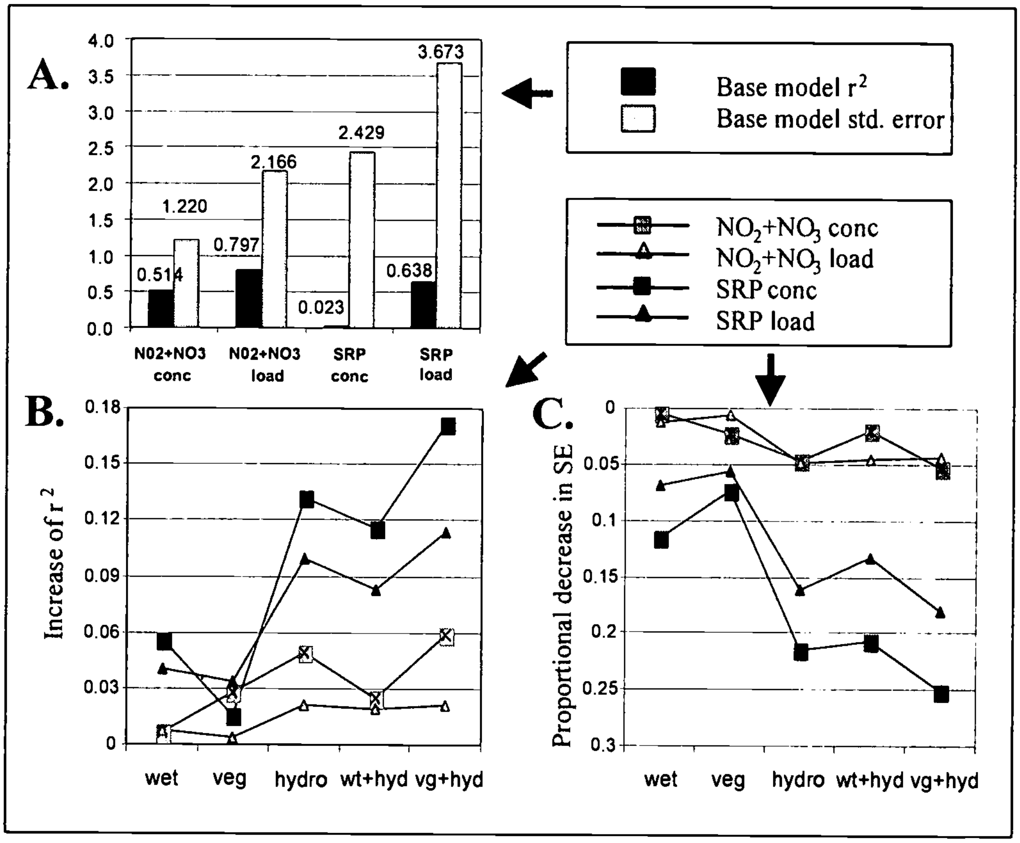

Figure 6. Comparison of Various Characterizations of Riparian Landscapes Showing Squared-Multiple-r Values and Standard Errors of Estimated Nutrient Levels Using the Base Model (A), Increases in Square-Multiple-r Values Over the Base Model (B), and Proportional Decreases of Standard Errors Relative to the Base Model (C). Categories in 6B and 6C correspond to the analyses in Figure 3.

The wetland hydrology model utilized the same number of independent variables as the hydrologic class model, yet restricted the GIS-derived predictions to locations already mapped as wetlands. As independent predictors, the derived hydrologic classes were not strongly correlated with mapped wetlands (Pearson product-moment r of 0.210, 0.621, and 0.620 for saturated, seasonal, and dryland classes versus mapped LU/LC wetlands). Characterizing LU/LC wetlands by hydrologic class seemed to improve predictive relationships with nutrient export over the mapped wetland model (Figures 6B and 6C). However, adding the initial LU/LC wetland classification did not improve predictive relationships with nutrient levels over the hydrologic class model. Similarly, the vegetation hydrology model used derived hydrologic classes to characterize the hydroperiod of LU/LC forest and herbaceous cover. Unlike the wetland hydrology model, augmenting vegetative structure with hydrologic predictions improved observed relationships with nutrient levels over either the vegetative structure or hydrologic class models in three out of the four comparisons (Figures 6B and 6C). In general, all models using predicted hydrologic classes showed stronger relationships with patterns of nutrient export than models based solely on mapped LC/LU information.

DISCUSSION

The Utility of Hydrologic Models

With riparian areas under ever-increasing development pressure in many landscapes, there is a very practical need for understanding their role in maintaining the ecological integrity of streams. Accounting for spatial patterns of surface and subsurface hydrologic transport is key to understanding the ecological significance of riparian processes. Given the complexity of hydrologic processes relevant to riparian function, there is a very practical need for the simplification and abstraction inherent in modeling.

In this context, GIS approaches can be a cost-effective and eminently practical alternative for understanding complex spatial phenomena (Levine and Jones, 1990, O'Neill *et al.,* 1997). Our GIS-based hydrologic classifications were not designed to make precise predictions about water table elevation or ground water flow rate, but to predict the spatial location of different hydrologic settings and improve our understanding of how patterns of hydrologic routing influence ecological character at specific sites.

Although the MRI-DARCY models provide estimates of the relative magnitude of potential subsurface flow paths involved in nutrient flux, they do not actually account for water movement. Nor, in fact, do the models account for deeper, regional ground water flows or overbank river flooding. Instead, the models are based on the idea that low-lying areas in conductive landscapes are more likely to receive shallow ground water from their surroundings than areas in less conductive or elevated landscape settings. Unlike other terrain-based hydrologic models, the MRI-DARCY models do not derive their ground water estimates as a consequence of surface flow patterns; only the elevation differentials between several often widely spaced points on the transect template are used. The significance of the transect template is its sampling and integration of a relatively broad surrounding landscape to compute the delivery value for a relatively small, yet distinct, receiving locale on the topographic surface. Rather than providing absolute estimates of flux, the utility of the MRI-DARCY models lies in their ability to call our attention to places where subsurface connectivity is likely to exist and from which direction shallow subsurface flux is likely to be important. According to O'Neill *et al.* (1997), it is the ability to account for spatial variation in hydrologic processes leading to soil saturation, vegetative character, and material transport that will result in a greater understanding of the water quality benefits of riparian buffers in different landscape settings.

The spatially complex delivery maps in Figure 4 illustrate the ability of the MRI-DARCY models to highlight areas where ground water is likely to occur at or near the surface, as well as the direction from which it is likely to come, given the character of the surrounding landscape. The significance of using the 30 m cell resolution of the MRI-DARCY model and the phreatic DEM for hydrologic predictions – as compared to the 100 m cells of the LU/LC map – is that we were able to generate hydrologic estimates for both broad valley bottoms and fairly narrow tributaries (Figure 5). Hence, not only were the hydrologic models able to distinguish between broad expanses of various wetland types and more patchy landscape patterns, they were also able to predict relatively narrow bands of streamside wetlands that larger cells might miss.

Although many riparian investigators acknowledge that hydrologic setting is an important determinant of riparian function, there is still an urgent need to accumulate, synthesize, and communicate the extent and implications of hydrologic variation to researchers and resource managers. Progress in river and riparian conservation and management may be hampered by generalized application of riparian concepts derived from a single hydrologic setting. Recognition of the potential for hydrologic variation needs to occur during study designs, in the analysis and interpretation of results, and during the development of management recommendations. Prior to the development of effective models of riparian function, there is a need to develop a conceptual framework that explicitly accounts for hydrologic variation and its implications for stream water quality.

A number of studies have described a range of distinct hydrologic settings and their potential influence on riparian buffer function. In the context of these examples, we present a summary of six general riparian hydrologic types we observe repeatedly throughout Lower Michigan (Figure 7). The first example describes those settings where riparian buffers are ineffective because subsurface flow paths bypass riparian soils and plant roots (Hill, 1990; Bohlke and Denver, 1995; Hill, 1996; Brunke and Gonser, 1997). The second type includes riparian areas that are bypassed by drainage tiles, ditches, sewer systems, or where nutrient sources occur immediately adjacent to the stream channel. The third type occurs in a runoff-dominated landscape where riparian soils and vegetation may contribute to P removal but limited N removal (Phillips, 1989; Soranno *et al.,* 1996). The fourth type of riparian area refers to those that experience seasonal inundation from phreatic fluctuation. Although plant roots may remain in contact with the water table for much of the growing season, the potential for root uptake relative to denitrification remains dependent upon spatial and seasonal variation in water levels (Pinay and Decamps, 1988; Cirmo and McDonnell, 1996). The fifth type includes riparian surfaces whose soils are in continuous or near-continuous contact with ground water. These areas often exhibit saturated soils and anaerobic conditions throughout much of the year. As a result, these areas are locations with relatively high denitrification potential and fairly limited root activity (Pinay and Decamps, 1988; Cirmo and McDonnell, 1996). It is important to remember that in any of these types, water may reach the river without being influenced significantly by riparian processes. All of these examples refer to hydrologic settings where the process of

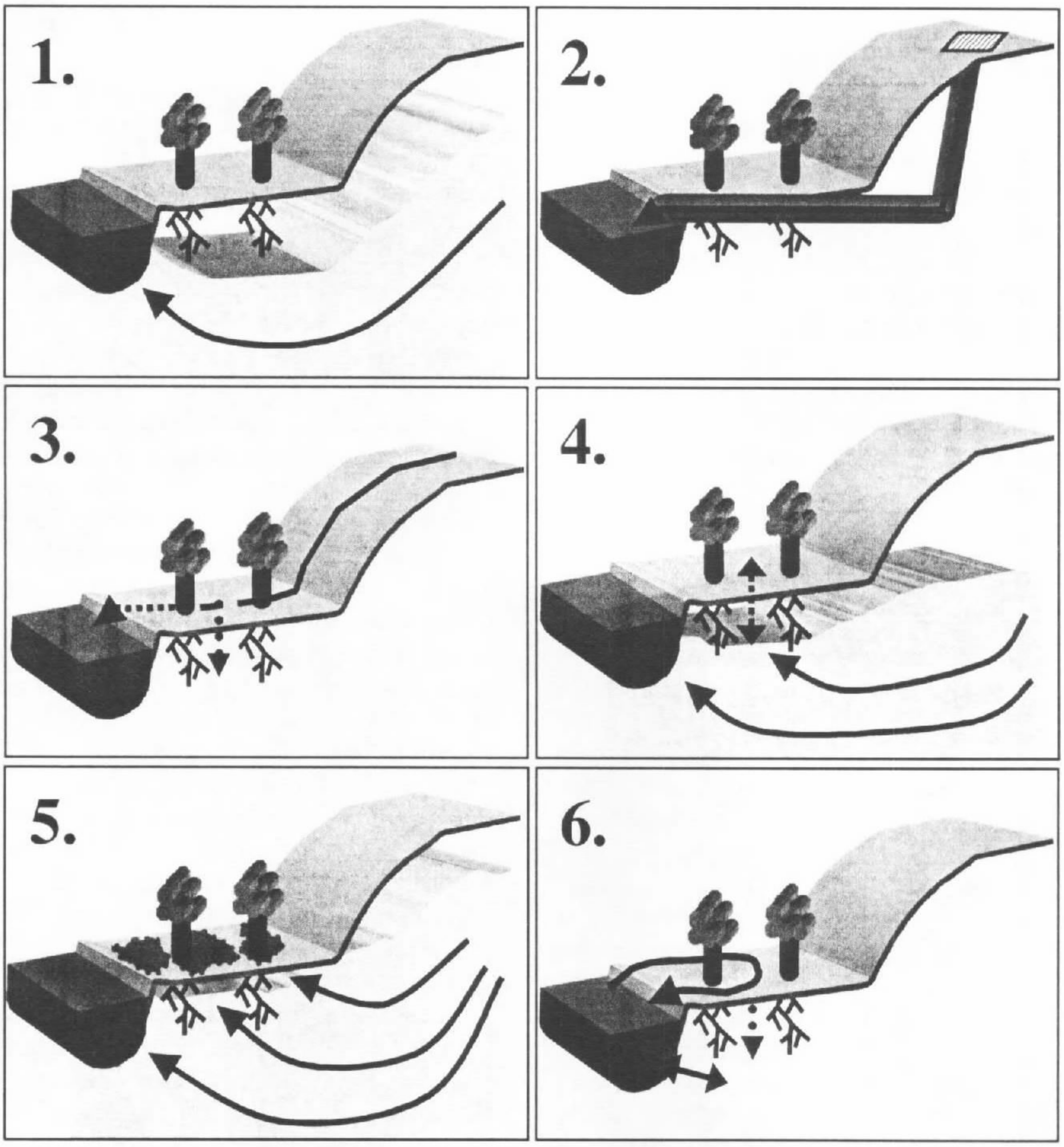

Figure 7. Six Types of Hydrologic Function in Riparian Areas: (1) Riparian Buffer Bypassed by Ground Water, (2) Riparian Buffer Bypassed by Sewer, (3) Runoff Buffer, (4) Seasonally Inundated Buffer, (5) Perennially Saturated Buffer, and (6) Overbank Flooding and Hyporheic Exchange.

nutrient removal is dependent upon hydrologic transport of nutrients from the landscape to a river. In addition, the sixth riparian type serves as a reminder that under any of these settings, lateral flux from the river as overbank flow or hyporheic exchange may augment riparian water levels and alter nutrient conditions (Elder, 1985; Brunet *et al.,* 1994; Tremoliers *et al.,* 1994; Brunke and Gonser, 1997).

In an ideal model of riparian nutrient dynamics, some estimate of the spatial complexity of all relevant processes would be included at an appropriate spatial and temporal resolution. Both surface runoff and subsurface flow would be estimated, including the flow paths that bypass riparian influence. Riparian inundation would include runoff detention, and phreatic saturation, as well as overbank flooding at the recurrence interval appropriate for each. To the extent that long-term hydrologic constraints influence soil development and plant assemblages within a region, spatial variation in soil processes and vegetation character would be included. The spatial pattern of vegetative cover would also be used to improve predictions of nutrient removal from surface and subsurface sources, and all of these processes would be reactive to potential human activity in both the riparian buffer and the source catchment.

As an early step in the iterative modeling process, we chose to focus on identifying Types 4 and 5 (Figure

7) since these are the scenarios under which riparian areas may have the greatest influence on ground water nutrient levels. Our GIS models are presently too general to predict precise riparian function, yet they do indicate locations where conditions necessary for significant denitrification and plant uptake are likely to occur. Saturated wetlands (Type 5) created by ground water seeps are often areas of high denitrification potential and may serve as a source, rather than a sink, for P (Cirmo and McDonnell, 1996; Tompkins *et al.,* 1997). Nutrient removal by plant roots in seasonally inundated wetlands (Type 4) requires a source of N and aerobic soils which are more likely to occur together where water table levels fluctuate yet remain within the reach of many plant roots. Broad expanses of such shallow riparian water tables may also indicate areas of poor drainage with prolonged inundation and additional denitrification potential in the late winter or spring.

Including Hydrologic Variation in Nutrient Export Models

Using general relationships between buffer land use, simple estimates of subsurface flux, and measurements of instream nutrient levels, we have illustrated the importance of including hydrologic information in spatial models of water quality. Our purpose here was not necessarily to develop the best possible prediction of nutrient export *per se*, but to illustrate that a simple hydrologic model – because it makes explicit simplifications of complex hydrologic processes – can improve our overall understanding and better address questions of riparian function. Our nutrient measurements were obtained during a wide variety of seasonal flow conditions, and many researchers describe strong seasonal and flow dependencies in nutrient data (Peverly, 1982; Hill, 1996; Cirmo and McDonnell, 1996; Johnson *et al.,* 1997; Castillo *et al.,* 2000). Nevertheless, a two-variable base model accounted for over half of the observed variation in nutrient exports (Figure 6). Our models clearly exhibited stronger relationships with load than concentration. Because drainage area was included in the analyses and water load generation is proportional to catchment area, this result was not surprising. Other researchers have found strong relationships between watershed size and patterns of nutrient export (Osborne and Wiley, 1988; Johnson *et al.,* 1997; Castillo *et al.,* 2000). The primary focus of our analysis was riparian interaction with agriculturally derived pollutants, and our base model related more strongly with NO_2+NO_3 than with SRP (Figure 6). This result is consistent with other nutrient export studies where agricultural areas are the predominant nutrient sources in catchment or channel buffer summaries (Johnson *et al.,* 1997; Castillo *et al.,* 2000; Jones *et al.,* 2001).

Our results showed that using predicted hydrologic conditions to augment our base model consistently improved our ability to explain nutrient exports over using LU/LC information alone (Figure 6). Although differences in degrees of freedom for our multiple regressions make statistical comparisons of all squared-multiple-r values somewhat inappropriate, adding more variables to the base model did not always improve the squared-multiple-r of the regression or the standard error of the estimate. Furthermore, where degrees of freedom were identical, modeled hydrologic classes alone generally performed as well or better than LU/LC wetlands augmented by the hydrologic predictions. Thus, these results indicated that some estimation of hydrologic function is desirable in spatial models of nutrient export beyond that provided by the presence or absence of mapped wetlands.

Although they identify location and aerial extent of wetlands, LU/LC maps do not capture the hydrologic processes responsible for their existence or characterize their function. The implicit assumption of a LU/LC wetland summary in a nutrient export model is that all wetlands have the same magnitude and direction of influence on nutrient export, regardless of their hydroperiod or hydrologic source. For example, in our mapped wetland model of NO_2+NO_3 load, the regression coefficients for mapped wetlands were significant and negative as we might expect given their potential for assimilation, denitrification, and interruption of nitrification (Cirmo and McDonnell, 1996; Tompkins *et al.,* 1997). Yet in our hydrologic class model, as well as in individual augmentations of the base model for NO_2+NO_3 load, the seasonally inundated class coefficient was significant and negative whereas the saturated class coefficient was significant and positive. Although assigning causality on the basis of a MLR coefficient would be inappropriate, it is clear that the influence of saturated and seasonally inundated areas on NO_2+NO_3 levels is distinctly different. Without the ability to account for the hydrologic processes and landscape characteristics that give rise to such phenomena, LU/LC indices may be unreliable predictors of ecological function in different landscape settings (Tischendorf, 2001). It is the hydroperiod in riparian areas and hydrologic routing from surrounding landscapes that ultimately determine the degree to which riparian buffers are effective at intercepting watershed-derived pollutants. These hydrologic processes are not simply a function of LU/LC patterns, but the result of underlying physical constraints and a functioning riparian ecosystem.

Making use of underlying geology and geomorphology can further inform us about the hydrologic setting in which we interpret LC/LU patterns, as well as alert us to the potential for LU/LC, geology, and geomorphology to be spatially auto-correlated.

When hydrologic classes were used to characterize vegetation structure, our ability to explain patterns of nutrient export increased somewhat (Figure 6). However, the observed increases over the hydrologic class model were less consistent and often relatively small compared to the increases we observed by adding hydrologic information to the base model or the vegetative structure model. The magnitude of these results suggested that the influence of forest versus grassy buffers or the composition of riparian vegetation on nutrient dynamics (as described by Correll *et al.*, 1992; Osborne and Kovacic, 1993; and Haycock and Pinay 1993) might well depend upon the hydrologic context of the observation. Moreover, because distinct riparian site conditions can result in distinct forest community composition (e.g., Hupp and Osterkamp, 1985; Pautou and Decamps, 1985; Baker and Barnes, 1998), it is likely that there is often co-variation between the character of riparian hydrology and character of riparian vegetation. Therefore, some estimate of relevant hydrologic processes seems important for assessing the role of vegetation in riparian buffer dynamics. Indeed, adding more explicit hydrologic information is consistent with the work of many other researchers, who have suggested that saturated, seasonally flooded, and other kinds of riparian hydrology have distinct buffer functions (Elder, 1985; Howard-Williams, 1985; Pinay and Decamps, 1988; Chauvet and Decamps, 1989; Brinson, 1993b; Cirmo and McDonnell, 1996; Hill, 1996).

Overall, despite the inclusion of hydrologic classes, the added predictive power of riparian buffer characteristics above our base model was variable and modest, especially for NO_2+NO_3 (Figure 6). Given the order-of-magnitude increases in nutrient concentrations generated across heterogeneous source landscapes, it seems unlikely that riparian factors alone can regulate observed rates of nutrient flux. However, the use of our hydrologic models did improve our estimates of SRP concentration and load by 13 and 10 percent, respectively. In the context of this range of variation, the integrated application of models reflecting rapid advective transport of river channels and storm runoff with relatively slow transport of subsurface flow paths holds much promise for future causal understanding of watershed and riparian function.

Implications of Hydrologic Variation

Given the spatial complexity of ecological function in riparian areas and widespread management policies geared towards riparian preservation and restoration, the need for spatially explicit information across large landscapes is apparent. It is our intention to encourage researchers to develop location-specific models of riparian hydrology and tools that aid in the adaptive implementation of riparian and watershed management guidelines. Our results suggest that using GIS models to characterize hydrologic processes can significantly increase our understanding of riparian nutrient dynamics. To date, much of our understanding of riparian nutrient dynamics has been based on transect level studies or broad-scale empirical relationships. Local studies are often unable to address the role of hydrologic context in their results, whereas many broad-scale analyses have tended to assume consistent underlying linkages between rivers, riparian areas, and surrounding landscapes and typically focus on spatial patterns of LC/LU. Moreover, there appears to be a trend in the applied literature to focus on vegetation width and continuity as a measure of ecological integrity and buffer protection. In contrast, our models predict considerable variation in the aerial extent of hydrologic conditions likely to facilitate nutrient removal at the scale of a stream reach, lakeshore, or wetland (Figures 4 and 5). Our models also suggest that the aerial extent of surrounding landscapes with the potential to contribute ground water relatively rapidly to valley bottoms varies along a river, and among rivers and landscapes. Whereas standard vegetated buffer widths of 10 to 150 m have been advocated to achieve various physical and biotic benefits (Barton *et al.*, 1985; Crow *et al.*, 2000), our models suggest the width of hydrologically connected riparian zones may range widely and extend up to 500 m or more in certain landscapes.

There is now ample evidence to suggest that the hydrology and ecological function of all riparian areas are not the same. Rather than relying on a single buffer dimension (e.g., vegetated width), a context-specific, place-based approach to understanding riparian nutrient dynamics and buffer delineation in the context of catchment sources and sinks seems necessary. While vegetative structure and spatial pattern are undoubtedly important aspects of riparian buffers, we advocate a shift in focus to the hydrologic processes ultimately responsible for material transport in and across streamside riparian zones.

ACKNOWLEDGMENTS

We would like to thank J. D. Allan, K. E. Wehrly, R. L. Cifaldi, and three anonymous reviewers for their helpful comments on earlier drafts of this manuscript. This work was supported through a research grant from the Michigan Department of Natural Resources, Virtual Geographic Information Laboratory (ViGIL) Program.

LITERATURE CITED

Albert, D. A., S. R. Denton, and B. V. Barnes, 1986. Regional Landscape Ecosystems of Michigan. School of Natural Resources, University of Michigan, Ann Arbor, Michigan.

Baker, M. E. and B. V. Barnes, 1998. Landscape Ecosystem Diversity of River Floodplains in Northwestern Lower Michigan, USA. Canadian Journal of Forest Research 28:1405-1418.

Baker, M. E., M. J. Wiley, and P. W. Seelbach, 2001. Spatially-Explicit Models of Groundwater Loading Across a Glaciated Landscape. Mich. Dept. Nat. Res. Research Report, Ann Arbor, Michigan (in press).

Band, L. E., 1989. A Terrain Based Watershed Information System. Hydrological Processes 3:151-162.

Band L. E., D. L. Peterson, S. W. Running, J. C. Coughlan, R. Lammers, J. Dungan and R. R. Nemani, 1991. Ecosystem Processes at the Watershed Level: Basis for Distributed Simulation. Ecological Modeling 56:171-196.

Barton, D. R., W. D. Taylor, and R. M. Biette, 1985. Dimensions of Riparian Buffer Strips Required to Maintain Trout Habitat in Southern Ontario Streams. North American Journal of Fisheries Management 5:364-378.

Beven, K. J. and M. J. Kirkby, 1979. A Physically Based Variable Contributing Area Model of Basin Hydrology. Hydrol. Sci. Bull. 24: 43-69.

Bohlke, J. K. and J. M. Denver, 1995. Combined Use of Groundwater Dating, Chemical, and Isotopic Analyses to Resolve the History and Fate of Nitrate Contamination in Two Agricultural Watersheds, Atlantic Coastal Plain, Maryland. Water Resources Research 31:2319-2339.

Brinson, M. M., 1993a. A Hydrogeomorphic Classification for Wetlands. Technical Report WRP-DE-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Brinson, M. M., 1993b. Changes in the Functioning of Wetlands Along Environmental Gradients. Wetlands 13:65-74.

Brunet, R. C., G. Pinay, F. Gazelle, and L. Roques, 1994. Role of the Floodplain and Riparian Zone in Suspended Matter and Nitrogen Retention in the Ardour River, Southwest France. Regulated Rivers Research and Management 9:55-63.

Brunke, M. and T. Gonser, 1997. The Ecological Significance of Exchange Processes Between Rivers and Groundwater. Freshwater Biology 37:1-33.

Castillo, M. M., J. D. Allan, and S. Brunzell, 2000. Nutrient Concentrations and Discharges in a MidWestern Agricultural Catchment. Journal of Environmental Quality 29:1142-1151.

Chauvet E. and H. Decamps, 1989. Lateral Interactions in a Fluvial Landscape: The River Garonne, France. Journal of the North American Benthological Society 8:9-17.

Christensen, S., K. R. Rasmussen, and K. Moller, 1998. Prediction of Regional Groundwater Flow to Streams. Ground Water 36:351-360.

Cirmo, C. P. and J. J. McDonnell, 1996. Linking the Hydrologic and Biogeochemical Controls of Nitrogen Transport in Near-Stream Zones of Temperate-Forested Catchments: A Review. Journal of Hydrology 199:88-120.

Cooper, A. B., 1990. Nitrate Depletion in the Riparian Zone and Stream Channel of a Small Headwater Catchment. Hydrobiologia 202:13-26.

Correll, D. L., 1997. Buffer Zones and Water Quality Protection: General Principles. *In:* Buffer Zones: Their Process and Potential in Water Protection, N. E. Haycock, T. P. Burt, K. W. T. Goulding, and G. Pinay (Editors). Quest Environmental, pp. 7-20.

Correll, D. L., T. E. Jordan, and D. E. Weller., 1992. Nutrient Flux in a Landscape: Effects of Coastal Land Use and Terrestrial Community Mosaic on Nutrient Transport to Coastal Waters. Estuaries 15:431-442.

Crow, T. R., M. E. Baker, and B. V. Barnes, 2000. Diversity in Riparian Landscapes. *In:* Riparian Management in Forests of the Continental Eastern U.S., E. S. Verry, J. W. Hornbeck, and C. A. Dolloff (Editors). Lewis Publishers, New York, New York.

Elder, J. F., 1985. Nitrogen and Phosphorous Speciation and Flux in a Large Florida River Wetland System. Water Resources Research 21:724-732.

Farrand, W. R and D. L. Bell, 1982. Quaternary Geology of Michigan. State of Michigan Department of Natural Resources, Geological Survey, Map (color).

Freeze, R. A. and J. A. Cherry, 1979. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Grayson R. B., I. D. Moore, and T. A. McMahon, 1992. Physically-Based Hydrologic Modeling. I. A Terrain-Based Model for Investigative Purposes. Water Resources Research 28(10):2639-2658.

Groffman, P. M., A. J. Gold, and R. C. Simmons, 1992. Nitrate Dynamics in Riparian Forests: Microbial Studies. Journal of Environmental Quality 21:666-671.

Harbaugh, A. W. and M. G. McDonald, 1996. User's Documentation for MODFLOW-96: An Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. U.S. Geological Survey Open-File Report 96-485.

Haycock, N. E. and G. Pinay, 1993. Groundwater Nitrate in Grass and Poplar Vegetated Riparian Buffer Strips During the Winter. Journal of Environmental Quality 22:273-278.

Hill, A. R., 1990. Groundwater Cation Concentration in the Riparian Zone of a Forested Headwater stream. Hydrological Processes 4:121-130.

Hill, A. R., 1996. Nitrate Removal in Stream Riparian Zones. Journal of Environmental Quality 25:743-755.

Hill, M. C., 1992. A Computer Program (MODFLOW) for Estimating Parameters of a Transient, Three-Dimensional Ground-Water Flow Model Using Nonlinear Regression. U.S. Geological Survey Open-File Report 91-484.

Holtschlag, D. J. and H. M. Crosky, 1984. Statistical Models for Estimating Flow Characteristics in Michigan Streams. U.S. Geological Survey, Water Resources Investigations Report 84-4207, Lansing, Michigan.

Howard-Williams, C., 1985. Cycling and Retention of Nitrogen and Phosphorous in Wetlands: A Theoretical and Applied Perspective. Freshwater Biology 15:391-431.

Hunsaker, C. T. and D. A. Levine, 1995. Hierarchical Approaches to the Study of Water Quality in Rivers. Bioscience 45:193-203.

Hupp, C. R. and W. R. Osterkamp, 1985. Bottomland Vegetation Distribution Along Passage Creek, Virginia in Relation to Fluvial Landforms. Ecology 66:670-681.

Hynes, H. B. N., 1983. Groundwater and Stream Ecology. Hydrobiologia 100:93-99.

Jacobs, T. C. and J. W. Gilliam, 1985. Riparian Losses of Nitrate From Agricultural Drainage Waters. Journal of Environmental Quality 14(4):472-478.

Johnson L. B., C. Richards, G. E. Host, and J. W. Arthur, 1997. Landscape Influences on Water Chemistry in Midwestern Stream Ecosystems. Freshwater Biology 37:193-208.

Jones, K. B., A. C. Neale, M. S. Nash, R. D. Van Remortel, J. D. Wickham, K. R. Riitters, and R. V. O'Neill, 2001. Predicting

Nutrient and Sediment Loadings to Streams From Landscape Metrics: A Multiple Watershed Study from the United States Mid-Atlantic Region. Landscape Ecology 16:301-312.

Jordan, T. E., D. L. Correll, and D. E. Weller, 1993. Nutrient Interception by a Riparian Forest Receiving Inputs From Adjacent Cropland. Journal of Environmental Quality 22:467-473.

Levine, D. A. and W. W. Jones, 1990. Modeling Phosphorous Loading to Three Indiana Reservoirs: A Geographic Information System Approach. Lake and Reservoir Management 6:81-91.

Lowrance, R. R., R. Todd, J. Fail, R. A. Leonard, and L. E. Assmussen, 1984. Riparian Forests as Nutrient Filters in Agricultural Watersheds. Bioscience 34:374-377

Lowrance R., L. S. Altier, J. D. Newbold, R. R. Schnabel, P. M. Groffman, J. M. Denver, D. L. Correll, J. W. Gilliam, J. L. Robinson, R. B. Brinsfield, K. W. Staver, W. Lucas, and A. H. To, 1997. Water Quality Functions of Riparian Forest Buffers in Chesapeake Bay Watersheds. Environmental Management. 21: 687-712.

Mandle, R. J. and D. B. Westjohn, 1989. Geohydrologic Framework and Ground-Water Flow in the Michigan Basin. *In:* Regional Aquifer Systems of the United States – Aquifers of the Midwestern Area, L. A. Swain and A. I. Johnson (Editors). AWRA Monograph Series 13, pp. 83-110.

Martin, P. J. and E. O. Frind, 1998. Modeling a Complex Multi-Aquifer System: The Waterloo Moraine. Groundwater 36:679-690.

McDonald, M. G. and A. W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Ground-water Flow Model. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6, Chap. A1.

Molson, J. W. and E. O. Frind, 1995. WATFLOW/3D: A 3D-Groundwater Flow Model, Version 1.0. Waterloo Centre for Groundwater Research, Waterloo, Ontario.

O'Loughlin, E M., 1981. Saturation Regions in Catchments and Their Relation to Soil and Topographic Properties. Journal of Hydrology 53: 229-246.

Omernik, J. M., A. R. Abernathy, and L. M. Male, 1981. Stream Nutrient Levels and Proximity of Agricultural and Forest Land to Streams: Some Relationships. Journal of Soil and Water Conservation 36:227-231.

O'Neill, R. V., C. T. Hunsaker, K. B. Jones, K. H. Riitters, J. D., Wickham, P. M. Schwartz, I. A. Goodman, B. L. Jackson, and W. S. Baillargeon, 1997. Monitoring Environmental Quality at the Landscape Scale. Bioscience 47:513-519.

Osborne, L. L. and M. J. Wiley, 1988. Empirical Relationships Between Land Use/Cover and Stream Water Quality in an Agricultural Watershed. Journal of Environmental Management 26:9-27.

Osborne, L. L. and D. A. Kovacic, 1993. Riparian Vegetated Buffer Strips in Water-Quality Restoration and Stream Management. Freshwater Biology 29:243-258.

Pautou, G. and H. Decamps, 1985. Ecological Interactions Between the Alluvial Forests and the Hydrology of the Upper Rhône. Archiv für Hydrobiologie 104:13-37.

Peterjohn, W. T. and D. L. Correll, 1984. Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of a Riparian Forest. Ecology 65:1466-1475.

Peverly, J. H., 1982. Stream Transport of Nutrients Through a Wetland. Journal of Environmental Quality 11:38-43.

Phillips, J. D., 1989. Nonpoint Source Pollution Control Effectiveness of Riparian Forests Along a Coastal Plain River. Journal of Hydrology 110:221-237.

Pinay, G. and H. Decamps, 1988. The Role of Riparian Woods in Regulating Nitrogen Fluxes Between the Alluvial Aquifer and Surface Water: A Conceptual Model. Regulated Rivers 2:507-516.

Pinay, G., H. Decamps, C. Arles, and M. Lacassin-Series, 1989. Topographic Influence on Carbon and Nitrogen Dynamics in Riverine Woods. Archive für Hydrobiologie 26:401-414.

Pinay, G., A. Fabre, Ph. Vervier, and F. Gazelle, 1992. Control of C,N,P Distribution in Soils of Riparian Forests. Landscape Ecology 6:121-132.

Pinay, G., L. Roques, and A. Fabre, 1993. Spatial and Temporal Patterns of Denitrification in a Riparian Forest. Journal of Applied Ecology 30:581-591.

Quinn, P. F., K. Beven, P. Chevallier, and O. Planchon, 1991. The Prediction of Hillslope Flow Paths for Distributed Hydrological Modelling Using Digital Terrain Models. Hydrological Processes 5:59-79.

Seelbach, P. W., and M. J. Wiley, 1997. Overview of the Michigan Rivers Inventory (MRI) Project. Michigan Department of Natural Resources, Fisheries Technical Report 97-3, Ann Arbor, Michigan.

Seelbach, P. W., M. J. Wiley, J. C. Kotanchik, and M. E. Baker, 1997. A Landscape-Based Ecological Classification System for River Valley Segments in Lower Michigan (MI-VSEC 1.0). Michigan Department of Natural Resources, Fisheries Research Report 2036, Ann Arbor, Michigan.

Seelbach, P. W., M. J. Wiley, P. A . Soranno, and M. T. Bremigan, 2001. Aquatic Conservation Planning: Using Landscape Maps to Predict Ecological Reference Conditions for Specific Waters. *In:* Concepts and Applications of Landscape Ecology in Biological Conservation, K. Gutzwiller (Editor). Springer-Verlag, New York, New York (in press).

Soranno, P. A., S. L. Huber, and S. R. Carpenter, 1996. Phosphorous Loads to Surface Waters: A Simple Model to Account for Spatial Pattern of Land Use. Ecological Applications 6:865-878.

Tischendorf, L., 2001. Can Landscape Indices Predict Ecological Processes Consistently? Landscape Ecology 16:235-254.

Tompkins, T., W. Whipps, L. Manor, M. J. Wiley, C. Radcliffe, and D. Majewski, 1997. Wetland Effects on Hydrological and Water Quality Characteristics of a Mid-Michigan River System. *In:* Northern Forested Wetlands: Ecology and Management, C. Trettin, M. F. Jurgensen, D. F. Grigal, M. R. Gale, and J. J. Jeglum (Editors). CRC Press Inc., Boca Raton, Florida.

Tremoliers, M., U. Roeck, J. P. Klein, and R. Carbiener, 1994. The Exchange Process Between River and Groundwater on the Central Alsace Floodplain (Eastern France): II. The Case of a River With a Functional Floodplain. Hydrobiologia 273:19-36.

Wehrly, K. E., M. J. Wiley, and P. W. Seelbach, 1998. Landscape-Based Models That Predict July Thermal Characteristics of Lower Michigan Rivers. Michigan Department of Natural Resources, Fisheries Research Report 2037, Ann Arbor, Michigan.

Weller, C. M., M. C. Watzin, and D. Wang, 1996. Role of Wetlands in Reducing Phosphorous Loading to Surface Water in Eight Watersheds in the Lake Champlain Basin. Environmental Management 20:731-739.

Weller, D. E., T. E. Jordan, and D. L. Correll, 1998. Heuristic Models for Material Discharge From Landscapes With Riparian Buffers. Ecological Applications 8:1156-1169.

Wiley, M. J., S. L. Kohler, and P. W. Seelbach, 1997. Reconciling Landscape and Local Views of Aquatic Communities: Lessons From Michigan's Trout Streams. Freshwater Biology 37:133-148.

Wolock, D. M. and C. V. Price, 1994. Effects of Digital Elevation Model Map Scale and Data Resolution on a Topography-Based Hydrologic Model. Water Resources Research 30:3041-3052.

Zorn, T. G., P. W. Seelbach, and M. J. Wiley, 2002. Distributions of Stream Fishes and Their Relationship to Stream Size and Hydrology in Michigan's Lower Peninsula. Transactions of the American Fisheries Society 131:70-85.