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The use of remote sensing and GIS in watershed level analyses of non-point source pollution problems

Prakash Basnyat*, L.D. Teeter, B.G. Lockaby, K.M. Flynn

School of Forestry, Auburn University, 207 M.W. Smith Hall, Auburn University, Auburn, AL 36849, USA

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Abstract

Basin characteristics such as land use/land cover, slope, and soil attributes affect water quality by regulating sediment and chemical concentration. Among these characteristics, land use/land cover can be manipulated to gain improvements in water quality. These land use/land cover types can serve as nutrient detention media or as nutrient transformers as dissolved or suspended nutrients move towards the stream. This study examines a methodology to determine nitrate pollution 'contributing zones' within a given basin based on basin characteristics. In this process, land use/land cover types were classified and basins and 'contributing zones' were delineated using geographic information system (GIS) and remote sensing (RS) analysis tools. A 'land use/land cover-nutrient-linkage-model' was developed which suggests that forests act as a sink, and as the proportion of forest inside a contributing zone increases (or agricultural land decreases), nitrate levels downstream will decrease. In the model, the residential/urban/built-up areas have been identified as strong contributors of nitrate. Other contributors were orchards; and row crops and other agricultural activities. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Because of the fact that some correlation exists between pollution loading and land use (Perry and Vanderklein, 1996), there is a potential for improving water quality with proper land use management practices. From a land use perspective, agricultural activities have been identified as major sources of non-point source (NPS) pollutants (sediments, animal wastes, plant nutrients, crop residues, inorganic salts and minerals, pesticides) (Viessman and Hammer, 1993) and are known to impact water quality. Residential/urban/built-up areas are another dominant factor in generating large amounts of non-point source (NPS) pollution from storm-water discharge. The imperviousness of many urban areas increases their storm-water discharge, and even small rains are capable of washing accumulated pollutants into surface waters.

Changes in water quality can indicate a change in some aspect of terrestrial, riparian, or in-channel ecosystem. From a pollution perspective, among the many water quality elements related to ecologically healthy systems, nitrogen is one of the most problematic nutrients (Perry and Vanderklein, 1996). Nitrogen concentration downstream is a function of multiple controlling factors, and different streams have different responses to the set of controlling factors. One of

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[*] Corresponding author.

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the important factors is vegetation, which at times can be manipulated to maintain or improve water quality. Riparian forests chemically alter nutrients transported in subsurface water as water flows pass through their root systems. Riparian forests absorb nutrients for growth and promote denitrification by subtle changes in the oxic-anoxic zones. The exact mechanism bringing this about is not well understood. Yet the presence of riparian forests can significantly regulate the amount of nitrogen reaching streams from upland areas (Karr and Schlosser, 1978; Schlosser and Karr, 1981a, b; Peterjohn and Correll, 1984).

The main purpose of this study was to establish the relationships among nitrate concentration in water emanating from agricultural and urban areas due to contact of those waters with riparian forests and wetlands. This was done by relating land use/land cover (LULC) patterns to measured in-stream nutrients concentrations, using a computer based GIS software system.

The study area (13,772 ha) covers a portion of the Fish River drainage basin. The Fish River watershed (40,852 ha) begins just south of Bay Minette, Baldwin county, AL, and flows in a southerly direction. The Fish River feeds into Weeks Bay, which is a part of Bon Secour Bay, a sub-estuary of Mobile Bay, which is directly connected to the Gulf of Mexico.

2. Methods

Activities occurred in two phases. In Phase 1, water quality samples were collected and analyzed. Satellite digital data, photographs, soil digital data, digital elevation model (DEM) data and geological digital data were procured and analyzed. In Phase 2, a simple model was developed to estimate potential nutrient fluxes from representative riparian ecosystems (determined using preliminary water sample analyses, classified imagery and watershed boundaries) along the tributaries of Weeks Bay.

2.1. Phase 1

2.1.1. Water quality

Surface runoff is primarily determined by rainfall, though it is strongly influenced by the soil-plant system. Several characteristics of a rainfall event are important including rainfall intensity, rainfall depth, rainfall drop size and the time since last rainfall (i.e., antecedent soil moisture content). There are limited studies of how rainfall affects nutrient loss (Meyers, 1981; Kinnell, 1983). Rose and Dalal (1988) reviewed the process of water erosion and the consequences for nitrogen loss. The estimates indicate the strong dependence of nitrogen loss on rainfall intensity. Since the study area covers only a small portion of the Fish river basin, apart from some local variation (if it indeed exists), rainfall and other climatic factors were assumed to be uniform.

For the purpose of collecting water quality data, sample points were located on a topographical map at the pour point of each watershed and water samples were collected from the streams at these points. Water samples were collected biweekly during winter and spring (the seasonal period which has been shown to be associated with the most NPS pollutant movement into water in this region (Lockaby et al., 1993). Sampling interval was approximately 2 weeks. In total, water samples were collected 23 times from eight different independent basins over a 2 year period. Water sample analysis was conducted in a School of Forestry laboratory, using ion chromatography (Dionex HPIC AS4A separation column).

2.1.2. Basin delineation

A basin is the up slope area contributing flow to a given location. Such a feature is also referred to as a catchment, or watershed, and comprises part of a hierarchy in that a given basin is generally part of a larger basin. Increasing catchment size affects nutrient export due to the increasing capacity for sediment (and associated nutrient) storage in both channel bars and flood-plain deposits. For particulate associated nutrient transport, the increase in storage with catchment size will reduce catchment nutrient exports.

Basin boundaries were delineated first manually, then compared with boundaries delineated using 1 : 24,000 digital elevation model data obtained from the US Geological Survey using the results of flow direction, flow accumulation and pour point coordinates information. Final basin boundaries were delineated by refining the manually delineated boundaries using the information from the computer generated boundaries. Each basin contains first and second order streams.

2.1.3. Land use/land cover (LULC) classification

LULC patterns for the study area were determined by interpreting digital imagery (LANDSAT Thematic Mapper (TM) (25 m resolution) and SPOT panchromatic data (10 m resolution)). Digital line graph (DLG) (1 : 24,000) information for the study area were obtained from United States Geological Survey (USGS) and used in the rectification of images. Classification was based on the composite image created using the spatial resolution of the SPOT panchromatic image and the spectral resolution of the LANDSAT TM data. The rationale behind creating such a composite is based on the fact that the visual content of remotely sensed images is a function of the combined influence of the radiometric, spatial, and spectral resolutions of the sensor. The apparent spatial resolution of multispectral digital images, and their interpretability, has been shown to be enhanced by merging these data with higher resolution digital data (Chavez, 1984; Cliche et al., 1985; Welch, 1985; Welch and Ehlers, 1987; Lillesand and Kiefer, 1994). When such a merger is performed to aid in visual interpretation, it is important that the operation maintain as much of the original spectral information as possible, while maximizing the amount of spatial information from the higher resolution data source. The intensity, hue, and saturation (IHS) color specification method as described by Carper et al. (1990) was used to create the composite image. Fundamentally, IHS transformation permits separation of spatial information as an intensity component from the spectral information in the hue and saturation components of a three-color composite image. The analyst is then able to manipulate independently the spatial information while maintaining overall color balance of the original scene. LANDSAT TM bands 4, 3 and 2 were used in this process. The composite image thus produced was found to be very superior to the LANDSAT bands 4, 3, 2 image composite.

Classification was done based on the information obtained during field visits and 1 : 40,000 National aerial photography program (NAPP) photographs. All processing and analyses were performed using the geographic resource analysis support system (GRASS) developed by the US Army Corps of Engineers, and ARC-INFO, developed by the Environmental Systems Research Institute (ESRI). In an attempt to make the results as widely applicable as possible, the modified classification system initially employed four general categories: urban/residential land, agricultural land; forest land; and orchards/tree crops. Forest land, agricultural land and orchards/tree crops were classified based on their distinct spectral signature and characteristic features. There were some difficulties in identifying urban/residential areas. Only urban/residential area with a cluster of man-made features showed a distinct spectral signature. Isolated or scattered houses and/or man-made features were difficult to recognize. Hence, when the choice was clear they were assigned to their correct class, otherwise these inconclusive signatures were merged with the dominant land use/land cover class. Once the image was classified (with an overall accuracy of 93%), areas under each land use/land cover were extracted for each basin.

2.1.4. Other information

Another important basin characteristic is soil type distribution. Every soil type does not contribute equally to nutrient transport in the same manner. If stream buffers are used as a tool to reduce NPS pollution, this variable is an important factor in determining how large a protective buffer should be maintained. Knowledge of the variation in the physical and chemical properties of soil types is a key in the contributing zone generation process. Information on soil types in the study area were extracted from the digital soil map (1 : 24,000) for Baldwin county, Alabama (source: United States Department of Agriculture (USDA) – Natural Resources Conservation Service (NRCS)). Sixty-three different soil map units can be found inside the study area. Individually, Mabis Sandy loam covers more than 3000 ha of the study area, and Bama Sandy Loam, which occupies more than 1400 ha, is the second largest soil type. Slope information for each watershed was obtained by producing a triangulated irregular network (TIN) from USGS DEM data.

2.2. Phase 2

2.2.1. Delineating buffer zones

First a buffer zone was created for each stream based on soil, slope and roughness characteristics of the riparian forest. At the core of the model is a riparian buffer delineation equation (RBDE) developed by Phillips (1989a), which evaluates the relative effectiveness of buffer zones in terms of soil hydrological features, land cover and topography. Accordingly, the RBDE can be represented

$$\frac{B_\mathrm{b}}{B_\mathrm{r}}=\left(\frac{n_\mathrm{b}}{n_\mathrm{r}}\right)^{0.6}\left(\frac{L_\mathrm{b}}{L_\mathrm{r}}\right)^{2}\left(\frac{K_\mathrm{b}}{K_\mathrm{r}}\right)^{0.4}\left(\frac{S_\mathrm{b}}{S_\mathrm{r}}\right)^{-0.7}\left(\frac{C_\mathrm{b}}{C_\mathrm{r}}\right) \tag{1}$$

where subscript b refers to a proposed buffer zone and subscript r refers to a 'reference zone'; $B_\mathrm{b}/B_\mathrm{r}$ is the 'buffer zone' effectiveness ratio; n is a Manning roughness coefficient (Engman, 1986); L is the buffer zone width (feet or meters); K is saturated hydraulic conductivity (in./h or cm/h), which is equivalent to permeability as given in US soil surveys; S is slope (%); and C is soil moisture storage capacity (inches or centimeters), which can be obtained by multiplying available water capacity by profile thickness above a confining layer or seasonal high water table. K, C, and S are found in US soil surveys (USDA SCS, 1980; USDA SCS, 1990).

The RBDE considers relative detention time over a range of conditions (slope, soil characteristics, Manning roughness coefficient, and land use) rather than absolute detention time for a specific hydrologic event. It compares the ability of a given vegetative zone to retain runoff to that of a user defined 'reference zone', providing a quantitative, dimensionless index of 'buffer zone' effectiveness. The ratio $B_\mathrm{b}/B_\mathrm{r}$ is easily explained. A value less than 1 indicates that the 'buffer zone' being evaluated is less effective than the reference; a value greater than 1 suggests a more effective assimilation/detention zone. After simple transformation, Eq. (1) can be rewritten as

$$L_\mathrm{b}=p^{0.5}L_\mathrm{r}\left[\left(\frac{n_\mathrm{r}}{n_\mathrm{b}}\right)^{0.6}\left(\frac{K_\mathrm{r}}{K_\mathrm{b}}\right)^{0.4}\left(\frac{S_\mathrm{r}}{S_\mathrm{b}}\right)^{-0.7}\left(\frac{C_\mathrm{r}}{C_\mathrm{b}}\right)\right]^{0.5} \tag{2}$$

where p represents the 'buffer zone' effectiveness ratio, i.e., p is equal to $B_\mathrm{b}/B_\mathrm{r}$, and L_b is the proposed width of a 'buffer zone'. With this rearrangement, we can specify the relative effectiveness as an objective and determine the appropriate zone width necessary to achieve it. For this study, the value of p has been set to 1 matching the assimilation/detention capability of the 'buffer zone' to that of the 'reference zone'. Since forest cover is assumed to be most efficient at nutrient assimilation, the value of Manning roughness coefficient ($n_\mathrm{r}=n_\mathrm{b}=0.46$) for riparian forest was used in the calculation. These assumptions will help in understanding the role of forested areas adjacent to streams by determining the widths of contributing zones if they were forested. Hence, Eq. (2) can be rewritten as

$$L_\mathrm{b}=L_\mathrm{r}\left[\left(\frac{K_\mathrm{r}}{K_\mathrm{b}}\right)^{0.4}\left(\frac{S_\mathrm{r}}{S_\mathrm{b}}\right)^{-0.7}\left(\frac{C_\mathrm{r}}{C_\mathrm{b}}\right)\right]^{0.5} \tag{3}$$

2.2.2. 'Reference zone' selection

The 'reference zone' was selected based on two criteria identified by Phillips (1989a). First, a 'reference zone' provides effective filtration under average runoff conditions. Second, a 'reference zone' represents typical soil, surface cover, and topographical conditions in the study area. Pollutant removal efficiencies of the reference zone are estimated by standard hydrologic analysis as described by Phillips (1989a). For this study, the 'reference zone' was designed by selecting typical values for soil characteristics associated with riparian forest soils and the average slope of the study area. The width of the 'reference zone' for 90% nitrate assimilation or detention (removal efficiency of a typical primary and secondary sewage treatment plant (Clark, 1977)) was estimated as 33.5 m (see Basnyat (1998) for details). The widths of the 'buffer zones' were computed and the 'buffer zones' around streams inside each basin were delineated using ARC-INFO GIS software.

2.2.3. Defining 'contributing zone'

A buffer zone calculated using Eq. (3) will assimilate or detain 90% of the nitrate passing through it if that zone is forested. But if there are other LULCs inside this buffer zone the assimilation or detention efficiency will be compromised due to the fact that different LULCs assimilate or detain nitrate at different rates. Hence, this area can be defined as a 'contributing zone'. A 'contributing zone' has been defined as the buffer zone surrounding the stream which, as a result of land use practices and other human activities, contributes nutrients and other NPS pollutants to the surface and sub-surface water sources, which end up in stream water. The definition of a 'contributing zone' is important to this study for two reason. First, it recognizes that the assimilation and detention are affected by soil, slope and vegetation types. Second, it recognizes the importance of spatial positioning of each LULC inside a basin. The area and proportion of each LULC within each 'contributing zone' were also calculated.

2.2.4. Land use/land cover and water quality linkage

This work addressed the problem of regional variability in water quality (Omernik, 1977; Omernik et al., 1981) by selecting basins within a larger watershed and considering the LULC pattern at two scales: (a) the entire basin, (b) the 'contributing zone'. The question of a relationship between LULC and water quality was examined at both scales by applying multiple regression techniques considering nutrient concentrations as dependent variables and the proportions of land uses as explanatory variables. These comparisons not only yielded information regarding the importance of spatial positioning of the LULC, but also helped in identifying the relative importance of different land use/land cover categories as nutrient contributors. The functional form of the relationship for each of the two cases: (1) Entire basin scale and (2) 'Contributing zone' scale, is as follows

$$\mathrm{NPS}_i = f\left(\frac{\mathrm{Land}_{ib}}{A_i}\right) \qquad (4)$$

where NPS_i is nutrient or sediment concentration in question in basin i, Land_{ib} is equal to land use/land cover Type b ($b = 1\ldots4$) in a basin i under one of the scale assumptions outlined above, A is equal to total area in question in a given basin or contributing zone i.

3. The linkage model

3.1. Non-point source pollution transport

Delivery of non-point source pollutants from discrete upstream contributing zones to a particular downstream point is a multi-step, often episodic, process (Phillips, 1989b). A first order rate equation can be used for modeling nutrient attenuation in flow through various land uses to the nearest stream (Phillips, 1989b). Thus, the concentration of nutrients (C_i) over an area can be described in the form of an exponential model (Fetter, 1994) as follows

$$C_i = \mathrm{e}^{(\beta_1\ \mathrm{Forest}_i + \beta_2\ \mathrm{Res}_i + \beta_3\ \mathrm{Orchards}_i + \beta_4\ \mathrm{Agri})} \qquad (5)$$

The coefficient for Forest is expected to have negative sign (Lowrance, 1992); the Residental/urban area, Agricultural land, and Orchards are expected to have positive signs (Park et al., 1994). Among these four explanatory variables, only statistically significant variables were included in the final estimation of the models due to the small sample size (eight independent watersheds). Explanatory variables used in the estimation were expressed as a percentage of the total area of each basin. Regression analysis was performed using log transformed dependent variables to reduce asymmetric distribution of the data using relationships given in Eq. (5). In the case of proportion or percentage data of explanatory variables, arcsine transformations were used to reduce collinearity as suggested by Sokal and Rohlf (1994). The models were validated using a 'bootstrapping' technique. This technique help in estimating the statistical accuracy of the results derived from a set of limited data points (Diaconis and Efron, 1983).

4. Results

4.1. Water sample analysis

A review of the analytical data for surface water samples shows the difference in the chemistry of the stream water in different basins Table 1. This variation has also occurred seasonally. In addition, there is variation in nutrient levels between the two sample years. In the first sample year, nutrient concentrations are relatively lower than during the second sample year. This may be due to the difference in total precipitation during the sample period (more precipitation in the second year than in the first year) and/or an increase in cotton cultivation in the area (cotton requires heavy application of nitrate fertilizers). In the first sampling season, there was a peak in nitrate levels at the end of April indicating an increase in agricultural activities in those basins. This phenomenon is also observed in the second year. This indicates the relationship with temporal land use activities and basin characteristics. Nitrate, although usually present in low concentrations in natural water, is often the most abundant inorganic form of nitrogen. Natural concentrations rarely exceed 10 mg/l and are frequently less than 1 mg/l especially during periods

Table 1
Summary of water sample analysis results[a]

Water-shed No.	First year				Second year			
	Mean	Median	STD	Range	Mean	Median	STD	Range
19	1.054	1.007	0.685	0.282–01.922	0.476	0.088	0.559	0.024–01.449
13	3.633	4.748	2.269	0.710–05.805	5.808	6.212	1.664	1.865–07.550
20	4.105	4.705	2.003	0.873–05.966	6.157	6.660	2.109	0.107–08.517
21	4.419	5.258	2.369	0.817–07.352	6.612	6.958	2.099	2.209–09.534
11	0.274	0.097	0.347	0.022–00.834	0.661	0.165	1.295	0.029–04.807
12	2.913	2.219	1.783	0.599–05.044	3.759	4.379	1.383	0.096–04.893
16	7.574	7.536	0.082	7.254–07.566	–	–	–	–
5	0.573	0.468	0.183	7.192–09.022	–	–	–	–

[a] Note: blank cell indicates no observation.

of high primary production (Lind, 1979). High concentrations of nitrate (greater than 20 mg/l) may be a health hazard to juvenile mammals (Lind, 1979). Concentrations of inorganic nitrogen in natural water vary considerably, but are seldom great in unpolluted waters. On the average, 0.332 mg/l of NO_3^- were observed in unfertilized wildland ponds in Alabama (Boyd, 1976).

4.2. 'Contributing zone' land use/land cover

Variable width zones (buffers) around the streams in each basin were generated using the method of Eq. (3). Land use/land cover information for the basins (Table 2) and 'contributing zones' (Table 3) were extracted from the classified LULC coverage using basin boundary and buffer boundary as clip coverage, respectively. Wide variations in the proportions of individual LULC were observed among the basins. For example, proportion of forested area range from 3–55%. Similar variations in other LULC classes were observed.

Table 2
Land use/land cover information (entire watershed)

Basin No.	Land use/land cover (ha)				
	Forest	Res./urban	Agri	Orchards	Total area
5	414.00	35.00	628.00	147.00	1224.00
11	496.00	14.00	180.00	120.00	809.00
12	169.00	27.00	1108.00	253.00	1556.00
13	382.00	138.00	2214.00	239.00	2973.00
16	120.00	36.00	981.00	96.00	1233.00
19	53.00	1.00	64.00	34.00	152.00
20	745.00	80.00	2843.00	416.00	4084.00
21	58.00	26.00	767.00	162.00	1014.00

4.3. Linkage model results

As noted above, there were variations in LULCs within the 'contributing zones'. If the initial assumption about the buffer zone had been true (i.e., areas inside the buffer zones were forested), there would not be significant differences in the nitrate levels among the basins at the pour-points. But this was not the case, hence, it was hypothesized that variations in nutrient levels in different basins were due to the variation in the LULC combinations in the 'contributing zones' given the assumption of minimal or no variation in other factors i.e., rainfall, geology, nitrate input, biologic influence etc. After obtaining all relevant data, a simple model was developed to integrate land use characteristics and water quality.

The regression equations developed from the nutrients and LULC data are presented in Table 4, with the corresponding value of r^2 and the level of statistical significance of the regression equation, p. The value of r^2 for the significant model (i.e., 'contributing zone' model) ($p < 0.01$) is over 0.95. We found no statistically significant relationships between land uses and nitrate level when proportion of LULCs inside the whole basin irrespective of their spatial positioning were used as explanatory variables. However, we have presented the result for comparison purposes. In the contributing zones model, we chose forests, residential/urban/built-up areas, agriculture and orchards as explanatory variables. The model suggests that forests act as sinks, and as the proportion of forests inside a contributing zone increases (or non-forested area decreases), nitrate levels downstream decrease. In the model, the residential/urban/built-up areas were

Table 3
Land use/land cover information (contributing zone)

Basin No.	Land use/land cover (ha)					Buffer zone (m)		
	Forest	Res./urban	Agri	Orchards	Total area	Mean	Range	STD
5	95.00	4.00	68.00	15.00	182.00	40.00	16.4–83.7	13.00
11	117.00	2.00	28.00	39.00	187.00	42.70	16.4–89.5	12.70
12	71.00	3.00	162.00	45.00	281.00	43.96	16.4–88.6	13.48
13	141.00	23.00	317.00	27.00	508.00	40.70	16.4–100.8	12.50
16	28.00	8.00	132.00	9.00	177.00	39.80	16.4–79.7	11.50
19	13.00	0.00	11.00	2.00	27.00	40.80	16.4–77.8	13.10
20	162.00	19.00	462.00	45.00	687.00	42.20	16.4–103.6	13.70
21	39.00	8.00	203.00	29.00	280.00	40.50	16.4–87.5	12.70

Table 4
Regression equations[a,b] for nitrate concentration changes due to variation in land use/land cover

(a) Whole watershed

$\ln(NO_3^-) = -0.516\,\text{Forests} - 25.244\,\text{Res} + 3.851\,\text{Agri} - 7.679\,\text{Orchards}$ $r^2 = 0.1861$ $p = 0.14$

(b) Contributing zone

$\ln(NO_3^-) = -3.402\,\text{Forests} + 22.355\,\text{Res} + 1.624\,\text{Agri} + 5.15\,\text{Orchards}$ $r^2 = 0.959$ $p = 0.01$

[a] In all cases units of the dependent variable are in ppm and independent variables are proportion of LULC area to total area at each scale (a) area of the basin, and (b) total area inside the contributing zone, respectively. SE in the parenthesis. $n = 8$.

[b] Standard errors: (a) Forests, 1.534; Res, 26.45; Agri, 1.33; Orchards, 4.96. (b) Forests, 0.548; Res, 10.26; Agri, 0.518; Orchards, 2.12.

identified as strong contributors of nitrate. The second largest contributor was orchards.

5. Discussion

The limited importance (as implied by the magnitude of the coefficient obtained for forests) of riparian forests in the present study, appears related to the overriding influence of other land uses on nitrate concentration within the basin or to a lack of riparian zone integrity. Nitrate (NO_3^-) concentrations appear more clearly related to the buffer zone proportion of urban/residential areas.

The above results and analyses provide insight into the linkages between land use and stream water quality similar to Craig and Kuenzler (1983) and Osborne and Wiley (1988). The model can help in examining the relative sensitivity of water quality variables to alterations in land use inside the contributing zone. The model has also further demonstrated the importance of stream-side management zones, which are important in the maintenance of water quality. The linkage model can be considered a first step in the integration of GIS and ecological models. The concept is not new, but the definition of 'contributing zone' may open additional windows for visualizing the problem. The results on the importance of spatial variability of LULC corroborate those of Osborne and Wiley (1988).

The contributing zone model which was used in this study was adopted from previous work by Phillips (1989a). The 'contributing zone' is affected by many factors, including the water-quality parameter being assessed and geomorphic/climatic setting of the watershed or reach. There have been attempts by the forestry research community to define zones of contribution for several variables (i.e., FEMAT, 1993). In most cases the relationships are not linear. The greatest influence occurs immediately adjacent to the stream and diminishes with distance from the stream. Most water-quality pollutants are also non-conservative, so a contributing zone immediately upstream might be expected to influence measured water quality more than overall LULC of an entire watershed. It is an important statement about the value of even crude measures of the near-stream riparian influence that the artificially calculated contributing zone provides such a strong model of water quality, even without consideration of additional complicating factors.

While the model presented here provides a gross measure of land use and water quality relationships, it is equally important to address the fine-scale management issues relating to riparian areas. This involves weighing the economic and environmental trade-offs of alternative riparian management restrictions. Often the zone of contribution is the focus of analysis without considering the management options. We have already noted that the presence of riparian forest significantly regulates nitrogen reaching streams, but the exact mechanisms are not well understood. For example, plant uptake may be a valuable sink for nitrogen, but will harvesting be required to maintain plant uptake? By understanding the relative importance of the mechanisms and processes which control non-point source pollution loads, both overall land management goals and detailed riparian practice guidelines can be identified.

6. Conclusions

The results indicate that the land use combination of forest, residential/urban/built-up area and agricultural activities (agriculture and orchards) inside a contributing zone (areas in close proximity to the stream) can be linked to the concentration of NO_3^- at the pour-point. The residential/urban/built-up area, orchards and agricultural lands inside the 'contributing zones' are associated with higher NO_3^- levels, whereas forests act as a sink. The results also indicate that with the integration of GIS and ecological modeling a LULC management decision support system can be developed to manage NPS pollution (in this case nitrate) at the basin and watershed scales.

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