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NONPOINT WATER QUALITY CONTRIBUTIONS FROM LAND USE

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ABSTRACT

Stream loads of total phosphorus and nitrate-nitrogen were studied as a function of land use in a midwestern watershed of 5,853 square kilometers by means of ordinary least squares (OLS) regression analysis. The purpose was to test the general hypothesis that the variance in chemical water quality from undefined sources is a function of land use within the watershed, and to begin to study the hypothesis that land use near the stream is more important than land use far from the stream in affecting water quality from nonpoint sources. Results support both hypotheses. Further, these results suggest the importance of considering the means by which chemicals are delivered to the stream. Nitrate-nitrogen and phosphorus can apparently both be purposely intercepted, but by different means because of their different delivery systems. Nitrate-nitrogen can be intercepted by removal of fast-growing floodplain crops, and phosphorus by sediment barriers outside the floodplain. Evidence also suggests trap efficiency in reservoirs is important in improving downstream water quality.

In earlier research, Wilkin and Flemal demonstrated that the majority of chemical constituent loadings in three midwestern streams came from undefined, and probably nonpoint, sources [1]. One assumption was that these undefined loadings derived from land uses in the watershed. This, in turn, led to the assumption that modifying land use patterns could modify stream water quality.

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The study reported herein advances the general hypothesis that chemical water quality from undefined sources varies as a function of land use within the watershed.

The hydrologic budget of streams is known to be significantly influenced by the area immediately adjacent to the stream [2, 3]. In studying sediment delivery to streams, Hebel [4] and Wilkin and Hebel [5] also discovered evidence that land uses adjacent to streams had more impact on water quality than land uses farther from streams. This article will show that controlling land uses close to streams may be an important land management strategy in modifying stream water quality.

THEORETICAL BASIS

For purposes of this study, a chemical constituent is considered *delivered* when it becomes part of stream flow. Its *delivery system* refers to the means by which it is moved from its point of entry in the watershed to the stream.

The delivery system of a chemical constituent controls its impact on water quality. Its delivery pathway depends on solubility in water, tendency to adsorb to soil particles, and stability of the chemical form. Regardless of where a chemical constituent enters a watershed, if it has low water solubility, large particle sizes, adsorbs readily to soil particles, and/or is relatively unstable chemically, then relatively little is likely to be delivered in that form to the stream. On the other hand, if it has high solubility or colloidal particle sizes, does not adsorb readily to soil particles, and/or is relatively stable chemically, there is a much higher probability of delivery to the stream [6].

Nitrate-nitrogen and phosphorus, for example, are very different in water solubility and tendency to adsorb to soil particles. Phosphorus adsorbs readily to soil particles, whereas nitrate-nitrogen is highly soluble. These two chemical constituents could be predicted to have different delivery systems. Phosphorus moves largely over the land surface with eroded soil, and nitrate-nitrogen moves largely in dissolved form in shallow ground water. Because most of the shallow ground water is presumed to be delivered to the stream at some later time, nitrate-nitrogen has a relatively high probability of being delivered, regardless of where it enters the watershed, if it does not volatilize or is not taken up by plant growth at some point in its journey.

Eroded soils from upland areas, however, have a high probability of being intercepted by fencerows, hedgerows, roadside ditches, and native vegetation [5]. The probability of sediment delivery to the stream is inversely related to distance from the stream. This should also be true for phosphorus, since phosphorus adsorbs to soil particles. The water quality impact of introducing phosphorus into a watershed should be strongly dependent on location.

This is a study to examine the impact of land uses in the watershed on instream loadings of nitrate-nitrogen and total phosphorus.

METHOD

The Sangamon River basin in east-central Illinois was selected for study. Sixteen water quality monitoring stations subdivided the basin into sixteen "water quality subbasins" comprising the basin's upper 5,853 square kilometers (see Fig. 1). The results should be highly meaningful for the Sangamon River basin and for east-central Illinois in general.

Median constituent stream load values for nitrate-nitrogen and total phosphorus, the dependent variables, were used in the statistical analysis instead of mean values. By so doing, the few extreme errors in the record had minimal impact on the statistics. Each median value was based on between fifty and seventy-five monthly water quality samples analyzed by the Illinois Environmental Protection Agency over a six-year period starting in 1972, as part of its ambient water quality monitoring network. The stream loads were calculated by multiplying the median concentration at each station in milligrams per liter by its contributing drainage area in square kilometers and by a constant that relates flow to area and adjusts the instantaneous rate to metric tons per year. This analysis does not attempt to predict the true annual load but rather a load characteristic of the median river condition, both in flow and concentration.

U.S. Geological Survey maps describing the limits of the 100-year floodplain for the basin were used to delimit the study area. Land cover data derived from LANDSAT imagery were used to infer land use. Computer classification was used to estimate the number of hectares in each water quality subbasin of row-crop agriculture, field crops, pasture and other agricultural land, forested land, and urban lands. These land use data, with the upstream contribution measured at the water quality station immediately upstream of the subbasin, a dummy variable for Lake Decatur and a dummy variable for the Decatur waste treatment facility were the independent variables. In an early analysis the waste treatment variable fell quite short of statistical significance and was eliminated in the final analysis. Distance of flow between measuring stations also was incorporated in early analysis, but it also had no statistical significance and was subsequently eliminated.

In this study, only data for nitrate-nitrogen and total phosphorus were analyzed. The presumption was that they would show significantly different results, reflecting different delivery systems. The final four equations to be analyzed by ordinary least squares (OLS) regression for each constituent are as follows:

$$L = f(\text{IN, ROW, FIELD, PASTURE, FOREST}) + \mu \quad (1)$$

$$L = f(\text{IN, ROW, FIELD, PASTURE, FOREST, URBAN}) + \mu \quad (2)$$

$$L = f(\text{IN, ROW, FIELD, PASTURE, FOREST DUMMY}) + \mu \quad (3)$$

$$L = f(\text{IN, ROW, FIELD, PASTURE, FOREST, URBAN DUMMY}) + \mu \quad (4)$$

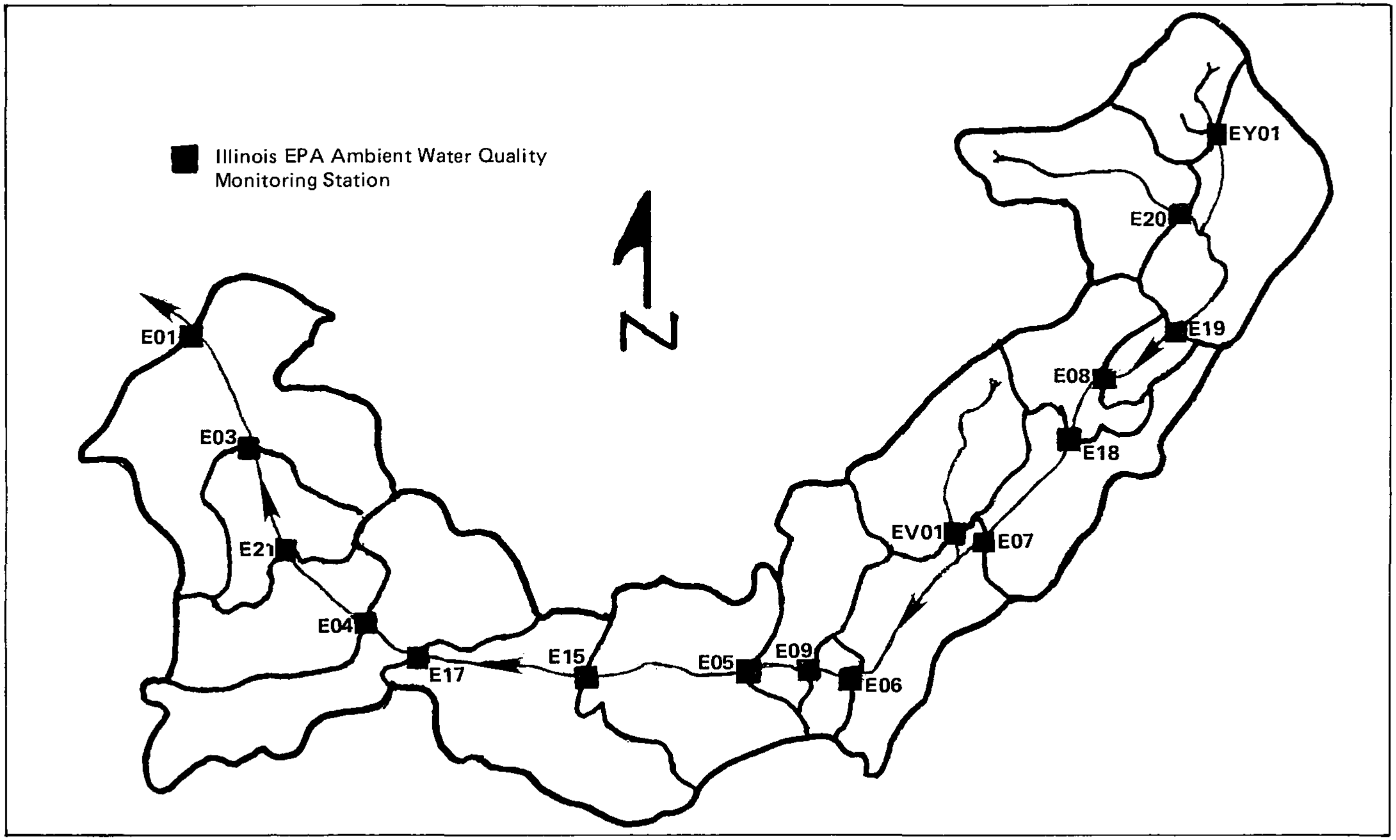

Figure 1. Upper Sangamon River Basin comprising 5,853 square kilometers, showing location of Illinois EPA water quality monitoring stations.

where:

L denotes median stream loading for nitrate-nitrogen or total phosphorus in metric tons per year;
IN denotes median upstream loading in metric tons per year;
ROW denotes hectares of subbasin floodplain in rowcrop agriculture;
FIELD denotes hectares of subbasin floodplain in field crops;
PASTURE denotes hectares of subbasin floodplain in pasture or other unspecified agricultural use;
FOREST denotes hectares of predominantly wooded floodplain;
URBAN denotes hectares of urban land use throughout the subbasin;
DUMMY denotes the presence or absence of Lake Decatur in the subbasin;
μ denotes a random error term.

Spatial autocorrelation of error terms in a regression model can be a significant problem, and few methods for dealing with it have been shown to be entirely adequate. Correction for temporal autocorrelation is conceptually more straightforward. A common practice for time series models is to add the lagged dependent variable as a treatment variable [1]. For the present analysis, the spatial equivalent to this procedure is to use the upstream loading as a predictor of the downstream loading. This allows the use of the Durbin H statistic, which is a combination of the Durbin-Watson statistic for autocorrelation and the variance of the coefficient on the lagged dependent variable. This combination yields a normally distributed statistic and provides an adequate test for autocorrelation in the presence of the lagged dependent variable. Like the Durbin-Watson, the statistic is most appropriate for large sample tests (that is for n greater than 30), and although nothing is known about its small sample properties, it does present an alternative to the straight Durbin-Watson statistic. It will be presented along with the ordinary least squares (OLS) regression results. A Durbin H of greater than 1.64 leads to the rejection of the hypothesis of zero autocorrelation.

RESULTS AND DISCUSSION

Regression coefficients, standard errors, and related statistics derived from the OLS regression analyses are presented in Tables 1 and 2. The results for total phosphorus and nitrate-nitrogen will be discussed separately below.

Total Phosphorus

Because the regression analysis, in this case, deals directly with only floodplain land use and urban land use outside the floodplain, the effects of other land use in the watershed, primarily agriculture outside the floodplain, are represented in an average sense by the regression constant. In this case, the constant varies in sign and is never significantly different from zero. The

Table 1. Total Phosphorus[a,b]

CONST	*IN*	*ROW*	*FIELD*	*PASTURE*	*FOREST*	*URBAN*	*DUMMY*	R^2	*H*	*EQUATION*
14.62	.882	–.010	–.420	.393	n.089			.973***	–1.579	(1)
23.46	.131***	.010	.489	.203**	.116					
15.30	.928	.002	–.534	.297	–.030	.027		.975***	– .532	(2)
22.66	.131***	.012	.479	.208*	.121	.022				
–4.54	.981	–.037	.381	.114	–.163		–159.83	.979***	–3.129	(3)
22.97	.127***	.010**	.598	.230	.109*		82.12**			
–8.90	1.077	–.010	.440	–.104	–.096	.040	–204.49	.987***	–1.886	(4)
18.14	.106***	.010	.469	.200	.089	.015**	66.88***			

[a]Standard errors displayed beneath coefficients.
*Coefficient significantly different from zero at .1
**Coefficient significantly different from zero at .05
***Coefficient significantly different from zero at .01

[b]Coefficients are metric tons per hectare per year, except for "CONT" and "DUMMY" whose dimensions are metric tons per year, and "IN" which is dimensionless.

Table 2. Nitrate-nitrogen[a,b]

CONST	IN	ROW	FIELD	PASTURE	FOREST	URBAN	DUMMY	R^2	H	EQUATION
429.93	.782	.049	–7.957	3.477	1.475			.993***	–1.507	(1)
125.26***	.058***	.047	1.915***	.867***	.507***					
486.71	.813	.146	–9.457	2.807	2.110	.237		.996***	– .739	(2)
96.21***	.046***	.049***	1.564***	.707***	.450***	.084***				
442.10	.802	.022	–6.430	2.918	1.374		–354.01	.992***	–1.935	(3)
145.40***	.064***	.062	2.844***	1.164**	.536**		477.97			
393.81	.853	.114	–6.926	1.693	2.024	.274	–640.37	.997***	–2.257	(4)
95.42***	.044***	.047***	1.853***	.828**	.393***	.074***	320.42**			

[a]Standard error displayed beneath coefficients
*Coefficient significantly different from zero at .1
**Coefficient significantly different from zero at .05
***Coefficient significantly different from zero at .01

[b]Coefficients are metric tons per hectare per year, except for "CONT" and "DUMMY" whose dimensions are metric tons per year, and "IN" which is dimensionless.

implication from this is that agricultural land use outside the floodplain has minimal effect on phosphorus levels in surface waters. This further implies that upland agricultural erosion, with its phosphorus, is largely prevented from being delivered to the active floodplain.

The coefficient for "IN" represents the average fraction of the upstream load persisting to the downstream measuring station. The implication is that phosphorus, once delivered, is relatively persistent in flowing streams.

The coefficients for "FOREST" indicate that forested land consistently reduces the phosphorus loadings even though the effect appears to be relatively small. If the majority of phosphorus is adsorbed to clay particles, and if floodplain forest does a relatively inefficient job of trapping clay particles as opposed to the larger silt and sand particles, phosphorus would tend to persist in the flowing stream.

The coefficients for "URBAN" in equations (2) and (4) are both positive, and in equation (4) it is significant. Urban runoff may be a nonpoint source contributor to phosphorus loadings.

The most significant finding in this case study for control of instream phosphorus levels is the Lake Decatur "Dummy" variable. From this analysis, it is clear that this reservoir has a significant trap efficiency and reduces instream total phosphorus, primarily particulate phosphorus [8].

Nitrate-nitrogen

The strongly positive and highly significant regression constants indicate that factors outside the floodplain and outside urban areas are contributing nitrate-nitrogen to the stream in significant amounts. Shallow groundwater delivery of nitrate-nitrogen may be important.

The "IN" coefficient suggests that nitrate-nitrogen has a tendency to persist but is assimilated more strongly than phosphorus from station to station. Algal and other instream plant growth could be a substantial "sink" for dissolved nitrate-nitrogen.

An unexpected result, however, is the strongly negative regression coefficient for field crop land. One possible explanation derives from the fact that most of this land is in hay and undergoes several cuttings a year. Because the main value of hay is a rich source of nitrogen-based protein for livestock, it follows that the crop's nitrogen uptake is rapid. Most such crops are fastgrowing, with dense, fibrous root systems. Since the above-ground growth is harvested and removed from the system, it is conceivable that floodplain crops of hay could be withdrawing a significant amount of nitrate-nitrogen from shallow groundwater.

The major per-acre contributor for nitrate-nitrogen seems to be pasture land. Livestock concentrations are well known to contribute substantial levels of nitrogenous waste. If the plant community in the pasture has a considerable representation of legumes, grazing could prolong such plants in a rapid-growth state, ultimately resulting in a significant positive contribution as livestock waste. The high "FOREST" contribution could also be explained as livestock and wildlife nitrogenous wastes, because the forested floodplain regions that were grazed in the study area could not be distinguished from those that were ungrazed using LANDSAT interpretation.

One land management possibility inferred by the foregoing would be to graze livestock in floodplain pastures separated from the stream by fields of hay. Such an arrangement should both mitigate the effects of the livestock waste and promote the growth of the hay crop.

Urban land contributes positively to instream nitrate-nitrogen concentrations, as expected. The "DUMMY" variable for Lake Decatur indicates that impoundments have a major impact on downstream nitrate-nitrogen concentrations.

General

It is important to note that either constituent can be purposely intercepted. For example, any barrier to sediment movement on the land surface is likely to intercept phosphorus. Since an eroded sediment could be considered delivered to the stream on arriving at the active floodplain, sediment barriers just above and outside the active floodplain will prevent its delivery to the stream. Nitrate-nitrogen, on the other hand, would be largely unaffected by sediment traps, but could be removed by a fast-growing crop in the floodplain whose roots take nitrogen from shallow groundwater. Hay is one such crop. In either case, interception of the chemical to prevent its delivery to surface waters can be an important management strategy for improving water quality, and it is probably advantageous to apply such techniques very near the stream channel.

There are two major conclusions from this work. First, stream water quality is a function of land use within the watershed. Second, there is general support for the hypothesis that lands closer to the stream have greater impact on water quality than lands farther from the stream for phosphorus and other sediment-related contaminants. It follows that those land uses with a tendency to contribute large amounts of chemical contamination to the watershed are best located as far as possible from the stream channel. Those with a tendency to intercept chemical constituents should be located as near as possible.

A combination of accurate water quality data, land cover data and understanding of the physical properties and delivery systems of chemical contaminants may help guide attempts to control nonpoint contributions to water quality in the future.

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