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Watershed level risk assessment of nitrogen and phosphorus export☆

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Abstract

Land cover composition across a watershed is a principal factor in controlling the amount of nitrogen and phosphorus exported from a watershed. A well developed literature of nutrient export coefficients by land-cover class was used to model the risk of equaling or exceeding specified levels of nutrient export. The model was applied to about 1000 comparatively small watersheds mapped for the state of Maryland for environmental analysis and planning. Risk estimates generally increased from west to east, but numerous areas of high variability were evident. Risk of exceeding specified levels of nitrogen and phosphorus export were nonlinearly related to the amount of forest in the watershed. Risk increased more dramatically for phosphorus and nitrogen when forest dropped below between 90 and 95%, respectively. Bifurcations in this nonlinear relationship were the result of the relative abundance of agriculture and urban land in the watershed. The nonlinear relationship between percentage forest and risk increased more dramatically for phosphorus and less dramatically for nitrogen when urban was relatively more abundant than agriculture. Regional-scale variation in risk is discussed in terms of its relevance to environmental management.

Keywords: Land-cover; Maryland; Modeling; Water pollution

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1. Introduction

Empirical studies have shown the dominant influence of land cover (e.g. forest, agriculture, urban) in determining the amount of nitrogen (N) and phosphorus (P) in rivers, lakes, and estuaries (Hunsaker et al., 1992; Hunsaker and Levine, 1995; Jones et al., in press). Generally, the concentration or load of nitrogen and phosphorus in receiving waters increases as the amount of agriculture or urban land increases in a watershed (Parry, 1998). This relationship is also supported by a well developed literature of nutrient export coefficients by land-cover class (Omernik, 1977; Reckhow et al., 1980; Beaulac and Reckhow, 1982; Frink, 1991). Nutrient export coefficients are scalars that are multiplied by the area of a given land-cover class to estimate the nutrient load contributed by that land-cover class.

Distributions of nutrient export coefficients by land-cover class can be developed from these literature surveys (Reckhow et al., 1980; Frink, 1991), and used to estimate the probability or risk of exceeding specified thresholds for watersheds with heterogenous land cover (Wickham et al., 2000; Wickham and Wade, 2000). The conceptual basis for using distributions of nutrient export coefficients stratified by land-cover class is evident in the empirical data collected by Omernik (1977), Beaulac and Reckhow (1982), and Frink (1991). These data show distinct ranges of N and P export coefficients for watersheds with either homogeneous (or nearly so) forest, agriculture, or urban land cover, and these broad land-cover categories can be mapped reliably across watersheds and broader geographic regions (Zhu et al., 2000; Yang et al., in press). In contrast, other physical and anthropogenic factors that contribute to variability in nutrient export are difficult to estimate at watershed and larger scales, and interactions among them are largely unknown. Examples of these other factors include: (1) inter-annual changes in precipitation (Lucey and Goolsby, 1993), (2) soil type, (3) cropping practices (Renard et al., 1997), (4) timing of fertilizer application relative to precipitation events (Beaulac and Reckhow, 1982), (5) amount of atmospheric deposition (Jones et al., in press), (6) geology (Dillon and Kirchner, 1975), and (7) density of impervious surfaces (Arnold and Gibbons, 1996), and (8) the spatial pattern of land-cover in the watershed (Hunsaker and Levine, 1995; Jones et al., in press).

The purpose of this paper is to demonstrate how land cover can be used to develop a regional-scale risk assessment of nutrient export by watershed. The study is conducted across the state of Maryland, USA, using comparatively small watersheds that were developed for environmental analysis, planning, and management. Estimating the risk of exceeding specified N and P export levels is appropriate for environmental planning, since land-use plans are supposed to address environmental impacts (Fabos, 1985).

2. Methods

The watershed risk model is based on compilation of empirical distributions of nutrient export coefficients by land-cover class from existing literature, fitting the empirical distributions to theoretical distributions, and using repeated trial simulation to estimate the frequency of equaling or exceeding a specified threshold taken from the empirical distribution (Wickham et al., 2000). The frequency of equaling or exceeding a specified threshold divided by the total number of trials is treated as a probability. This approach is consistent with other regional-scale, water quality risk assessments (Graham et al., 1991; Hession et al., 1996).

Empirical distributions of nutrient export coefficients for the general land-cover classes of forest, agriculture, and urban were compiled from Reckhow et al. (1980) (Table 1). The empirical distributions were compared to normal, lognormal, exponential, and weibull theoretical distributions, and found to best fit the lognormal. Random numbers were drawn from the fitted lognormal distributions (Table 2) over 10 000 trials for each watershed. Simulated values were restricted to be within the minimum and maximum values of the observed ranges to provide conservative estimates of risk.

Simulated nutrient export coefficients for each watershed were calculated after Beaulac and Reckhow (1982) (Eq. (1)).

$$\mathrm{N,P} = \sum_{i=1}^{n} c_i A_i \quad (1)$$

Table 1
Empirical data on nitrogen and phosphorus export coefficients (from Reckhow et al., 1980)

Land cover	WS size (ha)	Nitrogen		Phosphorus	
		# of Obs	Distribution[a]	# of Obs	Distribution[a]
Agriculture	40–8000	30	2.10 (min)	27	0.08
			6.60 (Q_{25})		0.49
			11.10 (Q_{50})		0.91
			20.30 (Q_{75})		1.34
			53.20 (max)		5.40
Urban	4–4800	19	1.50	24	0.19
			4.00		0.69
			6.50		1.10
			12.80		3.39
			38.50		6.23
Forest	7–47 000	21	1.37	62	0.01
			1.92		0.04
			2.46		0.08
			3.32		0.22
			7.32		**0.83**

Units for coefficients are kg/ha/yr. Risk estimates are based on the numbers in bold.
[a] Values are minimum, 25th, 50th and 75th percentiles, and maximum from the empirical distributions, as annotated in the block for agriculture/nitrogen.

Table 2
Mean and variance estimates for fitted lognormal distributions

Land cover	Nitrogen		Phosphorus	
	Mu	Sigma	Mu	Sigma
Agriculture	2.460	0.914	−0.221	1.036
Urban	1.900	0.913	0.233	0.989
Forest	1.024	0.506	−2.351	1.105

Using Eq. (1), simulated nitrogen (N) or phosphorus (P) loads were estimated as the proportion of land-cover class, A_i (forest, agriculture, urban), in the watershed times the randomly drawn export coefficient, c_i, for that land-cover class. By using percentages of land-cover classes, Eq. (1) gives a weighted average of nutrient export per unit area for the watershed. Typical units would be kilograms per hectare per year (kg/ha/yr).

Risk estimates were based on the number of times the simulated value equaled or exceeded the maximum values from the empirical distributions of N and P for forest (7.32 [N] and 0.83 [P] kg/ha/yr; see Table 1). For example, if 1000 iterations of the 10 000 trials for a watershed exceeded the maximum value for forest, then the risk estimate for that watershed would have been 10%. The thresholds for estimating risk could have been based on any number within (or outside) any of the distributions in Table 1. Larger numbers represent rarer events that would have lower estimates of risk (O'Neill et al., 1982). There are no clear and unambiguous nutrient export values to use to establish risk (Wickham et al., in press). We chose the maximum observed values for homogeneously forested watersheds because the potential natural vegetation for most of the state of Maryland is forest (Whittaker, 1975) and the maximum nutrient export values for forest approximate lower quartile to median nutrient export values for urban and agriculture (Table 1). Our choices of thresholds for estimating risk represent reasonable targets for basing land management decisions in mixed land-use watersheds.

The land-cover data used for A_i in Eq. (1) were from the Multi-Resolution Land Characteristics (MRLC) consortium (Loveland and Shaw, 1996) National Land Cover Data (NLCD) for Maryland (Vogelmann et al., 1998). Watershed boundaries were from the Maryland Department of Natural Resources (MDDNR). MDDNR watersheds ranged in size from about 12 to 7500 ha, which is consistent with the watershed size range of the nutrient export data (Table 1).

Geographical information system software was used to tabulate proportions of forest, agriculture and urban by watershed. Areas mapped as wetlands were treated as forest since wetlands also reduce nutrient loads to surrounding waters (Preston and Bedford, 1988). Land-cover percentages were based only on the total amount of forest (and wetland), agriculture, and urban in each watershed.

3. Results

Overall, the spatial pattern of risk generally increased from west to east across the state (see also Jones et al., 1997), reflecting the increasing prevalence of urban and agricultural land in the east (Fig. 1). Nevertheless, N and P risk maps also showed areas of watershed-to-watershed variability. There were several areas where watersheds with low risk estimates were surrounded by watersheds with higher risk estimates, and vice versa.

For nitrogen, watersheds with the highest risk estimates dominated in the north-central portion of the state, as well as another group of generally contiguous watersheds on the DelMarVa peninsula. For phosphorus, the areas of greatest risk were coincident with the metropolitan areas of Baltimore and Washington, DC. The

Fig. 1. Spatial pattern of nitrogen (top) and phosphorus (bottom) nutrient export risk estimates for Maryland watersheds. Watersheds are grouped into four, equal-interval categories.

differences in the magnitude and spatial pattern of risk between nitrogen and phosphorus are evident in the empirical distributions (Table 1). Agriculture tends to produce greater nitrogen exports than urban areas, while urban areas tend to produce slightly higher phosphorus exports than agriculture. Hence, the areas with the highest N export risk tend to identify watersheds dominated by agriculture, while the areas with the highest P export risk tend to identify urban-dominated watersheds.

Risk estimates increased nonlinearly as the amount of forest in a watershed declined (Fig. 2). The nonlinear nature of risk estimates as a function of percentage forest provides potential land-use planning thresholds for decision making. For phosphorus, risk estimates increased more rapidly when forest dropped below about 90%. For nitrogen, risk estimates increased more rapidly when forest dropped below about 95%. The 90 and 95% forest thresholds in Fig. 2 are a function of the nutrient export coefficients used to estimate risk. Use of higher nutrient export coefficients to estimate risk would represent rarer events, which would lower the 90 and 95% thresholds in Fig. 2. The 5% difference between N and P positions of rapid slope changes (95 and 90% respectively) reflects the influence of the relative abundances of agriculture and urban on rarity and estimation N and P export risk. Agriculture tends to produce greater amounts of N export but lower amounts of P export than urban (Table 1). Therefore, when agriculture is more abundant, the N export threshold (7.32 kg/ha/yr) used to estimate risk represents a less rare event than the P export coefficient (0.83 kg/ha/yr). Since agriculture is more abundant statewide, the N risk position of rapid slope change occurred at a higher percentage forest than that for P risk.

The complex relationship between nutrient export risk and land-cover composition resulted in bifurcations in Fig. 2 that were a function of the relative proportions of agriculture and urban. At about 70% forest, risk estimates for phosphorus split into two groups. The group forming the steeper slope represented watersheds with higher percentages of urban than the group forming the more gentle slope. A similar but weaker pattern also existed for nitrogen. At about 90% forest, watersheds with higher percentages of urban tended to form a more gentle slope. Placed in a temporal domain, replacing agriculture with urban development may decrease risks of excessive nitrogen export but increase risks of excessive phosphorus export, based on these data. Encroachment of urban development onto former agricultural lands is a well documented trend (Healy and Short, 1981).

4. Discussion

In its essence, risk assessment is estimating the probability of an event (Barnthouse and Suter, 1986). In this paper, we estimated the probability of exceeding the maximum exports of N and P from homogeneously forested watersheds (an event) based on the current distribution of land cover. The empirical distributions of nutrient export coefficients by land-cover class provided a basis for estimating uncertainty attributable to factors other than land cover.

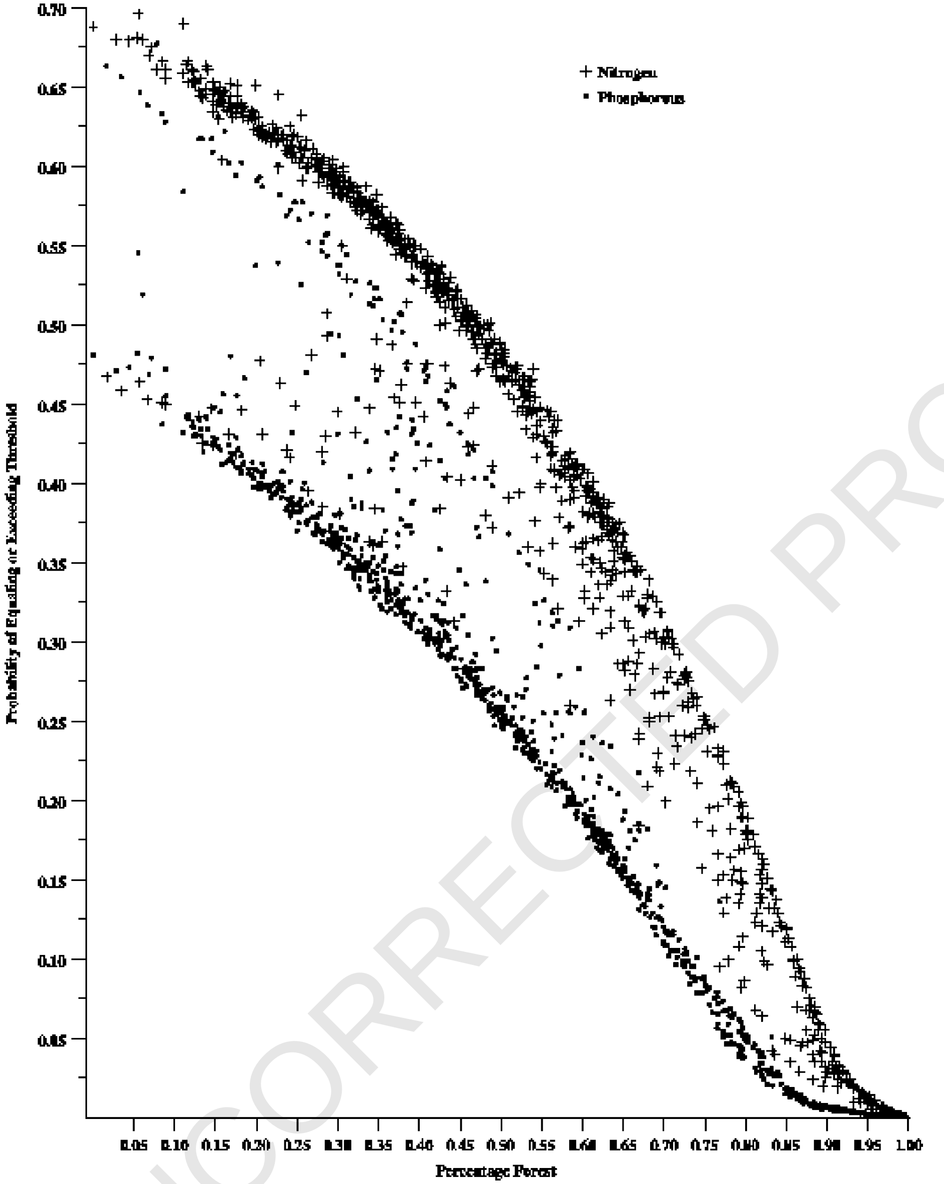

Fig. 2. N and P risk estimates as a function of the percentage forest in the watershed.

Ecological risk analysis is a relatively new discipline (Bartell et al., 1992; Suter, 1993), and regional-scale applications are few. Our approach is similar to other regional-scale, water quality risk assessments. Graham et al. (1991) used repeated trial simulation to model the probability of a location undergoing pest-induced coniferous forest decline. Randomness in the location of coniferous forest loss was used to estimate the risk of a change in pH in headwater lakes across the Adirondacks, New York. Like Graham et al. (1991), the focus of our analysis was to show geographic variation in risk, using watersheds to summarize and communicate that variation. Hession et al. (1996) generated probability distributions for several parameters used in a eutrophication model to estimate the risk of a lake being in different trophic states. Hession et al. (1996) introduced regional variability by splitting the lake's watershed into several subwatersheds, and estimating cumulative distributions of phosphorus loads for each. Introduction of geographic variation in phosphorus loads permitted identification of relative contributions of each subwatershed to the lake's eutrophication risk.

Each study highlights the utility of identifying geographic variation for identifying and informing risk reduction options. In applications like ours or Graham et al. (1991), a geographic scope identifies which watersheds present the highest risks. These watersheds could be targeted for risk reduction. In applications like Hession et al. (1996), geographic variation helps to identify where (e.g., which subwatershed) mitigation strategies should have the greatest impact on reducing risk for a single resource (lake).

5. Conclusion

Land cover composition is a principal factor in controlling the amount of nitrogen and phosphorus exported from a watershed. A well developed literature of nutrient export coefficients by land-cover class was used to model the risk of equaling or exceeding specified levels of nutrient export. Modeling nutrient export as risk permitted incorporation of uncertainty attributable to factors other than land cover that are more difficult to measure across entire watersheds and larger regions. Examples of some other factors are soil type, geology, cropping practices, and impervious surface density.

Risk estimates generally increased from west to east following the same geographic pattern of increasing prevalence of agriculture and urban land. Notwithstanding this general geographic trend, there are numerous areas throughout the state with high variability in watershed-to-watershed risk. There are several areas where neighboring watersheds have markedly different risk estimates.

Risk estimates increased nonlinearly as the percentage of forest decreased. Phosphorus risk estimates increased more dramatically when the percentage of forest dropped below about 90%. Nitrogen risk estimates increased more dramatically when the percentage of forest dropped below about 95%. These thresholds are perhaps useful for guiding local decisions on the amount of nonforest land to permit in a watershed, whereas watershed-to-watershed variations provide regional-scale information for risk management.

The relative proportions of agriculture and urban land in a watershed caused bifurcations in the relationship between percentage forest and risk. When the amount of forest dropped below about 70%, phosphorus risk estimates for watersheds with relatively more urban land increased more dramatically than those with relatively less urban land. When the amount of forest dropped below about 90%, nitrogen risk estimates for watersheds with relatively more land in agriculture increased more dramatically than those with relatively less agriculture. However, the bifurcation pattern for nitrogen was less strongly developed than that for phosphorus.

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