# LAND COVER AS A FRAMEWORK FOR ASSESSING THE RISK OF WATER POLLUTION[Ψ]

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## Abstract

*A survey of numerous field studies shows that nitrogen and phosphorous export coefficients are significantly different across forest, agriculture, and urban land-cover types. We used simulations to estimate the land-cover composition at which there was a significant risk of nutrient loads representative of watersheds without forest cover. The results suggest that at between 20 percent and 30 percent non-forest cover, there is a 10 percent or greater chance of N or P nutrient loads being equivalent to the median values of predominantly agricultural or urban watersheds. The methods apply to environmental management for assessing the risk to increased nonpoint nutrient pollution. Interpretation of the risk measures are discussed relative to their application for a single watershed and across a region comprised of several watersheds.*

**Key words**: nutrient export; risk analysis; simulation.

## Introduction

Urban and agricultural land cover are considered principal sources of excess loads of nitrogen (N) and phosphorous (P) in receiving waters (Parry, 1998). Both N and P are important factors in eutrophication (over enrichment) of water bodies. Eutrophication leads to overproduction of autotrophic organisms, which in turn leads to decreased oxygen levels and threatens aquatic life (Correll, 1998). Excessive N levels may also result in elevated nitrite *(N02)* concentrations, which can have adverse effects on human health (Mueller *et al.*, 1997). Seasonal hypoxia in the Gulf of Mexico has been attributed to nitrate discharges from the Mississippi River (Rabalais *et al.*,1996). Phosphorous is the principal cause of eutrophication in freshwater, both *N* and P are contributors in estuaries, and nitrogen is the principal cause of eutrophication in the ocean (Correll 1998).

Three decades of field-based research have provided a broad literature of nutrient export coefficients by land-cover type (Uttormark *et al.*, 1974; Reckhow *et al.*, 1980; Beaulac and Reckhow, 1982; Frink, 1991). Nutrient export coefficients are numbers, that are multiplied by the amount (area) of a given land-cover type to estimate the amount of nutrients received by waters from that type. Export coefficients have been used in numerous ways, including: (1) calibration to particular places (Young *et al.*, 1996; Jordan *et al.*,1997); (2) estimation of national averages (Rast and Lee, 1983); (3) improving coefficient estimation (Frink, 1991); (4) improving the simple area-weighted models in which the coefficients are generally applied (Soranno *et al.*, 1996); (5) planning (Adamus and

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Bergman, 1995; Mattikalli and Richards, 1996); and (6) identification of regional spatial patterns (Jones *et al.*, 1997).

Nutrient export coefficients have never been treated as a distribution of possible values and used in random simulations to estimate the probability of increased nutrient loads as a result of differences in land-cover composition. The reason for such simulations is that factors other than land cover that contribute to nutrient export are rarely known with certainty across a watershed. Examples of other factors that may vary across a watershed but are difficult to estimate include: (1) year-to-year changes in precipitation (Lucey and Goolsby, 1993); (2) soil type; (3) slope and slope morphology (convex, concave); (4) geology (Dillon and Kirchner, 1975); (5) cropping practices (e.g., factors C and P in USLE) (Renard *et* al., 1997]); (6) timing of fertilizer application relative to precipitation events (Beaulac and Reckhow, 1982); (7) density in impervious surface (Arnold and Gibbons, 1996); (8) residential lot sizes; and (9) ratio of sewered versus septic households, etc. In contrast, broad land-cover categories (e.g., forest, urban, agriculture) can be estimated reliably across watersheds (Vogelmann *et* al., 1998a, 1998b; Zhu *et al.*, in press). Significant differences in nutrient export coefficients across these land-cover categories are well-documented (e.g., Reckhow *et al.*, 1980; Frink, 1991).

The purpose of this paper is to estimate the risk of increased nutrient loads based on the composition of land cover within a watershed. One approach to risk assessment is to fit parameters of interest to a distribution, apply the parameters to a model over a series of trials, and examine the resulting distribution for the probability of an event based on model conditions (Suter, 1993). Graham *et al.* (1991) used probabilities of changes in forest cover and water quality from simulated ozone-induced bark beetle infestations as estimates of risk. Hession *et al.* (1996) estimated the risk of lake eutrophication from excess phosphorous by incorporating uncertainty in a watershed pollution model.

In this paper, we fit nutrient export coefficients to a distribution and use them in a model to estimate the risk of an event based on given land-cover conditions. An example of an event in this study is equaling or exceeding the upper quartile value of N or P nutrient export coefficients from forested watersheds. Risk is measured as the number of times (frequency) an event occurs divided by the total number of trials. We use the term probability as equivalent to the number of times an event occurs divided by the total number of trials.

## Methods

We used the appendices from Reckhow *et al.* (1980) to create a distribution of nutrient export coefficients by land-cover type. We used these data instead of summaries of them (Beaulac and Reckhow, 1982) because they more accurately represent the influence of inter-annual variability. In some cases, the summary tables (Beaulac and Reckhow, 1982) reported means or medians for two or more years of observations at the same site. Factors influencing nutrient export such as year-to-year changes in precipitation and the timing of fertilizer application relative to precipitation events are incorporated better when each year is treated as a single observation.

We used the data for forest, mixed agricultural, and urban watersheds to create distributions of nutrient export coefficients by land-cover type (Table 1). We did not use the data for cropland and pasture because these data were typically estimated on very small watersheds (< 0.1 ha). Watershed size influences nutrient export (Prairie and Kalff, 1986). Some of the extreme values for cropland in Beaulac and Reckhow (1982) may be influenced by their small size. Treating pasture and cropland as a single agricultural class is consistent with other studies (Rast and Lee, 1983; Frink, 1991). Watershed size for these classes (4-4800 ha) is also more representative of watershed units being used by local jurisdictions. For example, a watershed map used by the Maryland Department of Natural Resources (MDDNR) has sizes ranging from about 12 to 24,000 ha.

Nutrient export coefficients generally came from homogenous watersheds. The mixed agricultural group had three observations that listed forest at greater than 10 percent of the area. Agriculture (cropland and pasture combined) was at least 75 percent of the area in 26 watersheds. The urban watersheds were combinations of residential, commercial/ industrial, and transportation corridors. One observation for urban watersheds listed forest as 12 percent of the area and agriculture as eight percent. Only one of the observations for forest reported another kind of land cover (urban), but it was estimated at only one percent. We kept all observations for each group.

The data in each group were compared to different distributions. A two-parameter log-normal distribution provided a consistently good fit (Table 2). Random numbers were drawn from the fitted log-normal distributions (Table 3). Simulated values outside the observed ranges were not included. We restricted inclusion of simulated values to within the observed ranges to provide conservative estimates of the probability of encountering high values.

Equation 1 (e.g., Beaulac and Reckhow, 1982) was used to model nutrient loads as a function of landcover composition.

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

N and P loads are estimated as the product of the area (A) of land-cover type i times its export coefficient (ci) summed across all land-cover types in the watershed (Equation 1). This equation can be used in two ways. If areal estimates are known for the different land-cover types, the equation provides a weighted average estimate of nutrient load. In this case, units would typically be kilograms per year (Kg/yr). If Only two land-cover types at a time were consid percentages of different land-cover types are used, the equation provides a weighted average estimate of a nutrient export coefficient. In this case, units typically would be kilograms per hectare per year (Kg/ha/yr). We used the latter case of Equation (1) in this study.

TABLE 1. Characteristics of Observed Data (from Reckhow et al., 1980).

| Land Cover | Watershed Size (ha) | Variable | Number of Obs. | Minimum | Lower Quartile | Median | Upper Quartile | Maximum |
|---|---|---|---|---|---|---|---|---|
| Mixed Agriculture | 40-8000 | N | 30 | 2.10 | 6.60 | 11.10 | 20.30 | 53.20 |
| | | P | 27 | 0.08 | 0.49 | 0.91 | 1.34 | 5.40 |
| Urban | 4-4800 | N | 19 | 1.50 | 4.00 | 6.50 | 12.80 | 38.50 |
| | | P | 24 | 0.19 | 0.69 | 1.10 | 3.39 | 6.23 |
| Forest | 7-47000 | N | 21 | 1.37 | 1.92 | 2.46 | 3.32 | 7.32 |
| | | P | 62 | 0.01 | 0.04 | 0.08 | 0.22 | 0.83 |

TABLE 2. Goodness-of-Fit Estimates Between Nutrient Export Coefficients and Selected Distributions. Kolmogorov D measures the maximum vertical distance between the observed and specified distributions. Smaller values suggest better agreement. The p-values (Pr > D) test the null that the observed data are a random sample from the specked distribution. Smaller p-values suggest the null should be rejected.

| Distribution | Variable | Forest | | Agriculture | | Urban | |
|---|---|---|---|---|---|---|---|
| | | Kolmogorov D | Pr > D | Kolmogorov D | Pr > D | Kolmogorov D | Pr > D |
| Normal | N | 0.2273 | < 0.01 | 0.2030 | < 0.01 | 0.2538 | < 0.01 |
| | P | 0.2205 | < 0.01 | 0.2952 | < 0.01 | 0.2411 | < 0.01 |
| Lognormal | N | 0.1260 | > 0.15 | 0.0769 | > 0.15 | 0.1183 | > 0.15 |
| | P | 0.0907 | > 0.15 | 0.1289 | > 0.15 | 0.1272 | > 0.15 |
| Exponential | N | 0.3512 | < 0.01 | 0.1236 | > 0.15 | 0.1479 | > 0.15 |
| | P | 0.1264 | 0.0905 | 0.1651 | > 0.15 | 0.1241 | > 0.15 |
| Weibull | N | 0.1888 | 0.0416 | 0.1015 | > 0.10 | 0.1708 | > 0.10 |
| | P | 0.1388 | < 0.01 | 0.1680 | 0.0396 | 0.1544 | > 0.10 |

TABLE 3. Mean and Variance Parameters for Fitted Log-Normal Distributions.

| Land Cover | Variable | Mu | Sigma |
|---|---|---|---|
| Mixed Agriculture | N | 2.406 | 0.914 |
| | P | -0.221 | 1.036 |
| Urban | N | 1.900 | 0.913 |
| | P | 0.233 | 0.989 |
| Forest | N | 1.024 | 0.506 |
| | P | -2.351 | 1.105 |

Only two land-cover types at a time were considered in the simulations: either forest and agriculture or forest and urban. Simulations were applied to six combinations. One combination was 95 percent forest and 5 percent agriculture or urban. The other five combinations were from systematically decreasing forest by five percent and increasing agriculture or urban by the same amount. The land-cover combinations ranged from 95 percent forest and 5 percent agriculture or urban to 70 percent forest and 30 percent agriculture or urban.

The randomization was repeated 10,000 times for each land-cover combination. Summary statistics from the simulations were then examined for trends in nutrient export coefficients as a result of incremental increases in non-forest land cover. Using this approach, we were able to determine land-cover compositions at which there was a significant risk of replicating nutrient export coefficients representative of watersheds lacking forest.

Three summary statistics, events, were used to examine trends in nutrient export coefficients as a result of incremental increases in non-forest cover. These were: (1) probability of equaling or exceeding the observed maximum value for forest ($Q_{Fmx}$); (2) probability of equaling or exceeding the observed median value for agriculture ($Q_{A50}$) or urban ($Q_{U50}$); and (3) probability of equaling or exceeding the observed 75th percentile of agriculture ($Q_{A75}$) or urban ($Q_{U75}$) (see Table 1).

There is some logic in the use of several measures of risk because they address management options (Suter, 1993). The probability measures have a declining likelihood of occurrence. Selection of the first ($Q_{Fmx}$) would represent a more conservative management decision than selection of the third ($Q_{A75}$, $Q_{U75}$).

## Results

The results show an increasing likelihood of nutrient loads typical of entirely agricultural or urban watersheds as the amount of these land-cover types is increased (Tables 4a, 4b, 4c, and 4d). The probability of equaling or exceeding $Q_{A50}$ or $Q_{U50}$ reached 10 percent or greater when non-forest cover was between 20 percent and 30 percent of the area. Non-zero probabilities of equaling or exceeding $Q_{A75}$ or $Q_{U75}$ occurred when non-forest cover was 30 percent in three out of four cases (Tables 4a, 4b, and 4c).

TABLE 4. Simulation Results for Nutrient Export Coefficients for Different Combinations of Forest and Anthropogenic Land Cover.

P > Q is the number of times the threshold was equaled or exceeded out of 10,000 trials. $Q_{Fm}$,, $Q_{A50}$, $Q_{U50}$> $Q_{A75}$, and $Q_{U75}$ are (respectively) the maximum value for forest, the median value for mixed agriculture, the median value for urban, the 75th percentile for mixed agriculture, and the 75th percentile for urban. These values are listed in Table 1.

(a) Forest and Agriculture, N.

| Thresholds | 95% Forest 5% Agric. | 90% Forest 10% Agric. | 85% Forest 15% Agric. | 80% Forest 20% Agric. | 75% Forest 25% Agric. | 70% Forest 30% Agric. |
|---|---|---|---|---|---|---|
| $P \geq Q_{Fmx}$ (7.32) | 0.018 | 0.066 | 0.141 | 0.208 | 0.273 | 0.331 |
| $P \geq Q_{A50}$ (11.1) | 0.0 | 0.0 | 0.007 | 0.039 | 0.077 | 0.116 |
| $P \geq Q_{A75}$ (20.3) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.002 |

(b) Forest and Agriculture, P.

| Thresholds | 95% Forest 5% Agric. | 90% Forest 10% Agric. | 85% Forest 15% Agric. | 80% Forest 20% Agric. | 75% Forest 25% Agric. | 70% Forest 30% Agric. |
|---|---|---|---|---|---|---|
| $P \geq Q_{Fmx}$ (0.83) | 0.002 | 0.008 | 0.021 | 0.100 | 0.139 | 0.152 |
| $P \geq Q_{A50}$ (0.91) | 0.0 | 0.002 | 0.010 | 0.076 | 0.114 | 0.119 |
| $P \geq Q_{A75}$ (1.34) | 0.0 | 0.0 | 0.0 | 0.008 | 0.030 | 0.045 |

(c) Forest and Urban, N.

| Thresholds | 95% Forest 5% Urban | 90% Forest 10% Urban | 85% Forest 15% Urban | 80% Forest 20% Urban | 75% Forest 25% Urban | 70% Forest 30% Urban |
|---|---|---|---|---|---|---|
| $P \geq Q_{Fmx}$ (7.32) | 0.004 | 0.014 | 0.038 | 0.074 | 0.112 | 0.148 |
| $P \geq Q_{U50}$ (6.5) | 0.028 | 0.045 | 0.079 | 0.126 | 0.167 | 0.206 |
| $P \geq Q_{U75}$ (12.8) | 0.0 | 0.0 | 0.0 | 0.0 | 0.001 | 0.008 |

(d) Forest and Urban, P.

| Thresholds | 95% Forest 5% Urban | 90% Forest 10% Urban | 85% Forest 15% Urban | 80% Forest 20% Urban | 75% Forest 25% Urban | 70% Forest 30% Urban |
|---|---|---|---|---|---|---|
| $P \geq Q_{Fmx}$ (0.83) | 0.003 | 0.011 | 0.050 | 0.110 | 0.167 | 0.224 |
| $P \geq Q_{U50}$ (1.10) | 0.0 | 0.002 | 0.067 | 0.038 | 0.080 | 0.123 |
| $P \geq Q_{U75}$ (3.39) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

The results suggest that anthropogenic effects on nutrient loads may be disproportionately greater than the actual amount of anthropogenic cover in a watershed. Hession et al. (1996) found that 80 percent of lake phosphorous load was attributable to agriculture, which accounted for only 25 percent of the watershed area.

## Application to Risk Management

Our probability measures ($\geq Q_{Fmx}$; $\geq Q_{A50}$ and $\geq Q_{U50}$ ; $\geq Q_{A75}$ and $\geq Q_{U75}$ ) can be examined to highlight how different measures might be used in risk management - decision making based on measures of risk (Suter, 1993). Respectively, each measure is more difficult to exceed, with one exception. For the forest to urban scenario for N, $Q_{Fmx}$ is slightly larger than $Q_{U50}$. Conservative management would base decisions (e.g., land use plans) on a measure such as $\geq Q_{Fmx}$. The simulation results found here indicate that chances are approximately one out of ten that nutrients loads will equal or exceed $Q_{Fmx}$ when non-forest land cover is between 15 and 25 percent. Less conservative management would use a measure that was more difficult to exceed (e.g., $\geq Q_{A50}$ / $Q_{U50}$).

One potentially useful measure for risk management might be the probability of equaling or exceeding the median value for agricultural or urban watersheds ($\geq Q_{A50}$ / $Q_{U50}$), since it represents the likelihood of nutrient loads that are representative of "average" conditions in agricultural or urban systems. At a threshold of 20 percent to 30 percent nonforest cover, there was approximately a one out of ten chance of generating nutrient loads more typically found in entirely agricultural or urban watersheds. Taking N and the forest/urban case as an example, this represents a one out of ten chance of about a 260 percent increase in that nutrient export coefficient (e.g., $6.5 \div 2.46$).

The risk measures have different implications depending on whether they would be used in management decisions for a single watershed or several watersheds across a region. For example, our results suggest that a watershed with 20 percent to 30 percent nonforest cover has a one in ten chance of generating nutrient exports coefficients typical of entirely agricultural or urban watersheds. For a single watershed, this risk might be acceptable. For a region that has 10 watersheds with 20 percent to 30 percent nonforest cover, the likelihood that one of the ten is generating nutrient exports typical of agricultural or urban watersheds begins to approach one (1.0).

## Summary and Conclusions

Numerous field studies have consistently shown significant differences in nutrient export across broad land-cover categories (forest, agriculture, and urban). The variance in nutrient export within any one of these land-cover categories is attributable to numerous factors that fall under the general categories of climate and weather, physiography, and land use practices. Most of these factors are difficult to measure at a watershed or larger scale.

The variance in nutrient export within broad land cover categories was used to estimate the risk of high nutrient loads (those typical of entirely agricultural or urban systems) based on different compositions of land cover. Our results suggest that at 20 percent to 30 percent non forest cover, there was a one in ten chance of replicating nutrient loads typical of entirely agricultural or urban watersheds. These simulation results are consistent with other studies that suggest nutrient export from agriculture is disproportionately greater than its area within a watershed (Hession et al., 1996).

The risk measures have different implications depending on whether they would be used for management of a single watershed or several watersheds across a region. At the regional-scale there is greater likelihood of several watersheds with land-cover compositions around the 20 percent to 30 percent non forest cover threshold. The greater the number of watersheds at the non forest cover threshold, the greater the chance that one or more will replicate nutrient loads more representative of watersheds without forest.

Frink (1991) suggests that nutrient export studies do not have to be based on homogenous land cover because watersheds will integrate the effects of all the different types. Land-cover composition across a watershed is the result, to some degree, of policies implemented through land use plans, and these plans typically must address environmental impacts (Fabos, 1985). Risk analysis can provide information that is relevant to land use planning. Future field-based studies of nutrient export would likely be more informative for land use planning if watersheds dominated by a single land-cover type were selected.

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