Predicting Stream Ecosystem Responses to Landcover-Related Stressors

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1 Overview

Here we present a model that combines elements of spatially distributed hydrologic models, spatially referenced regression models, and ecological risk assessment. It is designed to have manageable data requirements, a relatively small number of parameters, and a level of mechanistic detail that is high enough so parameters have reasonably clear interpretations but low enough so the model remains transparent to the principles underlying its behavior. We outline the conceptual basis of the model, then develop the model equations. For background information, discussion, and a detailed example of the model's application, see Johnson et al. (2007), on which the present document is based.

2 Conceptual framework

The conceptual basis of the model consists of four key ideas:

1. Each spatial unit (grid cell) of a catchment acts as a source of landcover-related materials that are transported along hillslope pathways to a stream, where they act as stressors on the stream ecosystem.

2. The stressor loading from each grid cell declines during downslope and downstream transport, with the attenuation rate depending on landcover types and, possibly, stream properties (e.g., order) encountered along the transport route.

3. The level of stress that the stream ecosystem experiences at any given location is determined by the cumulative residual (non-attenuated) stressor loads contributed by all upstream/upslope grid cells

4. The condition or integrity of the stream ecosystem at any given location is determined by the cumulative stressor load at that location and a stressor-response function that maps stressor load (or concentration) to ecosystem integrity.

Thus, watershed landcover contributes materials to the stream which, together with their longitudinal rate of instream loss or dilution, determine the cumulative stressor load to which the stream ecosystem at any point is subject. This cumulative stressor load then determines stream ecosystem integrity via a stressor-response function.

By a stressor, we mean any material (or more generally, form of energy; e.g., light or heat) entering the stream that is capable of producing a negative ecological impact, whether through an increase (e.g. increased nutrient loading resulting in excessive algal growth) or decrease (e.g., decreased loadings of leaf litter and large woody debris that reduce habitat available for benthic macroinvertebrates) relative to an appropriate reference condition. The level of stress refers to the magnitude of change in stressor load or concentration relative to an appropriate reference. Stressor attenuation during transport results from various processes of deposition, uptake, adsorption, decay, transformation (e.g., photolysis or biotransformation of chemical compounds), and filtering (e.g., sediment trapping).

Conceptually similar approaches have been used to model material loading to streams (Smith et al., 1997; Preston and Brakebill, 1999; Endreny and Wood, 2003) and to describe the retention of materials derived from upslope locations by forested riparian buffers (Weller et al., 1998). However, these earlier approaches do not relate predicted instream loads or concentrations to stream ecological integrity. We take this additional step by employing stressor-response relationships, which describe in a simple way the complex processes that determine how stream ecosystems respond to stress (e.g., U.S. EPA, 1998). Stressor-response relationships can be empirically derived and can provide valuable information about ecological responses important to evaluating management options. The functional forms of stressor-response relationships between landcover and stream ecosystem characteristics are not well known, but nonlinear forms are likely for impacts on biological attributes (Dale-Jones et al., 1999; Harris, 2002; Yuan and Norton, 2003).

3 Basic equations

We now translate the conceptual framework presented above into a suitable set of equations. The form of the equations depends on whether space is treated as discrete or continuous. Here we restrict attention to the discrete case. The discrete form of the equations provides a basis for applying the model to real catchments using raster spatial data (e.g., landcover, elevation) in a geographic information system (GIS).

3.1 Assumptions and notation

Let the catchment be divided into discrete subunits, or grid cells, labeled $1, 2, \ldots, N$. In practice, these grid cells typically will be arranged in a rectangular array, with cell size determined by the resolution of the spatial data being used. Each grid cell can be either terrestrial or aquatic. To simplify the present exposition, we assume all aquatic grid cells lie in streams, and we assume that streams are one grid cell wide. Associated with each grid cell, we assume there is an elevation and a landcover type. We assume there is a finite collection of landcover types, denoted $t_1, t_2, \ldots, t_K$. To reduce the complexity of model notation, we include stream characteristics among these landcover types. For example, terrestrial landcover types might include forest, meadow, agriculture, and urban, while stream landcover types might include first-, second-, and third-order streams.

Associated with each landcover type, we assume there is an initial stressor loading (possibly zero) and an exponential stressor attenuation rate. The stressor loading rate represents the amount of stressor generated within a grid cell per unit time (e.g., mass per year). The stressor attenuation rate represents the exponential rate, per unit distance, at which the stressor load is attenuated during transport through a grid cell. To simplify the present exposition, we assume there is a single dominant stressor, but the model can easily be extended to address multiple stressors. Similarly, the model can be extended to allow factors other than landcover (e.g., soil properties, management practices) to influence stressor loadings and attenuation rates.

Let T be a generic symbol denoting the landcover type of a grid cell (with possible values $t_1, t_2, \ldots, t_K$). Then under our assumptions, the stressor loading from a grid cell is simply a function of T, which we will call $\lambda(T)$. Similarly, the stressor attenuation rate of a grid cell is simply a function of T, which we will call $\alpha(T)$. The proportion of transported stressor that is *not* attenuated during transit through a grid cell is therefore given by $\exp(-\alpha(T)d)$, where d is the transport distance through the cell.

We assume that for each grid cell, there is a unique hydrologic flow path that connects it to the catchment outlet. Each flow path is assumed to consist of a sequence of straight line segments connecting the midpoints of neighboring grid cells (see Figure 1). Thus, if grid cells i, j, and k are three consecutive cells along a flow path, the portion of the flow path lying within cell j has two components: the second half of the segment connecting cells i and j, and the first half of the segment connecting cells j and k. In practice, flow paths can be estimated using GIS software to determine the direction of steepest descent from each grid cell, based on cell elevation and the distance between midpoints of neighboring cells.. Thus, starting from a particular grid cell, the next grid cell along the flow path will be the neighboring cell for which the slope between cell midpoints is negative and greatest in absolute value (unless there is no such single cell, in which case additional criteria must be employed, as in the r.fill.dir function of GRASS and the FlowDirection function of ArcView Spatial Analyst and ArcGIS).

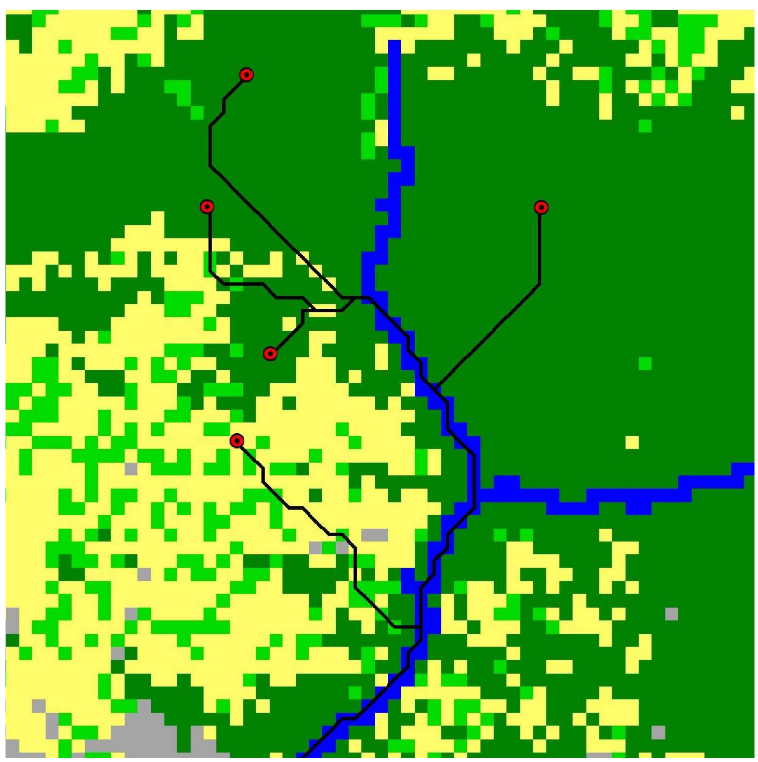

Figure 1. Examples of hydrologic flow paths determined using a geographic information system and a digital elevation model. Hydrologic flow paths from five arbitrarily chosen grid cells are shown (black lines). Grid-cell colors indicate landcover classes (dark green: forest, light green: meadow/pasture, yellow: crops, grey: developed, blue: water).

3.2 Landcover-derived stressor loadings and the terrestrial phase of transport

Consider a representative terrestrial grid cell i. The hydrologic flow path connecting cell i to the catchment outlet will have two parts: an initial terrestrial part and a subsequent aquatic (instream) part. We are presently concerned with the terrestrial part.

Let us label consecutive cells along the terrestrial part of the flow path from cell i $(i, 0)$, $(i, 1)$, $(i, 2), \ldots,$ (i, m_i), where $(i, 0)$ is grid cell i and (i, m_i) is the last cell on the terrestrial part of the flow path and therefore borders the stream. Let the first instream cell along the flow path be labeled (i, m_{i+1}), to which it will be convenient to give the special name s_i. Let T_{ij} denote the landcover type of flow path cell (i, j), with possible values $t_1, t_2, \ldots, t_K$. Cell $(i, 0)$ contributes loading $\lambda(T_{i0})$, which is transported along the flow path. (We will follow the convention of assuming that $\lambda(T_{i0})$ is the *net* loading from cell i after accounting for within-cell attenuation of the gross loading.) Attenuation processes within each grid cell along the flow path reduce the transported load. Under our assumptions, the proportion of the load entering cell (i, j) that survives attenuation and is transported to cell $(i, j + 1)$ is $\exp(-\alpha(T_{ij})d_{ij})$, where d_{ij} is the transport distance through cell (i, j). The proportion surviving attenuation through m consecutive cells is simply the product of the survival proportions in the various cells. The residual load from cell i that reaches the stream and enters cell s_i, denoted $\rho(i \to s_i)$, is therefore given by

$$\rho(i \to s_i) = \lambda(T_{i0}) e^{-\sum_{j=1}^{m_i} \alpha(T_{ij})d_{ij}}. \tag{1}$$

We can simplify this expression somewhat by noting that each landcover T_{ij} must be one of the types $t_1, t_2, \ldots, t_K$, and (under our assumptions) every grid cell with the same landcover type will have the same attenuation rate. Thus, the residual load reaching instream cell s_i from terrestrial cell i can also be expressed as

$$\rho(i \to s_i) = \lambda(T_{i0}) e^{-\sum_{k=1}^{K} \alpha(t_k)d(t_k; i \to s_i)}, \tag{2}$$

where the summation is now over landcover types rather than flow path cells. Here, $d(t_k; i \to s_i)$ denotes the cumulative transport distance through cells along the flow path between i and s_i (excluding i and s_i) whose landcover type is t_k; that is,

$$d(t_k; i \to s_i) = \sum_{j: T_{ij} = t_k,\, 0 < j < m_i} d_{ij}. \tag{3}$$

3.3 Stressor loadings to a stream and the aquatic phase of transport

The stressor load contributed by grid cell i to the stream is subsequently routed downstream, essentially as we did for the terrestrial portion of the flow path. We again must take into account the rate (per unit distance) of attenuation during transport, which may vary along a stream with properties such as discharge and current velocity (Stream Solute Workshop, 1990; Alexander et al., 2000). Let the grid cells on the instream portion of the flow path be labeled (i, m_{i+1}), $(i, m_{i+2}), \ldots,$ (i, n_i), where cell (i, n_i) is the catchment outlet or other stream location of interest, to which it will be convenient to give the special name x (the same for all grid cells in the catchment). Since we have included stream properties among the landcover types t_1, $t_2, \ldots,$ t_K, we can immediately extend equation (1) to include the entire flow path from i to x. The residual load reaching cell (i, n_i) is therefore given by

$$\rho(i \to x) = \lambda(T_{i0}) e^{-\sum_{j=1}^{n_i - 1} \alpha(T_{ij})d_{ij}}. \tag{4}$$

Similarly, equation (2) becomes

$$\rho(i \to x) = \lambda(T_{i0}) e^{-\sum_{k=1}^{K} \alpha(t_k)d(t_k; i \to x)}, \tag{5}$$

3.4 Cumulative stress at a stream location

We have routed the stressor load contributed by representative grid cell i downslope to the stream, which it enters at cell s_i, and then downstream to the catchment outlet at cell x. But grid cell i is not the only cell whose residual load reaches cell x. The cumulative stressor load in cell x, denoted $\rho(x)$, is the sum of the residual stressor loads from all grid cells whose flow paths pass through x. That is,

$$\rho(x) = \sum_{i=1}^{N} \rho(i \rightarrow x), \tag{6}$$

where $\rho(i \rightarrow x) = 0$ for grid cells i whose hydrologic flow paths do not reach x. We assume that impacts on stream ecosystem integrity at x are the result of exposure to this cumulative load, as discussed below.

Before proceeding, we note that the instream stressor level has thus far been quantified by a mass load. However, in many applications, it may be more reasonable to quantify this level using an instream concentration, as when addressing impacts of elevated nutrients on algal growth. To do this, average instream loads (mass per year) can be divided by average stream flow (volume per year) or by some other quantity closely linked to average stream flow (e.g., catchment area).

3.5 Ecological integrity and the stressor-response function

Equation (6) expresses the dependence of cumulative stress at a particular stream location on landcover-related stressor loadings and attenuation rates throughout the catchment. To complete the model, we also need an equation that expresses the dependence of stream integrity on the cumulative stressor load. Given the complexity of stream ecosystems, it is not feasible to determine the impact of cumulative stress on ecological integrity using a mechanistic model. Instead, we utilize the concept of a stressor-response function from ecological risk assessment. By integrity, we simply mean a representative measure of the reach-scale condition of stream ecosystems (Barbour et al., 1999). In applications of the model, integrity can be quantified by an index that collapses multivariate data on the composition of biological assemblages into a single number per sample. Common examples include diatom species diversity, the Hilsenhoff Biotic Index for benthic macroinvertebrates, and the Index of Biotic Integrity for fish (Barbour et al., 1999). We assume that an appropriate index has been chosen for use, but we do not tie our model to any particular choice.

We assume that stream integrity $I(x)$ at any location x is simply a function of the cumulative stressor load $\rho(x)$. Thus,

$$I(x) = f(\rho(x)), \tag{7}$$

where $f(\rho)$ is the stressor-response function. For many anthropogenic stressors, it is likely that stream integrity will be greatest when the stressor is absent ($\rho = 0$) and will decrease with increasing stress loads, as shown in the examples of Figure 2. For other stressors, however, stream integrity will be greatest when the stressor is present at some level $\rho_1 > 0$ and will be reduced if the stressor level is either lower or higher than ρ_1. This phenomenon, where a stressor improves a desirable response at intermediate levels, is known in toxicology as hormesis and has been observed in bioassay tests with a wide variety of organisms (e.g., Calabrese and Baldwin, 1998). An example of a hormetic stressor in the context of stream integrity is nitrate-nitrogen.

In equations (6) and (7), we now have a complete model relating stream integrity at stream location x to landcover-related stressor loadings and attenuation rates throughout the catchment.

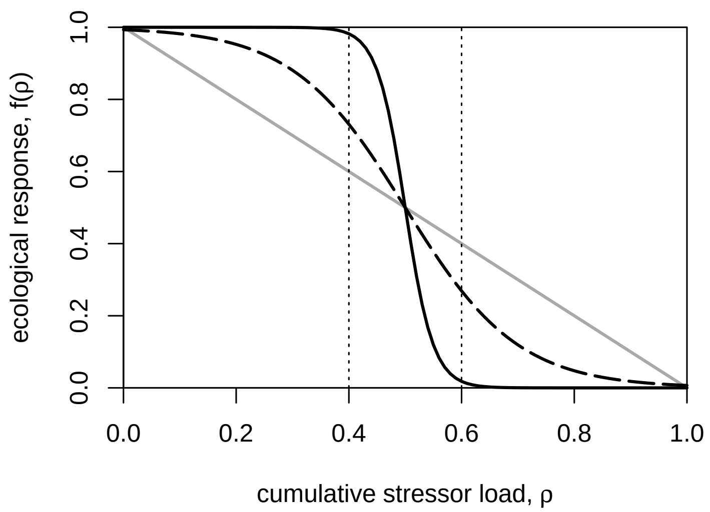

Figure 2. Three examples of stressor-response functions. Gray curve: linear stressor-response function. Dashed and solid curves: nonlinear (sigmoid) stressor-response functions. The vertical dotted lines mark the approximate range of sensitivity to changes in cumulative stressor load for the solid curve; outside this range, changes in the stressor load produce little change in response.

It consists of the following pair of equations:

$$\left.\begin{array}{rcl} \rho(x) & = & \sum_{i=1}^{N} \rho(i \to x) \\ I(x) & = & f(\rho(x)), \end{array}\right\} \tag{8}$$

where $\rho(i \to x)$ is given by equation (4) or (5). The first equation in (8) characterizes the dependence of the cumulative stressor load on catchment loadings and attenuation rates; the second characterizes the dependence of stream integrity on the cumulative stressor load.

3.6 Extensions of the model

The model developed here includes a number of simplifying assumptions. It is possible, however, to extend it in various ways. One of these is to include a method for estimating grid-cell loadings (λ) of specific stressors, such as sediment, nitrogen, and phosphorus. These loadings could be estimated directly from landcover and landuse information for each grid cell, roughly similar to the approach employed on a catchment-aggregated basis by the General Watershed Loading Functions (GWLF) model (Haith and Shoemaker, 1987). Currently, implementation of the model requires that we interpret the grid-cell loadings as unspecified landcover-related influences that are transported through the catchment along hydrologic pathways and exhibit attenuation with transport distance. Other features that could be incorporated in the model include allowing instream habitat attributes to influence biological metrics, and more generally, allowing stressor-response functions to depend on loads or concentrations of multiple stressors. The model could also be extended to address differences in functional attributes of riparian habitats depending on local topography, physiographic, or hydrologic characteristics (Correll, 2000).

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