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# ADAPTING EXISTING MODELS TO EXAMINE EFFECTS OF AGRICULTURAL CONSERVATION PROGRAMS ON STREAM HABITAT QUALITY[1]

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ABSTRACT: Annual expenditures by the federal government in the United States for agricultural conservation programs increased about 80 percent with passage of the 2002 Farm Bill. However, environmental benefits of these programs have not been quantified. A national project is under way to estimate the effect of conservation practices on environmental resources. The watershed models intended for use in that project are focused on water quantity and quality and have minimal habitat assessment capability. Major impairments to aquatic ecosystems in many watersheds consist of physical habitat degradation, not water quality, suggesting that current models for this national initiative do not address one of the most significant aspects of aquatic ecosystem degradation. Currently used models contain some components relevant to aquatic habitat, and this paper describes specific components that should be added to allow rudimentary stream habitat quality assessments. At least six types of variables could be examined for ecological impact: land use, streamflow, water temperature, streambed material type, large woody debris, and hydraulic conditions at base flow. All of these variables are influenced by the presence, location, and quality of buffers. Generation of stream corridor ecological or habitat quality indices might contribute to assessments of the success or failure of conservation programs. Additional research is needed to refine procedures for combining specific measures of stream habitat into ecologically meaningful indices.

(KEY TERMS: aquatic habitats; water quality; agricultural watersheds; buffers; stream ecosystems; modeling, Index of Biotic Integrity.)

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## INTRODUCTION

Agricultural practices can have major impacts on environmental quality across large regions of the United States. Numerous studies documenting statistical associations between land use and measures of stream condition collectively provide strong evidence of the importance of surrounding landscape and human activities to stream ecological status (Allan *et al.,* 1997; Allan, 2004). The 1996 National Water Quality Inventory identified agriculture as the leading contributor to water pollution, affecting 70 percent of the streams classified as impaired (USEPA, 2000). Only 3 percent of the land area of the United States is classified as urban, while about 46 percent (419 million ha) is classified as either cropland or grassland. Of some 150 major river basins of North America, agricultural land use varied from near zero in some northern river systems to 66 percent of the Upper Mississippi Basin (Benke and Cushing, 2004). Six major river basins of the United States have over 40 percent of their area in agriculture: the Lower Mississippi, Upper Mississippi, Southern Plains, Ohio, Missouri, and Colorado. Within the Upper Mississippi, the extent of agriculture in large tributary basins varies from 25 percent in the St. Croix and Wisconsin to 95 percent in the Minnesota River basin. An analysis of the watersheds of 368 wadeable streams in the Mid-Atlantic region found average surrounding land cover to be 77 percent forest, 20 percent agriculture, and only 1 percent urban (Herlihy *et al.,* 1998).

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### *Conservation Effects Assessment Project*

The U.S. Federal government invests about US$4 billion annually in agricultural conservation programs, but environmental benefits of the programs supported by these funds have not been quantified at the national level, and smaller scale assessments show limited effectiveness for similar conservation activities (e.g., Wolf, 1995; Wang *et al.,* 2002). A national project is under way to estimate the effect of conservation practices on the environmental resources (i.e., water, soil, and air quality; water conservation; and habitat quality) of the United States. The project (Conservation Effects Assessment Project, CEAP) has two main components: a national assessment based on application of existing hydrologic computer models to eight-digit watersheds (i.e., those with eight-digit hydrologic unit code catalog numbers assigned by the U.S. Geological Survey, USGS) across the coterminous United States; and detailed analyses of conservation effects within selected watersheds. The first and second authors of this paper are involved in the latter component. A key aspect is the use of hydrologic simulation models to assess impacts of conservation measures on downstream water quantity and quality. These models have minimal habitat simulation capability and even more limited links to ecological condition, primarily because habitat has rarely been considered in the design phase of model development. However, specific components within these models could be adapted, refined, or added to allow rudimentary stream habitat quality assessments as part of the modeling work. Clearly, models designed solely for habitat simulation or ecological assessment would be superior to adaptation of hydrologic simulation models, but the time and expense involved in such a large scale project mean that it will probably be a very long time, if ever, before such simulations are developed. Accordingly, presented here is an overview of the potential for adapting modeling systems for stream habitat quality assessment.

### *Stream Habitats*

Stream habitats are composed of the stream channel, contiguous habitats in shallow ground water, adjacent wetlands, and other riparian habitats and floodplain waterbodies. These habitats are often tightly linked with a corridor of natural vegetation and more or less natural topography that is surrounded by developed lands – the stream corridor. Threats to stream corridors within agricultural landscapes are especially severe. The major threat in many watersheds is physical habitat degradation and not water pollution (Karr, 1991, 1993). Sedimentation and habitat degradation accounted for 53 percent of the impaired river and stream miles in the 2000 National Water Quality Inventory (USEPA, 2002).

Channel evolution and hydrologic perturbations associated with land use change or channelization (Shields *et al.,* 1994; Doyle and Shields, 1998), large wood (LW) removal (Shields and Smith, 1992), and deposition of fine sediments within coarse streambeds substantially degrade stream habitat quality throughout entire watersheds. These types of habitat destruction threaten 85 percent of the 2,500 plant and animal species listed as imperiled, while only 25 percent are threatened by pollution (Stein *et al.,* 2000). Furthermore, stream channels throughout much of the U.S. agricultural landscape have been so drastically modified (usually by straightening) that instream physical habitat bears little resemblance to pre-European settlement conditions (Urban and Rhoads, 2003). Since links between physical habitat and instream biota are well established (e.g., Rabeni, 2000), it follows that biological communities have also experienced significant impacts (Hauer *et al.,* 2003).

## ECOLOGICAL ASSESSMENT CAPABILITIES OF CEAP MODELS

Despite the importance of stream habitats, the watershed models designated for the CEAP assessments (Table 1) have minimal stream condition assessment capability and even more limited links to ecological condition. These models are designed to provide information about water quality and quantity, the initial focus of CEAP. Because most conservation measures are applied to grasslands or croplands upslope of stream corridors, the designated watershed models emphasize simulation of loads leaving watershed slopes at the field scale and de-emphasize stream corridor processes. The watershed models AnnAGNPS (Bingner and Theurer, 2001) and SWAT (Neitsch *et al.,* 2002) simulate runoff and soil erosion from the landscape and transport of agrichemicals by surface and subsurface flow. They were developed to study the effects of watershed management on water quality and quantity and soil erosion. The channel evolution model CONCEPTS (Langendoen 2000, 2002; Langendoen and Alonso, unpublished; Langendoen and Simon, unpublished) simulates the long term morphological changes of streams caused by changes in loadings of water and sediments and by instream hydraulic structures given an inflow hydrograph. The riparian ecosystem management model, REMM (Lowrance *et al.,* 2000), is used to assess the water quality impacts of riparian and other edge of

TABLE 1. An Overview of Numerical Models Being Used by CEAP for Assessment of Environmental Effects of U.S. Agricultural Conservation Programs.

| Model | Characterization | Reference |
|---|---|---|
| AnnAGNPS | Watershed Model. Watershed is subdivided into subwatersheds and reaches. Daily runoff, sediment, and chemical yield are simulated. Peak runoff is computed using TR-55 (SCS unit hydrograph). In-channel transport simulated via simplified reach routing processes. Output consists of daily and average annual values for subwatersheds and reaches. | Bingner and Theurer, 2001 |
| CONCEPTS | Channel Evolution Model. Channel is subdivided into a series of cross sections and hydraulic structures. Channel hydraulics and morphology are simulated at time intervals that vary from 30 seconds to 10 minutes. Output consists of time series and runoff event summaries at cross sections, and longitudinal profiles of hydraulic and geomorphic variables. | Langendoen, 2000, 2002 |
| REMM | Riparian Ecosystem Management Model. Riparian buffer comprises three zones and three soil layers. Daily plant growth, runoff, sediment, and chemical yield across a riparian buffer are simulated. Output consists of daily, monthly, or annual values for each zone. | Lowrance *et al.,* 2000 |
| SWAT | Watershed Model. Predicts daily runoff, sediment, and chemical yield. Generates peak runoff using rational method. In-channel transport simulated via simplified reach routing processes. Output consists of daily, monthly, annual, and average annual values for subwatersheds and reaches. | Neitsch *et al.,* 2002 |

field buffer systems of different lengths, slopes, soils, and vegetation. It simulates the hydrologic, chemical, physical, and biological processes in riparian buffers or forests. Hence, the instream ecological simulation capabilities of REMM are limited. However, it can simulate LW and leaf litter inputs into the stream. Work is underway to link REMM with AnnAGNPS, CONCEPTS, and SWAT. Langendoen *et al.* (2005) report initial results of integrating REMM and CONCEPTS. The combined model was used to study the effects of riparian vegetation on streambank erosion.

Despite the limitations of these models, it should be noted that they provide a wealth of data detailing physical aspects of stream channels and, in some cases, riparian zones. These outputs potentially include simulated flows, hydraulics, channel geometry, water quality, and bed composition at numerous locations and all time steps, all of which are useful for habitat assessment. Such output is too voluminous to provide useful information under current model designs, so additional processing is needed. In other cases, key aspects of aquatic habitat are not simulated at all, and new algorithms may be called for. However, these algorithms could be based on inputs or outputs of the existing models.

## MODELING STREAM HABITAT QUALITY

There are many protocols for qualitative and quantitative assessment of existing stream habitat quality based on visual inspection or instream measurements (Somerville and Pruitt, 2004). Simulation of instream habitat suitability for a particular life stage of a particular species given a certain discharge or hydrograph based on one-dimensional numerical models of stream hydraulics is common (e.g., PHABSIM) (Bovee, 1982). Some workers (e.g., Crowder and Diplas, 2000; Lacey and Millar, 2004) suggest that more detailed multidimensional hydraulic models are needed for accurate assessment, while others have developed sophisticated, individual-based modeling systems (e.g., Goodwin *et al.,* 2001). While appropriate for specific reaches and species of interest, all instream habitat suitability approaches require substantial data on the project reach geometry and life history attributes of the species of interest, making broad application of these models to entire watershed ecosystems unrealistic. Further, the authors are not aware of tools that simulate general stream habitat quality based on assumed or predicted future climatic, streamflow, or watershed land use conditions at spatial and temporal scales appropriate for the CEAP; however, see work by the U.S. Forest Service and others using a geographic information system (GIS) to assess stream aquatic habitat quality in the Oregon Coast Range (Coastal Landscape Analysis and Modeling Study. 2004).

In view of the need for watershed ecosystem assessments and the information provided by the CEAP models, a more detailed analysis of the capabilities of these models to simulate the effects of land retirement, conservation buffers, and tillage management on stream corridor habitats is needed. Here, stream habitat refers to the combined quality, quantity, and spatial distribution of physical characteristics within the stream corridor that influence the distribution and abundance of species, structure, and function of communities and ecosystem processes. Both the variety and the variability of habitats are important in influencing the biological diversity of streams, and both are linked to the larger stream system and surrounding landscape (Hauer *et al.,* 2003). It is proposed that key attributes of stream corridors known to govern physical habitat quality and stream ecosystems (Young and Sanzone, 2002; Hauer *et al.,* 2003) be selected for simulation within or along with the selected CEAP watershed models. These attributes include watershed land use, water discharge, water temperature, large wood density, bed material composition, and base flow width, depth, and velocity. The CEAP models might be adapted to predict how these attributes change over time and space in response to various conservation measures but would not be useful in predicting actual attribute values on a future date.

### *Land Use*

Numerous studies have documented declines in water quality, habitat, and biological assemblages as the extent of agricultural land increases within catchments. Streams draining agricultural lands are commonly reported to support fewer species of sensitive insect and fish taxa than streams draining forested catchments (Genito *et al.,* 2002). Allan *et al.* (1997) showed that a fish-based watershed land use in a large (2,776 km$^2$) agricultural watershed governed stream ecological integrity as measured by habitat quality and index of biotic integrity. Watershed models designated for use in CEAP (Table 1) require preparation of GIS layers containing land use. It should be possible to rapidly compute summary statistics (e.g., percent land in a given cover or management category by watershed or subwatershed) or other metrics (percent of channels bordered by forest) at least at a coarse scale of resolution. A more sophisticated analysis drawing on concepts from landscape ecology could assign greater values to distributions of wetlands and other stands of natural vegetation that provide ecological networks and infrastructure (van Lier, 1998).

### *Water Discharge*

Flow is perhaps the most important physical determinant of stream ecological condition. Five critical components of streamflow regimes have been identified: magnitude, frequency, duration, timing, and rate of change of hydrologic conditions (Richter *et al.,* 1996; Poff *et al.,* 1997). Stormflows commonly increase in magnitude and frequency with increasing agricultural land use, especially where runoff is accelerated by drainage ditches, subsurface drains, and loss of wetland area. Runoff may be further accelerated by channel incision, which reduces floodplain storage and thus produces sharper storm hydrographs. Watershed models designated for use within CEAP simulate changes in runoff associated with changes in land use. Figure 1 provides an example. Here the responses of a 359 km$^2$ watershed near Birmingham, Alabama, under 2001 land use (70 percent forest, 16 percent pasture, 11 percent urban, 3 percent water) and more urbanized conditions are compared using AnnAGNPS output based on identical climatic inputs (Simon *et al.,* 2004). Hydrologic time series output from CEAP models representing watersheds under different land use or conservation scenarios could be analyzed using statistical approaches (e.g., Table 2 and Olden and Poff, 2003) to obtain useful attributes. This type of analysis of AnnAGNPS outputs is hindered by the convention used for reporting runoff – all runoff due to a given precipitation event is assumed to occur on the date of initiation of precipitation. No simulated flow occurs on other dates, which eliminates ecologically important base flows. Base flow characteristics are known to be highly responsive to land use. Modifications of this convention are planned (R.L. Bingner, USDA-ARS National Sedimentation Laboratory, May 15, 2004, personal communication).

### *Water Temperature*

Streams are usually warmer during summer when natural riparian forest is removed and cultivation or grazing extends to the stream margin (Quinn, 2000). The CEAP models might indicate that erosion or sediment yield have been reduced due to conservation, but ecological responses may be negative or weak due to excessive water temperatures (e.g., Wang *et al.,* 2002). SWAT simulates water temperature as a function of air temperature using the method of Stefan and Preud'homme (1993) and therefore cannot account for localized effects of riparian vegetation. AnnAGNPS may be used to simulate water temperatures throughout a channel network using the auxiliary program SNTEMP (Theurer *et al.,* 1984). This program is designed to simulate effects of most variables affected by conservation activities on stream temperatures (e.g., Bartholow, 2000). Example outputs from a simplified version of the software are shown in Figure 2. Linkage between the watershed models and SNTEMP is rudimentary and requires the user to formulate SNTEMP input files.

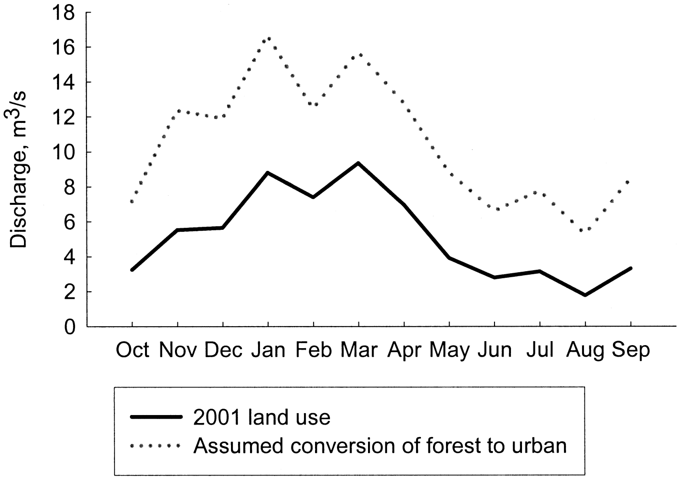

Figure 1. Mean Monthly Discharges Predicted by AnnAGNPS for Shades Creek, Alabama, Using 2001 Land Use Patterns (70 percent forest, 16 percent pasture, 11 percent urban, 3 percent water) and Assuming Conversion of All Forest to Urban Land Use (0 percent forest, 16 percent pasture, 81 percent urban, 3 percent water).

*Large Wood Density*

Streams draining agricultural watersheds tend to contain smaller volumes of LW than those in forested or most lightly developed regions (Johnson *et al.,* 2003). Stable wood substrate in streams performs multiple functions: providing cover for fish, perching habitat for invertebrates, and a substrate for biofilm and algal colonization (Johnson *et al.,* 2003; Gregory *et al.,* 2003). Inclusion of LW in simulations of streams influenced by LW in their undegraded state would be valuable. Although CEAP watershed models do not simulate large wood transport or instream processes, recruitment might be estimated based on other processes. For example, although SWAT does not simulate the recruitment of LW, it models channel widening, which can be combined with riparian vegetation data to estimate LW recruitment. However, the modeled channel widening is user-specified rather than process-based. The CONCEPTS model employs a process-based streambank erosion algorithm, and the modeled channel widening can be combined with riparian vegetation data to estimate LW recruitment. The REMM contains a forest growth algorithm and can simulate LW and leaf litter inputs to a channel. Downs and Simon (2001) present an example of LW budgeting through an unstable, 800 km$^2$ watershed based on channel evolution modeling. Hassan *et al.* (2005) review 14 simulation models for the dynamics of LW in streams (e.g., Berg *et al.,* 2003; Fox *et al.,* 2003), and at least two software packages are available. STREAMWOOD is an individual-based stochastic model designed to simulate the dynamics of wood in small streams of the Pacific Northwest (Meleason *et al.,* 2002), and RAIS (Welty *et al.,* 2002) interfaces the ORGANON growth and yield model with forecasting of large woody debris and shade for varying

TABLE 2. Comparison of Hydrologic Regimes Predicted by AnnAGNPS Under Different Land Uses, Shades Creek, Alabama.

| Means | 70 Percent Forest, 16 Percent Pasture, 11 Percent Urban, 3 Percent Water | 0 Percent Forest, 16 Percent Pasture, 81 Percent Urban, 3 Percent Water |
|---|---|---|
| Mean Annual Flow (m$^3$/s) | 4.94 | 10.35 |
| 30-Day Minimum Flow (m$^3$/s) | 0.14 | 0.36 |
| 3-Day Maximum Flow (m$^3$/s) | 103 | 144 |
| 30-Day Maximum Flow (m$^3$/s) | 20 | 35 |
| Julian Date For Maximum | 64 | 83 |
| Rise Rate (m$^3$/s/day) | 14 | 29 |
| Flows > 28.3 m$^3$/s (per year) | 15 | 24 |

channel widths and riparian zone widths (Figure 3). Curves in Figure 3 reflect tree growth and mortality for a hypothetical case. In this case, LW loading is similar for riparian zone widths equal to half and twice the channel width until trees growing more than 7.5 m from the channel become tall enough to contribute significant amounts of LW.

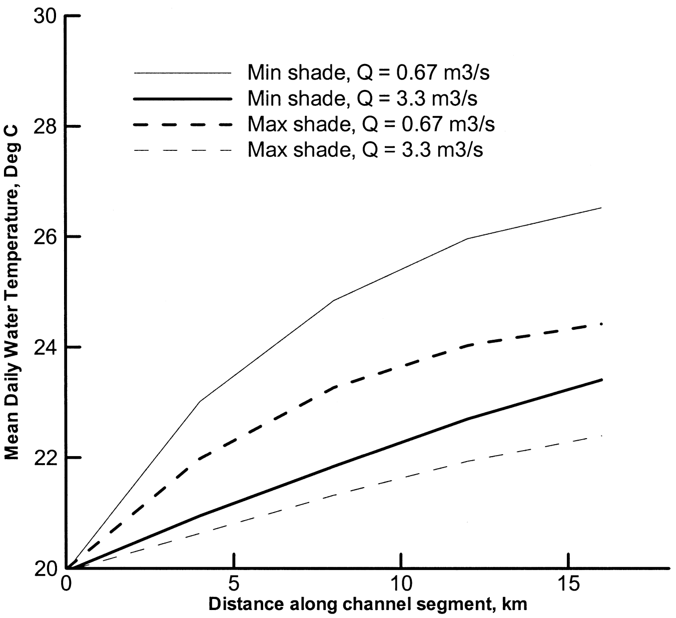

Figure 2. Output from SSTEMP (Bartholow, 2000) Showing Stream Temperature Versus Stream Distance Along Channel Centerline for a Two Flows Assuming a Temperature of 20°C at Head of Reach and Minimum or Maximum Levels of Shading From Riparian Vegetation.

### *Bed Material Composition*

Bed material composition governs benthic macroinvertebrate populations and directly or indirectly influences many higher level organisms (Ryan, 1991; Shields and Milhous, 1992; Waters, 1995). Coarse, porous sediment beds seem to be disproportionately impacted, as they are vulnerable to interstitial filling or covering by fines, immobilization by lowered flow regimes, or degradation due to reduction in upstream supply. For example, coarse bed streams in highly agricultural landscapes tend to have greater deposition of fine sediments on and within the streambed than those in less-developed settings (Walser and Bart, 1999). Sediments in runoff from cultivated land and areas affected by livestock trampling (Strand and Merritt, 1999; Quinn, 2000) are considered particularly influential in stream impairment (Waters, 1995). The CEAP watershed models do not simulate bed material composition, but the CEAP channel model CONCEPTS, which may be run in tandem with the watershed model AnnAGNPS, performs detailed computations to account for bed material size distribution due to its importance for hydraulic and sediment transport processes. The CONCEPTS model is also the only one of the CEAP models that simulates streambank erosion processes, which often are the primary source of sediments in agricultural watersheds. However, no assessment of habitat implications is currently planned. Figure 4 shows CONCEPTS output that illustrates the impact of deforestation on bed sediment gradation for Shades Creek, Alabama. Due to the noisy scatter in the bed sediment size data, five-point moving averages of the percent gravel and cobble in the bed under two land use scenarios are plotted, showing the increasing dominance of fines in the downstream direction under the urbanization scenario.

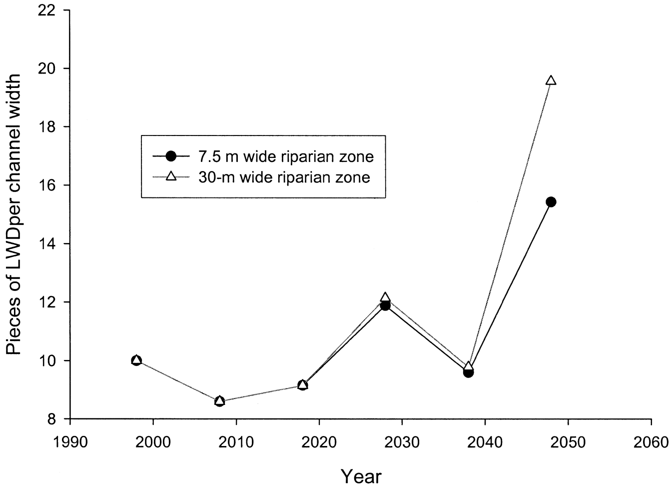

Figure 3. Total Number of Pieces of Instream Large Wood Debris (LWD) Per Channel Length (in units of channel width) Versus Time for a Hypothetical Stream in the Pacific Northwest Predicted by RAIS Software (Welty *et al.*, 2002). Channel width = 15 m, bed slope = 0.1 percent, riparian zone slope = 10 percent, buffer planted in 1998, and initial conditions include 10 pieces of LWD per unit channel length.

### *Base Flow Hydraulics*

Streams draining agricultural watersheds are often extremely shallow and lack pool habitats in comparison to lightly degraded streams draining forested watersheds (Shields *et al.,* 1994). Adding pool habitats to degraded streams by using minor channel manipulations often triggers strong response in fish communities (TerHaar and Herricks, 1989; Shields *et al.,*

1998) that may persist over the long term when combined with upstream erosion controls (Shields and Knight, 2004). However, the CEAP watershed models cannot assess impacts of management on instream habitat since they possess very limited capabilities to predict flow width, depth, and average velocity during base flows due to the absence of base flow simulation (AnnAGNPS) or due to the crude representation of the channel geometry (SWAT). More detailed computations are performed by CONCEPTS, but habitat values (say, the area of pool habitat) are not computed.

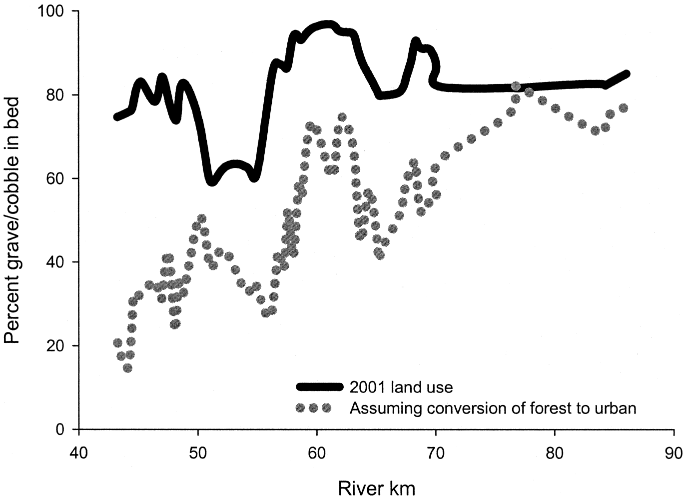

Figure 4. Gravel/Cobble Content (percent) in Surficial Streambed Sediment Predicted by CONCEPTS for Shades Creek, Alabama, Versus River Kilometer Using 2001 Land Use Patterns (70 percent forest, 16 percent pasture, 11 percent urban, 3 percent water) and Assuming Conversion of All Forest to Urban Land Use (0 percent forest, 16 percent pasture, 81 percent urban, 3 percent water). Plotted curves are five-point moving averages.

## FROM HABITAT VARIABLES TO HABITAT QUALITY

Even if CEAP assessments include selected stream habitat attributes, some type of synthesis will be needed for evaluation. Compilation of physical habitat attributes into a reliable overall indicator of stream condition is fraught with difficulty. Wide ranging results have been reported by workers seeking to correlate biotic and stream habitat indices (Rankin, 1989; Petersen, 1992; Shields *et al.,* 1995, 2000; Richards *et al.,* 1997). The utility of the habitat metrics as ecological indicators could be studied by developing relationships between physical metrics and indices of biotic integrity for test sites. Biotic indices could be computed using standard (Angermeier and Karr, 1986) and trait-based approaches (Townsend and Hildrew, 1994; Poff and Allan, 1995; Rader, 1997; Richards *et al.,* 1997; Townsend *et al.,* 1997; Shields *et al.,* 2000; Usseglio-Polatera *et al.,* 2000).

## CONCLUSIONS

Environmental resources and the ecological services they provide will face accelerating demands in the near term due to increasing human populations and perhaps climate change. U.S. Federal agricultural programs, initially designed to encourage soil conservation, may now be used to foster wise choices in ecosystem management at the landscape and regional scales. Are these programs as currently administered a positive influence on stream corridors? The lack of a clear answer to this question drives the CEAP effort. Review of the current state of knowledge regarding stream ecosystems in regions that support most cultivation shows that the physical characteristics that govern stream habitat quality are known but poorly represented in watershed models used in the CEAP project. Many of these characteristics might be simulated through model extension or modification. Although new models abound in the literature, the proposed “leveraged” approach is somewhat novel. Perhaps this proposal will provide impetus for others to explore other existing modeling systems to see if they also may provide relevant habitat management information.

The CONCEPTS model provides the best representation of channel processes important to stream ecosystems, but current CEAP plans do not include derivation of habitat parameters from CONCEPTS outputs. Additional research is needed to refine procedures for combining either simulated or measured habitat quality parameters into meaningful indices of habitat quality. Developing new tools and approaches for simulating and assessing stream habitats would enhance the ability to measure or estimate the ecological effects of conservation practices. The authors advocate an adaptive modeling approach in which the tools proposed above would be used as the coarsest scale for assessing the direction of habitat quality change, and more detailed, customized models could be nested within the system to focus on significant degradation issues.

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