PROCESS-BASED STREAM-RIPARIAN MODELING SYSTEM TO ASSESS STREAM TMDLS

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Abstract: This paper describes a comprehensive stream-riparian modeling system to evaluate the effects of channel-riparian zones on stream Total Maximum Daily Loads (TMDLs). Nonpoint source pollutants emanating from agricultural fields are major contributors to the ecological impairment of stream channels. Nutrients and sediments are the principle sources of surface water impairment. The edge-of-field system or riparian zone and stream corridor play an important role in the management of sediments and processing of contaminants. A particular challenge we face today is the lack of integrated, comprehensive modeling tools to evaluate Best Management Practices designed to meet proposed TMDL levels for agricultural watersheds. Scientists at the U.S. Department of Agriculture-Agricultural Research Service-National Sedimentation Laboratory (USDA-ARS-NSL) are integrating the ARS Riparian Ecosystem Management Model (REMM) and the CONservational Channel Evolution and Pollutant Transport System model (CONCEPTS). ARS operates field sites in Mississippi and Georgia to study the effects of riparian vegetation on streambank stability and pollutant transport. CONCEPTS has been validated using long-term morphological data from the Goodwin Creek in North-Central Mississippi. The hydrology, soil erosion, and nutrient transport components of REMM have been validated against data obtained at the Gibbs Farm near Tifton, Georgia.

INTRODUCTION

TMDL Development: Section 303(d) of the Clean Water Act requires that states, territories, and authorized tribes identify waters within their boundaries that do not meet water quality standards for their designated use. A TMDL (Total Maximum Daily Load) is a tool for implementing state water-quality standards based on the relationship between sources of pollutants and in-stream water quality conditions. The TMDL establishes the allowable loadings for specific pollutants that a waterbody can receive without violating water quality standards and is defined as:

$$\mathrm{TMDL} = \mathrm{LC} = \sum \mathrm{WLA} + \sum \mathrm{LA} + \mathrm{MOS}, \tag{1}$$

where LC is loading capacity or the maximum amount of pollutant loading a waterbody can assimilate without violating water quality standards, WLA is wasteload allocation or the portion of the TMDL allocated to existing or future point sources, LA is load allocation or the portion of the TMDL allocated to existing or future nonpoint sources, and MOS is margin of safety. MOS accounts for the uncertainty about the relationship between pollutant loads and receiving water quality.

The development of TMDLs can be complicated because of the lack of adequate or proven tools or information on the fate, transport, and impact of each pollutant within the natural system. The U. S. Environmental Protection Agency (EPA) is therefore developing TMDL protocols to provide guidance on TMDL development. EPA (USEPA, 1991) divides the development of

TMDLs into seven components: (1) problem identification, (2) identification of water quality indicators and target values, (3) source assessment, (4) linkage between water quality targets and sources, (5) allocations, (6) follow-up monitoring and evaluation plan, and (7) assembling the TMDL.

During source assessment (step 3), the sources of loading for the pollutant of concern are identified and characterized by type, magnitude, and location. For each TMDL, a linkage between the selected indicator(s) and target(s) and the identified sources must be defined (step 4). This linkage establishes the cause-and-effect relationship between pollutant sources and the in-stream pollutant response and allows for an estimation of loading capacity. Consequently, pollutant loadings that will not exceed the loading capacity can be determined. These pollutant loadings are distributed among the significant sources of the pollutant (step 5), see also equation (1).

Sediment Pollution: Nonpoint source pollution is the major cause of surface water impairment in the United States (USEPA, 1998b). The nonpoint sources of pollution vary, but nutrients and sediments are the principle sources of surface water impairment. This paper, however, mainly focuses on tools to assess sediment TMDLs. Sediment is a vital natural component of waterbodies and the uses they support. Excessive amount of sediment can adversely impact aquatic life and fisheries. Excessive sediment deposition can choke spawning gravels, impair fish food sources, and reduce habitat complexity in stream channels. Excessive suspended sediments can make it more difficult for fish to find prey and at high levels can cause direct physical harm. Stream scour can lead to destruction of habitat structure. Sediments can cause taste and odor problems for drinking water, block water supply intakes, foul treatment systems, and fill reservoirs. High levels of sediment can impair swimming and boating by altering channel form, creating hazards due to reductions in water clarity, and adversely affecting aesthetics. Figure 1 shows the sedimentation processes across a landscape. Sediment production can occur both on hillslopes by surface erosion, gully erosion, or mass wasting, and in the channel through bank erosion and gross degradation of the channel bed. Sediments delivered to the stream channel move downstream. They often go through cycles of storage and removal.

USEPA (1999) categorizes sediment TMDL indicators as: (1) water column indicators, e.g., suspended sediment, bedload sediment, and turbidity; (2) streambed sediment indicators, e.g., particle size distribution and substrate properties, (3) other channel indicators, e.g., pool/riffle ratios, sinuosity, bank stability, and width/depth ratios; (4) biological and habitat indicators, e.g., presence, diversity, and productivity of invertebrate and fish species; and (5) riparian/hillslope indicators, e.g., riparian buffer width sizes and riparian vegetation character, large woody debris, and landslide area. Tools used in the TMDL development process must be capable of representing these indicators.

Watershed Approach: To address the combined, cumulative impacts of both point and nonpoint sources, EPA has adopted the same watershed approach that parallels those pioneered by the U. S. Department of Agriculture (USDA)-Agricultural Research Service (ARS) and Natural Resources Conservation Service (NRCS). EPA's watershed approach is a coordinating framework for environmental management that focuses public and private sector efforts to

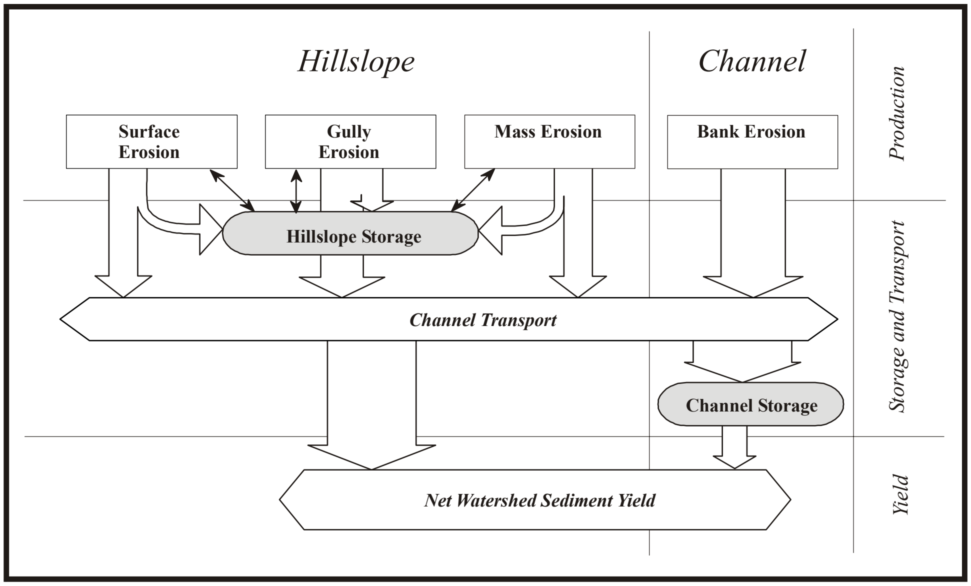

Figure 1 Sedimentation process (after USEPA, 1999).

address the highest priority problems within hydrologically-defined geographic areas, taking into consideration both ground and surface water flow (USEPA, 1996). This approach provides a means to integrate governmental programs and improve decision making by both government and private parties. This approach enables a broad view of water resources that reflects the interrelationship of surface water, groundwater, chemical pollutants and nonchemical stressors, water quantity, and land management. Accordingly, EPA has developed a system, BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) (USEPA, 1998a), to meet the needs of agencies that develop TMDLs. BASINS addresses three objectives: (1) to facilitate examination of environmental information, (2) to provide an integrated watershed and modeling framework, and (3) to support analysis of point and nonpoint source management alternatives. BASINS is a sophisticated package comprising various EPA water quality models. However, BASINS has limitations when used to develop sediment TMDLs. Especially, if sediment delivery and in-stream processes are important.

ARS is developing technologies to characterize the movement of water and any associated constituents on agricultural watersheds. These technologies include models needed to rehabilitate degraded landscapes, stream corridors, and aquatic ecosystems. The NRCS and ARS have developed the AGNPS 98 suite of models and the Riparian Ecosystem Management Model (REMM) in partnership with other organizations. Integration of these technologies allows studies and assessments to be performed on the hydraulic, geomorphic, and biologic interactions between a stream, the riparian zone, and adjacent farmland.

MODELING APPROACH

EPA's TMDL protocols emphasize the use of rational, science-based methods and tools for TMDL development. "The availability of data influences the types of methods analysts can use. If long-term monitoring data are lacking, the analyst will have to use a combination of monitoring, analytical tools (including models), and qualitative assessments to collect

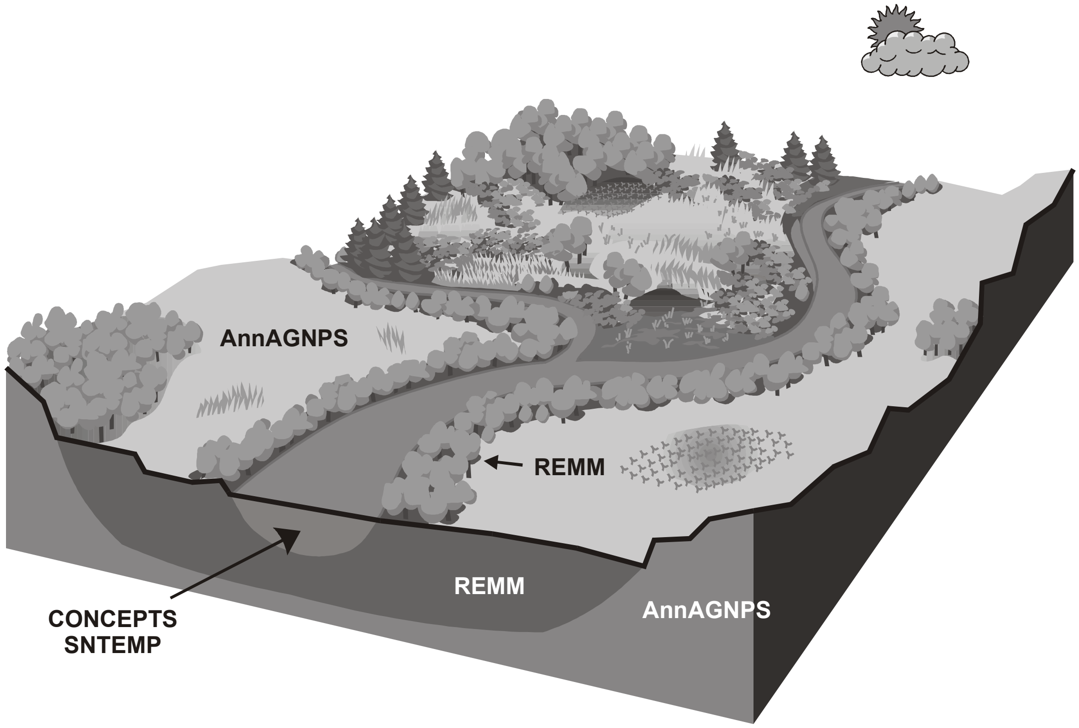

Figure 2 Landscape scales applicable to the ARS AGNPS 98 and REMM models.

information, assess system processes and responses, and make decisions. Although some aspects of TMDLs must be quantified (e.g., numeric targets, loading capacity, and allocations), qualitative assessments are acceptable as long as they are supported by sound scientific justification or result from rigorous modeling techniques" (USEPA, 1999).

The AGNPS 98 suite of models and REMM can be used in steps 3 through 5 of the TMDL development process. Figure 2 shows a view of the landscape scales applicable to the various models.

AGNPS 98: The AGricultural NonPoint Source pollution model 98 (AGNPS 98) is a joint NRCS-ARS system of computer models developed to predict nonpoint source pollutant loadings within agricultural watersheds (Bingner, 2001). The set of computer programs consist of: (1) a GUI for input generation and editing as well as associated data bases, (2) the annualized science and technology pollutant loading model AnnAGNPS, (3) output reformatting and analysis, (4) the integration of comprehensive routines for in-stream processes (CONCEPTS), (5) an in-stream water temperature model (SNTEMP); and (6) several related salmonid models (SIDO, Fry Emergence, Salmonid Total Life Stage, and Salmonid Economics).

AnnAGNPS: The Annualized AGricultural NonPoint Source pollution model (AnnAGNPS) (Cronshey and Theurer, 1998) is a continuous simulation, daily time step, watershed scale, pollutant loading model. AnnAGNPS analyzes a watershed divided into subareas of homogeneous landuse management, climate, and soils, which can adequately approximate site conditions. Runoff, sediment, and other pollutants are routed from each subarea through a channel network, including surface water impoundments, to the outlet of the watershed.

AnnAGNPS uses the Revised Universal Soil Loss Equation (RUSLE) (Renard et al, 1997) to predict soil erosion from agricultural landscapes.

REMM: REMM is a computer simulation model of riparian forest buffer systems (Lowrance et al, 1998). The riparian buffer consists of three zones between the field and stream. Each zone includes litter and three soil layers that terminate at the bottom of the root system, and a plant community that can include six plant types in two canopy levels. Surface hydrology, erosion, vertical and horizontal subsurface flows, carbon and nutrient dynamics, and plant growth that occur in each zone are modeled on a daily time step.

CONCEPTS: The CONservational Channel Evolution and Pollutant Transport System (CONCEPTS) is a distributed, long-term channel evolution and water quality model for use in ungaged watershed systems (Langendoen, 2000). The basic components are channel hydraulics, stream morphology, and transport of sediments. Integration of CONCEPTS and AnnAGNPS provides a means to model the evolution of large-scale channel systems in disturbed landscapes such as those in the Demonstration Erosion Control Project, Yazoo River Basin, Mississippi (Langendoen and Bingner, 1998).

The above suite of models covers the entire sedimentation process across a landscape (Figure 1). AnnAGNPS simulates hillslope erosion (sheet, rill, and gully erosion) and delivery processes. REMM simulates the storage of sediments alongside stream channels due to riparian buffers. CONCEPTS accounts for channel sources such as bank collapse, in-channel storage, bedload and suspended sediment transport, and net sediment yield from the watershed. During source assessment, step 3 of the TMDL development process, one uses the models to characterize the types, magnitudes, and locations of sources of sediment loading to the waterbody (USEPA, 1999). The results can be used to connect excess sediment load at a point of impact to sources of sediment generation and can thus be used to target load reductions (steps 4 and 5 of the TMDL development process). Further, one can use the models to evaluate sediment BMPs, such as landuse management alternatives, riparian buffers, and in-stream grade control structures.

STREAM-RIPARIAN CORRIDOR

The stream-riparian corridor is the conveyor of pollutants through the watershed. It determines the short- and long-term fate of pollutants both on-site and off-site. Riparian buffers or forests have well-known beneficial effects on bank stability, biological diversity, and water temperature of streams (Karr and Schlosser, 1978). Lowrance et al (1985) showed that riparian forests effectively reduce nonpoint source pollution from agricultural fields. A riparian buffer is a well-established BMP to reduce nonpoint source pollution. The stream-riparian corridor can also be a producer of sediments. Many streams in the US have been channelized for flood control often leading to incision with increased sediment transport rates, bank collapse, and habitat degradation. Plans to restore or rehabilitate the stream corridor are then required together with technology to assess or evaluate these plans.

Riparian Zone: Welsch (1991) specified guidelines for a riparian buffer system with three zones. Zone 1 is permanent vegetation immediately adjacent to the streambank. Zone 2 is managed forest occupying a strip upslope from zone 1. Zone 3 is an herbaceous filter strip upslope of zone 2. The primary function of zone 3 is to remove sediment from surface runoff and to convert channelized flow to sheet flow. The primary function of zone 2 is to block transport of sediment and chemicals from upland areas into the adjacent wetland or aquatic ecosystem. The primary function of zone 1 is to maintain the integrity of the streambank and a favorable habitat for aquatic organisms.

ARS has developed REMM to provide a tool to assess the nonpoint source pollution control functions of riparian buffer systems (Lowrance et al, 1998). To assess sediment TMDLS, REMM simulates soil and channel erosion, and sediment transport by particle size class (clay, silt, sand, and small and large aggregates) within riparian buffer systems (Bosch et al, 1998). Bosch et al (1998) tested REMM using a data set collected at a riparian site at the University of Georgia Gibbs farm near Tifton, GA. The soil in the riparian forest is an Alapaha loamy sand on a 2.5% slope. The riparian buffer consists of a 8 m long grass filter in zone 3, a 50 m long managed pine forest in zone 2, and a 10 m long hardwood forest in zone 1. Figure 3 compares computed and simulated yields leaving each zone. Annual predicted sediment yields entering zone 2 were approximately double the observed value, while yields entering zone 1 were somewhat less than observed. Overprediction of the simulated runoff caused the larger, predicted sediment yields entering zone 2.

Stream Channel: Shields et al (1999) discussed various treatments to stabilize incised stream corridors. At the reach scale, restoration plans include re-alignment of the channel and bed and bank stabilization works, among others. Local, in-stream controls can be classified as ‘hard’ structures or vegetative treatments. Examples are drop structures, spur dikes, and large woody debris structures.

ARS has developed CONCEPTS to evaluate watershed scale, reach scale, and local control stream-corridor restoration projects. Using CONCEPTS, Langendoen and Bingner (1998) show that a system of 14 grade control structures in the stream network of the Goodwin Creek Watershed, MS, stabilizes the stream system and consequently reduces sediment yield. Langendoen et al (1999) showed the capabilities of CONCEPTS to simulate streambank failure processes. CONCEPTS accurately predicts timing and dimensions of bank failures along a bendway in the Goodwin Creek, Mississippi (Figure 4).

SUMMARY

The application of integrated watershed analytical tools provides a science-based foundation in the development of TMDLs. Without these tools, accurate assessments for ungaged watersheds will be very difficult.

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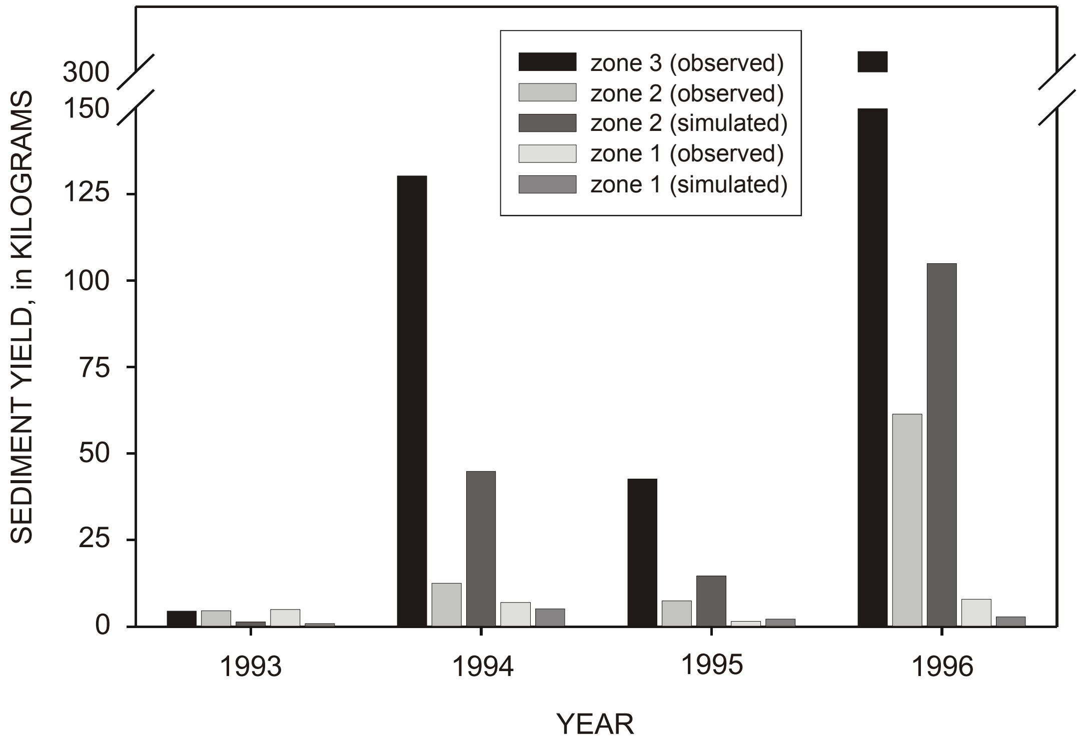

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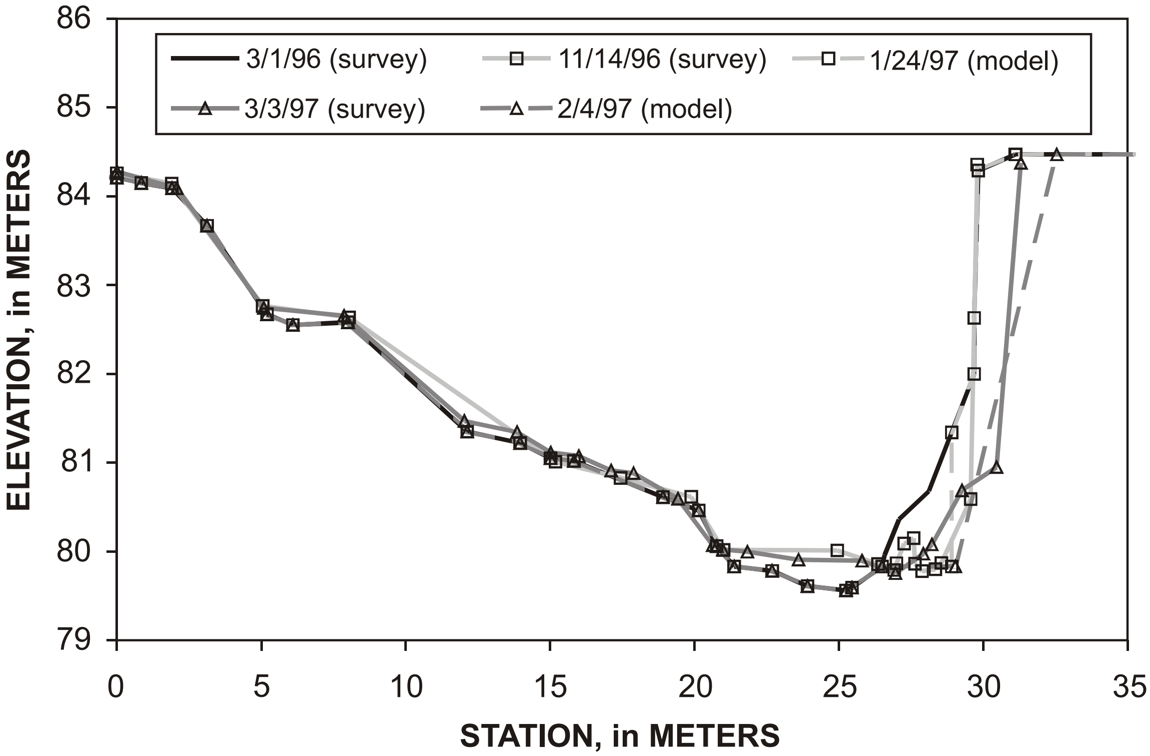

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