A COMPREHENSIVE STREAM-RIPARIAN CORRIDOR MODEL TO STUDY THE IMPACT OF RIPARIAN BUFFERS ON CHANNEL AND EDGE-OF-FIELD PROCESSES: SIMULATION OF STREAMBANK HYDROLOGY

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Abstract: Edge-of-field buffers are a core agricultural conservation practice, and installed along the stream are a proven technology to reduce sediment loadings from both hillslope and channel bank. This paper presents ongoing research to integrate the computer models CONCEPTS and REMM, which were developed to simulate stream channel morphology and riparian ecosystem function. The integrated model has been used to study the effectiveness of hypothetical woody and herbaceous riparian buffers in controlling streambank stability of an incised stream in Mississippi. Riparian vegetation controls streambank stability through pore-water pressure (i.e., soil water content) and root-reinforcement of the soil. The capability of the model to predict spatial and temporal variations of pore-water pressure in a streambank was tested against field data collected at Goodwin Creek, Mississippi. Model results showed that pore-water pressures are accurately predicted in the upper part of the streambank, away from the bottom boundary of the model domain. Results depended on imposed soil permeability, which is greatly affected by the development of macropores in the dry summer and fall period.

INTRODUCTION

Riparian buffer systems (RBS) are streamside ecosystems that are managed for the enhancement of water quality through the control of nonpoint source pollution and the protection of the stream environment. Studies in agricultural watersheds have indicated that riparian forests are important nutrient and sediment sinks (e.g., Lowrance et al 1983). Further, riparian vegetation has well-known beneficial effects on the bank stability, biological diversity, and water temperature of streams (e.g., Karr and Schlosser 1978). The use of RBS has become an increasingly popular means of improving habitat and streambank stability in stream restoration.

U.S. Department of Agriculture has developed the process-based computer models CONCEPTS (CONservational Channel Evolution and Pollutant Transport System) and REMM (Riparian Ecosystem Management Model) that simulate the physical processes within stream and riparian systems, respectively. CONCEPTS simulates the long-term morphology of streams including streambank erosion (Langendoen 2000). REMM estimates the nonpoint source pollution control by field-scale riparian ecosystems and the evolution of these ecosystems (Altier et al. 2002). To date, riverine sediment transport models have largely neglected streambank erosion and the effects of riparian vegetation. Likewise, hillslope and edge-of-field models have neglected the effects of the adjacent stream on the hydrology and fate of sediments and nutrients in the riparian zone. Therefore, the technologies in CONCEPTS and REMM are being integrated to produce a comprehensive stream-riparian corridor model that can be used to assess the effects of RBS on stream stability and ecology.

Riparian vegetation controls streambank stability in two ways: (1) hydrologically by affecting soil water, and (2) mechanically through root reinforcement of the soil (Simon and Collison 2002). REMM has components that simulate soil water and root biomass. Langendoen et al. (2005) provided a brief overview of the integrated model, and compared the effects of woody and herbaceous vegetation on streambank stability. This paper tests the capability of the model to accurately simulate the temporal and spatial pore-water distribution within vegetated streambanks against field data collected at Goodwin Creek, Mississippi.

MODEL OVERVIEW

CONCEPTS: The CONCEPTS computer model has been developed to simulate the evolution of incised streams and to evaluate the long-term impact of rehabilitation measures to stabilize stream systems and reduce sediment yield (Langendoen 2000). CONCEPTS simulates unsteady, one-dimensional flow, graded sediment transport, and bank-erosion processes in stream corridors. It can predict the dynamic response of flow and sediment transport to instream hydraulic structures. It computes channel evolution by tracking bed elevation changes and channel widening. The bank erosion module accounts for basal scour and mass wasting of unstable cohesive banks. CONCEPTS simulates transport of cohesive and cohesionless sediments, both in suspension and on the bed, and selectively by size classes.

REMM: The Riparian Ecosystem Management Model (REMM) has been developed as a tool to aid natural resource agencies and others in making decisions regarding management of riparian buffers to control nonpoint source pollution (Altier et al. 2002). REMM is also intended as a tool for researchers to study the complex dynamics of hydrology and water quality functions of riparian ecosystems. The structure of REMM is consistent with buffer system specifications recommended by the U.S. Forest Service and the USDA Natural Resources Conservation Service as national standards (Welsch 1991). The specified riparian buffer system consists of three zones parallel to the stream, representing increasing levels of management away from the stream (Fig. 1). These zones are zone 1, a narrow, undisturbed native forest area adjacent to the stream for protecting the stream bank and aquatic environment; zone 2, an area with a managed woody vegetation for sequestering sediment and nutrients from upland runoff; and zone 3, an herbaceous filter strip for dispersal of incoming upland surface runoff and sediment and for nutrient deposition. Although REMM is designed to simulate this type of buffer system, the model can be used with other types of vegetation within each zone. Processes simulated in REMM include storage and movement of surface and subsurface water, sediment transport and deposition, transport, sequestration, and cycling of nutrients, and vegetative growth.

Water movement and storage is characterized by processes of interception, evapotranspiration (ET), infiltration, vertical drainage, surface runoff, subsurface lateral flow, upward flux from the water table in response to ET, and exfiltration. The storage and movement of water between the zones is based on a combination of mass balance and rate controlled approaches. Vertical drainage from a soil layer occurs when soil water content exceeds the field capacity. The amount drained from a soil layer also depends on the capacity of the receiving layer, and is set equal to the lesser of the hydraulic conductivities of the draining and receiving layers.

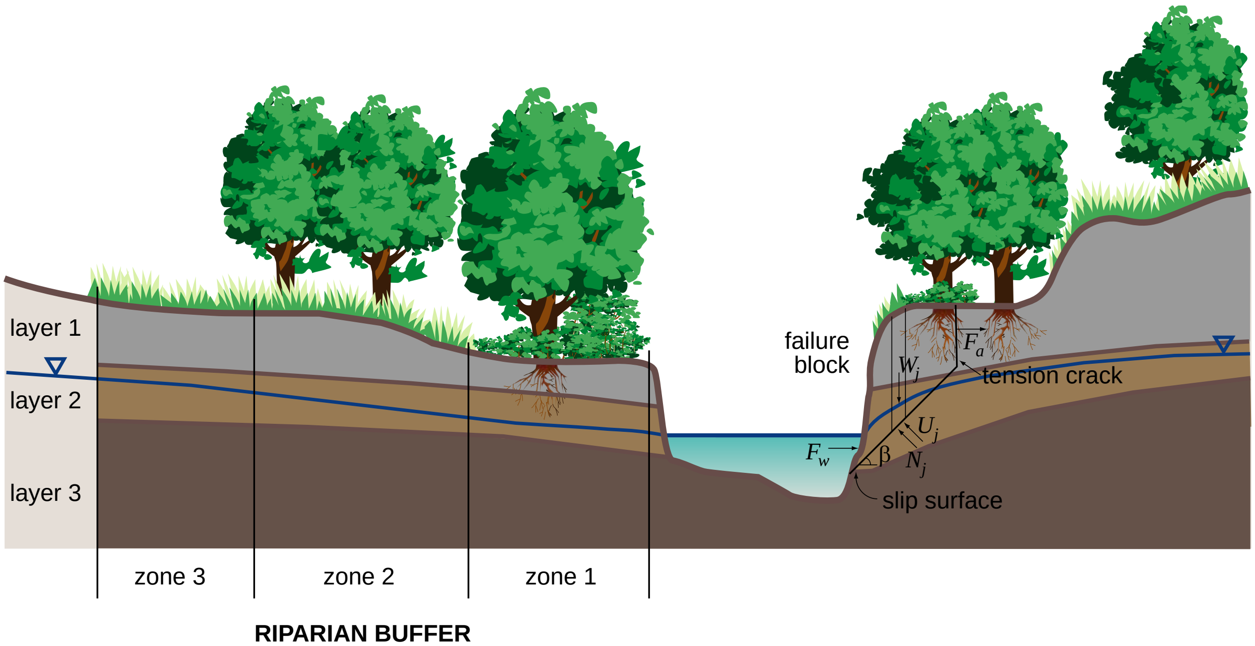

Figure 1 Definition sketch of riparian buffer system modeled by REMM and failure block configuration and forces used by CONCEPTS.

Unsaturated conductivity is simulated as a function of the soil water content using Campbell's equation (Campbell 1974):

$$\frac{\theta}{\lambda} = \left(\frac{H_b}{h}\right)^{\eta} \tag{1}$$

where θ is soil water, λ is porosity, H_b is bubbling pressure, h is matric head, and η is the pore size distribution index. Subsurface lateral movement is assumed to occur when a water table builds up over the restricting soil layer. The lateral movement of the water is simulated using Darcy's equation. Downslope subsurface flow between the component zones is driven by the gradient of the water table.

REMM simulates the growth of several types of herbaceous and woody vegetation in two canopy layers for even-aged forest stands. Individual species present in a particular buffer system may be characterized through the parameterization of various variables, which represent values for the initial sizes of the plants, rates of photosynthesis, respiration requirements, rates of growth and mortality, sensitivity to light and temperature, response to nutrients, and timing of phenostages.

CONCEPTS-REMM Integration: The above models, CONCEPTS and REMM, have been integrated to study the interactions between instream and riparian processes. At present, a daily feedback of several parameters has been established to calculate: (1) daily stream loadings of water, sediments, and nutrients emanating from the riparian buffer; (2) effects of water surface elevation on soil water in the riparian zone (seepage and recharge); (3) effects of pore-water pressure and root biomass on streambank stability; and (4) in case of bank failure, stream loadings of sediments, nutrients, and plant/tree biomass contained by the failure block. Furthermore, the buffer modeled by REMM has been adjusted to comprise an arbitrary number of zones and layers.

The groundwater table and vertical distribution of soil water computed by REMM in zone 1 are used to calculate pore-water pressure needed to evaluate bank stability. The pore-water pressure is assumed hydrostatic below the groundwater table. Soil water content above the groundwater table is converted to suction values using Eq. (1). The negative pore-water pressure (matric suction) is then $u_w = \gamma h$, where γ is unit weight of water.

The mechanical effect of roots is to enhance the confining stress and resistance to sliding and increase the shear strength of the soil/root mass through the binding action of roots in the fiber/soil composite (e.g., Coppin and Richards 1990; Gray and Sottir 1996). Failure occurs either by pull-out, that is slipping due to bond failure, or rupture, that is tension failure. The magnitude of the mechanical reinforcing effect of vegetation is a function of the following root properties: density, tensile strength, tensile modulus, length/diameter ratio, surface roughness, alignment, and orientation. Langendoen et al. (2005) presented a procedure to calculate the increase in shear strength as a function of root biomass concentration computed by REMM.

NUMERICAL EXPERIMENTS

Site Description: Since February 1996 extensive research on streambank failure mechanics has been conducted along a bendway of the Goodwin Creek, northern Mississippi (Simon and Darby 1997; Simon et al. 1999; Fig. 2). The following data are being collected at the study site: cross section geometry, water surface elevations, bank material properties, bank material shear-strength parameters, pore-water pressures in the bank, precipitation, root mapping and tensile strength, canopy interception, and plant stem flow. Two flow measuring flumes in upstream tributaries provide continuous discharge and fine sediment data. A NOAA SURFRAD station located in the watershed collects the following weather and climate data needed to run REMM: incoming solar radiation, air temperature, relative humidity, wind speed and wind direction.

Major failure episodes have occurred, resulting in up to 5.5 m of top-bank retreat between March 1996 to March 2001. Planar and cantilever failures were relatively common along the steepest section of the 4.7 m high banks. Cantilevers were formed by (1) preferential erosion of sands and silts by fluvial undercutting about 3.0 to 3.5 m below the top bank, and (2) by sapping and small pop-out failures in the region of contrasting permeabilities of the streambank material about 1.6 to 2 m below the top bank. It was observed that the loss of matric suction from infiltrating precipitation and subsequent seepage significantly contributes to mass-bank instability (Simon et al. 1999).

Bank material consists of about 2 m of moderately cohesive, brown clayey-silt of late Holocene age (LH unit) overlying 1.5 m of early Holocene gray, blocky silt of considerable cohesion and lower permeability (EH unit). These units are separated by a thin (0.1 to 0.2 m) layer containing manganese nodules and characterized by very low permeability, which perches water. These materials overlie 1 m of sand and 1.5 m of packed (often weakly cemented) sandy gravel.

Cohesion and friction angle were measured in situ using an Iowa Borehole Shear Tester (Luttenegger and Hallberg 1981). Core samples were also analyzed for bulk density (ρ_b), porosity, and particle size distribution (Wood 2001). For the LH unit, Clark (2000) measured saturated hydraulic conductivity (K_s), and derived bubbling pressure and pore size distribution index from the soil water-retention curve obtained by Simon et al. (1999). Main bank-material data are summarized in Table 1.

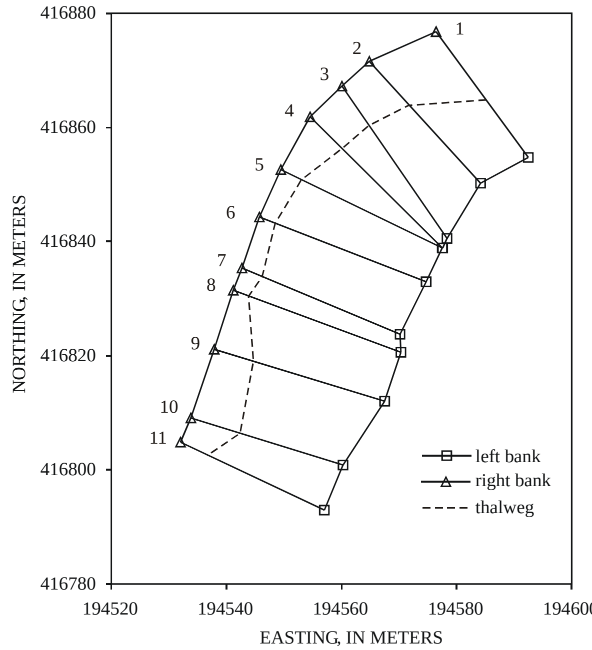

Figure 2 Plan view of the Goodwin Creek Bendway study site with surveyed cross sections.

Pore-water pressure data have been collected using tensiometers along the right bank of the bendway at: (1) an open plot (short cropped turf/bare) since December 1996; (2) a mature riparian tree stand (a mixture of sycamore (*Platanus occidentalis*), river birch (*Betula nigra*) and sweetgum (*Liquidambar styroflora*)) since July 1999; and (3) an eastern gamma grass (*Tripsacum dactyloides*) buffer since December 1999. Data were recorded every 10 minutes at depths of 30, 100, 148, 200, and 270 cm (corresponding to different layers within the bank profile). For model comparison, these data were time-averaged over a 24-hour (daily) interval.

Simulation Results: The riparian tree stand and gamma grass buffer were simulated with the integrated CONCEPTS/REMM model for the period of January 1996 to September 2003. The riparian buffer in both scenarios had a width of 15 m (three zones of 5 m) and four layers (two layers spanning the LH unit, one layer spanning the EH unit, and a fourth layer representing the sand unit). The properties of the trees at the start of the simulation were: height of 21 m, root depth of 1.0 m, a biomass of coarse roots of 48,000 kg/ha, and a biomass of fine roots of 15,500 kg/ha. The properties of the grass at the start of the simulation were: height of 0.1 m, root depth of 1.0 m, and biomass of fine roots of 4,000 kg/ha. The biomass values of fine roots are suitable values for woody and herbaceous riparian buffers along Goodwin Creek.

Table 1 Main streambank material properties.

Soil unit	Thickness m	c' kPa	ϕ' deg	ρ_b g/cm^3	K_s ‡ cm/hr	H_b cm	η	%sand	%silt	%clay
LH	1.7	2.7	28.1	1.5	0.1/10.0	35.7	0.17	5.1	91.1	3.8
EH	1.5	6.3	27.0	1.6	0.1/10.0†	12.0†	0.3†	52.1	41.8	6.1
Sand	1.0	0.0†	35.0†	1.6†	10.0†	7.0†	1.6†	95.0†	5.0†	0.0†

† estimated value

‡ lower value represents conductivity of soil matrix during wet periods; higher value includes effects of macropores that develop during dry periods

Initial testing of the model showed simulated soil water distribution to be highly sensitive to saturated hydraulic conductivity. Clark (2000) measured an average conductivity of the soil matrix of approximately 0.1 cm/hr using a falling head permeameter, but values measured *in situ* using the Inverse Auger Hole Method during late spring were two orders of magnitude larger. The latter test shows the impact of macropores and cracks that may develop during the dry summer and fall period. Commonly, the effects of macropores are simulated using a dual-porosity model. However, REMM uses a single porosity method. Therefore, hydraulic saturated conductivity for the EH and LH units was varied seasonally from the matrix value of 0.1 cm/hr during wet periods (winter and early spring) to 10 cm/hr during dry periods (summer and fall) to represent the development of cracks (Table 1).

For the grass buffer, the simulated pore-water pressures agree well with those observed (Fig. 3). Peak suction values in the fall and the temporal variation of pore-water pressure are accurately simulated, except for the fall of 2000 where suction values are overpredicted in the LH unit (layers 1 and 2). For the riparian tree stand, the simulated pore-water pressure distribution agrees well in the LH unit, but does not compare well in the EH unit (layer 3). Simulated pore-water pressure in the bottom (fourth) layer is fairly constant at -1.2 kPa for both buffers (not shown in Fig. 3).

The poor performance of the model lower in the soil column can be attributed to the close presence of the bottom boundary of the model domain and the lateral subsurface flow calculation method. If the soil column is unsaturated, the elevation of the phreatic surface is set to the elevation of the bottom boundary. To simulate lateral subsurface flow the elevation of the phreatic surface in each zone is determined by calculating the amount of free (moveable) water, and then using the free water to saturate the soil column from the bottom upward. Lateral movement across the buffer then occurs in the saturated zone. This procedure may lead to unrealistic and incorrect soil water values near the bottom boundary. For example, if the upper part of an unsaturated soil column becomes saturated after a rainfall event, the model will simulate lateral flow in the lower part (where it moved the free water), possibly reducing soil water content there which may even become negative.

CONCLUSIONS

The channel evolution model CONCEPTS and the riparian ecosystem model REMM have been integrated to create a comprehensive stream-riparian corridor model that will be used to evaluate the effects of riparian buffer systems on instream environmental resources. The capability of REMM to dynamically simulate streambank hydrology and plant growth has been used to study the effectiveness of a woody buffer and a grass buffer in controlling the stability of a streambank of an incised stream. The model is able to accurately simulate the effects of riparian vegetation on the temporal and spatial distributions of pore-water pressure within the upper part of the streambank. An improved groundwater model is necessary to better simulate lateral subsurface flow and hence reduce the discrepancy between observed and simulated pore-water pressure distribution in the lower part of the streambank.

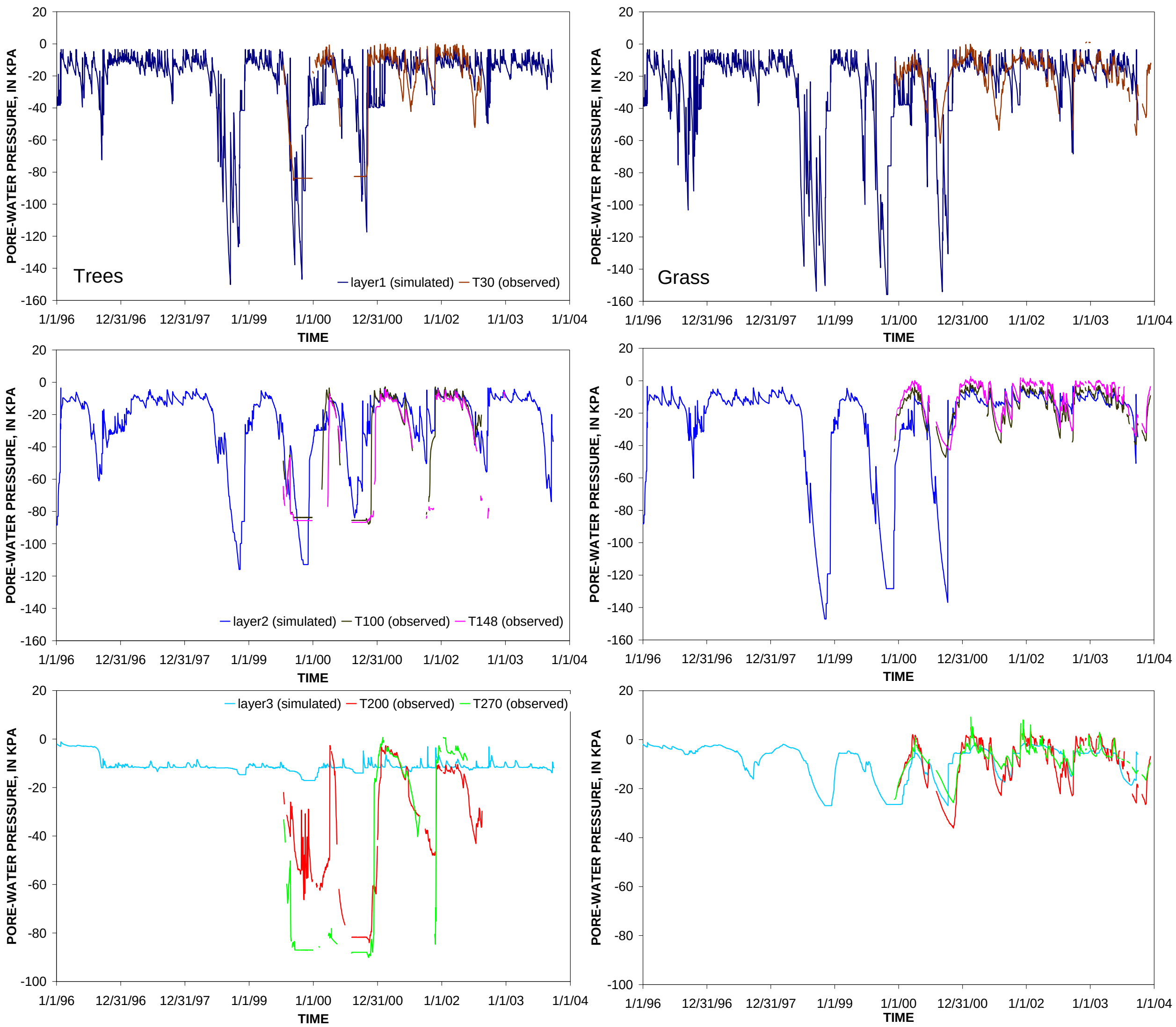

Figure 3 Comparison of simulated and observed pore-water pressures for the woody (left column) and grass buffer (right column): first layer and tensiometer at 30 cm (top row); second layer and tensiometers at 100 and 148 cm (middle row); and third layer and tensiometers at 200 and 270 cm (bottom row).

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