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NUMERICAL MODELING OF THE EFFECTS OF SURFACE AND GROUNDWATER INTERACTIONS ON STREAMBANK EROSION

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Summary. Riparian soil water dynamics greatly affect streambank erosion. The integrated computer models CONCEPTS and REMM, which were developed to simulate stream channel morphology and riparian ecosystem function, were used to study the effectiveness of riparian buffers in controlling streambank stability of an incised stream in Mississippi. Model results showed that pore-water pressures below different vegetation types can be accurately predicted in the upper part of the streambank with a fairly simple subsurface flow model.

1 INTRODUCTION

Long-term research on streambank erosion along a reach of the Goodwin Creek, Mississippi, USA showed that the timing and extent of streambank failure are closely related to changes in pore-water pressure in the bank soils[1]. Especially, the loss of matric suction in the upper profile of the streambank during storm events has shown to destabilize banks. Soil water affects streambank erosion by influencing the apparent shear-strength of the soil and soil erodibility. The spatial and temporal soil-water distributions in streambanks are difficult to quantify because of the varied sources and sinks, and soil heterogeneity. Field experiments showed that vertical pore-water distributions are also greatly impacted by the root distribution, which varies significantly between vegetation types. Much research has been conducted to quantify the effects of vegetation and soil water on soil shear-strength and streambank failure mechanics[2]. However, improved quantification of the spatial and temporal soil water distributions in streambanks are needed to accurately predict the extent of streambank erosion. This paper presents: (1) a numerical model developed by integrating the channel evolution model CONCEPTS and the riparian ecosystem management model REMM, and (2) an application of the model to an incised streambank.

2 EFFECTS OF RIPARIAN PROCESSES ON STREAMBANK EROSION

Bank failures often occur during the recession of stream flow[3]. Recharge of bank material by surface water during flood stage and infiltrating rainfall increase pore-water pressure. The loss of stabilizing hydrostatic force of stream water causes banks to fail. Also, perched water tables may develop due to less permeable streambank materials at depth, inducing lateral subsurface flow, bank seepage, and eventual seepage-induced erosion[4].

Pore-water pressure reduces the shear strength of saturated streambank materials and increases the shear strength of unsaturated streambank materials, which can be expressed as[5]:

$$\tau = c' + \sigma_n \tan\phi' - p \tan\phi^b \tag{1}$$

where τ is soil shear-strength, c' is effective cohesion, σ_n is normal stress, p is pore-water pressure, ϕ' is effective angle of internal friction, and ϕ^b is an angle indicating the rate of increase in shear strength for increasing matric suction. For saturated soil $\phi^b = \phi'$.

Pore-water distributions are also impacted by vegetation. Vegetation increases bank stability by intercepting rainfall that would otherwise have infiltrated into the bank, and by extracting soil moisture for transpiration[2]. The hydrologic behavior of streambanks is particularly important in incised and arid or semi-arid channels since these banks are normally unsaturated and are, therefore, sensitive to increases in moisture content[2]. Vegetation effects are also mechanical. The tensile strength provided by roots enhances soil strength[2]. In addition to stabilizing effects due to root reinforcement, vegetation can destabilize streambanks by increasing surcharge.

3 SIMULATION OF GROUNDWATER-SURFACE WATER INTERACTIONS

The following sections briefly introduce the CONCEPTS and REMM models and the science used to simulate soil water dynamics.

3.1 In-stream processes

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[6,7]. CONCEPTS simulates unsteady, one-dimensional flow, graded sediment transport, and bank-erosion processes in stream corridors. Flow depth and discharge are calculated by integrating the one-dimensional St. Venant equations[6]. The computed water surface elevation is used as a boundary condition for the riparian subsurface flow calculations. The bank erosion module accounts for basal scour and mass wasting of unstable cohesive banks[7].

3.2 Riparian processes

Riparian processes are simulated by the Riparian Ecosystem Management Model[8] (REMM). The structure of REMM is consistent with buffer system specifications recommended by the US Forest Service and the US Natural Resources Conservation Service as US standards[9]. The riparian buffer system consists of three zones parallel to the stream, representing increasing levels of management away from the stream. 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 are characterized on a daily time step by processes of precipitation, interception, evapotranspiration (ET), infiltration, vertical drainage, surface runoff, subsurface lateral flow, upward flux from the water table in response to ET, and seepage operating over three layers in each zone[8] (Fig. 1). The water balance equation for each layer of each zone in units of mm is:

$$\theta^n = \theta^{n+1} + P^n + \Delta F_v^n + \Delta F_h^n - ET^n + U^n - F_s^n - S^n \tag{2}$$

where θ is soil moisture, n is day index, P is incoming surface water (the sum of throughfall, upland surface runoff, and surface seeps), ΔF_v is net incoming vertical drainage, ΔF_h is net incoming lateral drainage, ET is evapotranspiration loss, U is the upward flux of soil water from the water table to the soil layer, F_s is outgoing surface runoff, and S is seepage of saturated water from the lowest soil layer.

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 (F_v) occurs when soil water content exceeds field capacity. Soil water content is related to pressure head (h) using Campbell's equations[10]. The pressure head is approximated by the height above the water table. 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. In the absence of a shallow water table, ET losses from a soil layer are limited by the wilting point water content. In the presence of a shallow water table, a steady upward flux will occur from the water table to the soil layer to replenish ET losses. The rate of upward water movement (U) is determined by the matric potential gradient, unsaturated hydraulic conductivity, and the depth of the water table below the soil layer[8]:

$$U = K\left(h\right)\frac{\partial h}{\partial z} - 1 \tag{3}$$

where unsaturated hydraulic conductivity $K(h)$ is calculated using Campbell's equations[10].

The lateral movement of the water within the riparian buffer is simulated using Darcy's equation:

$$F_h = -KA\frac{\Delta h}{L} \tag{4}$$

where A is saturated cross-sectional area of the soil layer, Δh is the difference in water surface elevations between two zones, and L is the distance between the centers of two adjacent zones. Rates of lateral subsurface movement between zones are constrained by the lesser of the respective hydraulic conductivities of the soil layers in each zone. If rates of soil water movement for the upslope zone exceed the transmission rates for the downslope zone, the soil water excess is accumulated in the upslope zone until it is saturated. A seep will then occur to the surface of the downslope zone.

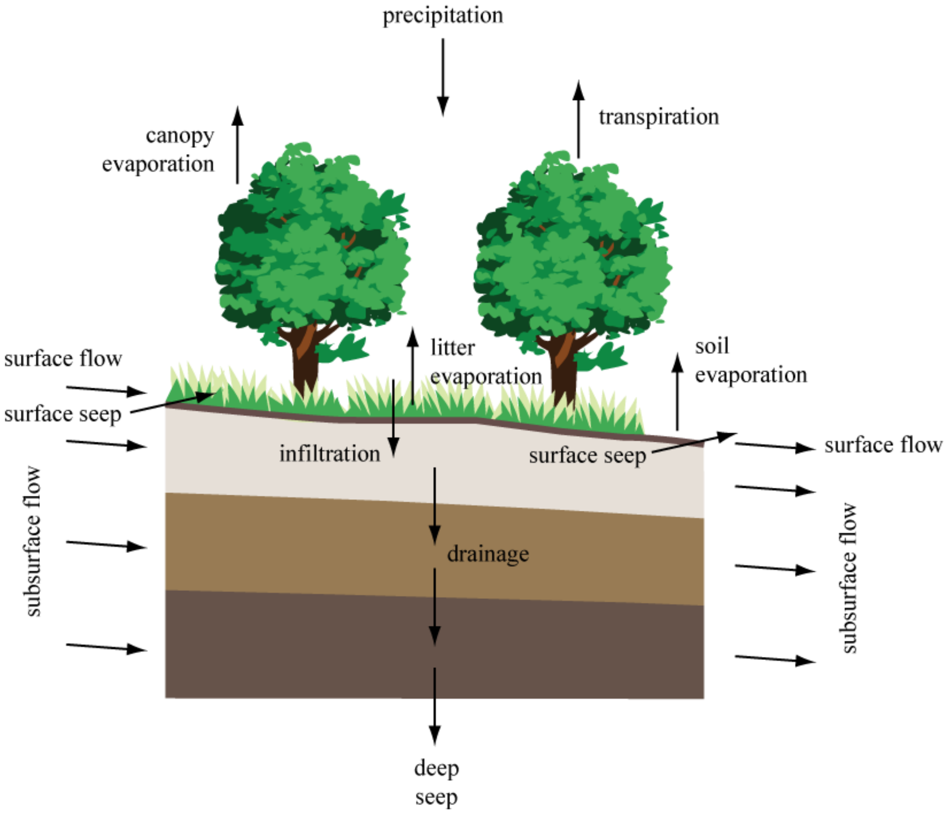

Figure 1: Simulated water movement in REMM

ET is computed in two stages[8]. In the first stage evaporation of intercepted water on the vegetative canopy is calculated. During the second stage potential plant transpiration is computed, and corrected for evaporation of intercepted water on the plant canopy. Actual transpiration is limited by the availability of water in the soil and competition among the roots of the various plant types present. Transpiration losses from each soil layer are determined by proportions of root masses and the soil hydraulic conductivity.

REMM simulates the growth of several types of herbaceous and woody vegetation in two canopy layers for even-aged forest stands. Individual species in a buffer system are characterized through the parameterization of variables which represent values for the 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[8].

3.3 Integrated processes

CONCEPTS and REMM have been integrated to study the interactions between in-stream and riparian processes[11]. A daily model feedback 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; and (3) effects of pore-water pressure and root biomass on streambank stability.

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 Campbell's equation[10]. The vertical distribution of root biomass concentration calculated by REMM is converted to root-area-ratio at the base of each slice and used to calculated root cohesion.

4 MODEL APPLICATION

4.1 Site description

Between 1996 and 2006 extensive research on streambank failure mechanics was conducted along a bendway of the Goodwin Creek, Mississippi[1]. Major failure episodes have occurred, resulting in up to 5.5 m of top-bank retreat along the right bank. Planar and cantilever failures were relatively common along the steepest section of the 4.7 m high banks. It was observed that the loss of matric suction from infiltrating precipitation and subsequent seepage significantly contributes to mass-bank instability. The following data were collected at the study site: cross section geometry, water surface elevations, bank material properties, pore-water pressures in the bank, precipitation, incoming solar radiation, air temperature, relative humidity, wind speed and direction, root mapping and tensile strength, canopy interception, and plant stem flow.

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 age gray, blocky silt of considerable cohesion and lower permeability (EH unit), 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. Core samples were analyzed for bulk density, porosity, particle size distribution, and saturated hydraulic conductivity.

Pore-water pressures were collected using tensiometers along the outer bank at[2]: (1) an open plot (short cropped turf) 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 gamagrass (*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).

4.2 Model setup

The riparian tree stand and gamagrass 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.

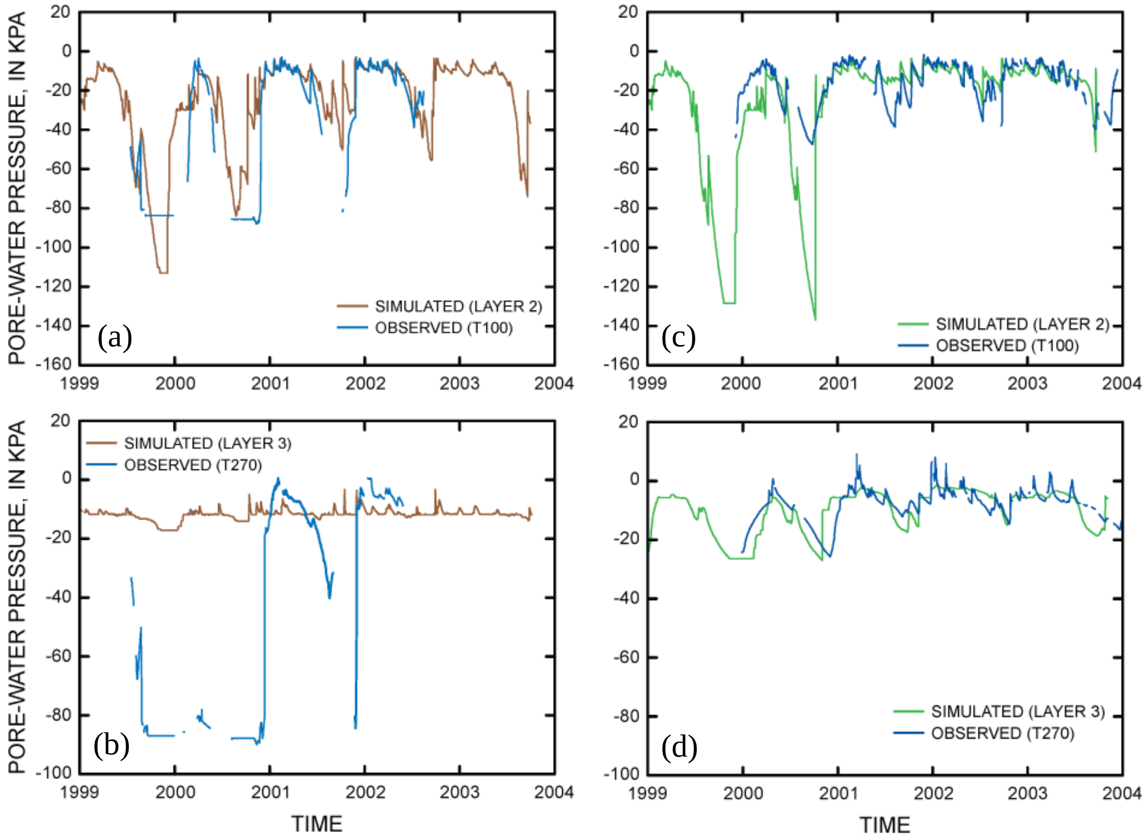

Figure 2: Comparison of simulated and observed pore-water pressures within the right bank of the Goodwin Creek Bendway study site for a deciduous tree stand (left) and an eastern gamagrass buffer (right)

4.3 Simulation results

The temporal and spatial distributions of pore-water pressure reflect the effects of infiltrating rainfall and evapotranspiration (Fig. 2). For the grass buffer, the simulated pore-water pressures agree well with those observed in the LH and EH layers (Fig. 2c and d). 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 (Fig. 2c). For this time period the planted grasses were in their first year of development, whereas they were already well established in the model simulation. For the riparian tree stand, the simulated pore-water pressure distribution agrees well in the LH unit (Fig. 2a), but does not compare well in the EH unit (Fig. 2b). The discrepancies between tree stand and grass buffer are partly due to smaller simulated ET for the tree stand that leads to higher pore-water pressures in the EH unit. Simulated pore-water pressures in the bottom (fourth) layer is fairly constant at -1.2 kPa for both buffers (not shown in Fig. 2), which indicates that the model is not adequately simulating the temporal variations in the groundwater table.

Improved subsurface flow formulations for riparian soil water dynamics at different temporal scales have been evaluated[12]. Currently, a hybrid model of the Boussinesq and REMM formulations is being implemented.

Fig. 3a compares the simulated increase in channel top width for the two riparian buffer scenarios to that observed and that obtained in validating the streambank erosion component of CONCEPTS[7]. The woody buffer greatly reduced streambank erosion by preventing any planar failures. The anchoring effects of coarse roots in the upper one meter of the streambank significantly increased stability. Though, undercutting of the streambank produced some cantilever failures along the central part of the bendway, leading to near vertical streambanks at the end of the simulation (Fig. 3b). With progressive undercutting the bank will eventually fail in case of the riparian tree stand.

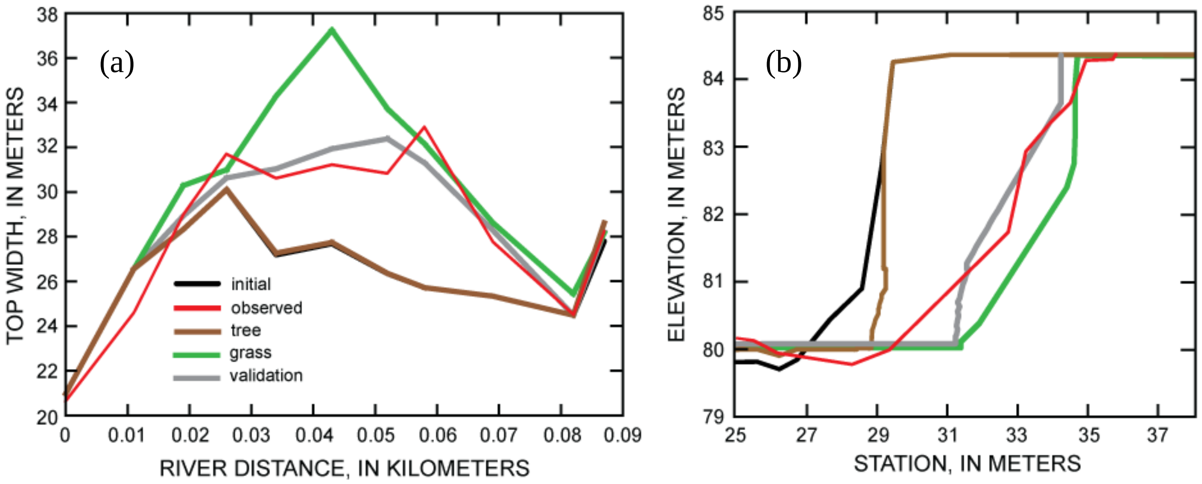

Figure 3: Comparison of simulated bank retreat at the Goodwin Creek Bendway study site between January 1996 and September 2003 for the two vegetative treatment scenarios against that observed and simulated (validation[7])

The change in top width along the central part of the bendway is larger in the presence of a grass buffer than that observed and simulated by CONCEPTS for the unvegetated, validation scenario[7]. The large simulated change in top width is primarily caused by failures that occurred during a large precipitation event that greatly elevated pore-water pressures in the LH unit, thereby reducing the shear-strength of the bank material (cf. Eq. (1)). The added cohesion due to the grass roots did not noticeably contribute to total shear strength due to the height of the streambank with respect to rooting depth. That is, only the soil shear-strength along the top one meters of the failure plane is affected by the grass roots. Further, the grass buffer does not have a coarse root system that can act as anchors. Though failures were observed for this precipitation event, their magnitudes were smaller than that simulated.

5 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 in-stream 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.

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