ENHANCING THE SEDIMENT TRANSPORT MODELING CAPABILITY OF A WATERSHED MODELING FRAMEWORK

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Abstract

The Strategic Environmental Research and Development Program (SERDP) identified the need to provide Fort Benning, Georgia (and eventually other military installations) with models that can be implemented for long-term watershed planning and management. This paper discusses one of the objectives of this SERDP-funded project that focuses on the development of a watershed modeling system for Fort Benning, GA using the U.S. EPA BASINS (BASINS) modeling framework. The project objective described in this paper is the enhancement of BASINS through the integration of more robust models for channel flow (EFDC) and channel sediment transport (SEDZLJ) into BASINS, as well as the capability to represent channel bank erosion using an empirical bank erosion algorithm. This paper reports the project's approach for accomplishing the stated objective.

INTRODUCTION

Observations have identified the vulnerability of the stream banks within the portion of the Upatoi Creek watershed within Fort Benning, GA to erosion and failure under both wet and dry weather conditions. Fort Benning is located on the fall line between the Piedmont and Coastal Plain provinces in Central Western Georgia (see Figure 1). Wet weather bank erosion can occur due to several water-driven phenomena on top of or within the bank materials (e.g., rotational or planar failure) or within the stream channel (e.g., scour of the bank toe). Dry weather bank/gully destabilization can occur due to tracked vehicular travel during training activities. Representing the additional stream load caused by these sediment-generating phenomena requires improved algorithms for bank erosion and sluffing, as well as instream sediment erosion and deposition of multiple size classes of sediment. The effectiveness of these enhancements can be heightened by using an enhanced flow model in HSPF, the current primary watershed model in BASINS; these enhancements will provide a flow model that is able to more accurately simulate the dynamic nature of flows within the Upatoi Creek watershed during flashy runoff events, including out-of-bank flow events. The enhanced flow model would yield a more accurate calculation of the spatial variation in stream velocities and flow-induced bed shear stresses. The latter are used in predicting 1) the erosion rates of sediment in the surface layer of the sediment bed, and 2) the deposition rates of suspended sediment.

Representing bank erosion in watershed-scale models is at this point in time a research topic, and little exists in terms of methods or useful results. Currently the Fort Benning HSPF watershed model lacks a method for representing the generation of sediment loads due to events of bank erosion/failure. This is an extremely important mechanism that needs to be represented, especially in incised streams and rivers that are prevalent in Piedmont physiographic regions as

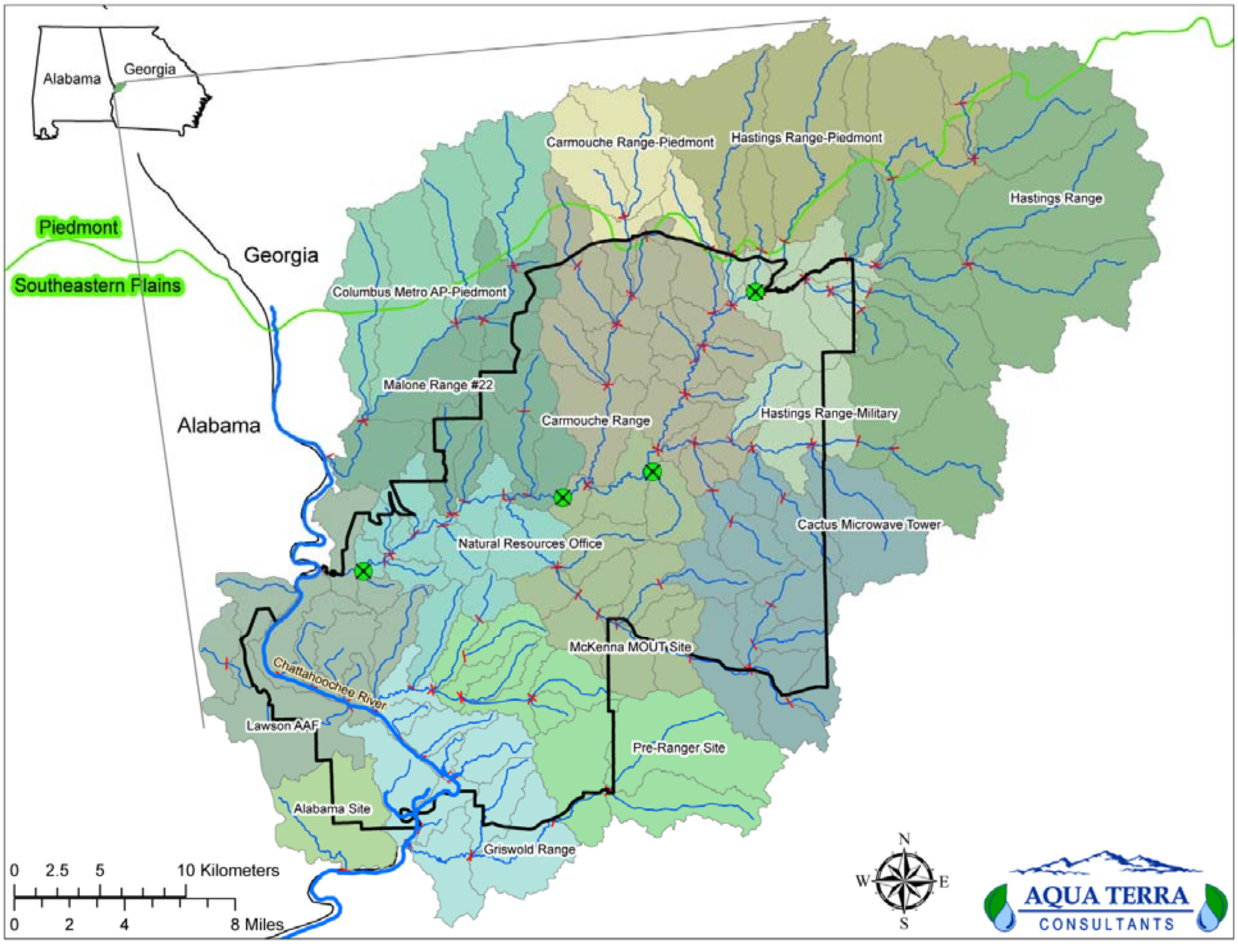

Figure 1 Fort Benning, GA Watersheds

eroding/failing banks are often the major non-point source of sediment to these waters. Further, once the sediment loads from landscape and bank erosion are introduced into the Fort Bennings' stream channels, the need exists to improve the model's capability to represent sediment transport during both low and high flow events.

Appropriate representation of high flow events is particularly critical to sediment transport simulations. Improved flow modeling capabilities provide the starting point for satisfying a third need for improvement: the ability to better represent channel scour and deposition by incorporating improved algorithms. One of the important benefits of these improved formulations is to enable the modeling of multiple size classes of non-cohesive sediment, a capability that the model currently lacks. Adding this capability will enable the simulation of bed armoring of both cohesive and non-cohesive dominated sediment beds. The ability to represent bed coarsening and subsequent armoring is crucial in simulating sediment transport during high flow events. If the simulated sediment bed is not capable of armoring, then excessive (i.e., unrealistic) scour may be predicted.

Addressing these model enhancement needs requires an approach that assures conceptual and practical compatibility among the improvements, as well as compatibility with related HSPF formulations that will remain intact. The subject of this paper is a discussion of an ongoing effort to accomplishment these needed model enhancements. The ongoing project is one of the objectives of a SERDP-funded project that focuses on the development of a watershed modeling system for Fort Benning, GA using the U.S. EPA BASINS modeling framework. The specific project objective described in this paper is the enhancement of BASINS through the integration of more robust models for channel flow (EFDC) and channel sediment transport (SEDZLJ) into BASINS, as well as the capability to represent channel bank erosion using an empirical bank erosion algorithm. For background purposes, a brief description of BASINS is given below.

DESCRIPTION OF THE BASINS MODELING SYSTEM

The BASINS modeling system provides an advanced model framework to evaluate runoff and constituent transport in watersheds in this country and abroad. The Better Assessment Science Integrating point and Nonpoint Sources (BASINS) software is a multipurpose, GIS-based environmental analysis modeling system designed to be used to perform watershed and water quality-based studies (US EPA, 2007). The BASINS system was first released in 1996, and has benefited from over 13 years of development effort. This modeling system features a well developed GUI for two different watershed models (HSPF and SWAT), and numerous pre- and post-processing tools that are shared by these models. BASINS was initially developed to support the development of Total Maximum Daily Loads (TMDL) as required by the Clean Water Act. Through subsequent enhancements, it has developed into an effective tool for performing many other types of watershed assessments. The latest version of the BASINS modeling system (BASINS 4.0) uses an open source GIS software architecture (MapWindow (Watry, 2007)), and combines the following five components to provide the range of analyzes needed for performing watershed and water quality assessments: 1) a collection of national cartographic and environmental databases; 2) environmental assessment tools (e.g., to summarize results; establish contaminant source - impact inter-relationships; and retrieve selective data); 3) utilities (e.g., import tool, download tool, post-processor, and land use, soil classification and overlay tool); 4) automated watershed characterization reports; and 5) numerical surface water models (HSPF, KINEROS, PLOAD-BEHI). The BASINS versions of these models are updated as the model developers continue their enhancements. For example, the HSPF watershed loading model is currently in its 12th distribution version (Bicknell, 2005). BASINS 4.0 (hereafter referred to as BASINS) also provides a direct linkage between watershed model results and a well developed dynamic aquatic ecosystem model (AQUATOX).

Imhoff et al. (2003) performed an evaluation of contaminated sediment transport models for EPA, and identified the following capabilities of the sediment transport model in BASINS and HSPF (HSPF-RCHRES):

- Ability to simulate the transport of three different sediment classes, i.e., clay, silt, and sand.
- Settling, deposition, and resuspension rates of sediment are computed internally, as opposed to these rates being provided as input parameters.

The identified limitations of HSPF-RCHRES are the following:

- The sediment transport formulations used in HSPF-RCHRES are based on equations given in scientific literature published during the 1960s and 1970s.
- Bedload transport of non-cohesive sediment is not represented.
- The resuspension and deposition rates are not calculated as a function of the bed shear stress.
- A flow routing routine is used in HSPF to simulate stream hydraulics and not a hydrodynamic model that solves the conservation of mass and non-linear linear momentum equations. As such, HSPF is only capable of simulating uni-directional gradually varied open channel flow. In addition, the simulated flows by HSPF are not as accurate as those calculated by a hydrodynamic model that accounts for driving forces (e.g., stream gradient, wind, vertical stratification, etc.), retarding forces (e.g., bottom friction due to skin friction and form drag), and convective and temporal accelerations in the flow field. Convective and temporal flow accelerations can be substantial during high flow events when most sediment is eroded and transported downstream, and as such, the identified limitation of HSPF (and therefore BASINS) should be addressed to improve upon this model's capability of simulating sediment transport during non-baseflow conditions.
- The inability to simulate the critical process of bed coarsening and subsequent armoring in non-cohesive sediment dominated sediment beds using only one size class of sand has previously been discussed.
- HSPF-RCHRES is limited to a single surficial sediment bed to represent the exchange of sediment between the bed and the water column, whereas most advanced sediment transport models typically represent the coupled interaction of sediment deposition and erosion.
- HSPF-RCHRES does not represent primary consolidation of fine-grained, i.e., cohesive, sediment since the HSPF sediment bed is defined only by a surficial bed, i.e., only one layer.
- Over the course of a model simulation HSPF does not account for changes in bed elevations that result from erosion and deposition of sediment from and to a sediment bed, respectively, in predicting changes in the flow field during the next time step. This limitation can lead to over prediction in the amount of erosion and deposition that is simulated to occur due to the hydrodynamic model not accounting for the resulting decrease and increase in bed elevation, respectively, and consequently not accounting for the corresponding change in the flow depths or current velocities.

All of these limitations would need to be addressed to significantly improve the sediment transport capabilities in BASINS and HSPF.

ENHANCEMENTS TO BASINS

The recommendations to enhance the flow, sediment transport and bank erosion capabilities of BASINS are described in this section.

FLOW COMPONENT

To improve the flow module in BASINS, a hydrodynamic model needs to be added to HSPF. A hydrodynamic model will provide a more accurate calculation of the flow field and resulting bed shear stresses (particularly during runoff events when the flow is unsteady and typically accelerates rapidly during the rising limb of the flow hydrograph) than is achievable with the flow routing routine currently in HSPF.

The project team chose to integrate the three-dimensional (3D) hydrodynamic model EFDC into BASINS. EFDC (Environmental Fluid Dynamics Code) is a multi-dimensional hydrodynamic model (EFDC) that is capable of simulating both uni-directional and oscillatory open channel flow (Hamrick 2007a, 2007b, and 2007c). EFDC is a public domain surface water modeling system that contains dynamically linked hydrodynamic and sediment transport modules. EFDC can simulate barotropic and baroclinic flow in a water body due to astronomical tides, wind, density gradients, and river inflow. When this substantial enhancement is completed, BASINS will be capable of accurately simulating: a) tide-driven flows in rivers that drain lower coastal plain watersheds; b) rapidly accelerating flows during the rising limb of a flashy runoff hydrograph; c) flows through hydraulic structures such as dams and culverts; and d) flow onto floodplains during the rising limb of an out-of-bank event and flow back into the river during the falling limb of out-of-bank flow events by representing the floodplain using grid cells that are adjacent to the cells that represent the channel, i.e., stream/river, network. Additional capabilities of EFDC and reasons why this model was selected for the hydrodynamic model to be incorporated into BASINS include the following:

- EFDC can represent a multi-order stream network with a more general approach than is capable with a one-dimensional (1D) model, e.g., HEC-RAS. For example, EFDC can represent first- and second-order streams using a 1D approach where the stream cross-section is approximated as a rectangle that has the width of the stream and the average depth, whereas third- and higher-order streams can be represented in a two-dimensional, vertically integrated (2D-H) manner in which more than one cell is used to represent the cross-section of the stream/river. This approach would be appropriate to use when vertical density stratification over the flow depth does not occur. If vertical density stratification due to temperature or salinity does occur in higher order streams closer to the outlet of the modeled watershed, then it is possible to represent these streams/rivers using EFDC in either the two-dimensional, laterally integrated (2D-V) or full 3D mode in which the water column can be divided into a model user specified number of vertical layers.
- EFDC has been in the public domain since its development in the early 1990’s and has been applied to hundreds of water bodies.
- The application history for EFDC includes applications by the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC) and the U.S. Environmental Protection Agency (EPA).

The version of EFDC that is being incorporated into BASINS is the version referred to as EFDC-ERDC, hereafter referred to as EFDC. This is the version that is being used by the Coastal and Hydraulics Lab (CHL) and the Environmental Lab (EL) at ERDC for several ongoing sediment transport and contaminant transport modeling studies. The main reason for choosing this particular version of EFDC is discussed later in this paper.

SEDIMENT TRANSPORT COMPONENT

Because of the identified limitations of the current sediment transport module in HSPF, an enhanced sediment transport model needs to be integrated into BASINS. The project team chose the SEDZLJ sediment bed model developed by Jones and Lick (2000, 2001). The specific reasons for making this recommendation are the following:

- State-of-the-science equations that have been developed in the past 20 years are included in SEDZLJ to allow simulation of the following sediment transport processes: bedload transport of non-cohesive sediment; resuspension of both cohesive and non-cohesive sediments, both calculated as a function of the local bed shear stress; deposition of cohesive sediments calculated as a function of the bed shear stress. Figure 2 shows the sediment mass balance achieved by SEDZLJ. In this figure, U = near bed flow velocity, δ_{bl} = thickness of layer in which bedload occurs, U_{bl} = average bedload transport velocity, D_{bl} = sediment deposition rate for the sediment being transported as bedload, E_{bl} = sediment erosion rate for the sediment being transported as bedload, E_{sus} = sediment erosion rate for the sediment that is eroded and entrained into suspension, and D_{sus} = sediment deposition rate for suspended sediment.

- Whereas a hydrodynamic model is calibrated to account for the total bed shear stress, which is the sum of the form drag due to bed forms and other large-scale physical features (e.g., boulder size particles) and the skin friction (also called the surface friction), the correct component of the bed shear stress to use in predicting sediment resuspension and deposition is the skin friction. The skin friction is calculated in SEDZLJ as a function of the near-bed current velocity and the effective bed roughness. The latter is specified in SEDZLJ as a linear function of the mean particle diameter in the active layer.

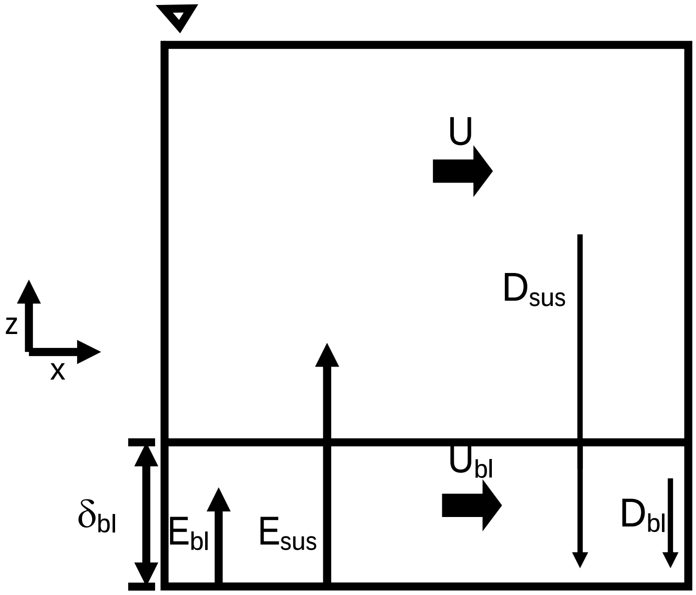

Figure 2 Sediment Mass Balance Achieved in SEDZLJ

- Multiple size classes of both fine-grain (i.e., cohesive) and noncohesive sediments can be represented in the sediment bed. As stated previously, this capability is necessary in order to simulate coarsening and subsequent armoring of the surficial sediment bed surface during high flow events.

- To correctly represent the processes of erosion and deposition, the sediment bed in SEDZLJ can be divided into multiple layers, some of which are used to represent the existing sediment bed and others that are used to represent new bed layers that form due to deposition during model simulations. Figure 2 shows a schematic diagram of this multiple bed layer structure. The graph on the right hand side of this figure shows the variation in the measured gross erosion rate (in units of cm/s) with depth into the sediment bed as a function of the applied skin friction. SEDFLUME (described below) was used to measure these erosion rates.

- Erosion from both cohesive and non-cohesive beds is affected by bed armoring, which is a process that limits the amount of bed erosion that occurs during a high-flow event. Bed armoring occurs in a bed that contains a range of particle sizes (e.g., clay, silt, sand). During a high-flow event when erosion is occurring, finer particles (i.e., clay and silt, and fine sand) tend to be eroded at a faster rate than coarser particles (i.e., medium to coarse sand). The differences in erosion rates of the various sediment particle sizes creates a thin layer at the surface of the sediment bed, referred to as the active layer, that is depleted of finer particles and enriched with coarser particles. This depletion-enrichment process can lead to bed armoring, where the active layer is primarily composed of coarse particles that have limited mobility. The multiple bed model in SEDZLJ accounts for the exchange of sediment through and the change in composition of this active layer. The thickness of the active layer is normally calculated as a time varying function of the mean sediment particle diameter in the active layer, the critical shear stress for resuspension corresponding to the mean particle diameter, and the bed shear stress. Figure 3 shows a schematic of the active layer at the top of

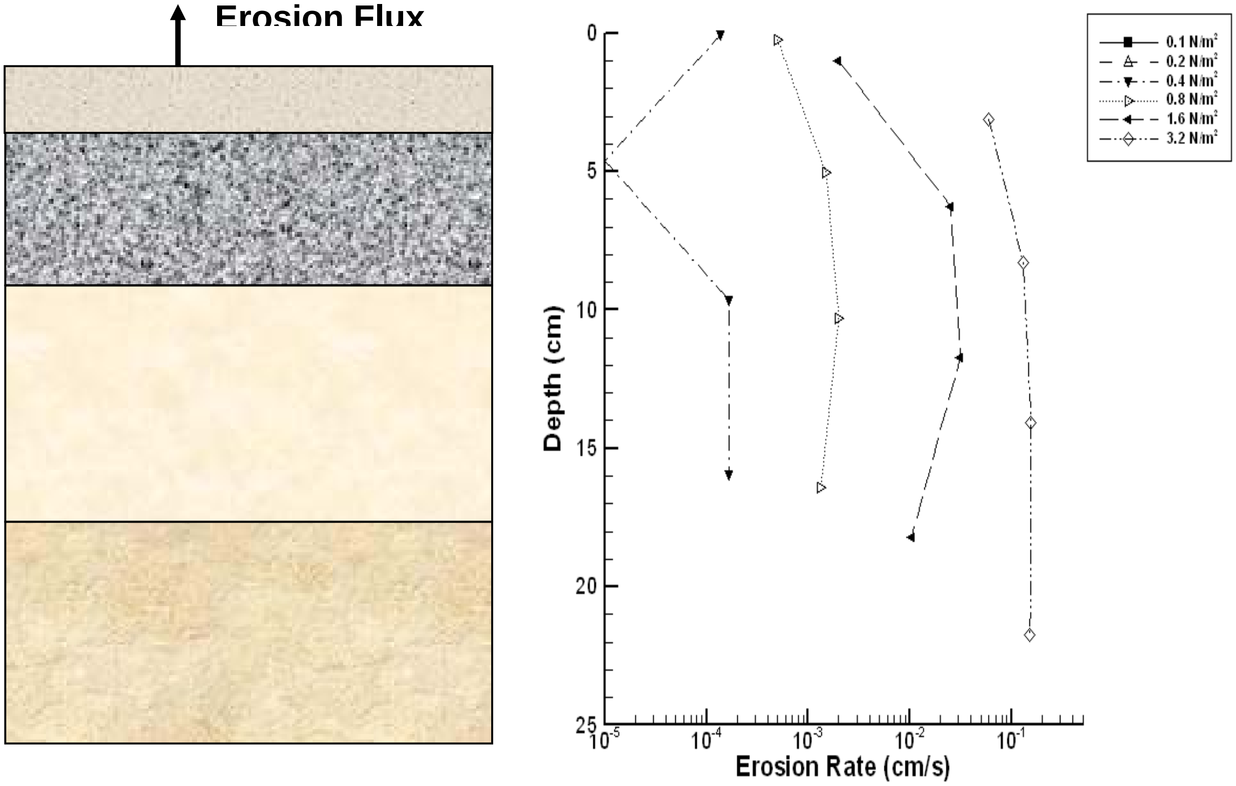

Figure 3 Multi-Bed Layer Model Used in SEDZLJ

the multi-bed layer model used in SEDZLJ.

- SEDZLJ was designed to use the results obtained with SEDFLUME, which is a straight, closed conduit rectangular cross-section flume in which detailed measurements of critical shear stress of erosion and erosion rate as a function of sediment depth are made using sediment cores dominated by cohesive sediment collected at the site to be modeled (McNeil et al. 1996). However, when SEDFLUME results are not available, it is possible to use a combination of literature values for these parameters as well as the results of SEDFLUME tests performed at other similar sites. In this case, a detailed sensitivity analysis should be performed to assist in quantifying the uncertainty that results from the use of these non-site specific erosion parameters.

- SEDZLJ can simulate overburden-induced consolidation of cohesive sediments. An algorithm that simulates the process of primary consolidation, which is caused by the expulsion of pore water from the sediment, of a fine-grained, i.e., cohesive, dominated sediment bed is included in SEDZLJ. The consolidation algorithm in SEDZLJ accounts for the following changes in two important bed parameters: 1) increase in bed bulk density with time due to the expulsion of pore water, and 2) increase in the bed shear strength (also referred to as the critical shear stress for resuspension) with time. The latter parameter is the minimum value of the bed shear stress at which measurable resuspension of cohesive sediment occurs. As such, the process of consolidation typically results in reduced erosion for a given excess bed shear stress (defined as the difference between the bed shear stress and bed shear strength) due to the increase in the bed shear strength. In addition, the increase in

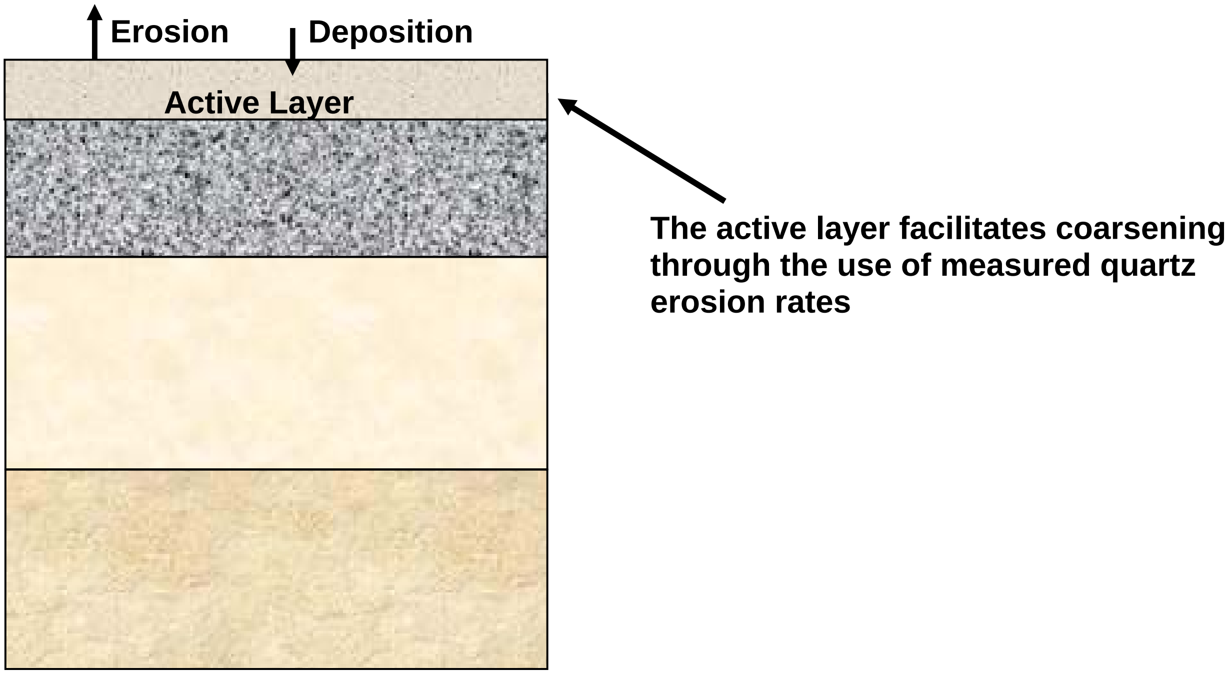

Figure 4 Schematic of Active Bed Layer Used in SEDZLJ

bulk density needs to be represented to accurately account for the mass of sediment (per unit bed area) that resuspends when the bed surface is subjected to a flow-induced excess bed shear stress. Models that represent primary consolidation range from empirical equations that approximate the increases in bed bulk density and critical shear stress for resuspension due to porewater expulsion (Sanford, 2007) to finite difference models that solve the non-linear finite strain consolidation equation that governs primary consolidation in saturated porous media (e.g., Arega and Hayter, 2008). An empirical-based consolidation algorithm is included in SEDZLJ.

- SEDZLJ is the sediment transport model that is incorporated in EFDC-ERDC.

- As previously discussed, HSPF does not account for changes in bed elevations that result from erosion and deposition of sediment from and to a sediment bed, respectively, in predicting changes in the flow field during the next time step. SEDZLJ contains a morphologic algorithm that, when enabled by the model user, will adjust the bed elevation to account for erosion and deposition of sediment. It is proposed to add an option so that the user can activate this algorithm so that the bed elevations and flow depths are adjusted, when and where necessary, during every time step. The adjusted flow depths would be used during the next time step by the flow routing routine in HSPF to update the flow field.

In addition to the advantages gained by using the SEDZLJ sediment transport model, the advantages of using the EFDC model to perform the dynamically linked hydrodynamic and sediment transport modeling are the following:

- More accurate predictions of the sediment transport that occurs during a rainfall induced high-flow runoff event. This increased accuracy will be possible due to the more accurate predictions of the hydrodynamics in the stream network as a result of using a hydrodynamic model to predict the rapidly changing flow depths and current velocities that occur during runoff events.

- The ability to simulate out-of-bank flows and the resulting transport and possible deposition of sediment onto the floodplains.

BANK EROSION COMPONENT

As stated previously: a) simulating bank erosion in watershed-scale models is at present a research topic, and little exists in terms of methods or useful results; and b) currently the Fort Benning HSPF watershed model lacks a method for representing the generation of sediment loads due to events of bank erosion/failure. Therefore, a bank erosion model needs to be added to HSPF to account for the sediment that is introduced to streams from eroding/failing banks.

The approach chosen by the project team to accomplish this goal is to develop an empirical-based bank erosion model be added to EFDC such that the estimated sediment mass from the eroding bank is added to the sediment bed in the grid cell where the eroding bank is located. Specifically, the empirical bank erosion model by Ikeda et al. (1981) was chosen to be incorporated into HSPF. This empirical model calculates the lateral bank erosion rate (normally in units of meters/day) as a linear function of the difference between the near-bank, depthaveraged velocity and the reach-averaged velocity at bank-full flow. An empirical erosion constant, which is estimated from measurements of bank erosion rate and adjusted during model calibration, relates the bank erosion rate to the difference in these velocities. The volume of bank that is eroded per unit length of the bank is obtained by multiplying the lateral bank erosion rate by the average bank height.

ENHANCEMENT METHODOLOGY

This section contains a discussion of the procedures being used to implement the chosen model enhancements to BASINS.

FLOW COMPONENT

Specific steps that are being performed during the incorporation of EFDC into HSPF are the following:

- The EFDC model has been incorporated into HSPF such that the model user can choose whether to use the existing flow routing module in HSPF or use the EFDC model.

- A second option to be added is to enable the spatial and temporal averaging of the EFDC simulated flow field over user selected EFDC grid cells and over user selected time steps to match the spatial and temporal scales in the HSPF model reach segment.

- Another option to be added will allow the model user to select whether the linkage between HSPF and EFDC is static, in which simulated watershed and groundwater loading from HSPF (in the form of binary files) is read into EFDC and used to simulate the hydrodynamics, or dynamic, in which there is dynamic feedback between HSPF and EFDC.

- If the static linkage is specified, the modified user manual for HSPF would instruct the model user to first run HSPF to generate the binary output file in which the time series of nonpoint loadings from the watershed and groundwater would be written at specified time intervals. With the static linkage specified in the input files, code will be added to EFDC to read the binary output file at specified time intervals and interpolate stream reach loadings to the grid cells in each HSPF reach.

- If the user chose the dynamic linkage option, the EFDC model would be invoked by a call statement that would be added to HSPF. A routine would be written that converts the HSPF calculated nonpoint loadings during a model run to the required format for use in EFDC.

SEDIMENT TRANSPORT COMPONENT

It is proposed to use SEDZLJ in the following manner:

- When the existing flow routing module in HSPF is used for the HSPF run, an external linkage routine will be written to pass the calculated flow information from HSPF to a stand-alone SEDZLJ routine. The latter will be run to solve the governing equations that represent the suspended load transport of cohesive sediments and both the bedload and suspended load transport of non-cohesive sediments. The latter will be run to solve the governing equations that represent the suspended load transport of cohesive sediments and both the bedload and suspended load transport of non-cohesive sediments. The stand-alone SEDZLJ routine that works with the HSPF calculated flow field will be developed as a component of this task.

- When EFDC is used as the hydrodynamic model, the version of SEDZLJ that is in EFDC-ERDC will be run in the dynamic mode with the hydrodynamic model in EFDC. This will result in the simulated changes in the bed elevations due to erosion and deposition of the sediment bed during a particular time step being used by the hydrodynamic model in the next time step to update the flow field in the model domain.

BANK EROSION COMPONENT

Specific steps that are being performed during the incorporation of the bank erosion model into EFDC are the following:

- An algorithm for the empirical-based bank erosion model has been developed to calculate the rate per unit length of the bank at which the bank erodes as a function of the water surface elevation in the adjacent stream/river.
- The bank erosion rate will be multiplied by the specified number of model time steps (the number will depend on whether an hourly or daily bank erosion rate is calculated) to give the mass of sediment that is eroded per unit length of the bank per specified time interval, i.e., day.
- The mass of sediment eroded will be multiplied by the cell length (or by multiple cell lengths if spatial averaging is specified) to give the mass of sediment that will be added uniformly (i.e., a layer of uniform thickness will be added) to the top of the sediment bed in that cell (or cells) at the end of the current time step. The composition of sediment in the eroding bank will be reflected in the sediment mass added to the top of the sediment bed in the adjacent cell(s).

Data that would be required to estimate bank erosion rates and develop the site-specific empirical equations include (at a minimum) the following:

- Spatial distributions along river shorelines of bank height and geometry, areas of active erosion, and empirical bank erosion/bulk properties (e.g., grain size composition of banks).
- Long term erosion rate estimates that can be determined using aerial photographs of the river shoreline taken at two different times, or measurements of bank erosion rates at a few locations along the stream/river to be modeled.

PROJECT STATUS

EFDC and SEDZLJ have been statically coupled to HSPF, and the empirical bank erosion algorithm has been added to EFDC. At present, EFDC and SEDZLJ are being setup to simulate the hydraulics and sediment transport in the Upatoi Creek watershed as a test case for the enhanced version of BASINS. Measurements need to be taken at the site to determine the coefficients in the empirical bank erosion equation. Work is continuing on this SERDP-funded research effort.

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