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Modeling of Fluvial Geomorphic Processes in River Channels Impacted by Agriculture

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ABSTRACT: Sediment in water resources is a major contributor to water quality degradation. Fine-grained sediment emanating from agricultural watersheds is a concern for protecting water resources and environment. A large portion of the sediments may be contributed by channel erosion processes including channel incision, headcut migration, bank erosion, or local scouring. In-stream structural measures such as drop structures to control channel grade, and spur dikes, large wood and planting of riparian vegetation to control bank erosion have been constructed to reduce channel erosion and its resulting sediment load.
In the past decades, computer simulation models have been developed to help researchers and engineers understand and resolve these sedimentation problems. Among others, the U.S. Department of Agriculture has developed the one-dimensional CONservational Channel Evolution and Pollutant Transport System (CONCEPTS) for flow and sediment transport routing including bank erosion in river channels at the stream corridor scale. The National Center for Computational Hydroscience and Engineering has developed the multi-dimensional suite of CCHE2D/3D computer models for simulating these processes in more detail at smaller spatial scales, thus emphasizing localized problems. Successful applications of these models have demonstrated their effectiveness and usefulness. Due to the complexity of sediment transport and soil erosion processes, models designed for problems of distinct spatial and time scales will have to be applied in an integrated fashion. An integrated approach to make state-of-the-art numerical models available for research and practical applications will be the most cost-effective.

Keywords: *River sedimentation, Channel migration, Local scour, Bank erosion, Numerical simulation, CCHE2D, CCHE3D,* CONCEPTS

1 INTRODUCTION

Geomorphic processes in stream channels of agricultural watersheds can produce large amounts of sediment, alter the local landscape of streams and damage farm lands. Physical models and field observations have been used to understand these processes and in-stream structures have been installed to mitigate the adverse effects of stream sedimentation processes. Due to the large spatial scale of watersheds and the complexity of the sedimentation problems, these studies can only provide treatment or solutions to local problems; the effects of mitigation measures and in-stream structures have scarcely been evaluated at the watershed scale.

In recent decades, numerical models have been developed to simulate flow and sedimentation processes in watersheds. Based on extensive understanding of the flow and soil erosion physics, numerical models have been applied successfully to reproduce observed physical changes in the channel network and around instream structures and, to certain extent, predict what may happen in the future. Even with limited applications in the area of river sedimentation, numerical models have shown their effectiveness, efficiency and necessity over other methodologies. Though, additional efforts are still needed to enhance numerical models for application to more detailed local problems and watershed system approaches for water resource engineers and managers.

This paper introduces several numerical models: the one-dimensional model CONCEPTS, developed by the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS); and the two- and three-dimensional models, CCHE2D and CCHE3D, developed by the National Center CCHE for Computational Hydroscience and Engineering (NCCHE). We review their capabilities of simulating stream sedimentation processes. The potential of further model development, refinement and future modeling needs for agricultural watersheds will be discussed as well.

2 THE CONCEPTS COMPUTER MODEL

2.1 *Overview*

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 et al., 2008a; 2008b). CONCEPTS simulates unsteady, one-dimensional (1D) flow, graded sediment transport, and bank erosion processes in stream corridors. It can predict the dynamic response of flow and sediment transport to in-stream structures.

CONCEPTS models streamflow as 1D along the channel's centerline. Hence, it is limited to fairly straight channels; it cannot predict bar formation and channel migration. CONCEPTS simulates gradually varying flow (described by the Saint-Venant equations) as a function of time along a series of cross sections representing stream and floodplain geometry. The governing system of equations are solved using the generalized Preissmann scheme, allowing a variable spacing between cross sections and large time steps conducive to long-term simulations of channel evolution. The implementation of the solution method contains various enhancements to improve the robustness of the model, particularly for flashy runoff events.

CONCEPTS calculates sediment transport rates by size fraction for 14 predefined sediment size classes ranging from 10 μm to 64 mm. It uses a total-load evaluation of bed-material transport and treats movement of clays and fine silts (<10 μm) as pass-through background wash load. The differences in transport mechanics of suspended and bed load movement are accounted for through nonequilibrium effects. The composition of bed surface and substrate is tracked, enabling the simulation of vertical and longitudinal fining or coarsening of the bed material.

CONCEPTS simulates channel width adjustment by incorporating the two fundamental physical processes responsible for bank retreat: fluvial erosion or entrainment of bank material particles by flow and bank mass failure due to gravity. The detachment of cohesive soils is calculated following an excess shear-stress approach. An average shear stress on each soil layer is computed. If the critical shear stress of the material is exceeded, entrainment occurs. CONCEPTS is able to simulate the development of overhanging banks. Stream bank failure occurs when gravitational forces that tend to move soil downslope exceed the forces of friction and cohesion that resist movement. The risk of failure is expressed by a factor of safety, defined as the ratio of resisting to driving forces or moments, using the method slices. CONCEPTS performs stability analyses of wedge-type failures and cantilever failures of overhanging banks. The effects of pore water pressure and confining pressure exerted by the water in the stream are accounted for.

2.2 *Determining the relative contributions of channel sources at the watershed scale.*

Developing BMPs at the watershed scale to reduce in-stream fine-grained sediment loadings is ineffective if channel sources are excluded. Channels in agricultural lands are often disturbed by runoff and sediment from uplands, which may result in extensive channel erosion. Current watershed models do not adequately incorporate channel erosion processes. CONCEPTS was used to determine in-stream sources of fine sediment and their rates relative to upland sources at the watershed scale for the Shades Creek watershed, Alabama. The Shades Creek watershed is located near Birmingham, Alabama, in an area experiencing rapid urbanization. Nearly the entire length of Shades Creek is listed as impaired due to sediments. Surveys conducted between 1990 and 1993, and again in 1997, indicated impairment caused by collection system failure, road and bridge construction, land development, urban runoff, removal of riparian vegetation, and bank/shoreline modification. Simon et al. (2004) carried out a study to determine bed material composition, sediment yields, and sources in the Shades Creek watershed and to compare these to "reference" sediment yields for unimpaired streams in the region.

As part of the study, CONCEPTS was used in combination with the watershed model AnnAGNPS (Bingner and Theurer, 2001) to evaluate, among others: (1) the effects of urbanization on channel erosion and bed material gradation and (2) the potential reduction in fine-grained sediment yield provided by stream bank stabilization measures. AnnAGNPS provides peak flow discharge, runoff volume, and clay, silt, and sand mass for each runoff event for reaches and cells draining into the modeling reach. These data are then converted into triangular-shaped hydrographs. The presented results below describe three simulation scenarios using (1) current (2001) land use (70% forest, 16% pasture, 11% urban, and 3% water), (2) current land use with selected stream bank protection (hereafter referred to as 2001LURP), and (3) land use change from forest to urban, that is, 81% urban and 0% forest (2001LUFU).

Both runoff and average annual suspended-sediment load showed a discernible increase for the modeling scenario where all forest land was changed to urban (2001LUFU), see Figure 1. Increases in sediment load are a direct result of greater runoff rates. Stream banks are the greatest source of sediments to suspended load, except for the 2001LURP scenario, which simulated protected banks (see Figure 1). Uplands were the main source of fines for the 2001LURP scenario because of the 10,200 t yr^{-1} or 40% reduction in contributions from the banks. This 40% reduction was the result of protecting 11% of the stream length. The 46% (12,300 t yr^{-1}) increase in loads for the 2001LUFU originated mainly from the stream banks (8950 t yr^{-1}) as opposed to uplands (3460 t yr^{-1}).

CONCEPTS was also used to determine the change in bed material composition caused by land use changes. Embeddedness is used to characterize bed material composition. Embeddedness is defined as the percentage of bed material finer than 2 mm (sand, silt, and clay) in gravel or gravel/ cobble-dominated streambeds. Shades Creek is located in the Ridge and Valley ecoregions, which reference median embeddedness value is 4% and the reference third quantile embeddedness value is 13.4% (Simon et al., 2004). Along Shades Creek, there are 53 sections with a coarse-grained streambed, 42 of which are located within stable reaches. The embeddedness of 10 cross sections is smaller than 4%, and the streambed of 26 cross sections has an embeddedness value smaller than 13.4%.

For the 2001 land use scenario, the number of coarse-grained cross sections has reduced to 24 due to aggradation. Only three sites have an embeddedness value smaller than 4%. There are seven sites with an embeddedness value smaller than 13.4%. For the 2001LURP scenario, the number of coarse-grained cross sections has reduced to 29; however, this is five more than for the 2001 land use scenario. Only three sites have an embeddedness value smaller than the reference median of 4%. There are eight sites with an embeddedness value smaller than the reference third quartile of 13.4%. The average embeddedness is slightly smaller for the 2001LURP scenario than that for the 2001 land use scenario. For the 2001LUFU scenario, the number of coarse-grained cross sections has reduced to 26, two more than for the 2001 land use scenario. Only one site has an embeddedness value smaller than the reference median of 4%. There are nine sites with an embeddedness value smaller than the reference third quartile of 13.4%.

The above modeling scenarios show that targeted bank protection is needed to prevent the fining of coarse-grained beds caused by ongoing urbanization of the watershed. For example, a 40% reduction in fine-grained sediment loadings from stream banks can be realized by protecting 11% of the stream length.

	Uplands (%)		Streambanks (%)		Total (T/y)	
Scenario	Fines	Sands	Fines	Sands	Fines	Sands
2001 Land Use	40.3	31.2	59.7	68.8	18,700	8,000
2001 LU & Bank stab	88.7	33.8	11.3	66.2	8,500	7,390
2001 LU Forest to Urban	37.2	27.6	62.8	72.4	27,200	11,800

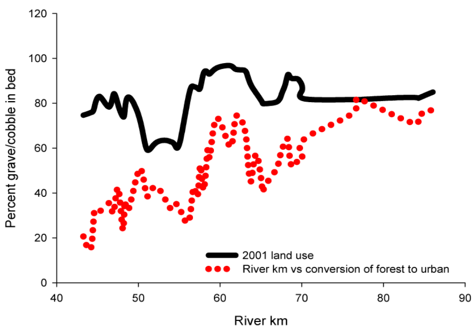

Figure 1. Continued urbanization of the Shades Creek watershed, AL increases the erosion of fine-grained sediments from streambanks and reduces streambed material grain size thereby endangering streambed aquatic habitat.

2.3 *Channel morphologic adjustment*

Many flood control dams in the United States are reaching their design life or sediments emanating from agricultural activities have severely reduced reservoir storage capacity, which may require the decommissioning of dams resulting in large downstream increases in sediment loads when stored material in the reservoir is eroded. CONCEPTS has specific capabilities to study the rate at which the sediments in the reservoir are evacuated and the downstream impact on water resources.

CONCEPTS was used to simulate sediment loadings from polychlorinated biphenyl (PCB)-contaminated stream banks and channel changes for a section of the Kalamazoo River between Plainwell and Otsego, Michigan, which contains the Plainwell and Otsego City Dams. The impoundments of these dams have been the depositories of upstream sediment and industrial waste materials containing PCB and kaolinite clays. During the 1960s, water levels behind the decommissioned hydroelectric dams were lowered, exposing the previously inundated material. In response to the lowering of water levels, the river began to erode the sediments and transport them downstream, but much of this waste clay remains impounded behind the dams mainly as floodplain deposits. The state of Michigan is interested in removing the dams while minimizing impacts locally and to downstream reaches.

Figure 2 shows the post-dam removal incisional erosion processes upstream of the Otsego City Dam (POC reach, model kilometer 6) and the downstream transport simulated by CONCEPTS. Large-scale erosion of the deposits upstream of the dams occurred very quickly as the fine-grained particles were unable to resist the increased shear. The channel incises down to its parent bed material (predam elevations), limiting the extent of erosion to the depth of the reservoir deposits. Net bed erosion in the POC reach increased 1346% to 6580 t yr^{-1} for the Dam-Out scenario. Bank erosion also increased greatly (1645%) in the POC reach from about 157 to 2740 t yr^{-1} on average, due to higher shear stresses exerted by the flow caused by the initial steepening of the channel, especially upstream of the Otsego City Dam location.

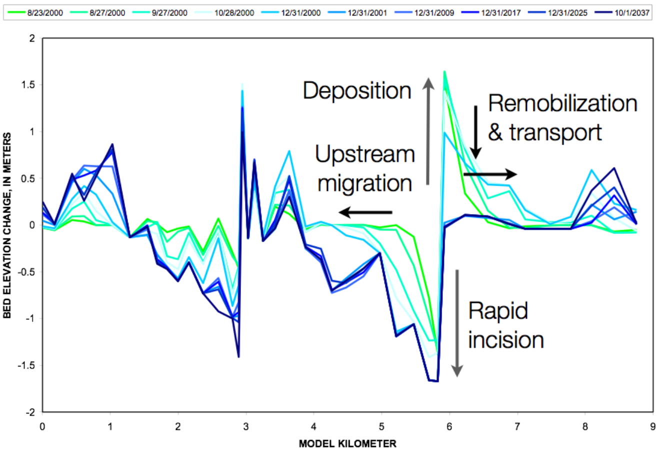

Figure 2. Simulated thalweg adjustment of the Kalamazoo River between Plainwell and Otsego City, Michigan using the CONCEPTS model.

3 CCHE2D AND BANK EROSION AND CHANNEL MIGRATION PROCESS SIMULATION

CCHE2D is a finite element based depth-integrated two-dimensional model for simulating flow, sediment transport, channel morphology and pollutant transport (Jia and Wang, 1999, 2002). The CCHE2D bank erosion model is capable of simulating unsteady flows with non-uniform sediment transport and bed and bank erosion comprising cohesive/non-cohesive materials.

3.1 *Modeling Secondary Flow Effect*

Bank erosion of alluvial river channels often results in the encroaching of valuable farm land, channel migration and degrading water quality. A bank erosion study is in general a very complex problem, because it involves multiple processes such as bank surface erosion, bank toe erosion and bank material mechanical failure. These processes are related to several parameters: sediment properties of bank and bed materials, bank slope and height, and bank-material erodibility and shear strength, as well as the flow conditions in the river channel (boundary shear stress, water depth, channel curvature, etc.).

Numerical models can be applied to bank erosion studies by considering most of the processes and parameters. Due to the specific natural of the open channel flows, the bank erosion is closely related to the helical (secondary) current. Both bedload and suspended sediments tend to be moved toward the inner bank resulting in a shallower water depth near the inner bank and deeper water near the outer bank, which stimulates the development of bank erosion and channel migration. In general, three dimensional models are needed to simulate the channel flow and sediment transport of this case. In order to increase the computing efficiency, two dimensional models with secondary flow capabilities have been developed and are applied to channel bed change and bank erosion simulations. The bed load moving direction in a curved channel is formulated to be that of the combined main flow, helical flow and side-slope effect (Fig. 3b). Equilibrium shall be reached when the effects of helical flow and side-slope gravity cancel each other, the sediment particles move along the main flow (longitudinal) direction (Figure 3a). The suspended sediment transport in a curved channel is also affected by the helical flow (Fig. 3c), more sediment moves to inner side due to the distribution of a higher concentration near the bed and low concentration near water surface. The effects of suspended sediment is modeled using depth averaged suspended sediment transport equation with a dispersion term accounting for the secondary current effect. The sediment movement direction finally computed under the flow and secondary current conditions will be used to determine the bed load direction.

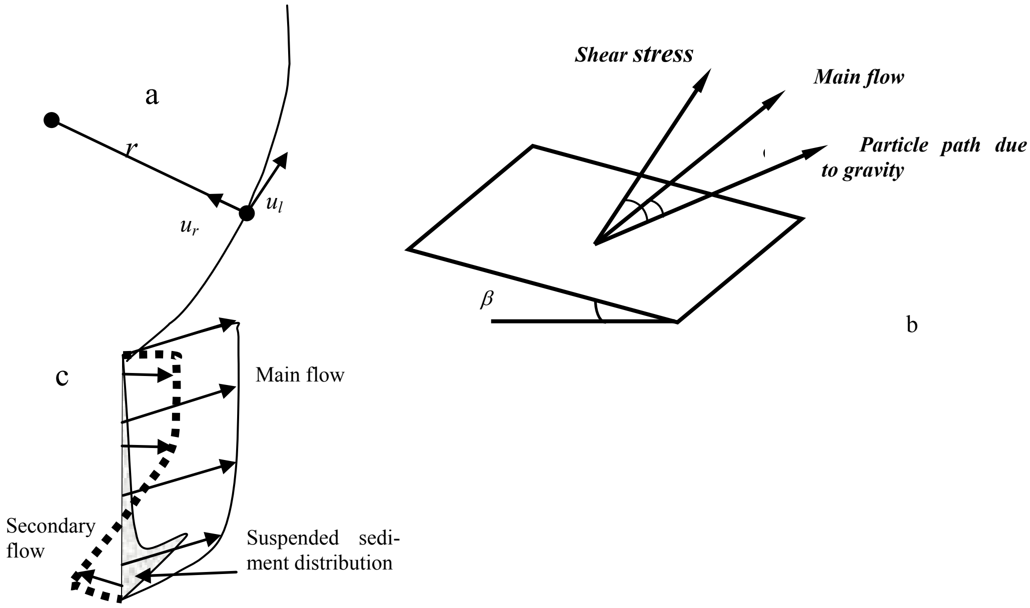

Figure 3. Suspended load and bed load motion affected by the secondary flow and the gravity. a) Definition of longitudinal and secondary current velocities. b) Effect of transverse bed slope and secondary flow. c) Effect of secondary current on suspended sediment.

Figure 4 shows examples of bed change and bank erosion simulation of a prototype scale river. When the bank is non-erodible, the flow is confined (Fig. 4a), the flow attacks the stoss-side bank of the curved channel, the curvature of thalweg of the channel becomes larger than that of the center line. The impact of the main flow and the secondary flow can deepen the channel near the stoss-side, and move the sediment toward the lee side of a bend wave. An equilibrium channel morphology can be established when the channel bank is non-erodible. If the banks are erodible (Fig. 4b), the stoss-side bank will retreat while the lee side bank will not because of the local sediment deposition and resultant formation of a bar. The asymmetric bank erosion would eventually lead to channel migration.

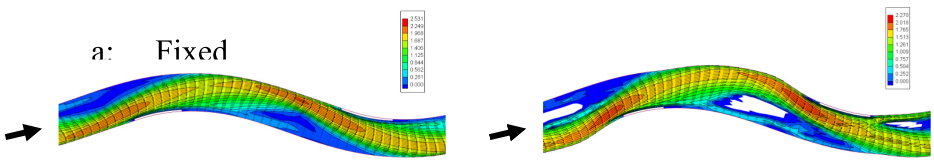

Figure 4. Modeling of morphologic adjustment of a meandering channel: (a) non-erodible banks and (b) erodible banks.

3.2 *Application of bank erosion model to a field case*

ChoShui River originates in the central mountains of Taiwan Island; it forms a large alluvial fan and then empties into the South China Sea. The channel slope in the mountain area is very steep. The valley of the river is very wide and a typical braided river pattern with multiple curved sub-channels can be observed from aerial photos and satellite imagery. The study reach is situated at the connection part of the mountain and the alluvial fan of the river. The channel slope is about 0.69% for the mountain part and it reduces suddenly to about 0.41% over the alluvial fan. The channel flow discharge varies greatly, particularly during typhoon seasons. The multiple channels become a single one when the discharge is very large during typhoon seasons. Due to the nature of the channel pattern, the main channel and secondary channels in the study reach change courses randomly and quickly. Sediment transport is dominated by the pattern of the flow discharge. The computational model, CCHE2D, has been applied to simulate the bank erosion process in one reach of the river, a 26 km stretch (Figure 5).

Even in a braided river, each sub-channel is a curved one. Because sediment transport in curved channels is affected by the secondary current, creating a lateral sediment motion and channel change, the computational model should include this mechanism to reflect the realistic transport processes. Figure 5 shows the nature of the braided river. The river sedimentation process is particularly active in Typhoon seasons. The bank erosion process was carried out using about 10 typhoon events in 10 years. Non-uniform sediment in bed materials and bank materials are considered. Due to the strong hydraulic power and mobile sediment property, several hundred meters of channel bank retreat at some locations of the river was observed in this period. The numerical model produced very good bank erosion and channel bed change results. The bank erosion was about 500 meters near the section 70 (Figure 6), for example, was predicted very well.

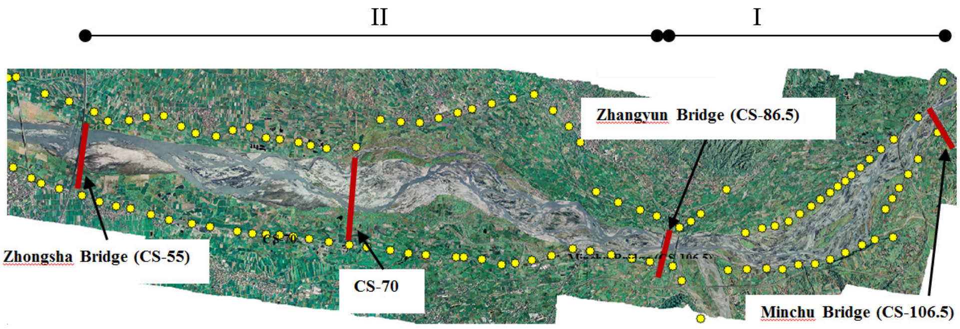

Figure 5. Study reach of Choshui River.

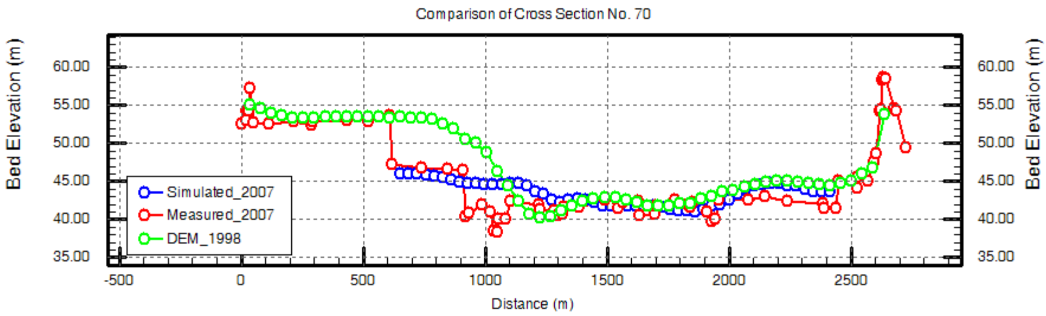

Figure 6. Comparison of measured and simulated bank erosion. Green: Cross-section in 1998, Red: measured cross-section in 2007 and Blue: simulated cross-section in 2007.

4 LOCAL SCOURING AND CCHE3D MODEL APPLICATIONS

4.1 *Simulations of flow around spur dikes for bank protection*

Local scouring is a common threat to in-stream structures such as bridge piers or river training dikes constructed in alluvial rivers; it may result in bridge failures or bank erosion. Spur dikes are effective structures to protect stream banks from erosion, however, the structure itself introduces localized erosion which may cause damage to the dikes. Detailed flow field around a spur dike and inside the scour hole has been measured by many researchers, for example Kuhnle et al. (1999). To improve understanding of the flow and scour processes associated with spur dikes, numerical simulation was performed using the free surface turbulent flow model, CCHE3D (Jia et al. 2005, Jia et al. 2013). The experiment setup, flow parameters and the scour hole are indicated in Figures 7 and 8.

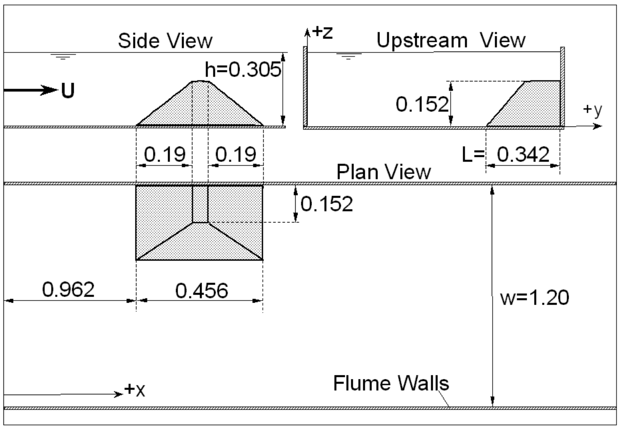

Figure 7. Definition sketch of experimental setup. The shaded block represents the model spur-dike. All dimensions are in meters. The coordinate convention used was x – streamwise direction, y – cross stream, z - vertical, with the origin at the upstream right wall on the bed of the channel. h is defined as the flow depth upstream of the structure.

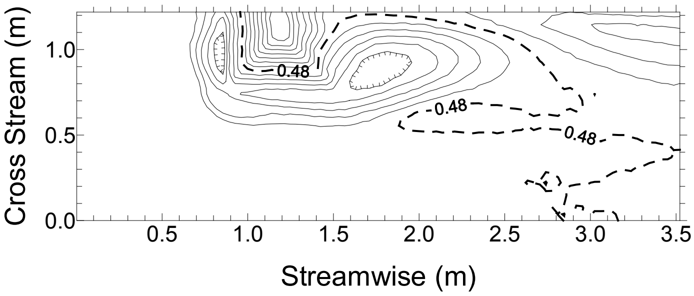

Figure 8. Topographic map of scoured fixed bed. Bed was allowed to scour for 30 hours before it was fixed with a thin layer of cement. Contour interval is 0.02 m.

CCHE3D is a finite element based free-surface turbulent flow model and sediment transport model. The *k*-ε turbulence closure model was applied to this simulation. The numerical simulation of the flow generally showed very good agreement between the computational results and the measurements (Figure 9). The flow recirculation near the bottom of both scour holes, one in the front and one behind the dike, can be simulated. The numerical simulation results indicate the CCHE3D model can be used to reasonably predict near-field flows around hydraulic structures.

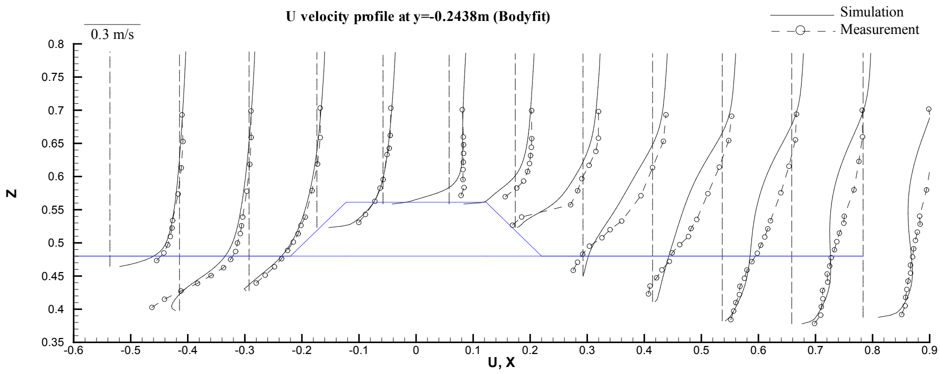

Figure 9. Comparison of measured and simulated stream-wise velocities near the dike and in scour hole.

4.2 *Bridge Scouring Studies With CCHE3d Model*

Bridge piers often affect the flow and sediment transport of streams and to certain extent, affects the trend of rivers' natural migration. The hydrodynamic force of the approach flow is blocked by the structures standing in its path way and additional turbulence fluctuations are stimulated which provide excessive erosional power and thus create a deep scouring hole around the structures.

Studies using laboratory experiments, field measurements, and numerical simulations have contributed to the understanding of the complex three-dimensional nature of the near field flows around bridge piers and the associated turbulence characteristics. Recently, a new approached has been developed in the

CCHE3D model for simulating bridge scouring. In this approach, the turbulence kinetic energy of the approach flow and that generated around the cylindrical bridge pier are approximated and assumed to be dominant factors in scouring the bed. The turbulence energy penetrating into the bed sediment due to the vertical flow is formulated and used as forcing to entrain the sediment from the bed in addition to the bed shear stress. A non-equilibrium bed load transport approach is used to model the erosion and sediment transport processes. Numerical simulations are conducted using experiment data of clear water scour and live-bed scour cases. The former is of steady flow and uniform sediment, the latter is of unsteady flow and non-uniform sediments. Good agreements of the simulation results and the measured data have been obtained.

5 DISCUSSIONS AND CONCLUSIONS

This paper presented progress in the development and application of numerical models to watershed stream sedimentation problems. Results of three models, CONCEPTS, CCHE2D and CCHE3D, are introduced. All of these models have shown to effectively study real-world stream sedimentation problems. In-stream sedimentation includes many complex processes of the flow and sediment transport. Numerical simulations can provide solutions of different spatial and time scales. 1D models are applicable to long term watershed scale problems, 2D models are applicable to flow and sedimentation problems in long channel reaches, and 3D models can be used for short channel reach and localized problems. These models can make reasonable predictions if used appropriately for the problems they are designed for.

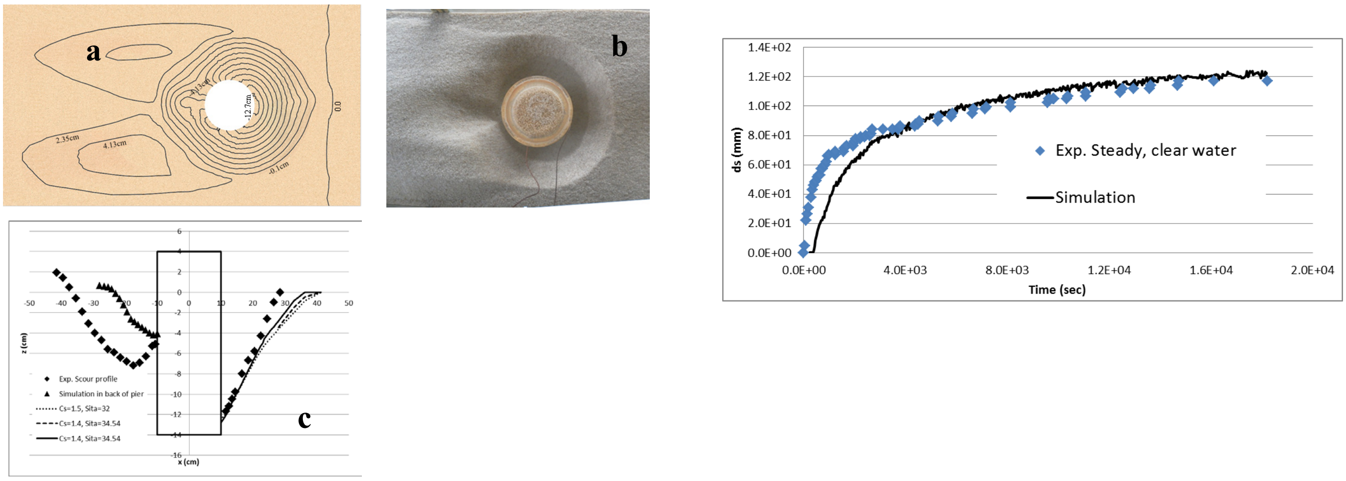

Figure 10. Simulated scour hole evolution in the front of a pier (D=0.2m, Cs=1.5, angle of repose=32.0) under steady flow and clear water scour condition. 10a: Simulated scour depth contours of the steady flow, clear water scour case. 10b. A photo of the equilibrium scour. 10c Comparison of simulated and measured scour profiles. 10d: comparison of scour hole depth development in time.

To further enhance the efficiency of research and management of watershed flow and sedimentation problems, an integrated approach is needed. It is envisioned that a platform for residing different numerical models are needed, one can study any watershed problem using this system. Recently, a downscaling approach has been developed and implemented in the integrated CCHE2D/CCHE3D model. Users can easily simulate channel scale problems with the CCHE2D model and save results at multiple preselected zones; a 3D simulation can then be readily launched to obtain local details around in-stream structures in a much refined mesh and with local boundary conditions. The integrated approach of numerical models can change the study scale with little effort and increases overall simulation accuracy. Similar implementation can also be developed for downscaling 1D to 2D models. To make the system more efficient and reliable it will need to include not only models but also necessary data related to topography, land-use, hydrology, weather, geology, sediment properties, geo-chemistry, eco-system and environment. With this comprehensive data base, the integrated model system can carry out numerical simulations for research and applications most efficiently and cost-effectively.

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REFERENCES

Bingner, R.L., Theurer, F.D. (2001), AnnAGNPS: Estimating sediment yield by particle size for sheet and rill erosion. Proceedings of the Seventh Federal Interagency Sedimentation Conference, Subcomm. on Hydrol. and Sediment., Advis. Comm. on Water Inf., Reno, Nev., 25–29 March.

Jia, Y., Chao, X., Zhu, T. (2013), Technical Manual of CCHE3D, Version1.0, NCCHE-TR-01-2013.

Jia, Y., Scott, S., Xu, Y.C., Huang, S.L., and Wang, S.S.Y., 2005, "Three-Dimensional Numerical Simulation and Analysis of Flows around a Submerged Weir in a Channel Bendway", Journal of Hydraulic Engineering, Vol. 131, No. 8:682-693, August 1, 2005.

Jia, Y., and Wang, S.S.Y., (1999). "Simulation of horse-shoe vortex around a bridge pier", Proceedings of the International Water Resources Engineering Conference". CD-ROM, 10 p.

Kuhnle, R., Alonso, C.V., and Shields, F.D., (1999)."Geometry of scour holes associated with 90o spur dikes", Journal of Hydraulic Engineering, ASCE, 125(9), 972-978.

Langendoen, E.J., Alonso, C.V. (2008a). Modeling the evolution of incised streams: I. Model formulation and validation of flow and streambed evolution components. Journal of Hydraulic Engineering, Vol. 134, No. 6, pp. 749-762.

Langendoen, E.J., Simon, A. (2008b). Modeling the evolution of incised streams: II. Streambank erosion. Journal of Hydraulic Engineering, Vol. 134, No. 7, pp. 905-915.

Simon, A., Langendoen, E.J., Bingner, R.L., Wells, R.R., Yuan, Y., Alonso, C.V. (2004). Suspended-sediment transport and bed- material characteristics of Shades Creek, Alabama and Ecoregion 67: Developing water-quality criteria for suspended and bed-material sediment. Res. Rep. 43, Natl. Sediment. Lab., Agric. Res. Serv., U.S. Dep. of Agric., Oxford, Miss.