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Regional Sediment Management (RSM) Modeling Tools: Integration of Advanced Sediment Transport Tools into HEC-RAS

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) summarizes the development and initial testing of new sediment transport and modeling tools developed by the U.S. Army Corps of Engineers (USACE), Institute for Water Resources (IWR), Hydrologic Engineering Center (HEC), to increase the functionality of numerical modeling of sediment transport within the USACE HEC River Analysis System (HEC-RAS) software package and to determine its applicability to Regional Sediment Management (RSM) challenges.

HEC-RAS SEDIMENT MODELING BACKGROUND: HEC-RAS performs (1) one-dimensional (1D) steady and unsteady hydraulic river calculations, (2) sediment transport mobile-bed modeling, and (3) water temperature analysis. The first version of HEC-RAS (version 1.0) was released in July 1995. Several major releases followed; the current version 4.1 was released in January 2010 (U.S. Army Corps of Engineers (USACE) 2010).

HEC-RAS version 4.0 was the first to include the original sediment transport modeling functionality including most of the capabilities of the legacy 1D sediment transport model HEC-6. Sediment transport functionality in HEC-RAS was primarily a product of the USACE Civil Works System Wide Water Resources Research Program (SWWRP), but subsequent improvements have been implemented in conjunction with the USACE Flood and Coastal Storm Damage Reduction Research and Development (R&D) Program, a number of USACE District partners (e.g., Omaha (NWO), Sacramento (SPK), Kansas City (NWK), St. Paul (MVP), Albuquerque (SPA)), and recently, the USACE RSM Program.

HEC-RAS is one of several hydraulic modeling codes available for river analysis in the USACE and is the primary choice for 1D hydraulic analyses. Numerous USACE and private consulting hydraulic modelers have used HEC-RAS for 1D hydraulic and sediment analysis throughout their careers, which makes it an attractive platform for expanding 1D regional sediment modeling capabilities.

IDENTIFYING THE NEED FOR NEW TOOLS: USACE District projects are the primary model-development drivers. As studies become more complex, modelers must manage larger datasets, larger physical extents, more complex processes, more creative alternatives, and must provide more detailed output. When these models also require sediment transport analysis, the complexity can increase dramatically.

Project needs from many Districts including NWO, SPK, NWK, MVP, Rock Island (MVR), Detroit (LRE), and Memphis (MVM) have defined the requirement for an expanded set of detailed sediment transport tools. A brief discussion of each tool follows.

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INTEGRATING THE U.S. DEPARTMENT OF AGRICULTURE, AGRICULTURAL RESEARCH SERVICE (USDA-ARS) BANK STABILITY AND TOE EROSION MODEL (BSTEM): Early versions of HEC-RAS were limited to vertical bed change. To expand the utility of the model, a set of algorithms was added to compute lateral morphological changes to the sediment transport model in HEC-RAS. HEC worked with Andrew Simon (Cardeno Entrix), Eddy Langendoen (USDA-ARS), and several USACE Districts (as well as several funding partners, including RSM) to include the USDA-ARS BSTEM in HEC-RAS. There are several potential algorithms that could have been integrated with the HEC-RAS sediment transport model to simulate lateral processes, but the USDA-ARS BSTEM model was selected because of an optimal level of detail, complexity, and data requirements. This is a powerful model linkage because vertical channel incision or deposition (the capabilities in HEC-RAS 4.1) interacts with lateral toe scour and the gravitational processes that control bank stability (Simon et al. 2000; Langendoen and Simon 2008) (schematized in Figure 1 and depicted in Figure 2), and deliver the sediment from bank failures directly to the channel. Bank processes are a critical component in determining (1) the amount and character of sediment entrainment from the channel bed and effects on downstream projects and habitat as well as (2) how the cross-section shape and, therefore, the boundary shear changes over time. The combined model can now predict the effects of these separate processes and their interactive feedbacks on local infrastructure, erosion mitigation, downstream reservoirs management, and restoration activities. By combining these models, the important process and their interactions can be simulated within the HEC-RAS modeling framework (Gibson 2013a).

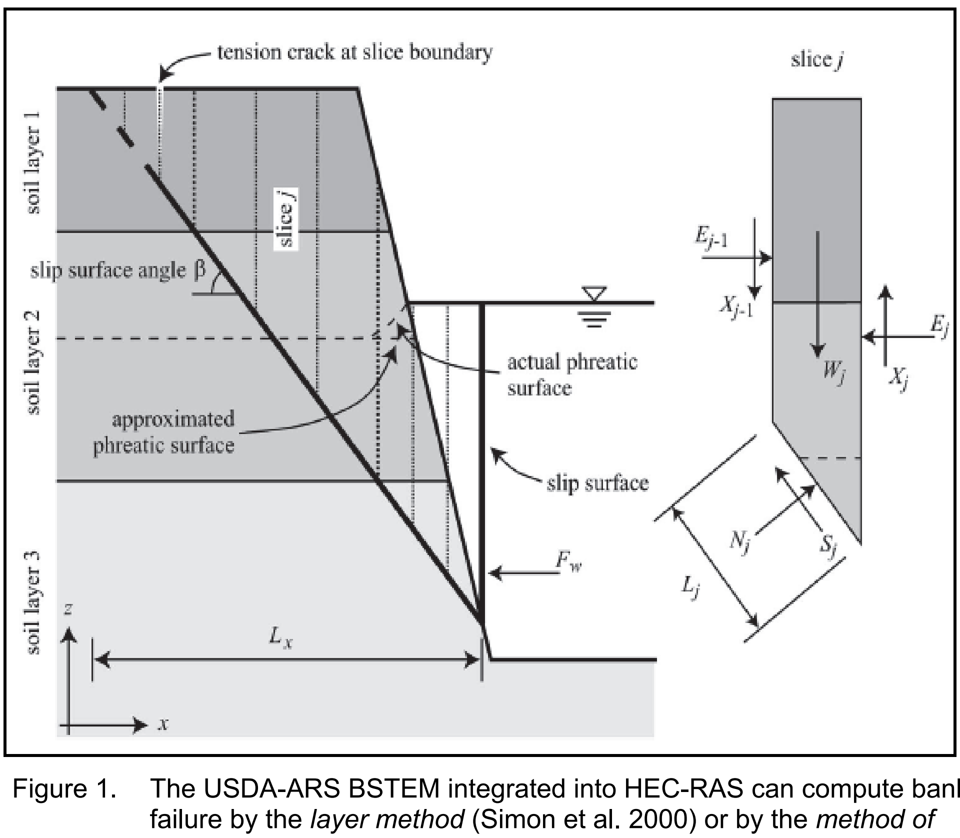

Figure 1. The USDA-ARS BSTEM integrated into HEC-RAS can compute bank failure by the *layer method* (Simon et al. 2000) or by the *method of slices* shown above (from Langendoen and Simon 2008).

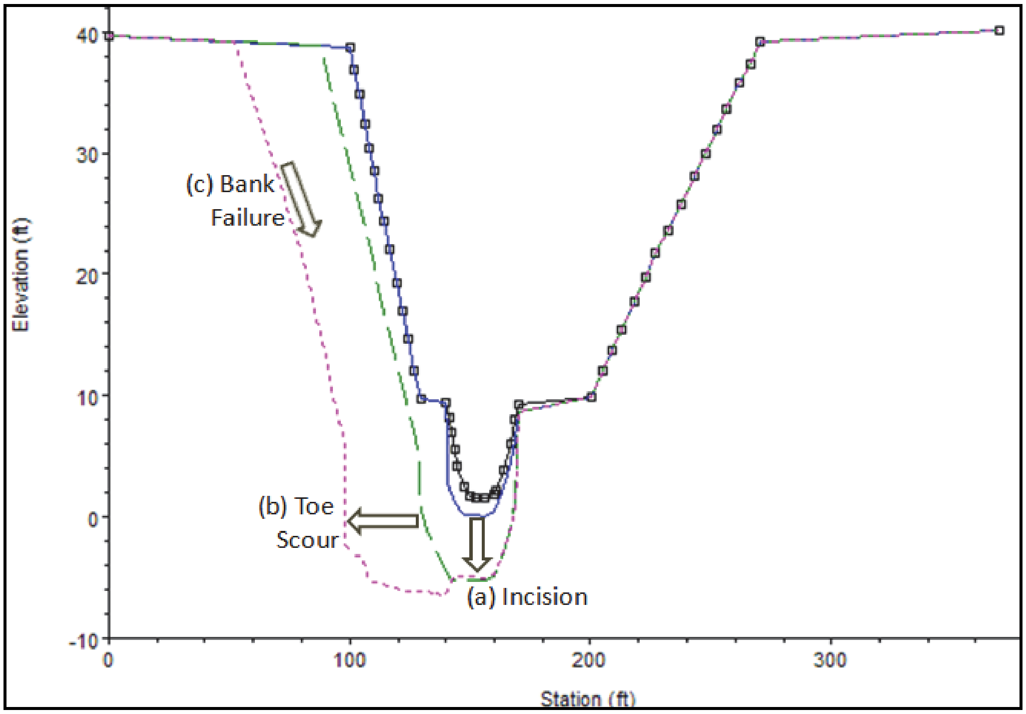

Figure 2. Change in channel geometry due to the three processes of (a) incision, (b) toe scour, and (c) bank failure, calculated by the USDA-ARS BSTEM module and the classical sediment transport capabilities in HEC-RAS.

UNSTEADY SEDIMENT TRANSPORT: Sediment management in reservoirs is an increasing concern to USACE project managers (Jonas et al. 2010). Many Federal reservoir projects are more than 50 years old, and sediment accumulation in the reservoir pool can limit operational flexibility and reduce flood control storage and water supply. As agencies examine ways to manage sediment in reservoirs, it is vital to accurately predict future sediment movement through the reservoir and delta development. USACE Districts need tools to predict and evaluate results of long-term sediment management alternatives such as dredging, sediment-trap structures, and hydraulic sluicing and flushing.

HEC integrated sediment transport with the HEC-RAS unsteady flow capabilities primarily to model the complex hydraulic and sediment interactions in a river and reservoir system. Previous versions of HEC-RAS (4.0 and 4.1) and its predecessors (HEC-6 and HEC-6T) utilize a *quasi-unsteady* hydrodynamic model that simulates sediment transport. This is a good approximation for most sediment transport studies because the time scale of sediment mobility is much longer than that of hydrodynamic time scales. However, the quasi-unsteady assumption begins to introduce significant errors into a sediment analysis if there is substantial water storage in the system, making it a particularly difficult limitation for integrated river/reservoir models.

Simulating sediment transport with unsteady flow also leverages several existing modeling tools native to the unsteady flow environment for sediment transport analysis. Powerful unsteady modeling tools like the operational rules functions in HEC-RAS can now be used to model and evaluate sediment objectives. Operational rules increase modeler flexibility by modeling reservoir control activities automatically based on defined management objectives without manipulating boundary conditions manually. NWO is currently using operational rules for reservoir management (USACE 2013) at Gavins Point Dam (Figure 3) and is developing complex hydrologic alternatives for sediment management (Figure 4) with relatively simple operational rules that eliminate time-consuming iteration between hydrologic and hydraulic models and stability issues. Figure 4 shows the stage and flow response to simple operational rules that automate the coordinated control of spillway gates and flushing tunnels to automatically model a five-stage flushing alternative with specified operational constraints in the Omaha District study.

ADDITIONAL MODELING METHODS: A number of other tools were developed specifically to meet the needs of NWO/NWK regional models and are expected to be in future releases of RAS, including the following.

Advance dredging features. Classical dredging methods were designed for navigation applications where channels are generally dredged regularly to a uniform elevation and extent that were established a priori. Dredging on the Missouri River and its tributaries, however, is typically commercial where sediment is removed for sale. Evaluating historic and future commercial dredging is a fundamentally different problem and requires specifying a time series of dredged mass to be removed from specified cross sections and then allowing the system to respond (Boyd and Gibson 2013). Therefore, HEC added mass-based dredging to HEC-RAS that allows users to specify dredged masses that are gradually removed over a defined period.

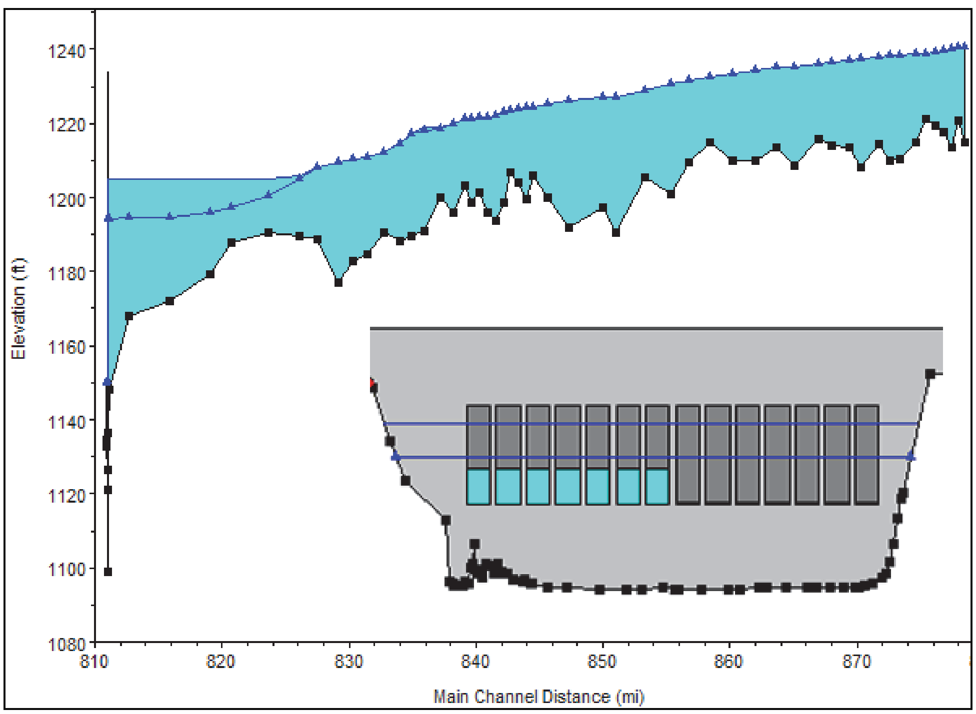

Figure 3. Spillway gate layout and river/reservoir stage for Omaha District study, Gavins Point Dam (USACE 2013).

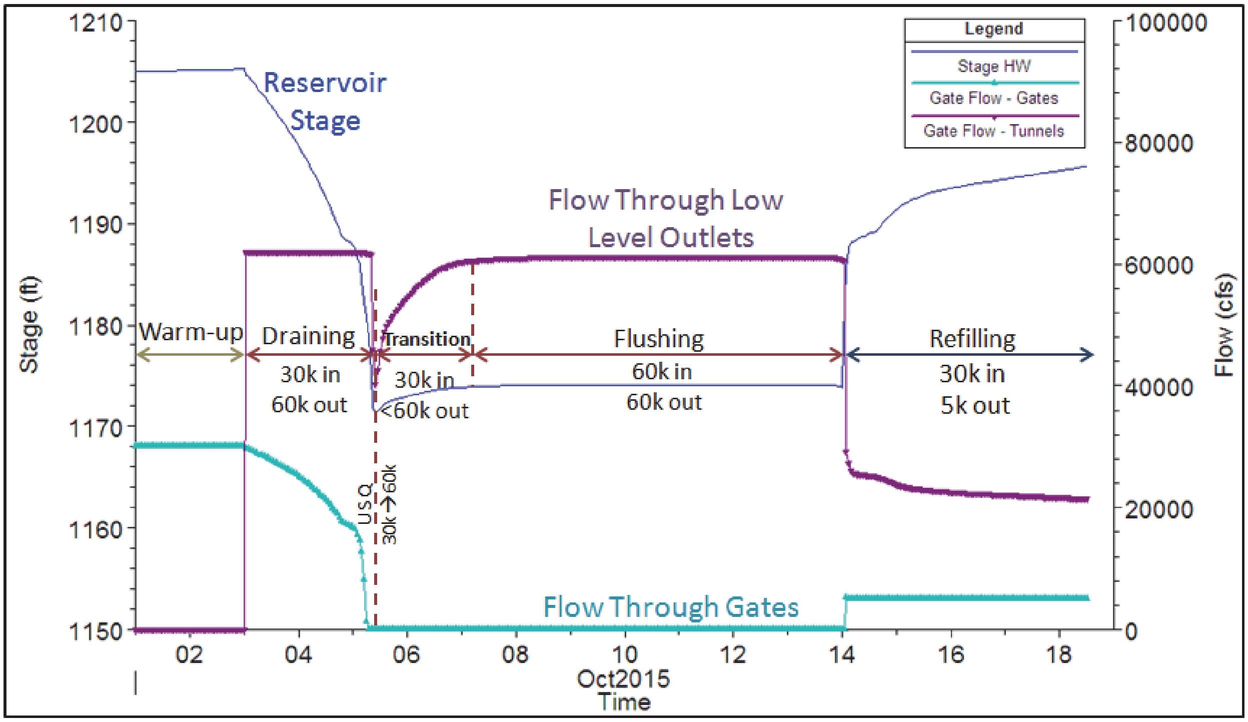

Figure 4. Stage and flow response to operational rules in dam spillway model, Gavins Point Dam (USACE 2013).

Additionally, Districts increasingly want to model the re-introduction of sediment (particularly fine-grained sediment) into the system as a byproduct of the dredging process or to model riverine disposal at another location. Methods to simulate these dredging alternatives have been added to HEC-RAS (Gibson 2013b).

Multiple erodible channels. The standard 1D limitation of a single, movable channel can complicate 1D sediment simulation of reservoir draw-downs. When large reservoir deltas scour, erosion is usually concentrated into several subchannels. When the 2011 Missouri River event scoured the Lewis and Clark Reservoir delta, scour was concentrated in two to three movable channels while the submerged vegetated islands between them were essentially static. Therefore, a multiple erodible channel feature was added to HEC-RAS that allows users to specify several discrete, movable bed limits that delineate laterally discontinuous regions of the channel that will or will not erode. Deposition can also be limited to these specified regions or allowed over the whole cross section. This feature improved the calibration of the HEC-RAS Lewis and Clark model using the 2011 actual event. Erosion of multiple channels using this function is depicted in Figure 5.

Sluicing and dam removal features. Classical bed change assumptions (i.e., the veneer method where every wetted node within the movable bed limits is raised or lowered an equal distance to reflect the eroded or deposited mass) can also limit 1D sediment modeling when simulating the development of a single channel in undisturbed reservoir sediments during a sluicing or dam removal simulation. Therefore, following the methods of Cui et al. (2006), Cantelli et al. (2004), and Greiman and Huang (2006), a simplified channel morphology model was added to HEC-RAS that allows channels to incise and widen according to more physical principles (Figure 6).

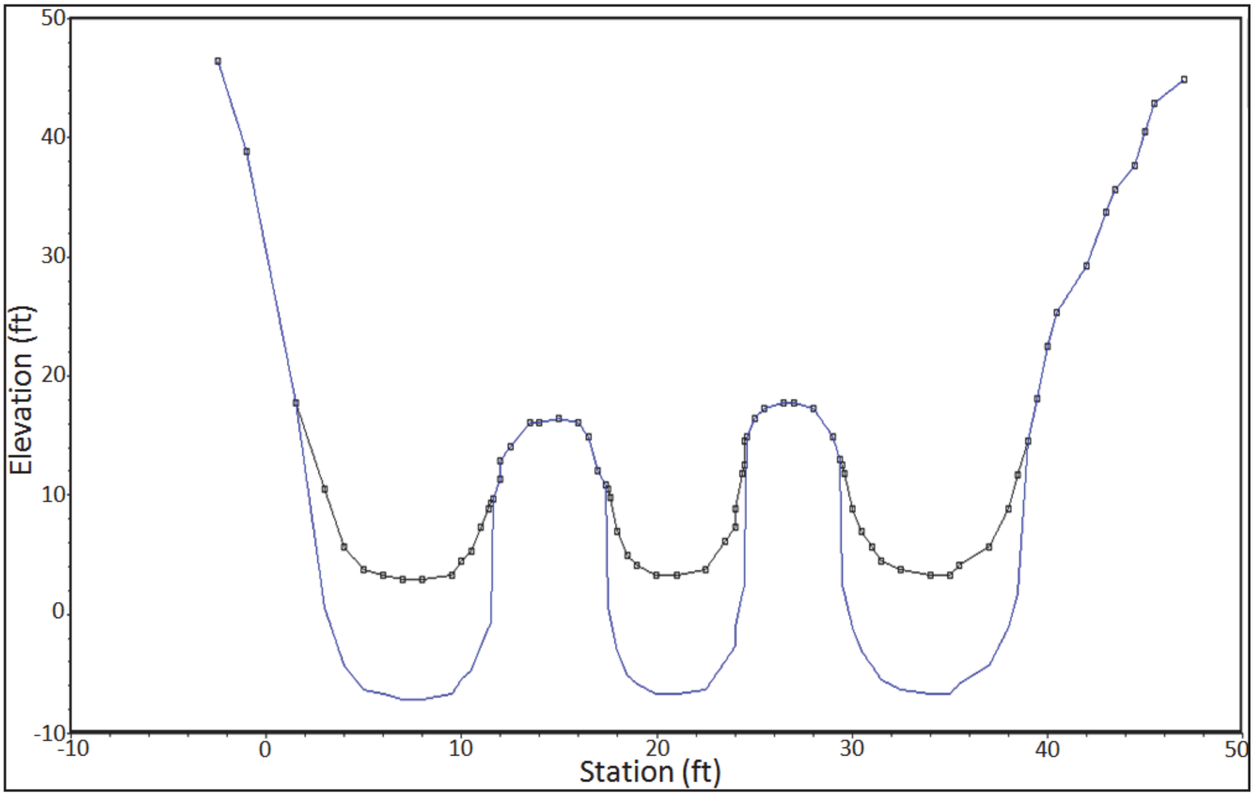

Figure 5. Response to multiple erodible channels.

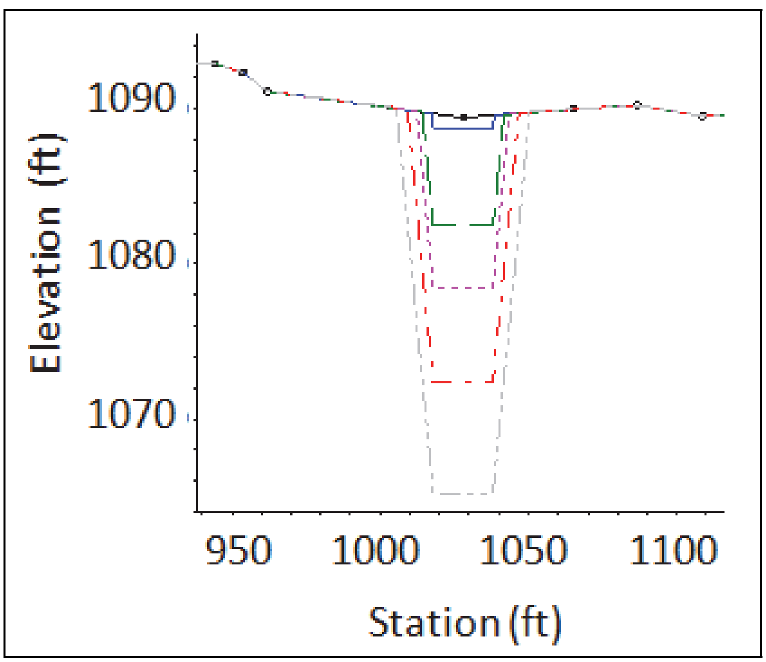

Figure 6. Simplified channel morphology method cutting a channel into reservoir sediments.

One of the challenges of using a simplified physical channel morphology model is parameterize-tion. A maximum channel width has to be selected a priori. This is a difficult parameter to estimate. Therefore, the Atkinson equation (Atkinson 1996) that incorporates the results of the best available database on the width of channels that formed in reservoir sediments was included in a calculator in the simplified morphology feature to allow users to select this parameter.

Finally, one of the challenges to reservoir scour applications like dam removals and sluicing is the vertical heterogeneity of reservoir sediments. Consolidated cohesive material or historic coarse layers can affect the volume and rate of scour through the exposed deposits (Evans et al. 2002). Version 4.1 of HEC-RAS can only allow a single material type per cross section and is limited to one set of cohesive parameters per project. Developmental versions of HEC-RAS include capabilities to specify multiple erodibility parameters (e.g., to reflect lower erodibility of deep, consolidated sediment), to define bed stratigraphy (i.e., different material types at different depths), and even to move sediment between grain classes depending on the process (e.g., if clay erodes in *clods,* it is transported in coarser grain classes and can deposit more easily downstream).

EXPECTED PRODUCTS: Beta versions of both the BSTEM module and unsteady flow sediment transport modeling are available in HEC-RAS version 4.2, expected to be released in final form by mid-2014. Many of the other features documented above will also be available in version 4.2. The additional modeling methods discussed remain in development and are being tested on multiple district projects. They will be included in future releases.

USACE District/Division staff with specific need for any of these tools, or who have ideas for additional new tools, are encouraged to contact the authors.

REGIONAL SEDIMENT MANAGEMENT IMPLICATIONS: As USACE considers aging infrastructure, climate change, limited budgets, and the need to more effectively manage sediment as a resource, the ability to accurately model future sediment movement is increasingly necessary. As the watershed approach is applied to sediment management, it is no longer acceptable to examine sediment at a local level.

Large watersheds can deliver upwards of 1 million tons of sediment per day in extreme events, which can result in significant geomorphic change to channels, cause erosion and deposition at navigation projects, and impact many project purposes.

The expanded sediment tools being added to HEC-RAS allow for more detailed assessment at a local level (BSTEM, multiple erodible channels), and allow for larger models to cover a greater portion of the watershed (unsteady flow, regional transport functions, reservoir operational rules) by integrating riverine and reservoir reaches.

Numerical models that include sediment transport are being used with more frequency as knowledge continues to develop about the impact that sediment has on infrastructure management, environmental restoration, and the economic value of sediments. Regional models that cover large portions of a watershed will be necessary to evaluate the interaction between multiple sediment sources and sinks. Using the expanded sediment tools in HEC-RAS will add detail and efficiency needed to evaluate sediment on a regional level.

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ADDITIONAL INFORMATION: Questions pertaining to this U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Coastal and Hydraulics Engineering Technical Note (CHETN), can be addressed to the USACE Omaha District Regional Sediment Management (RSM) Point of Contact, Dr. Paul M. Boyd (*Paul.M.Boyd@usace.army.mil*), or to Dr. Standford A. Gibson (*Stanford.Gibson@usace.army.mil*), USACE Institute for Water Resources, Hydrologic Engineering Center, Davis, CA. Additional information regarding this CHETN may be obtained from the USACE RSM Program Manager, Linda S. Lillycrop (*Linda.S.Lillycrop@usace.army.mil*). Additional information regarding RSM can be found at the Regional Sediment Management website *http://rsm.usace.army.mil*.

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