SEDIMENT TRANSPORT COMPUTATIONS WITH HEC-RAS

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Abstract: Sediment transport capabilities have been added to the Hydrologic Engineering Center's River Analysis System (HEC-RAS). HEC-RAS can be used to perform sediment routing and mobile bed computations. The initial version of this sediment model will leverage the wide range of hydraulic capabilities existing in HEC-RAS to compute a series of steady flow profiles used to develop hydrodynamic parameters for sediment transport. Hydraulic computations are "explicitly coupled" with transport, erosion, deposition, bed mixing and cross section change computations using the set of initial value-boundary value equations used in HEC-6. The result is a continuous simulation of the change in cross sections as sedimentation processes adjust to the hydraulic conditions imposed by the inflowing water-sediment hydrograph and the base level control boundary conditions.

INTRODUCTION

Sediment routing and mobile boundary simulations are commonly employed in support of various U. S. Army Corp's of Engineer missions. Traditional applications of dredging prediction, reservoir sedimentation and engineered channel stability have been joined by channel restoration and bed gradation response projects. HEC-6 has been the industry standard for one-dimensional mobile bed modeling since 1976. This DOS program has remained widely utilized while other popular HEC hydrologic and hydraulic models (HEC-1, HEC-2, and UNET) have been eclipsed by more powerful and user friendly products (e.g. HEC-RAS and HEC-HMS). However, many of the core capabilities of HEC-6 have recently been incorporated into HEC-RAS, leveraging the robust, existing, hydrodynamic capabilities in RAS and providing helpful user interfaces for one dimensional sediment transport modeling.

SCOPE

Sediment computations in HEC-RAS utilize one dimensional, cross-section averaged, hydraulic properties from RAS's hydraulic engines to compute sediment transport rates and update the channel geometry based on sediment continuity calculations. The initial objective is to replicate the functionalities of HEC-6 within the HEC-RAS framework. Once these capabilities are available new features and model advancements will be implemented.

METHODOLOGIES

Hydrodynamics: Flow specification for sediment transport computations currently follows the "quasi-steady" flow approach of HEC-6. An event or period of record is approximated by computing a series of steady flow profiles (Figure 1). Each of these each steady flow profiles is then associated with a duration and transport parameters are generated at each cross section. Usually, however, bathymetry updates are required more frequently than the flow increment duration, so a computational time step is specified. The geometry file is updated and new steady flow hydrodynamics are computed at the beginning of each computational time step.

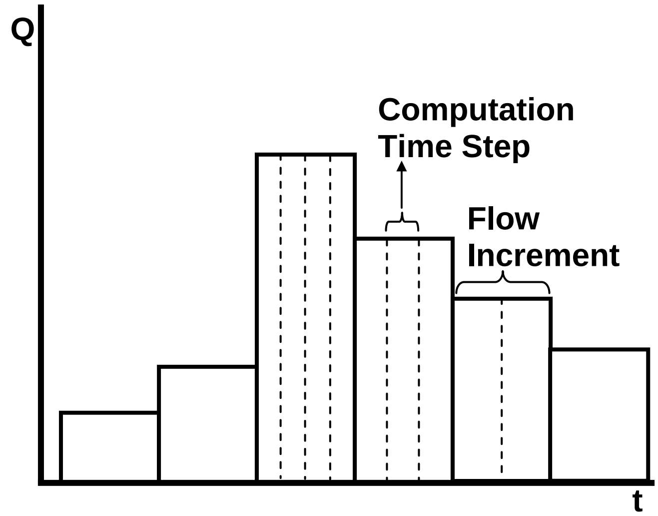

Figure 1 Schematic of quasi-steady flow division.

Transport Calculations: Six different transport functions are currently available in RAS including Ackers and White (1973), Englund-Hansen (1967), Laursen (1958), Myer-Peter-Muller (1948), Toffaleti (1968), and Yang (1972). Total transport capacity is calculated by invoking the *similarity hypothesis* (Armanini, 1992 and Vanoni 1975 after Einstein, 1950) by dividing the sediment gradation curve into discrete size classes, independently computing a transport potential for each size class and then weighted by the relative abundance in the active layer such that:

$$T_c = \sum_{j=1}^{n} \beta_j T_j$$

Where:

T_c=Total transport capacity
n=number of grain size classes
β_j=% of active layer composed of material in grain size class "j"
T_j=Transport potential computed for 100% of the material grain class "j"

The sediment continuity equation can then be solved over the control volume associated with each cross section, computing from upstream to downstream. The Exner equation is solved:

$$(1-\lambda_p)B\frac{\partial \eta}{\partial t} = -\frac{\partial q}{\partial x}$$

Where η is bed elevation, B is the width of the control volume, q is volumetric transport rate, λ_p is bed porosity. Qualitatively, this represents a change in bed elevation in response to a sediment deficit or surplus in the control volume when the capacity is subtracted from the supply. The Exner equation is solved separately for each grain size and material is added or removed to the active layer. At the end of each computational time step, the aggregation or degradation is translated into a uniform bed change over the entire wetted perimeter of the cross section. The cross sectional station-elevation information is updated and new hydraulics performed before the next transport capacity is computed for the next sediment routing iteration.

Physical Constraints to Erosion and Deposition: Physical constraints can result in a fraction of the sediment surplus or deficit computed by the Exner equation translating directly into aggregation or degradation in a given time step. RAS currently follows HEC-6 in applying temporal erosion and deposition modifiers as well as sorting and armoring routines to augment the simple continuity computations.

Temporal Modifiers: Solution of the Exner equation will result in 100% of the computed surplus or deficit translating immediately into deposition or erosion. This does not reflect actual physical processes, however, as both deposition and erosion are temporal phenomena. Therefore, time dependent modifiers are applied to the surplus or deficit HEC-RAS calculates at each cross section. Deposition efficiency is calculated by grain size based on the computed fall velocity and the expected center of mass of the material in the water column based roughly on Toffeletti's concentration relationships (Vanoni, 1975). The deposition rate as the ratio of sediment surplus that translates into deposition in a given time step is defined as:

$$\text{Deposition Rate} = \frac{V_s(i)\cdot \Delta t}{D_e(i)}$$

Where V_s(i) is the settling velocity for particle size i, D_e(i) is the effective depth for sediment size i (e.g. the midpoint of the depth zone in which transport is expected for the grain class), and Δt is the duration of the computational time step (USACE (1993) and Thomas (1994)).

A similar relationship was implemented to temporally modify erosion. This coefficient invokes "characteristic length" approach found in HEC-6 which includes the assumption that erosion takes a distance of approximately 30 times the depth to fully develop. Therefore, in cases where capacity exceeds supply, the capacity/supply discrepancy is multiplied by an entrainment coefficient (C_e) which limits the amount of material that can be removed from a cross section in a computational time step. The entrainment coefficient is:

$$C_e = 1.368 - e^{\frac{-L}{30\cdot D}}$$

where L is the length of the control volume and D is the effective depth (USACE (1993), Thomas (1994)). As the length of the control volume goes to thirty times the depth, the coefficient approaches unity and erosion approaches the full amount of computed deficit.

Sorting and Armoring: The other major process considered in the computation of continuity is potential supply limitation as a result of bed mixing processes. Currently HEC-RAS employs Exner 5, a "three layer" algorithm from HEC-6 to compute bed sorting mechanisms. Exner 5 divides the active layer into two sub-layers, simulating bed coarsening by removing fines initially from a thin cover layer. During each time step, the composition of this cover layer is evaluated and if, according to a rough empirical relationship, the bed is partially or fully armored, the amount of material available to satisfy excess capacity can be limited.

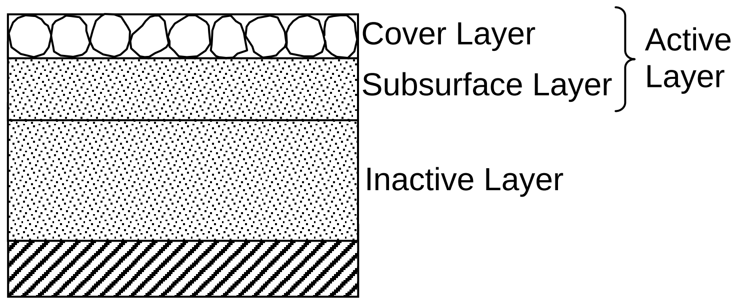

Figure 2 Schematic of 3-layers used in Exner 5 sorting and armoring method.

MODEL TESTING AND VERIFICATION

Comparison to Myer-Peter and Muller Data: Several tests have been conducted to evaluate these methodologies in HEC-RAS. First, HEC worked with Tony Thomas to simulate one of the original Myer-Peter and Muller (MPM) experiments (1948) with HEC-RAS and HEC-6T. Since the MPM transport function was derived from these experiments, they can be simulated with an expectation of reproducing the end result without the standard problems of transport function uncertainty. In the MPM experiment, a constant flow was run through a flat bed flume with a constant rate of gravel feed (grain size diameter 28.5mm) until it reached a stable, equilibrium slope of about 0.0081. This slope is plotted in Figure 3 with the equilibrium bed profiles computed by HEC-6T and HEC-RAS. There was very good agreement between the physical data and both numerical models.

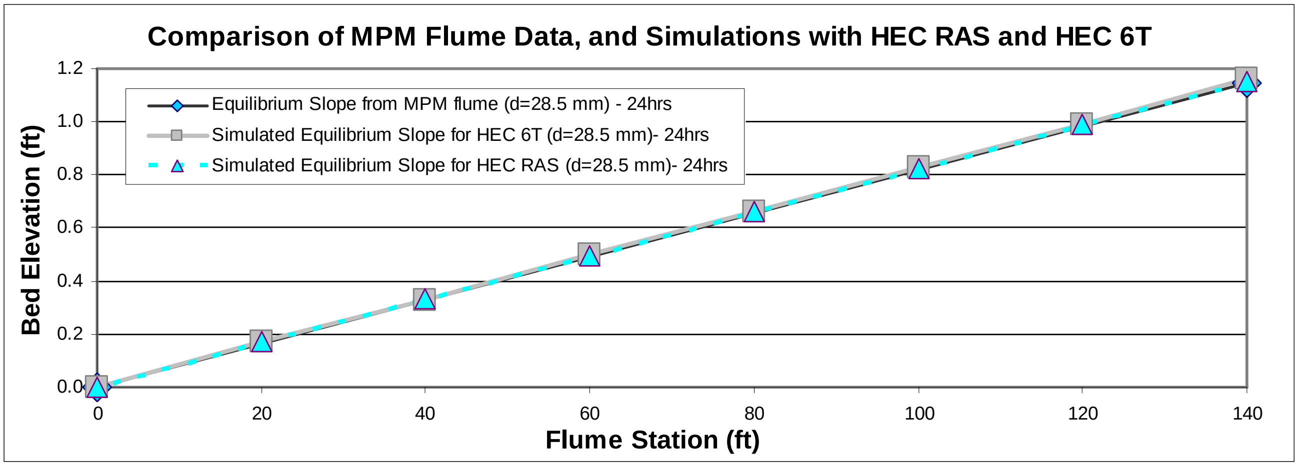

Figure 3 Myer-Peter and Muller flume data with HEC-6 and HEC-RAS simulations.

Comparison to HEC-6: There are several settings between HEC-6 and HEC-RAS that can produce divergent results (e.g. fall velocity method, hydraulic radius vs. hydraulic depth, and friction slope methods). In general, if these settings are harmonized, HEC-RAS does a reasonably good job replicating HEC-6 (e.g. Figure 3). However, sometimes small hydrodynamic differences can result in divergent sediment results. In the example depicted in Figure 4, Yang (1972) was applied to a trapezoidal channel with a single grain size material. Small differences in how HEC-6 and HEC-RAS compute water surface profiles resulted in a minor difference in calculated transport capacity (~0.56%). However, since supply was only slightly larger than capacity, this small capacity discrepancy translated into a 6% difference in total aggradation. Therefore the bed profiles diverge, despite very small calculated differences. It is of note that the computational differences implemented in RAS, though minor, are considered improvements by HEC and, therefore, the sediment responses to these are considered to be improvements as well.

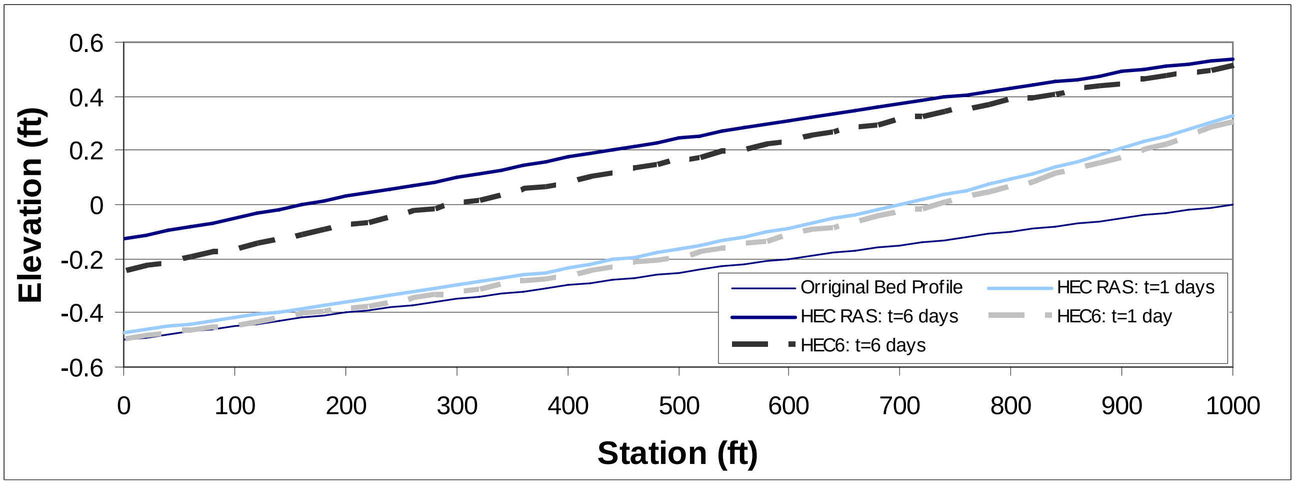

Figure 4 Single grain trapezoidal channel with supply slightly exceeding capacity simulated with HEC-RAS and HEC-6.

Finally, multiple grain size tests were conducted with HEC-6 and HEC-RAS to evaluate the effectiveness of the sorting and armoring routines. The Little and Mayer flume experiment (1972) where clean water was run over a graded bed to investigate armor development was used to test these algorithms. Because the inflowing sediment was set to zero, the sediment load exiting the upstream most cross section during a time step is equal to the eroded mass from that control volume. The material eroded from the upstream cross section is plotted for HEC-6 and HEC-RAS with transport capacities forced equal in Figure 5. As time passes and fine materials are removed from the bed. The bed coarsens and as grain classes are exhausted, there are significant, non-linear drops in the erosion rate. Finally, after approximately two thirds of a day, the armor layer fully forms and prohibits the removal of any more material. HEC-RAS produced the same pattern of grain-specific erosion and armoring as HEC-6 verifying the similarity of the algorithms.

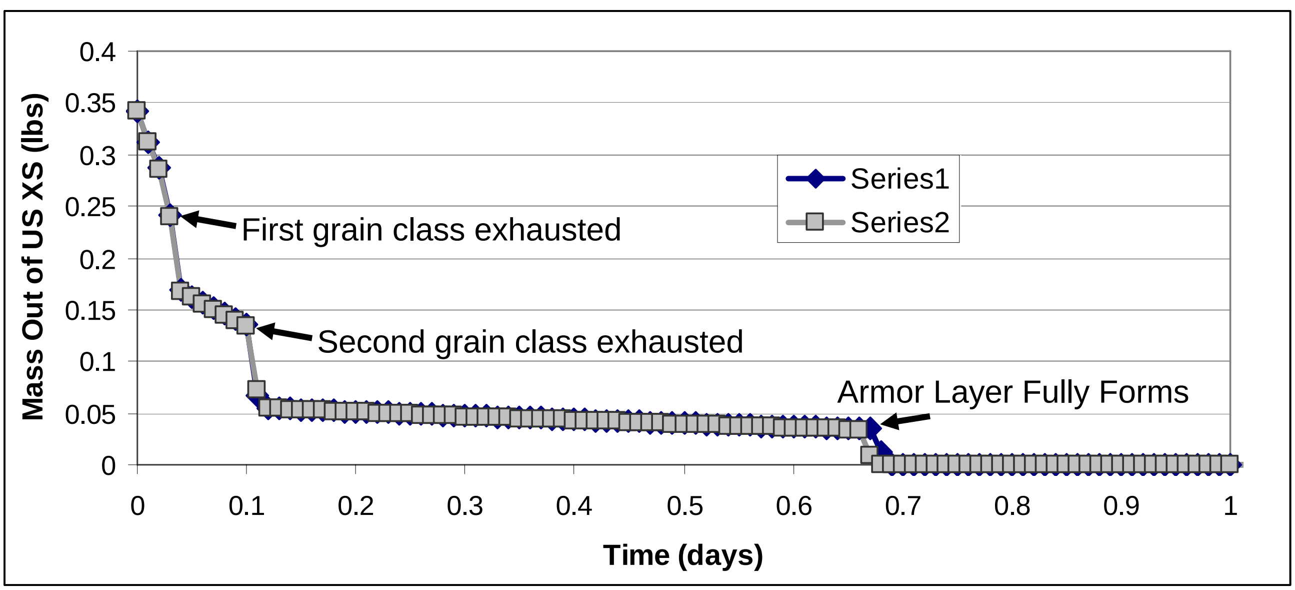

Figure 5 Mass removed from the upstream control volume of a graded bed flume with clear water inflow as simulated with HEC-6 and HEC-RAS.

USER INTERFACE

One of the benefits of implementing sediment transport functionalities into HEC-RAS is the ability to perform these analyses within the framework of the RAS graphical user interface. Sediment input screens have been added to this interface that allow users to specify the limits of their sediment control volumes (Figure 6). Each cross section is attributed with a bed gradation template (Figure 7) in order to allow the initial specification of bed gradation samples which are then associated with the appropriate range of cross sections with drag and click functions. The Flow-load relationships for the upstream boundary conditions and the corresponding gradational breakdowns are also specified through a table in the user interface (Figure 8)

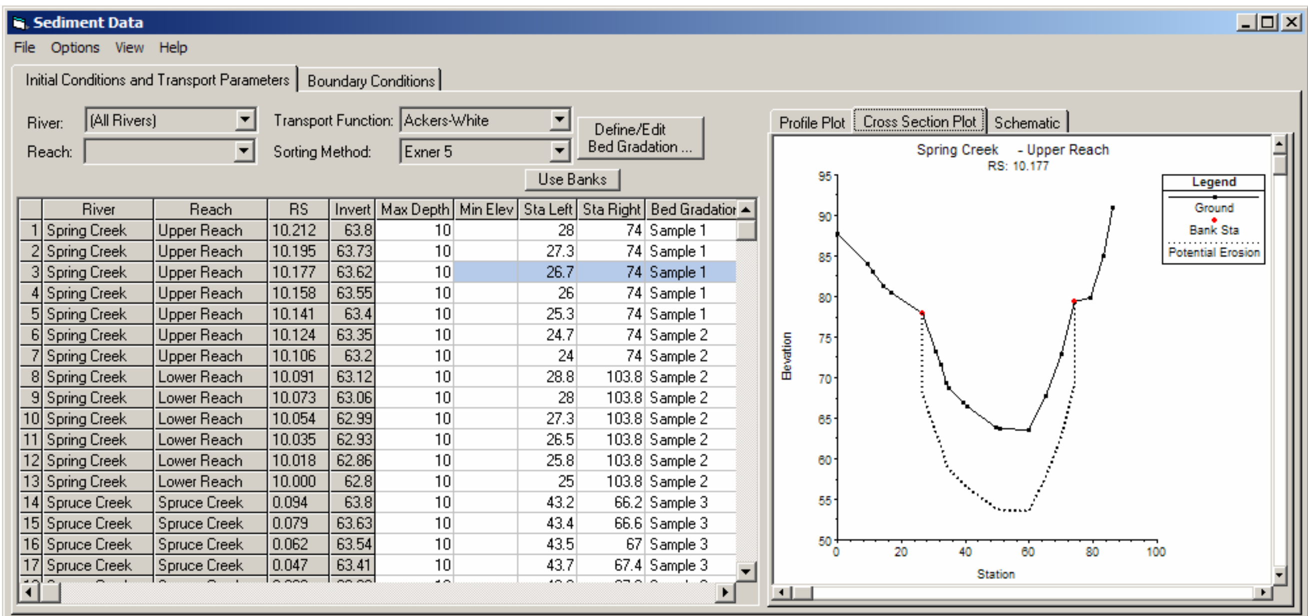

Figure 6 Sediment boundary conditions editor.

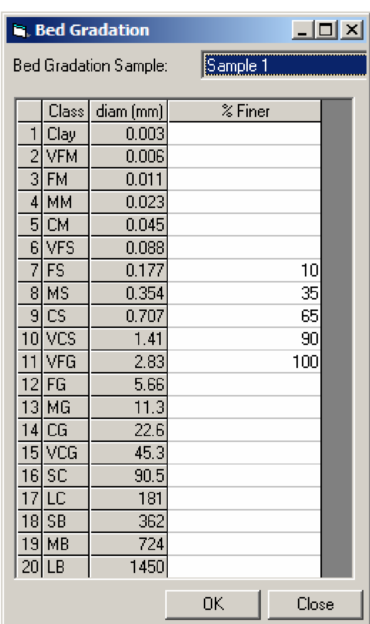

Figure 7 Bed Gradation Template.

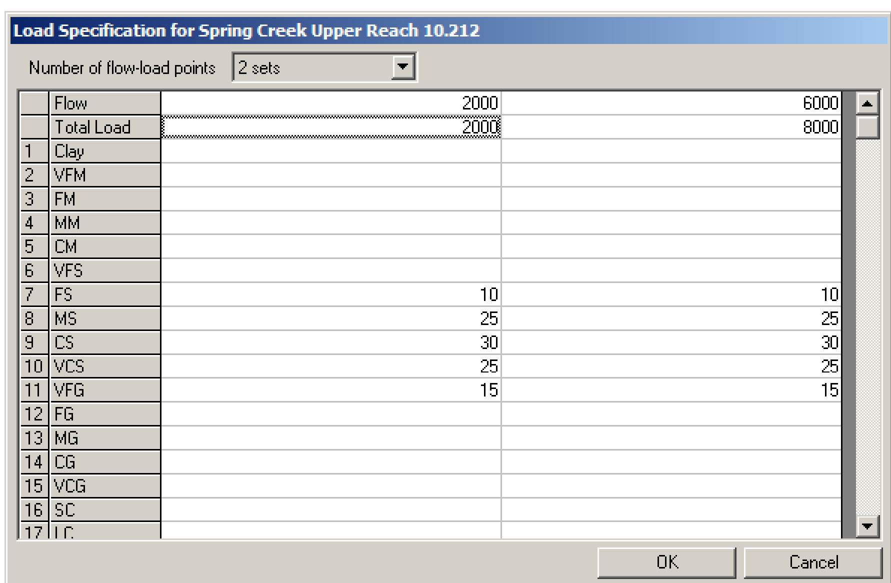

Figure 8 HEC-RAS load specification editor.

OUTPUT

HEC-RAS also has a wide range of variables accessible as output following a run. User output can be viewed as time series or profile data which can be animated.

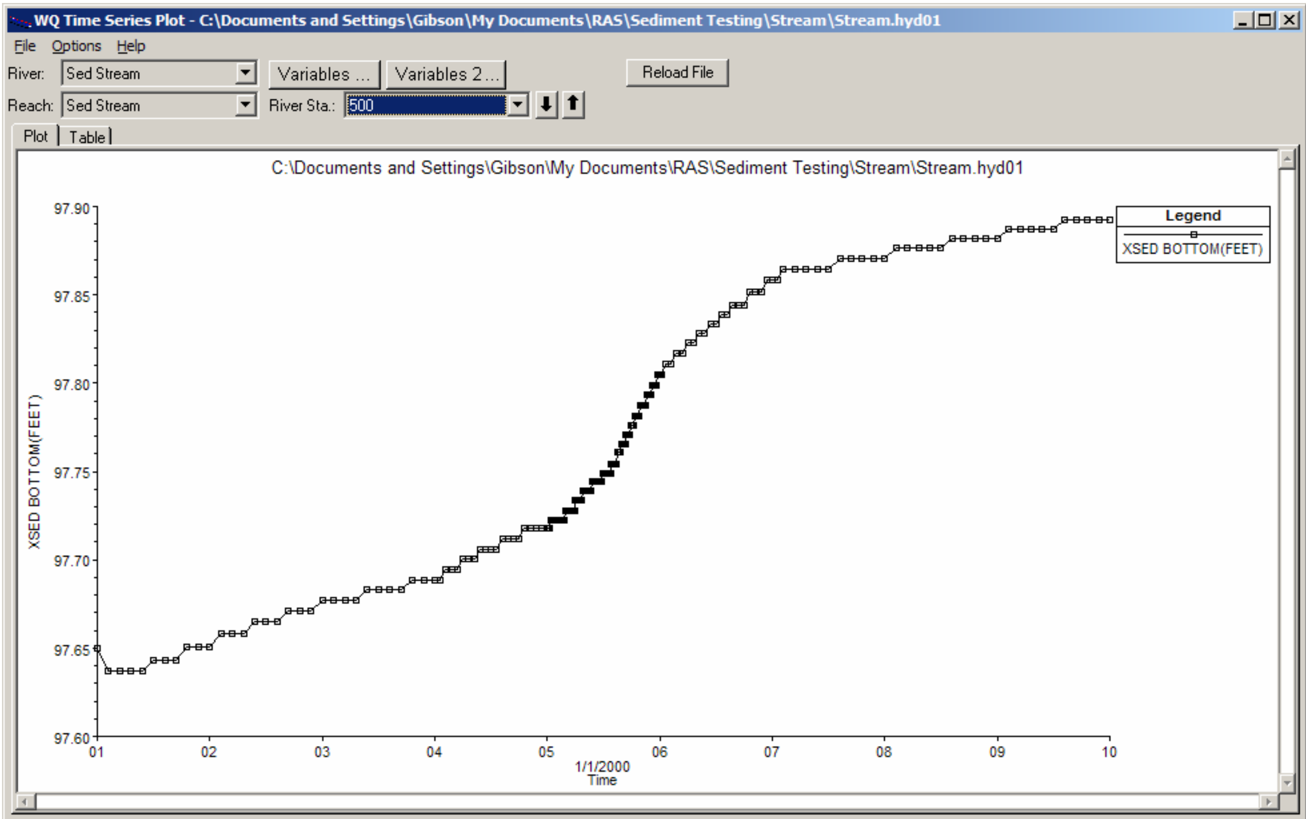

Figure 9 Example of a time series output of bed aggradation at a specified cross section.

CONCLUSION

HEC-RAS now has basic sediment transport capabilities. RAS utilizes quasi-steady hydrodynamics and one of several transport equations to solve the sediment continuity equation. Sediment surpluses and deficits are modified with temporal and physical constraints and translated into bed aggradation and degradation. After each computational time step the RAS geometry file is updated based on bed elevation changes for the hydrodynamics and sediment potential computations to use during the next time step. The model has generally performed well in testing against HEC-6 and flume data, but can differ slightly from HEC-6 in certain conditions due to minor differences in hydraulics. RAS includes a convenient user interface to specify the necessary data for a sediment analysis and a wide range of available outputs for analyzing a simulation.

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