COMPUTATIONAL MODEL FOR THE DEVELOPMENT OF SEDIMENT PLUGS IN ALLUVIAL RIVERS

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Abstract: Historical cases for sediment plug formation in alluvial rivers have been documented, but often plug development is attributed to such factors as a sudden decline in sediment transport capacity, the effect of debris in a channel, or human factors such as watershed management. These qualitative explanations are pertinent, but a study was conducted to identify the specific processes occurring at the location where plugs develop. A theory regarding plug formation was formulated following an extensive literature review, evaluation of data, and discussions with other researchers. Sediment plugs form at significant constrictions in alluvial rivers. As flows are lost to the overbank areas at these constrictions during higher flow events, sediment transport capacity decreases, but the total sediment load in the main channel does not reduce by the same proportion. As a result, deposition ensues in the main channel. If flows continue to overbank for weeks, the deposition will eventually completely clog the main channel of the river. An original numerical sediment transport/movable bed computer model was developed to test the theory. The one-dimensional, open channel, numerical model performs hydraulic calculations, computes sediment transport rates, and determines erosion/deposition. The sediment transport/movable bed numeric model was developed solely to analyze the development of sediment plugs with specific focus on the effects of the loss of flow to the overbank areas, the corresponding loss to the total sediment load, and the subsequent effects on erosion/deposition in the main channel. The model was calibrated and validated against plug formation in the Middle Rio Grande during 1995 and 1991. Ultimately, the model will be used to develop simplified criteria for the development of sediment plugs in alluvial rivers.

INTRODUCTION

There are several documented cases of sediment plugs forming in alluvial rivers. While there are general qualitative conclusions as to why these plugs formed, there has not been extensive study of the specific processes occurring at the locations where plugs develop. Research was conducted to identify the specific processes that cause plug formation. A theory on the cause of sediment plug formation was formulated. That theory was tested using an original sediment transport/movable bed computational model.

Definition: A sediment plug is aggradation (that may include debris) in a river which completely blocks the original channel (Diehl, 1994) and grows upstream by accretion (Diehl, 2000). The plugs, or local channel filling, may result from an obstruction combined with sediments derived from upstream (Shields *et al.*, 2000). Sediment plugs historically form over short periods – a matter of weeks in some cases (USBR, 1992). Plugs can grow to be miles in length and can cause numerous problems for river managers.

PLUG FORMATION THEORY

Several processes, associated parameters, and site characteristics exist that may influence the development of sediment plugs. After evaluating available information on historical sediment plug formation, a theory was formulated for the prediction of plug development (Boroughs, 2005). This theory focuses on the key processes that ultimately lead to the entire main channel of the river becoming clogged with sediment (i.e. a sediment plug) for a specified channel morphology.

For a reach of an alluvial river that is prone to sediment plug development due to a significant constriction such as a bend, structure, or debris snag that ultimately causes a reduction in conveyance capacity greater than 50%, a sediment plug will form if the following series of events occurs:

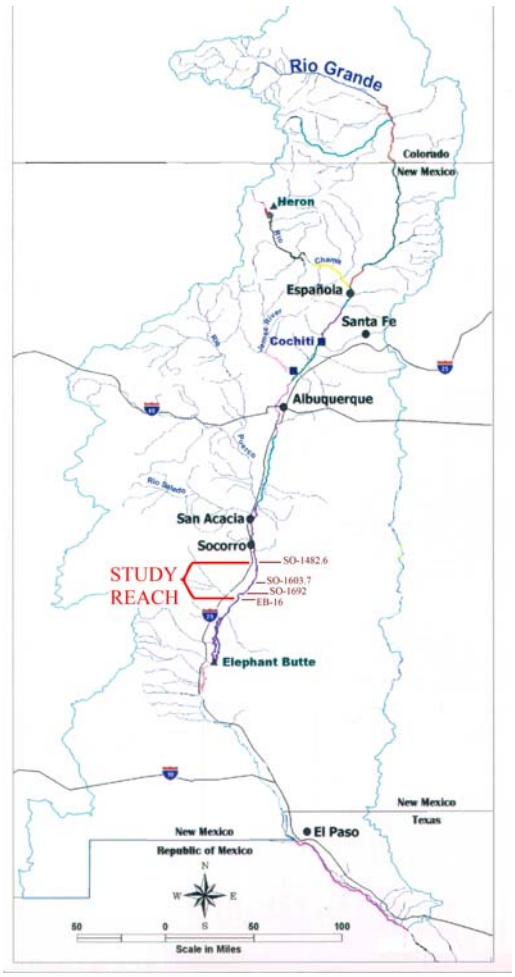
- daily total sediment load into the reach exceeds the historical average daily total sediment load (corresponding with above average flows),
- a significant portion of the flow abruptly overbanks (within a few thousand feet longitudinally along the river) combined with a non-uniform vertical distribution for the total sediment load – the sediment transport

capacity is reduced without the same proportional reduction in the total sediment load causing deposition to ensue in the main channel, and

- higher flows are prolonged, causing deposition to continue until the entire main channel of the river becomes completely clogged (i.e. a sediment plug has formed).

FOCUS STUDY REACH

The focus study reach (Figure 1) for calibrating and validating the computational model for sediment plug formation is the Tiffany Junction Reach of the Middle Rio Grande that extends from the Highway 380 bridge south of Socorro, New Mexico to below the railroad bridge near the United State Geological Survey (USGS) streamflow gage Rio Grande at San Marcial (ID# 08358400) (USGS, 1988-2003). An expansive set of USGS data was referenced which would also most closely represent conditions around the time of historical plug formation. The first upstream cross section is at the U.S. Bureau of Reclamation's (Reclamation) rangeline SO-1482.6 located just below the Highway 380 bridge, and the last downstream cross section is at Reclamation's rangeline EB-16 located below the San Marcial gage. The study reach is approximately 22 river miles in length.



Vicinity Map

Figure 1 Rio Grande Map with the Tiffany Junction Reach Depicted (w/ Vicinity Map)

Aerial photography (USBR, 2003) is available for reviewing the channel geometry along the study reach at the time of plug formation. The main channel is wider with widths exceeding 1000 feet through much of the upper portion of the reach, but the channel is narrower toward the southern end of the reach where the width does not exceed 300 feet. The sediment plugs that formed in 1991 and 1995 initiated in the narrowest portion of the reach immediately above Reclamation's rangeline SO-1692. The constriction at this location provides the key set-up condition for plug development.

COMPUTER MODEL METHODS

The theory of sediment plug formation was tested using a sediment transport/movable bed computer model of the Tiffany Junction Reach of the Middle Rio Grande. The one-dimensional, open channel, numerical model performs hydraulic calculations, computes sediment transport rates, and determines erosion/deposition. The sediment transport/movable bed numeric model was developed solely to analyze the development of sediment plugs with specific focus on the effects of the loss of flow to the overbank areas, the corresponding loss to the total sediment load, and the subsequent effects on erosion/deposition in the main channel. The model is referred to as the SPAR model for this discussion as an acronym for the Sediment Plug formation in Alluvial Rivers simulation model.

Hydraulics: Within the numerical model, information on the hydraulics is determined by solution of the unsteady flow equations. These calculations are completed using a timestep chosen with consideration for the Courant-Friedrich-Levy condition (Julien, 2002) to assure stability while reducing numerical diffusion.

Unsteady Flow Calculations: One-dimensional hydraulic calculations are completed in the SPAR model using the double sweep procedure to solve the linearized unsteady flow equations determined using the Preissman scheme (Hromadka *et al.*, 1985). Unsteady flow calculations are completed primarily to allow the effects of flow losses to the overbank areas to be considered. A stage-discharge curve is input for the downstream boundary condition. An inflow hydrograph is used for the upstream boundary condition. A weighting coefficient, θ, of 0.7 is utilized in the Preissmann scheme (Julien, 2002). An appropriate timestep is selected within the model to assure the Courant-Friedrich-Levy condition is satisfied (Julien, 2002):

$$C = c\frac{\Delta t}{\Delta x} = \beta V\frac{\Delta t}{\Delta x} \leq 1.0 \tag{1}$$

where C is the Courant Number,
c is the wave celerity,
Δt is the timestep,
Δx is the spatial step,
β is the exponent in the Q (discharge) vs. A (cross sectional area) relationship for the study reach, and
V is the mean velocity.

The spacing between the input cross sections, Δx, is known, and an input inflow hydrograph is referenced to determine an estimate for the highest expected mean velocity during a simulation. The corresponding wave celerity, c, is then computed assuming β equals 5/3 based on the Manning equation. The highest Δt is then computed such that the Courant number will be equal to 1.0 for the determined highest expected wave celerity. The Courant-Friedrich-Levy criterion will assure computational stability while reducing numerical diffusion as a result of the computational scheme.

Losses to the Overbank Areas: The lateral loss of flow to overbank areas is computed using the broad crested weir equation (Henderson, 1966):

$$Q = C\Delta x H^{3/2} \tag{2}$$

where Q is the flow over the weir (cfs),
C is the broad crested weir coefficient,
Δx is the width of the weir (ft), and
H is the head over the weir crest (ft).

The head over the weir is the elevation of the water surface over the bank elevation (velocity head is neglected for this computation of lateral outflow). The width of the weir is equal to the incremental spatial step in the computer model. As discussed later, the broad crested weir coefficient is the primary calibration parameter in the model. The

elevation of the banks along each incremental spatial step is determined using the main channel cross section endpoints. The computed loss to the overbank areas is then included in the solution of the unsteady flow equations.

Sediment Transport: Sediment transport is computed in the SPAR model using an input power function rating curve:

$$Q_S = aQ^b \tag{3}$$

where Q_S is the total sediment load (tons/day),
a is the coefficient from the regression relationship,
Q is the flow (cfs), and
b is the exponent from the regression relationship.

Parameters a and b in Equation 3 were determined by a regression analysis relating computed total sediment loads to flowrates measured at the USGS gage at San Marcial. Total sediment loads were computed using the Modified Einstein procedure (Yang, 2003) and data collected at San Marcial.

Vertical Distribution of Sediment Load: The vertical distribution of the total sediment load is computed in the SPAR model based on a computed vertical velocity profile and a vertical profile for the sediment concentration. The vertical distribution of the total sediment load is the product of the velocity and concentration profiles. The percentage of the total sediment load carried above a specific elevation can then be determined.

The vertical velocity profile, $v_x(z)$, is computed based on the equation for flow over a rough boundary (Julien, 1995):

$$\frac{v_x}{u_*} = \frac{2.3}{\kappa}\log\left(\frac{z}{k_s'}\right) \tag{4}$$

where v_x is the velocity (ft/s),
u_* is the shear velocity (ft/s),
κ is the von Kármán constant,
z is the elevation above the bed (ft), and
k_s' is the mean grain roughness height (ft).

The shear velocity, u_*, is computed during the model simulation along with the friction slope and hydraulic radius. The von Kármán constant, κ, is set to 0.4. A mean grain roughness height, k_s', is input.

The vertical distribution of the sediment concentration is computed using the Rouse equation (Julien, 1995):

$$C = C_a\left[\left(\frac{h-z}{z}\right)\left(\frac{a}{h-a}\right)\right]^{Ro} \tag{5}$$

where C is the concentration at elevation z,
C_a is the concentration at reference elevation a,
z is the elevation above a datum elevation,
h is the flow depth, and
Ro is the Rouse number.

A Rouse number, Ro, is input. The concentration, C_a, at a distance, a, above the channel bed is determined such that the total sediment load along the vertical at the deepest depth in a cross section matches that same parameter computed using the sediment transport power function (Equation 3). The distance, a, is set to 4/20th of the depth where the concentration is appreciably greater than zero but not too close to the bed where the concentration approaches infinity based on the Rouse equation. (The concentration is assumed to be uniform for the bottom 1/20th

of the vertical to prevent a concentration of infinity at the bed surface as computed using the Rouse Equation). The value of C_a is determined by dividing the total sediment load by the top width, then multiplying by the deepest depth and dividing by the hydraulic depth to determine the total sediment load along the vertical at the location of the maximum depth.

Loss of Sediment to Overbank Areas: As flows overbank, the river stage above the bank elevation at each cross section is referenced for determining the percentage of the total sediment load transported above that bank elevation. It is assumed that this portion of the total sediment load is lost to the overbank areas with the loss of flow. The lower total sediment load at the downstream node for an incremental spatial step – due to the reduction in flow – is computed using the power function rating curve; however, the amount of sediment lost to the overbank areas needs to be known before determining the amount of erosion/deposition along the incremental spatial step (i.e. any sediment lost to the overbank areas is not available for deposition in the main channel). The influx of sediment to the upstream node for an incremental spatial step is reduced by the amount of sediment lost to overbank areas.

Erosion/Deposition: After the appropriate sediment transport magnitudes are known for each cross section for a given timestep, the amount of erosion or deposition is computed and the cross section geometry is modified before progressing to the next timestep. The erosion/deposition is computed in the SPAR model using an immediate erosion/deposition method (or the Exner equation with a trap efficiency of 100%) (Julien, 2002):

$$T_{Ei}\frac{\partial Q_{txi}}{\partial x}+\left(1-p_0\right)\frac{W\partial z_i}{\partial t}=0 \tag{6}$$

where T_{Ei} is the trap efficiency,
Q_{txi} is the sediment discharge,
∂x is the incremental spatial step,
p_0 is the porosity of the bed material,
W is the channel width,
∂z is the vertical change in bed elevation (deposition or erosion), and
∂t is the timestep.

The lateral distribution of erosion/deposition is based on the depth along the cross section divided by the hydraulic depth (Cunge *et al.*, 1980). If the water surface elevation is above the bank elevation, the calculation is the same but the bank elevation is utilized as opposed to the water surface elevation when computing the depth along the cross section and the hydraulic depth (Cunge *et al.*, 1980). The erosion/deposition is evenly split longitudinally between the two adjacent cross sections bounding the incremental spatial step being analyzed (Julien, 2002).

MODEL CALIBRATION AND VALIDATION

The SPAR model developed to simulate sediment plug formation was created in FORTRAN using all the methods/procedures just discussed. Since software packages are not available that include all the necessary components, the original SPAR program was developed. The hydraulic calculations in the SPAR model were validated against the commonly used program, HEC-RAS, that is routinely used to solve the unsteady flow equations (USACE HEC, 2002). The SPAR model was then calibrated for sediment plug development along the Tiffany Junction Reach in 1995. The model was then validated against information from the Tiffany Junction Reach that plugged in 1991.

Calibration to Plug Formation in 1995: The SPAR model was calibrated for the 1995 plug formation event along the Tiffany Junction Reach. The input information consisted of a total sediment load power function, a downstream stage discharge curve, an inflow hydrograph, a constant Manning n roughness value of 0.017, a porosity of 0.43, a mean particle size of 0.25 mm, a corresponding particle fall velocity of 0.113 ft/s, and a Rouse number of 1.15. Data from cross section surveys completed prior to 1995 were utilized for the calibration simulation. The input initial depths at each cross section were determined by completing a steady state simulation with HEC-RAS with the initial inflow.

All the parameters input into the model are initially known except for the broad crested weir coefficient for computing the lateral loss of flow to the overbank areas. This value was determined such that the plug that developed in the SPAR model matched the plug that formed along the Tiffany Junction Reach in 1995. In addition to predicting the deposition in the main channel at individual cross sections, the calibration was completed to match the longitudinal extent of the plug as it existed in August of 1995.

The calibrated broad crested weir coefficient used for simulation is 0.5. This value represents the degree of submergence for flow over a weir. The lateral loss of flow over the banks of the main channel of an alluvial river simulates flow over a submerged weir. As the water surface elevation on the downstream side of a weir approaches the water surface elevation on the upstream side of a weir, the broad crested weir coefficient approaches zero (Davis, 1952), so the 0.5 value, which is lower than the typical value of 3.09 for free flow over a broad crested weir, reflects the effect of a higher water surface elevation on the downstream side of a weir.

A comparison of bed elevations predicted with the SPAR model versus bed elevations measured during 1995 is presented in Figure 2. Based on anecdotal information and data, the plug extended nearly five miles as of August 5, 1995. Deposition continued through 1996 before a pilot channel was dredged and the plug washed out in 1997. A plot of predicted deposition at Reclamation's cross section SO-1652.7 along the reach is presented in Figure 3. The SPAR model was successfully calibrated for plug formation along the Tiffany Junction Reach during 1995.

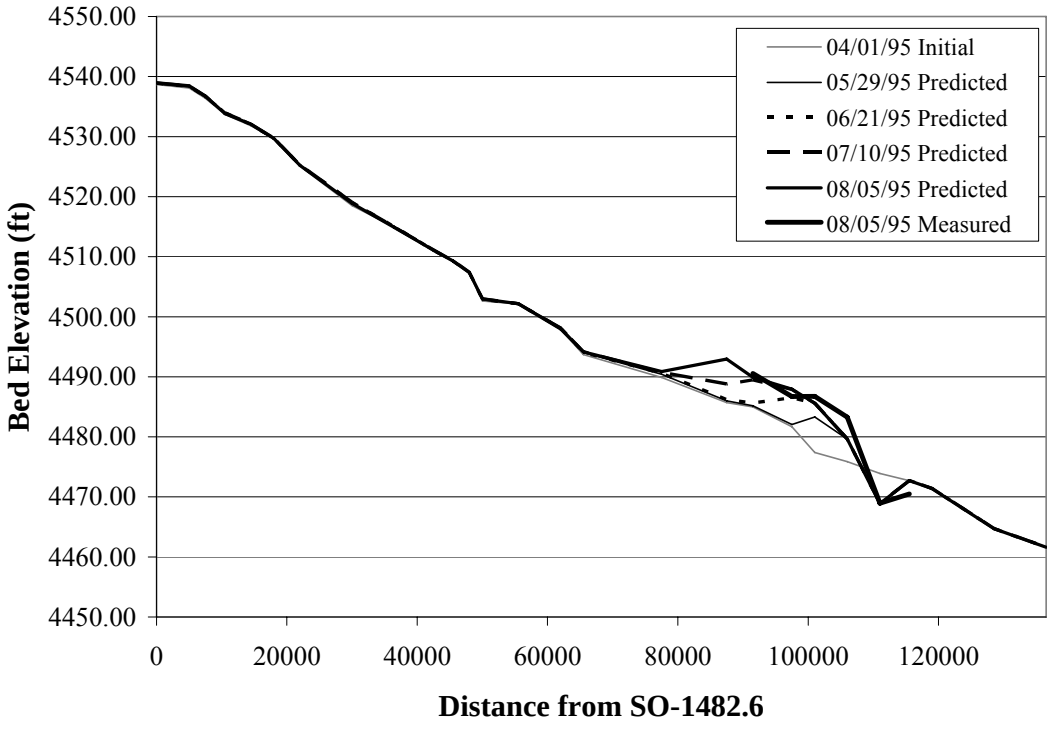


Figure 2 Plot of 1995 Initial, Predicted, and Measured Bed Elevations

Validation against Conditions in 1991: After the SPAR model was developed and calibrated with data from 1995, a model run was prepared for conditions along the Tiffany Junction Reach in 1991. The most recent cross section survey data prior to plug formation in 1991 were used and the upstream hydrograph was developed based on gaged flows. The simulation yielded a plug that, although was approximately 40% smaller by volume, matched the reported extents of the plug that developed in 1991 (USBR, 1992).

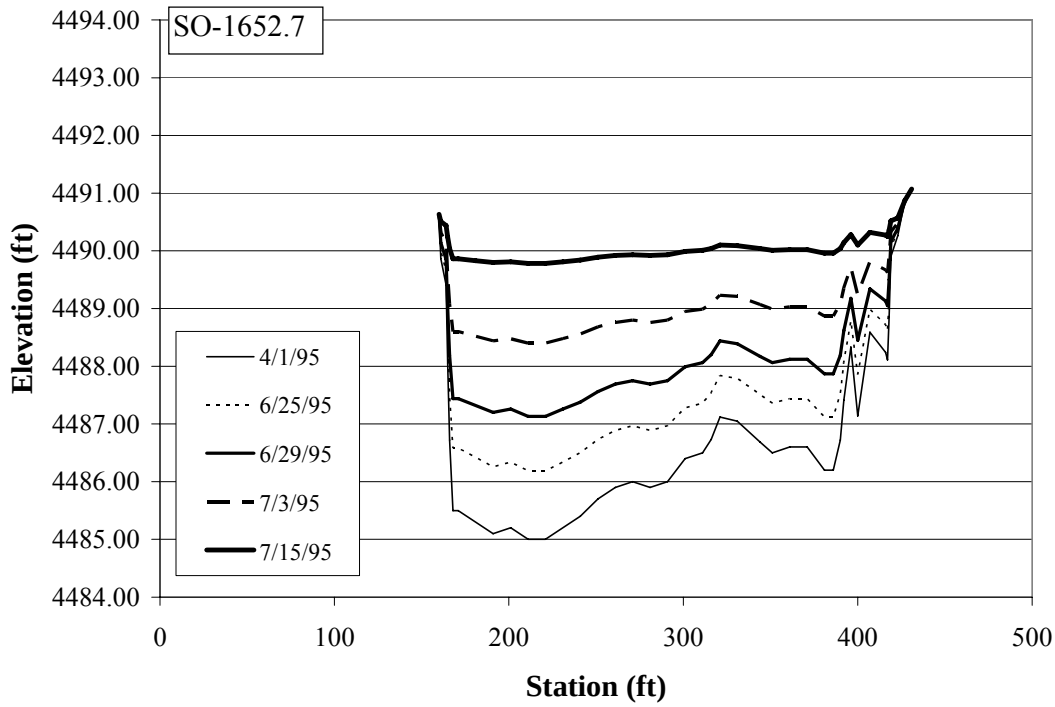


Figure 3 Plot of Predicted Deposition during 1995 at Cross Section SO-1652.7

The SPAR model was successfully calibrated and validated. While this program was calibrated and validated using data for the Tiffany Junction Reach of the Middle Rio Grande, this program is applicable to other alluvial river systems. The SPAR model can now be used to simulate different conditions along an alluvial river in regards to channel cross sections, reach inflows, river slope, etc. and analyze values of different parameters during plug formation.

SUMMARY AND CONCLUSIONS

An investigation was conducted to better understand why, how, where, and when sediment plugs form. A theory on sediment plug development was formulated. For a reach of an alluvial river that is prone to sediment plug development due to a significant constriction such as a bend, structure, or debris snag that ultimately causes a reduction in conveyance capacity greater than 50%; a sediment plug will form if the following series of events occurs:

- daily total sediment load into the reach exceeds the historical average daily total sediment load (corresponding with above average flows),
- a significant portion of the flow abruptly overbanks (within a few thousand feet longitudinally along the river) combined with a non-uniform vertical distribution for the total sediment load – the sediment transport capacity is reduced without the same proportional reduction in the sediment load causing deposition to ensue in the main channel, and
- higher flows are prolonged causing deposition to continue until the entire main channel of the river becomes completely clogged (i.e. a sediment plug has formed).

The theory regarding sediment plug formation was tested using a general sediment transport/movable bed computer model. The model includes methods for completing unsteady flow calculations while satisfying the Courant-Friedrich-Levy condition. The lateral loss of flow to the overbank areas is computed using the broad crested weir equation. A corresponding loss to the total sediment load is also determined. After the loss of flow and total sediment load is considered, a resulting immediate deposition/erosion in the main channel is computed based on the change to the sediment transport capacity.

The model was calibrated for plug formation along the Tiffany Junction Reach of the Middle Rio Grande in 1995. The model was then validated for plug development along that reach in 1991. As a result of this study, engineers not only have a better understanding as to how and why sediment plugs form but will be able to use the computer model better predict when and where a plug will develop and ultimately prevent or manage plug development.

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