RECLAMATION
Managing Water in the West

Sediment Plug Computer Modeling Study

Tiffany Junction Reach

Middle Rio Grande Project
Upper Colorado Region

U.S. Department of the Interior
Bureau of Reclamation
Albuquerque Area Office
Albuquerque, New Mexico

October 2005

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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EXECUTIVE SUMMARY

There are several documented cases of sediment plug development in alluvial rivers. General qualitative theories have been offered about the cause of plug formation that pertain 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 findings are pertinent but do not contribute to the understanding of the specific processes occurring at the location where plugs develop.

Site characteristics, processes, and associated parameters regarding sediment plug formation were evaluated based on a comprehensive literature review, evaluation of data, and discussions with other researchers. All of these topics were analyzed for a focus study reach along the Middle Rio Grande in New Mexico to identify consistencies between periods when plugs formed versus periods when plugs did not develop. The topics were also analyzed against information from other river systems where plugs developed. A theory was formulated regarding the cause of plug development.

Sediment plugs always occurred in alluvial rivers at the location of a constriction that abruptly forces a significant portion of flow overbank. As flows are lost, 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.

This theory was tested using a calibrated and validated original sediment transport/movable bed computer model. Criteria for plug formation were developed with the model and tested against a case for plug development and against another scenario when a plug did *not* form. These criteria can be used to identify critical thresholds for plug development. The level of plug formation (55% of the main channel, 70% of the main channel, etc.) can be determined to a specified level of confidence.

River managers not only have a better understanding as to why plugs formed along the Tiffany Junction Reach of the Middle Rio Grande but will be able to apply these criteria to evaluate scenarios for a site that is prone to plug formation and address the conditions that might lead to plug development.

I. 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. This research was conducted to identify the specific processes that cause plug formation and establish criteria for plug development along the Tiffany Junction Reach of the Middle Rio Grande.

1.1 Definition of a Sediment Plug

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). This study focuses on the short term phenomenon of plug formation in alluvial rivers at the location of a constriction which is defined as a local control or other physical feature that significantly reduces the main channel conveyance capacity of an alluvial river. These results are not applicable to cases where plugs form at the mouth of tributaries or at the mouth of rivers along coastal regions.

1.2 Problem Statement

There are numerous challenges associated with the formation of sediment plugs in alluvial rivers. As sediment plugs are initiated, sedimentation continues and progresses upstream. Plugs can grow to be miles in length and can cause numerous problems for river managers. The resulting overbank flows can compound a flooding condition. Water deliveries to downstream users may be affected, and habitat for wildlife, including endangered species, may also be impacted. As a result of these issues, critical maintenance activities are often undertaken immediately following plug development. Some researchers suggest that sediment plug development is a natural process that has positive impacts; regardless, there is no doubt that engineers need to be able to better predict how, why, when, and where a sediment plug will form.

1.3 Objectives of Research

The objective of this study is to formulate a theory on the cause of sediment plug formation and validate that theory. Criteria will be developed and tested for determining when and where sediment plugs may form. These criteria can then be used by engineers to predict plug development for sites that are prone to plugging and ultimately prevent or manage plug formation.

1.4 Case Studies of Sediment Plugs

Four cases of plug formation since the 1960s are documented. During 1991 and 1995, sediment plugs formed along the Tiffany Junction Reach of the Middle Rio Grande. The plug in 1991 was noticed on June 17th (USBR, 1992). Jeremiah Rivera was the manager of U.S. Bureau of Reclamation's (Reclamation) field office in Socorro when the plugs formed and provided information on the events. After the plug formed in 1991, river flows were forced against the levee around cross section SO-1664 (Rivera, 2003). The levee breached in July, and the entire river flowed to the west of the levee (USBR, 1992) (Figure 1.1). Emergency actions were implemented along the Atchison, Topeka, and Santa Fe railroad embankment as river flows through the levee breach damaged the railroad embankment and emergency repair work was required. A pilot channel was dredged through the plug to create a new channel (Gonzales, 2003) (Figure 1.2).

Figure 1.1 Levee Breach in 1991 as a Result of the Sediment Plug

Figure 1.2 Pilot Channel that was Dredged through the Plug in 1991

The plug initiated immediately below Reclamation's rangeline SO-1683 – at the upstream end of a straight narrow reach just before the river curves around the edge of the mesa to the east (Figure 1.3). Mr. Rivera *presumed* that flows started to go overbank when the river flow exceeded 1600 cfs.

A plug formed again in 1995 at the same location. Cross section surveys were completed that year for a three mile stretch of the river where the channel was plugged, but before the plug washed out it was five miles long and extended approximately a mile into the Bosque del Apache National Wildlife Refuge (Padilla, 2003). A pilot channel was again dredged, and the plug eventually washed out in 1997. Mr. Rivera was not aware of any specific processes such as a debris snag or macroform moving into the reach that caused the sediment plugs to form. It is noted that the plugs formed above the Atchison, Topeka, and Santa Fe railroad crossing, and the conveyance capacity at the railroad bridge was not reduced; however, if the levee breaches again, the railway embankment to the west of the river could be threatened.

Figure 1.3 Sediment Plug that Initiated below Rangeline SO-1683 in 1991

One of the more commonly referenced cases of sediment plug formation is along the Yalobusha River in north-central Mississippi (Shields *et al.*, 2000). The available quantitative data are limited for analyzing this case along with the plugs that developed in the Guadalupe River in Texas (Gergens, 2003) and in the Hatchie River Basin in west Tennessee (Diehl, 1994), but the testimonial information for these cases of plug development was valuable for isolating the specific processes that lead to a sediment plug.

1.5 Purpose and Need for Research

It has been documented that sediment plug formation occurs when sediment transport capacity is less than the sediment supply. Also, sediment plugs always form at a constriction. Prior to this study, limited criteria had been developed regarding the specific processes that ultimately lead to plug formation. To date, few criteria have been identified that allow the river manager or engineer the ability to predict where in the river system a plug might form.

The criteria to be identified are not only useful for understanding the processes that lead to a sediment plug but may also be useful for helping prevent plug development and minimizing the effects resulting from sediment plug formation. Engineers now understand the physical processes that affect plug development and can predict plug formation. In addition to potential river maintenance issues, sediment plugs may affect the efficiency of water deliveries to water users throughout a river basin.

Sediment plugs may also impact habitat for wildlife and endangered species. The sediment plugs that developed along the Middle Rio Grande during 1991 and 1995 were located in an area included in the designated critical habitat for the Rio Grande silvery minnow (*Hybognathus amarus*) (FWS, 2003) listed as "endangered" under the Endangered Species Act of 1973. The surrounding area also provides habitat for the Southwestern Willow Flycatcher (*Empidonax traillii extimus*) (habitat designation still under review). There is limited documentation regarding the effects of the sediment plugs on the habitat in the area, but for species recovery, there is a need to understand how, why, and when a plug may develop again.

1.6 Research Approach

A comprehensive literature review was conducted and available field data pertinent to sediment plug formation were gathered. Also, information was sought from researchers, engineers, and field personnel having expertise related to plug formation. Theories regarding sediment plug formation were gathered and/or devised and examined. A theory was formulated regarding the cause of sediment plug development. A numerical sediment transport/movable bed computer model was developed to test the theory. The model was calibrated and validated based on plug formation along the Tiffany Junction Reach of the Middle Rio Grande. Model runs were then completed to establish criteria for plug formation. Criteria for sediment plug formation were then developed and presented for plug prediction and ultimately plug prevention and/or management.

II. LITERATURE REVIEW

A literature review was conducted with concentration on three areas of interest: sediment plugs in alluvial rivers; sediment transport and sedimentation processes along the Middle Rio Grande; and specific sediment processes thought to be pertinent to sediment plug formation. Topics specifically addressed include:

- seasonal variations in total sediment load in alluvial rivers,
- non-uniform vertical distributions of suspended sediment,
- non-instantaneous methods for computing erosion/deposition of sediment, and
- non-uniform lateral erosion/deposition in alluvial rivers.

A summary of the pertinent literature will be presented.

2.1 Sediment Plugs

Sediment plugs have historically formed in alluvial channels although few specific findings citing the cause of sediment plug formation have been formally documented. There are testimonial records on several cases of sediment plugs such as

- Yalobusha River in northern Mississippi (Shields *et al.*, 2000),
- Drainage Canals in the Hatchie River Basin in west Tennessee (Diehl, 1994),
- below Canyon Dam on the Guadalupe River in Texas during the summer of 2002 (Gergens, 2003),
- Red River in Louisiana (1790 to 1873) (Shields *et al.*, 2000),
- Clear Branch Creek of the Middle Fork of the Hood River in Oregon during 1996 (Hickman, 2001), and
- Middle Rio Grande in 1991 (USBR, 1992) and 1995 (Padilla, 2003).

Along the Yalobusha River, a sediment plug formed following channelization in 1967. The sediment plug developed at the downstream end of the excavated channel at the transition to a naturally meandering reach (Shields *et al.*, 2000). The bankfull discharge for the river abruptly dropped from 570 m^3/s (~20,000 cfs) to 70 m^3/s (~2500 cfs) at the transition. The channel slope also changed from 0.0005 to 0.0002. There were several hydrologic events that yielded flows greater than 2500 cfs following channelization that were considered to be significant factors affecting plug formation in the Yalobusha River (Jones, 1998). Plug formation was attributed to the channelization and higher sediment inputs during subsequent years (Shields *et al.*, 2000).

Timothy Diehl with the United States Geological Survey (USGS) in Nashville, Tennessee completed a qualitative evaluation of the plugs that formed in the Hatchie River basin. Mr. Diehl was contacted, and he attributed plug formation to watershed management, channel maintenance, and debris in the study drainage canals (Diehl, 2003). Frequent overbank flooding was also referenced as an issue in the Hatchie River basin (Diehl, 2000).

Along the Guadalupe River in Texas, a sediment plug formed in 2002 below Canyon Lake Dam. A 250-yr return period hydrologic event occurred that caused the emergency spillway to be overtopped. The maximum outflow from the dam to the downstream channel was 66,800 cfs, but the main channel could only convey 40,000 cfs based on a

HEC-RAS analysis (Gergens, 2003). Flow went overbank through the inside of a large meander via a cutoff swale. The sediment plug formed just below the swale.

The sediment plug cases on the Red River (1790 to 1873) and the Middle Fork of the Hood River (1996) also corresponded with higher flow events. The cause of the aforementioned plugs was attributed to flooding and other human activities; however, the specific river mechanics processes resulting in sediment plugs have not been developed. Plug development has been speculated as a loss in sediment transport capacity (Happ, 1940), but a more detailed explanation and criteria pertaining, thereunto, is required to assist river managers with predicting when and where a plug will form. Wallerstein and Thorne (2003) concluded that debris can precipitate plug formation, but the specific processes that follow a debris jam and cause accelerated deposition need to be isolated.

While the amount of quantitative information for the cases of plug formation in these river systems is limited, the available testimony and qualitative information just discussed is valuable for evaluating theories regarding the cause of plug formation and testing the criteria for plug formation. This information is referenced further in Chapters 4 and 9. This study was completed with this testimonial information combined with the extensive database for the focus study reach along the Middle Rio Grande.

2.2 Information from Studies of the Middle Rio Grande

There have been numerous sediment investigations of the Middle Rio Grande. These investigations include studies to evaluate channel maintenance alternatives, recent evaluations of the geomorphology and sedimentology of the Middle Rio Grande, and detailed studies of sediment processes completed by the USGS during the 1960s.

One analysis that specifically focuses on the river mechanics processes along the Tiffany Junction Reach is being completed for the current Rio Grande and Low Flow Conveyance Channel (LFCC) Modifications DRAFT Environmental Impact Statement (EIS) (USBR, 2000). For the National Environmental Policy Act (NEPA) process, maintenance alternatives are being evaluated for the Rio Grande area that includes the Tiffany Junction Reach. One of the DRAFT proposed alternatives entails discontinuing maintenance along this reach. Under this scenario, pilot channels would no longer be dredged after plugs form along the Tiffany Junction Reach. For the alternative evaluation, the cause of sediment plugs is not analyzed in detail. The analysis focuses on the subsequent effects after a plug forms. The NEPA process involves a broader range of issues than the sediment plugs, but if river managers had a better understanding as to why the sediment plugs formed along the Tiffany Junction Reach, it would significantly help with alternative analysis. One important finding from the evaluation of alternatives was that a single Manning n roughness value of 0.017 is appropriate for the entire main channel of the Tiffany Junction Reach.

The sediment plugs that formed along the Tiffany Junction Reach have been discussed with focus on the potential impact of plugs on habitat for the endangered Rio Grande silvery minnow and Southwestern Willow Flycatcher. The plugs are discussed in the Biological Opinion on Reclamation’s water management operations on the Middle Rio

Grande (FWS, 2002). The effects of the plugs on habitat are not discussed in detail, but the impact that the plugs and subsequent dredging have on the channel morphology is noted. It has also been noted that sediment plugs could affect habitat for the Southwestern Willow Flycatcher as a result of "prolonged, detrimental inundation of riparian and willow flycatcher" habitat (USBR and USACE, 2003). These specific references to the plugs along the Tiffany Junction Reach emphasize the importance for gaining a better understanding as to why, when, and where a sediment plug forms.

Studies of river mechanics processes along the study reach include the more recent consulting report on the overall sedimentology and geomorphology of the Middle Rio Grande (MEI, 2002). Mussetter Engineering presents an evaluation of the hydrology and the effects of developments in the basin on river flows. A summary of sediment transport statistics is also presented along with a review of the historical evolution of the channel morphology with reference to geologic controls. One of the key findings related to the Tiffany Junction Reach is that changes to the channel morphology are largely a result of flow regulation at Cochiti Dam, diversions to the Low Flow Conveyance Channel (LFCC) which began in 1959, the cessation of these diversions in 1985, backwater effects of Elephant Butte Reservoir, and the constriction at the railroad bridge (MEI, 2002).

A similar report was prepared by Reclamation that focuses specifically on the reach of the Rio Grande from the San Acacia diversion dam to the Escondida Bridge (USBR, 2003). The key findings from this study also pertained to the channel morphology and explanations for the modifications that have taken place over the past 50 years. The suspended sediment (sand load) in the Rio Grande above the focus study reach has decreased by approximately 80% since Cochiti Dam was closed. These studies provide insight as to how the morphology of the Tiffany Junction Reach approached a plug prone state.

Historical studies that were reviewed include the work by Carl Nordin (Nordin and Beverage, 1965; Nordin and Beverage, 1964; Nordin and Culbertson, 1961; Nordin and Dempster, 1963) which were published by the USGS. These analyses include a review of sediment transport in the Rio Grande (Nordin and Beverage, 1965). One interesting finding is that at high flows, the sediment discharge in the Middle Rio Grande is greater in wide sections, and at low flows, the sediment discharge is greater in narrow sections. Another conclusion was that no clear relationship could be identified between total sediment load and water temperature. Culbertson and Dawdy (1964) completed a review of fluvial characteristics and hydraulic variables for the Middle Rio Grande. They concluded that in narrow sections, the streambed scours during rising flow and fills as flows decrease. They also noted that sediment transport rates can be 8 to 10 times higher if the bedforms are in upper regime as opposed to lower regime.

Nordin and Dempster (1963) presented the results from a study of the vertical distribution of suspended sediment in the Middle Rio Grande. Based on the data collected for their evaluation, values were computed for the parameters in a typical equation for the vertical concentration profile. The concentration is generally uniform for finer sediment (< 0.0625 mm), but the distribution follows the typical profile for larger sediment sizes.

Also, the profile for larger particle sizes is more uniform if the bedform characterization is in upper regime but follows the predicted distribution if the bedform characterization is in lower regime. They also concluded that the effect of hyperconcentrations is negligible for concentrations less than 10,000 ppm in the Rio Grande. Ernest Pemberton with the Bureau of Reclamation also documented a sediment investigation completed for the Middle Rio Grande (Pemberton, 1964). This document includes key quantitative findings regarding the parameters affecting the vertical concentration profile.

Nordin and Culbertson (1961) documented trends in the particle size distributions of bed material along the Middle Rio Grande. They concluded that the bed material is slightly coarser progressing upstream, but the effect is negligible along the focus study reach. Another study was completed on the temporary storage of fine sediment on islands and point bars (Nordin and Beverage, 1964). One important conclusion from this study is that sediment deposits in these high water areas serve as a source for sediment during sustained high flow events. Sandbar development and movement was also studied and it was determined that these bars can move about 350 feet per day (Culbertson and Scott, 1970).

2.3 Key Processes

During the initial phases of this study, key processes were identified that could be pertinent to the development of sediment plugs. These processes pertain to general issues such as the hydraulics in the reach, variations in sediment transport, and the distribution of erosion/deposition.

2.3.1 Hydraulics

Although the hydraulics along a reach of an alluvial river may not be a unique factor causing sediment plug formation, the hydraulics must be accurately represented before the processes that do affect sediment plug formation can be analyzed. The literature review identified factors affecting hydraulic calculations and include the following: solution of the unsteady flow equations, lateral losses of flow, the Courant condition and stability, and channel roughness.

Unsteady flow calculations become important if the hydraulic calculations include a lateral loss of flow. There are numerous studies on the numerical procedures that can be used to complete unsteady flow calculations. The reference by Hromadka, Durbin, and DeVries (1985) focuses specifically on the computer application for completing unsteady flow calculations and using the double sweep method to solve the linearized unsteady flow equations determined using the Preissman scheme. Chaudhry's Open Channel Flow text (Chaudhry, 1993) and Julien's River Mechanics book (Julien, 2002) also provide information on this routine along with the necessary information for completing an evaluation of the terms in the Saint-Venant equation to determine whether a kinematic or diffusive wave approximation to the full dynamic wave equation could be utilized.

If a lateral loss of flow is included in the solution of the unsteady flow equations, the equations must include the terms for accounting for the associated loss of momentum and loss of mass. These terms are discussed in the following three texts: Practical Aspects of

Computational River Hydraulics (Cunge *et al.*, 1980), Unsteady Flow in Open Channels (Mahmood and Yevjevich, 1975), and Open Channel Flow (Henderson, 1966).

Another issue that is key to the solution of the unsteady flow equations pertains to stability. To assure stability, the Courant condition must be satisfied (Ponce, 1989) which states that the timestep for solving the unsteady flow equations must be less than the time it takes for a floodwave to propagate along a computational spatial step. It would be important to monitor the Courant condition when completing hydraulic calculations when sediment plug development is an issue.

Channel roughness (expressed as a Manning n value) may be the greatest uncertainty when completing accurate hydraulic calculations. Manning n roughness values were calibrated for several Rio Grande studies. For most of these studies, a single value was used for extended reaches and another single value was used for the overbank areas. For the evaluation of alternatives for the Rio Grande and LFCC Modifications DRAFT EIS, a Manning n value of 0.017 was used for the main channel along the entire Tiffany Junction Reach (USBR, 2000). This value is also approximately the same as the values computed by FLO Engineering for cross sections at the upstream portion of the Tiffany Junction Reach. Values from 0.015 to 0.017 were calibrated with data from 1993 and 1994 for flows ranging from 2700 cfs to 5400 cfs by matching computed water surface elevations to measured water surface profiles (FLO, 1995).

Other reports on roughness that were reviewed include Barnes (1967), Hicks and Mason (1991), and Klumpp and Baird (1993). Karim's study on the variability of roughness (Karim, 1995) and the review of roughness values for streams in Arizona (Phillips and Ingersoll, 1998) were also reviewed. All of these documents were referenced to further justify the representation of channel roughness utilized for this study.

2.3.2 Sediment Transport

The development of sediment plugs is clearly related to the sediment influx to a study reach as well as changes in sediment transport; therefore, a literature review was completed on general issues related to sediment transport. These issues include different sediment transport equations, seasonal variations in sediment load along with lateral and vertical variations in the total sediment load. The literature was reviewed with focus on how these issues could affect plug formation.

Many sediment transport analyses have been completed for the Middle Rio Grande, and applicable sediment transport equations have been identified. These analyses were referenced to identify the published total sediment load function that most accurately replicates conditions along the Middle Rio Grande. Baird (2003) noted that Rio Grande computer modeling studies have suggested that Yang's method matches Rio Grande sediment load data. Discussion of the applicability of Yang's equation can be found in Yang and Stall (1976) in which Yang's method and Laursen's equation compare favorably with measured total sediment load data along the Rio Grande. The applicability index developed by Williams and Julien (1989) was also referenced for identifying an appropriate sediment transport function. Based on values for the dimensionless parameters in the applicability index computed for the focus study reach along the Middle Rio Grande, the applicability criteria for Yang's method are satisfied.

Laursen and Madden's equation was used in the analysis of alternatives for the Rio Grande and LFCC Modifications DRAFT EIS (USBR, 2000), and other total sediment load functions such as those developed by Ackers and White (1973), Shen and Hung (1971), and Toffaleti (1968) are available, but based on the previous studies completed for the Middle Rio Grande, Yang's method was identified as the most accurate method for computing total sediment load out of all the available published methods.

2.3.2.1 Seasonal Variations of Sediment Load

Seasonal variation in sediment transport in alluvial rivers was considered to evaluate the effect that such variation could have on plug formation. This included a review of studies on the effect of sediment waves moving out of phase with corresponding water waves from specific hydrologic events. Williams (1989) analyzed theories about this variability and concluded that such trends are common and are influenced by precipitation intensity and areal distribution. Another important finding about this phenomenon is that it is usually basin specific (Knighton, 1998).

Mussetter Engineering suggests that the seasonal variation in the sediment load in the Rio Grande is different from the variation in seasonal flows, but they focused on monthly data to identify the effect (MEI, 2002). They determined that the average monthly total sediment load (tons/month) along the Tiffany Junction Reach (at San Marcial) is highest during August long after the higher flows are passed in the spring. This effect is attributed to additional sediment inputs from arroyos during summer monsoon season storm events (MEI, 2002). It has been suggested that sediment inputs along the Middle Rio Grande from ephemeral tributaries during summer monsoon season storm events are stored on islands, bars, and high water areas (Nordin and Beverage, 1964). Sediment is later transported downstream during prolonged higher magnitude releases from Cochiti Dam. It is important to note that the sediment load along the Tiffany Junction Reach does not necessarily increase as a result of individual hydrologic events but this trend has only been identified as a general seasonal trend.

2.3.2.2 Vertical Distribution of Sediment Load

If flows are lost from the main channel of an alluvial river to the overbank areas, the vertical distribution of the sediment load becomes very important. The fraction of the sediment load that would be lost to the overbank areas has a significant impact on erosion and deposition in the main channel. If a significant amount of the flow is lost to the overbank but little sediment is being carried at the top of the water column, the sediment load is not reduced by the same proportion as the loss to the sediment transport capacity. As a result, deposition immediately initiates.

While the link between deposition in the main channel and the loss of flow to the overbank areas has not been documented, there has been extensive study of the vertical distribution of suspended sediment. One of the more commonly used relationships is the Rouse equation (Julien, 1995):

$$C = C_a \left[\left(\frac{h - z}{z} \right) \left(\frac{a}{h - a} \right) \right]^{Ro}$$ Equation 2.1

where C is the concentration at elevation z,

C_a is the concentration at reference elevation a,

z is the elevation above a reference elevation,

h is the flow depth, and

Ro is the Rouse number.

The Rouse number could be empirically derived by fitting a curve to data. Nordin and Dempster (1963) derived values for the Middle Rio Grande: a value of 1.15 corresponds with a mean particle size of 0.25 mm. If data are not available, the Rouse number can be computed with Equation 2.2 (Julien, 1995):

$$Ro = \frac{\omega}{\beta_S \kappa u_*}$$ Equation 2.2

where ω is the particle fall velocity,

β_S is the ratio of the turbulent mixing coefficient of sediment to the momentum exchange coefficient,

κ is the von Kármán constant, and

u_* is the shear velocity.

More recent analyses of the vertical distribution of suspended load have also been documented. Woo, Julien, and Richardson looked at the effect of high concentrations of sands on the vertical distribution and concluded that the distribution of sands in suspension is more uniform as sediment concentrations increase (Woo *et al.*, 1988), but Nordin and Dempster (1963) concluded that for the Middle Rio Grande, the effect of hyperconcentrations on fall velocity is negligible for concentrations less than 10,000 ppm.

2.3.2.3 Lateral Variability of Sediment Load

Lateral variation in sediment transport is another important parameter that could be key to sediment plug development in alluvial rivers. Most studies that evaluate the 2-dimensional effect reference 2-dimensional hydraulic information. Documentation of one investigation was provided by Huang, Greimann, and Yang from Reclamation's Technical Service Center (Huang *et al.*, 2003). Hydraulic information was computed in 1-dimension, but the sediment transport and erosion/deposition for the floodplain was computed separately from the erosion/deposition for the main channel. The analysis was completed for a reach of the Rio Grande from San Acacia to Elephant Butte using version 1.0 of the 1-dimensional General Sediment Transport Model for Alluvial River Simulation (GSTARS). They were able to favorably reproduce the differences in sediment transport in the overbank areas versus the main channel.

2.3.3 Erosion/Deposition

The process of erosion/deposition must be appropriately represented for an analysis of the accelerated deposition associated with plug formation. A commonly accepted method for determining erosion/deposition is based on an immediate vertical change to the channel bed elevation using the Exner equation (USACE HEC, 1991):

$$\frac{\partial G}{\partial x} + B_0 \frac{\partial Y_S}{\partial t} = 0 \qquad \text{Equation 2.3}$$

where B_0 is the width of the movable bed,

t is time,

G is the average sediment discharge (ft^3/s) rate during timestep dt,

x is the distance along the channel, and

Y_S is the depth of sediment in the control volume.

The equation may be written where trap efficiency is included, and the result is the same if a trap efficiency of 100% is assumed (Julien, 2002):

$$T_{Ei} \frac{\partial Q_{txi}}{\partial x} + (1 - p_0) \frac{W \partial z_i}{\partial t} = 0 \qquad \text{Equation 2.4}$$

where the additional parameters are defined as follows:

T_{Ei} is the trap efficiency,

Q_{txi} is the sediment discharge,

p_0 is the porosity of the bed material, and

W is the width of the movable bed.

Equation 2.4 also includes consideration for the effects of porosity of the bed material on the magnitude of erosion/deposition, and the parameter z is used to represent the vertical change in bed elevation as opposed to Y.

After the vertical erosion/deposition is computed for a timestep using Equation 2.4, the channel bed change can be longitudinally distributed over multiple cross sections. This may help with computational stability depending on the finite difference scheme that is being used for such computations (Julien, 2002). Equation 2.4 can be used to determine the uniform vertical change in channel bed, but more complicated non-uniform or non-instantaneous methods may be necessary to accurately reflect the processes causing a sediment plug.

2.3.3.1 Non-Uniform Lateral Erosion/Deposition

Actual erosion/deposition in alluvial rivers is more complicated than a uniform vertical change to the channel bed. It generally varies laterally across a river. Computer models have been created that represent the lateral movement of sediment using 2-dimensional hydraulic information, but this literature review focused on investigations of lateral variations in erosion/deposition that were determined using 1-dimensional hydraulics.

The GSTARS model discussed in Section 2.3.2.3 is one example where the erosion/deposition in the floodplain was computed separately from the erosion/deposition in the main channel (Huang *et al.*, 2003). The analysis was completed with a special 1-d version of GSTARS. Reclamation's regular GSTARS program includes consideration for 2-dimensional hydraulics through the use of the stream tube concept. The program simulates lateral movement of sediment using the theory of minimum stream power (Yang and Simoes, 2000). Essentially, if the total stream power is lower as a result of a change to the channel width as opposed to the channel bed elevation, then an alteration to the width is made. This methodology provides a means for capturing lateral movement of the main channel of an alluvial river.

In HEC-6, erosion/deposition is uniformly distributed across an entire cross section (USACE HEC, 1991), but during plug formation, deposition is primarily within the main channel. One alternate method for distributing erosion/deposition is to disperse deposition below the water surface elevation based on the ratio of the depth at a station along a cross section over the hydraulic depth (Cunge *et al*., 1980).

Another method for representing the lateral variability in deposition and erosion was developed by Zhou and Lin (1998). The erosion/deposition is distributed across a cross section using a computed adjustment coefficient. One key finding based on the model developed from their work is that deposition is generally uniform across a cross section, but erosion is not.

Other related studies focus on the dispersion of sediment in the floodplains. Data from the United Kingdom were analyzed to gain a better understanding of the temporal and spatial variability of overbank deposits. Conclusions were reached that pertained to the variation of sediment sizes in overbank deposits as a function of the distance from the main channel. The general conclusion is that sediment deposits further from the channel primarily consist of fine sediments, and sand sized particles generally settle closer to the channel (He and Walling, 1997). While this trend is clear, the overbank topography is still the primary factor affecting overbank deposition. Sedimentation can be expected in closed depressions and retention ponds as opposed to open areas with throughflow (Simm and Walling, 1998). Nicholas and Walling reached the same conclusion through their computer modeling study (Nicholas and Walling, 1997), and Pizzuto had similar findings in his modeling study for the floodplain of the Brandywine Creek in Pennsylvania (Pizzuto, 1987).

2.3.3.2 Non-Instantaneous Erosion/Deposition

When determining erosion/deposition for alluvial channels, it may be determined that the change to the channel bed does not immediately occur along a computational spatial step. This would be a critical factor affecting the rate of deposition and whether the main channel of a river would become completely clogged with sediment (i.e. a sediment plug would develop).

There are alternate methods for computing erosion/deposition. The deposition rate in GSTARS is computed as a function of the depth average concentration, settling velocity, and "deposition probability" (Yang and Simoes, 2000). The deposition probability is related to the ratio of the bed shear stress to the critical shear stress for full deposition.

The deposition rate could also be calculated using Equation 2.4 where trap efficiency is computed using Equation 2.5 as opposed to assuming a trap efficiency of 100% (Julien, 2002):

$$T_{Ei} = 1 - e^{-\frac{Xw_i}{hV}} \qquad \text{Equation 2.5}$$

where T_{Ei} is the trap efficiency,

X is the longitudinal distance (or incremental spatial step) (ft),

w_i is the fall velocity (ft/s),

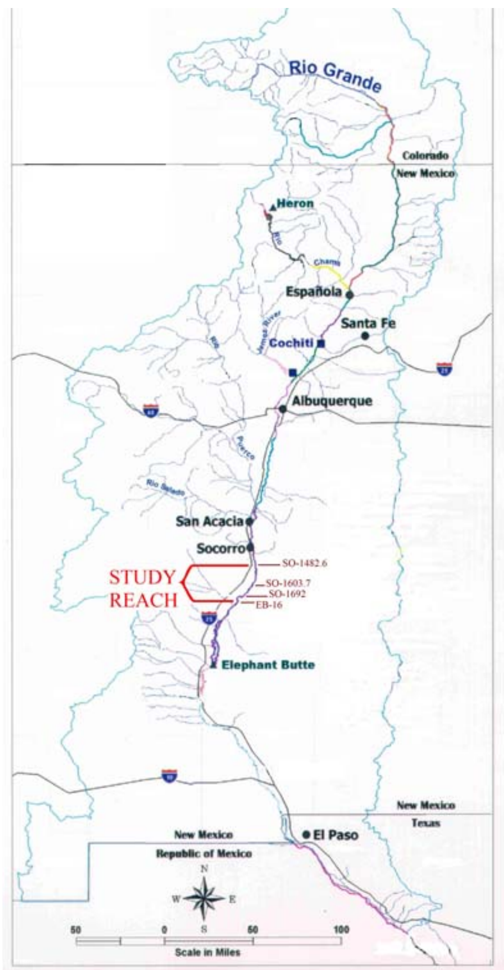
h is the flow depth (ft), and

V is the mean velocity (ft/s).

The necessity for a non-instantaneous erosion/deposition method is largely a function of the incremental spatial step selected for an analysis. Sample trap efficiencies can be computed for typical depths and velocities along a study reach to determine whether a trap efficiency of 100% could be assumed.

III. GENERAL DESCRIPTION OF THE FOCUS STUDY REACH

The focus study reach for this investigation 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 San Marcial as presented in Figure 3.1. The first upstream cross section is at rangeline SO-1482.6 presented in Figure 3.1, and the last downstream cross section is at rangeline EB-16. The study reach is approximately 22 river miles in length. The upper portion of the reach is located within the Bosque del Apache National



Vicinity Map

Figure 3.1 Rio Grande Map with the Tiffany Junction Reach Depicted (w/ Vicinity Map)
Map courtesy of the Upper Rio Grande Basin, Water Operations Review

Wildlife Refuge. The Low Flow Conveyance Channel (LFCC) extends along the west side of the main river channel.

3.1 Hydrology and Hydraulics

Flows through the Tiffany Junction Reach are regulated by Cochiti Dam located approximately 145 river miles north of the upstream end of the study reach. Cochiti Dam is a U.S. Army Corps of Engineers (Corps) facility that was closed in November of 1973. In addition to releases from Cochiti Dam, inflows to the study reach are also affected by tributary inflows from the Rio Puerco and Rio Salado which confluence with the Rio Grande approximately 40 and 32 river miles, respectively, above the upstream end of the study reach. Inflows to Cochiti Dam are primarily from snowmelt from the high mountains of northern New Mexico and southern Colorado. The major tributary above Cochiti Dam is the Rio Chama which also receives water from a trans-basin diversion.

There are several diversions located above the study reach including the Isleta, Angostura, and San Acacia diversion dams. Historically, diversions were made to the LFCC at the San Acacia Diversion Dam, but those diversions have ceased since 1985 except for a few short experimental diversions. The San Acacia Diversion Dam is approximately 29 river miles above the upstream end of the study reach.

For the period following the closure of Cochiti Dam, the 2 and 100-year return period peak flows through the study reach have been estimated as 4200 and 11,300 cfs, respectively, based on peak flow measurements from the USGS gage Rio Grande at San

Marcial (ID# 08358400) (Tetra Tech, 2003). A flow duration curve was developed with daily flow data collected at the gage since 1985 when diversions to the LFCC were ceased (Figure 3.2).

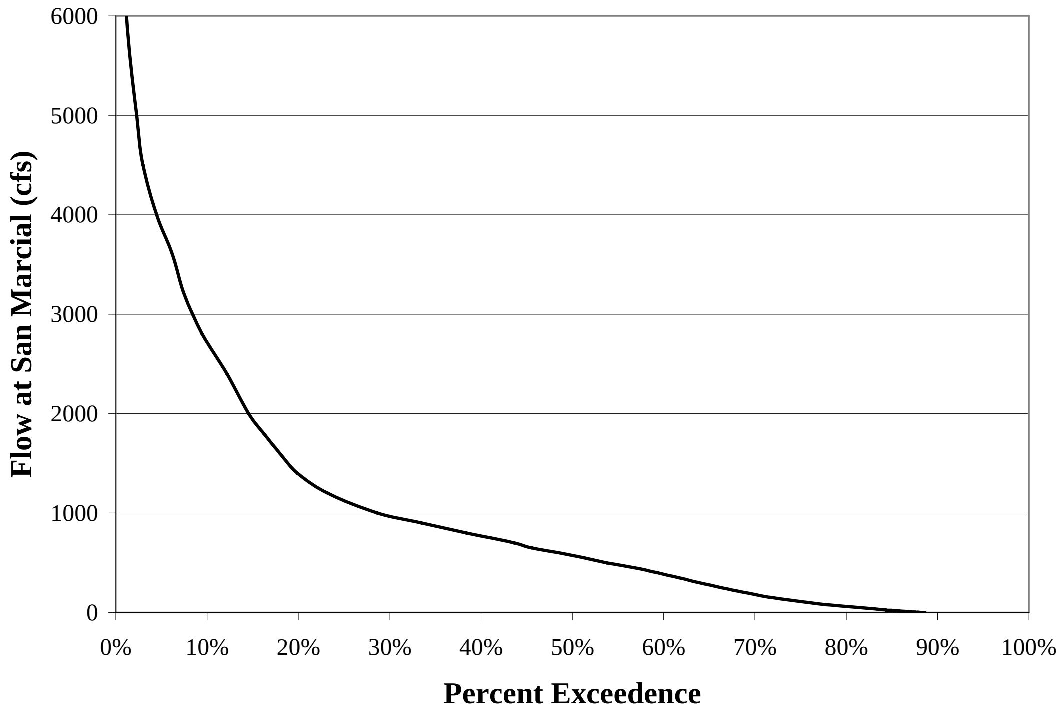


Figure 3.2 Flow Duration Curve for the Rio Grande at San Marcial (1985-2002 Data)

The hydraulic parameters along the study reach may be impacted by the railroad bridge near San Marcial. The main channel conveyance capacity at the bridge has been reported to be on the order of 3500 cfs before the stage reaches the bottom of the bridge (Rivera, 2003). There are several roughness factors affecting the hydraulics through the study reach. Within the main channel, the roughness is a function of the bedforms. Along the banks and in the overbank areas, dense riparian vegetation including salt cedars is the significant factor affecting roughness. Another issue affecting the hydraulics is water losses to seepage and evapotranspiration.

3.2 Sediment Transport

The total sediment load through the study reach is on the order of a few hundred tons per day to over 50,000 tons/day (MEI, 2002). A significant portion of the total sediment load in suspension is wash load. The study reach of the Rio Grande receives sediment from the entire basin below Cochiti Dam. Cochiti Dam reduces the sediment load along reaches of the Middle Rio Grande by 35% (MEI, 2002) as the dam traps sediment from the Upper Rio Grande basin. The Rio Puerco and Rio Salado introduce sediment below Cochiti Dam. This contribution is particularly high during summer monsoon season storm events. The San Acacia diversion dam, which serves as another sediment trap, is downstream from the confluences with the Rio Puerco and Rio Salado.

Based on a review of mean bed elevations from cross section surveys completed over the past 20 years (FLO, 1990-1996), there is a general long term trend of degradation immediately below the San Acacia diversion dam and aggradation further downstream above the next lake, Elephant Butte Reservoir. At the upstream end of the Tiffany Junction Reach – just south of the Highway 380 bridge near San Antonio, there is no evidence of long term degradation or aggradation. The lower portions of the study reach have exhibited some long term aggradation, but this deposition is a separate issue from the short term phenomenon of sediment plug development.

3.3 Aggradation/Degradation

The Tiffany Junction Reach is in an area that has experienced gradual aggradation over the past few decades (USBR, 2000). As a result, maintenance activities are undertaken every year. Reclamation is currently analyzing maintenance alternatives for the Rio Grande and LFCC Modifications EIS (USBR, 2000). The formation of sediment plugs are specifically referenced in the current 2000 DRAFT EIS. The results from this research will be useful during the continued evaluation of alternatives where sediment plug development is an issue.

3.4 Geomorphology

The geomorphology of the Tiffany Junction Reach has changed dramatically over the years due to numerous factors such as irrigation diversions and returns, dam construction, and trans-basin diversions. In addition, channel dredging, levee construction, and other maintenance activities have had an impact on the channel geometry (MEI, 2002). For this study, the analysis will focus on the conditions along the Tiffany Junction Reach at the time when the sediment plugs formed in 1995 and 1991.

Aerial photography (USBR, 2003) is available for reviewing the channel geometry along the study reach at the time of plug formation. The single main channel along the upper portion of the study reach, below the Highway 380 bridge, is narrower with a width of approximately 250 feet. The main channel in the northern section of the Bosque del Apache National Wildlife Refuge is wider with widths exceeding 1000 feet, but the channel is narrower toward the southern boundary of the refuge where the width does not exceed 300 feet. The sediment plugs that formed in 1991 and 1995 initiated in a narrow portion of the river immediately above rangeline SO-1692 as the river curves around the edge of the mesa to the east. The channel width within this area is approximately 140 feet, and this constriction is approximately seven river miles downstream from where the channel width reduces from 1000 feet to 300 feet. Plug formation will propagate upstream along the 300 feet wide reach, but plugs are not apt to propagate further upstream where the channel width exceeds 1000 feet.

While the lower portions of the study reach are narrower (< 300 ft), the slope is slightly flatter than the upper segment of the study reach based on data collected in 1992 (Figure 3.3). The slope in the upper portion of the reach above rangeline SO-1603.7 is approximately 0.0007 as opposed to 0.0005 for the lower portion of the study reach. The bed material in the main channel along the study reach of the Rio Grande is composed of sand with small traces of fines while the bed material in the overbank areas is predominantly composed of silts and clays with some sands. An effective discharge (post-Cochiti) at San Marcial has been computed to be 810 cfs (MEI, 2002).

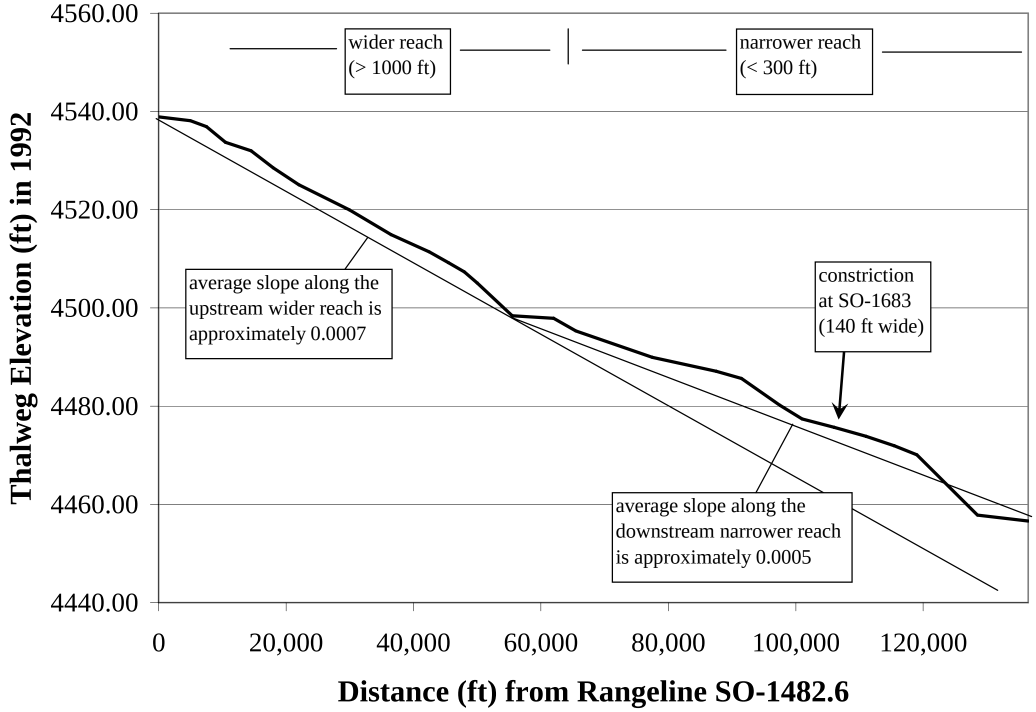


Figure 3.3 Thalweg Profile for the Tiffany Junction Reach

IV. REVIEW OF SITE CHARACTERISTICS, PROCESSES, AND ASSOCIATED PARAMETERS AFFECTING PLUG DEVELOPMENT

Sediment plugs have a direct and devastating impact on alluvial rivers. The impact on deliveries to water users in a basin could be severe, and habitat for wildlife and endangered species may be significantly impacted. In addition, ensuing maintenance activities could be extremely costly. It is important to be cognizant of site characteristics for river reaches that are prone to plug and know the specific processes that ultimately cause sediment plug development in alluvial rivers.

4.1 Site Characteristics

All the historical cases of sediment plugs occurred on reaches of alluvial rivers affected by constrictions. Constrictions are local controls or other physical features that significantly reduce the main channel conveyance capacity of an alluvial river. Examples of such constrictions include a debris snag, a bend in the river, a significant and abrupt reduction in the main channel width and/or depth, and an abrupt reduction in channel slope. The common effect of these constrictions is to force flow out of the main channel during periods with above average flows. On the Yalobusha River, an upstream portion of the river was channelized thus creating an abrupt reduction in main channel conveyance area between this channelized reach and the downstream meandering reach. The bankfull flow in the downstream meandering reach was less than 20% of the bankfull flow in the upstream channelized reach (Shields *et al.*, 2000). There is a sharp bend in the Guadalupe River below where a sediment plug formed in 2002 (Gergens, 2003).

Abrupt decreases in channel slope significantly affected sediment plug formation in streams in the Hatchie River Basin (Diehl, 1994). Accumulated debris served to further restrict flow for all these cases. Along the Tiffany Junction Reach of the Middle Rio Grande, the channel geometry has been impacted by the Atchison, Topeka, and Santa Fe railroad bridge and embankment, increased main channel sediment deposition caused by backwater effects from Elephant Butte Reservoir, and non-native riparian vegetation. The effect is a much narrower segment of the river just upstream of the railroad bridge with a bankfull main channel conveyance area that is less than 50 percent of the bankfull main channel conveyance area a few miles upstream – upstream of rangeline SO-1603.7. Debris was not a factor when the plugs formed along the Tiffany Junction Reach in 1991 and 1995 (Rivera, 2003).

Constrictions have an indirect impact on sediment plug formation in that such restrictions provide the key initial “set-up” conditions for plug formation, but other factors ultimately cause plug development. While the type of constriction varies, the net effect is the same: a reduction in main channel conveyance capacity. Specific types of constrictions are listed in Table 4.1 for four sites on alluvial rivers where plugs historically formed. While the effects of river bends, changes in slope, debris snags, or structures contribute to the development of a sediment plug, the evaluation should identify the specific processes that lead to the channel becoming completely clogged with sediment (i.e. a sediment plug). Constrictions are consistently present in reaches that are prone to sediment plug development, but the phenomenon of plug development involves other factors. Such restrictions serve as set-up conditions for plug development, but plugs form as a result of key physical processes. Otherwise, plugs would routinely form.

Table 4.1 Matrix of Site Characteristics for Cases of Historical Plug Development

Site	Bend in River	Abrupt Change in Channel Slope	Downstream Structure	Debris Snag	Significant and Abrupt Decrease in Main Channel Width and/or Depth
Middle Rio Grande	X		X		X
Yalobusha River		X	X	X	X
Guadalupe River	X			X	
Hatchie River		X		X	

The effects of three-dimensional hydraulics on sediment processes in bends are significant but are not considered to be key to plug formation. If the effect of the bend was the dominant variable, plugs would occur more often. Three-dimensional hydraulics in bends were not analyzed as part of this research.

4.2 Processes and Associated Parameters

Deposition is the result when the incoming total sediment load to a reach is less than the sediment transport capacity. This is indeed the case when sediment plugs form. The processes that cause the accelerated deposition associated with plug formation need to be identified, and the sensitivity of specific parameters assessed. The goal is to answer the following question: what causes the scenario where the sediment transport capacity is suddenly and significantly insufficient to transport the incoming sediment load? Several processes and associated parameters were identified as *possibly* affecting plug formation.

A higher influx of total sediment load to a study reach or variations in the total load could explain the sudden deposition associated with plug development. Changes in sediment transport capacity within a reach could also explain the accelerated deposition that occurs. Specific parameters that could affect the sediment transport capacity are water temperature, bed or bank roughness, and the concentration of sediment (or hyperconcentrations). Processes that could affect sediment transport capacity are water losses to seepage and evapotranspiration or the loss of flow from the main channel to the overbank areas (combined with a non-uniform vertical distribution of the total sediment load). The movement of macroforms was also reviewed to assess the impact that this process has on the formation of sediment plugs.

4.2.1 Above Average Daily Total Sediment Load

For all the historical cases of sediment plug development, the daily total sediment load into the reach that became plugged exceeded the historical average daily total sediment load during plug formation. The higher total sediment loads were not necessarily atypical; they generally corresponded with a higher flow condition. The incoming total sediment load along the Yalobusha River was higher due to erosion from the watershed and channel banks further upstream during periods of higher flow (Jones, 1998). The plug along the Guadalupe River formed during a 250-year hydrologic event which yielded higher sediment loads to the river (Gergens, 2003). For the Tiffany Junction Reach of the Middle Rio Grande, the daily total sediment load during the spring runoff flows of 1991 and 1995 (approximately 40,000 to 50,000 tons/day) exceeded the historical daily average, but this higher total sediment load was not unique to those years. A higher incoming total sediment load is a necessary ingredient for plug formation, but this process only explains the availability of sediment for plug formation but does not explain the sudden deposition that occurs.

4.2.2 Variations in Total Sediment Load

Variations in the incoming total sediment load to a study reach may explain the deposition that ultimately leads to a sediment plug. If the incoming sediment load suddenly increases but the sediment transport capacity in the reach does not increase at the same time, deposition may occur. No such variations in total sediment load were identified as causes for the sediment plugs that formed in the Yalobusha River and the Guadalupe River.

As discussed in Section 2.3.2.1, the average monthly sediment load in the Tiffany Junction Reach varies seasonally (MEI, 2002), but the reason for this fluctuation is not known in detail. The higher sediment loads during the summer monsoon season are likely the result of sediment inputs from ephemeral tributaries, but how this sediment is transported downstream is complex due to the lateral movement of sediment between the channel and the floodplain. The subsequent releases from Cochiti Dam can have a significant impact on the eventual transport of these sediment inputs to the Tiffany Junction Reach. This seasonal variation in sediment transport could affect plug development but is not a variable that is unique to sediment plug development (i.e. this seasonal variation is not unique to 1991 and 1995). Also, seasonal variation in total sediment load was not clearly evident from the daily total sediment loads computed from data collected at San Marcial.

Another process that may influence plug formation pertains to the potential for a sediment wave moving out of phase with an associated water wave from a single hydrologic event. Such a phenomenon may explain the movement of sediment into a reach that could not be transported through the reach, but there is little evidence of such a phenomenon from the historical cases of plug formation. Based on data collected in the Rio Grande basin at the USGS gage Rio Puerco near Bernardo (Gage ID 08353000), there were no recorded significant monsoon season tributary inflows to the Middle Rio Grande at the time that the plugs formed in 1991 or 1995 (Figures 4.1 and 4.2). Also, there were no recorded significant spikes in the river flow based on San Marcial gage data (Figures 4.3 and 4.4); therefore, sediment plug formation is not attributed to a sudden isolated increase in total sediment load associated with a hydrologic event.

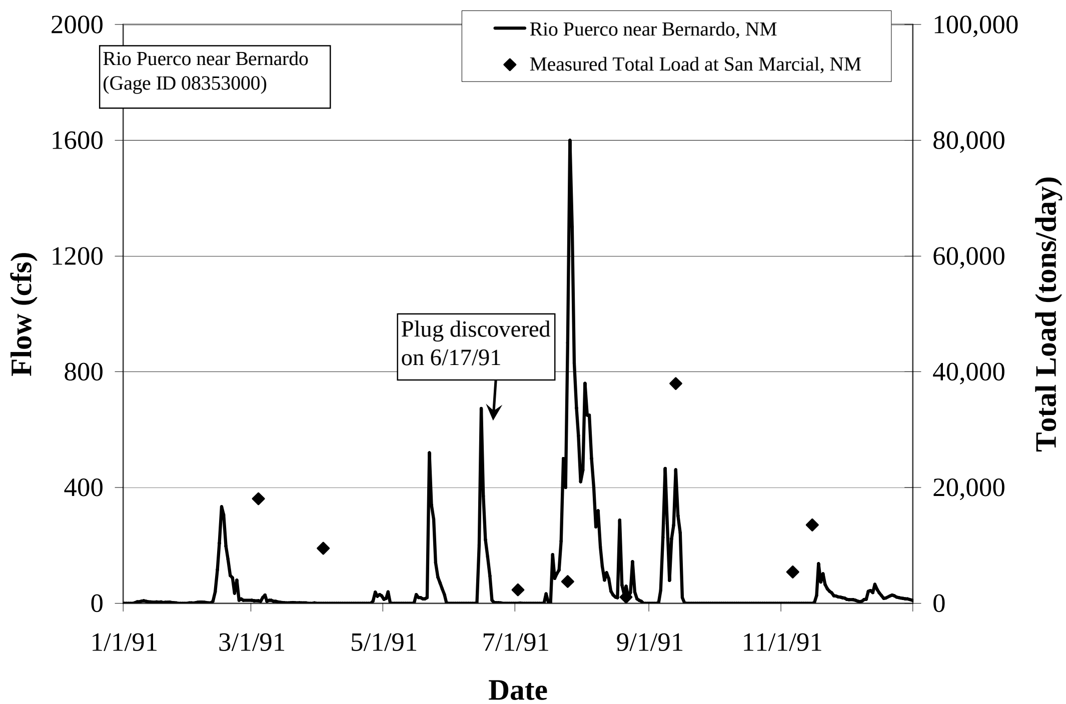


Figure 4.1 Plot of Gaged Rio Puerco Flows and Total Loads at San Marcial (1991)

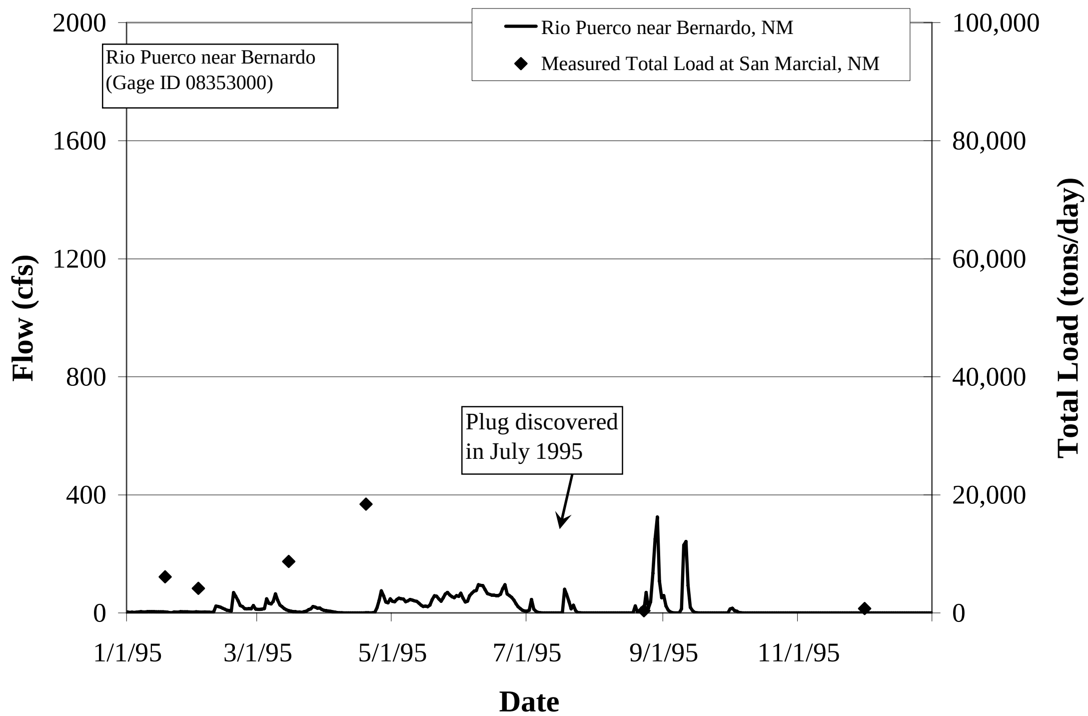


Figure 4.2 Plot of Gaged Rio Puerco Flows and Total Loads at San Marcial (1995)

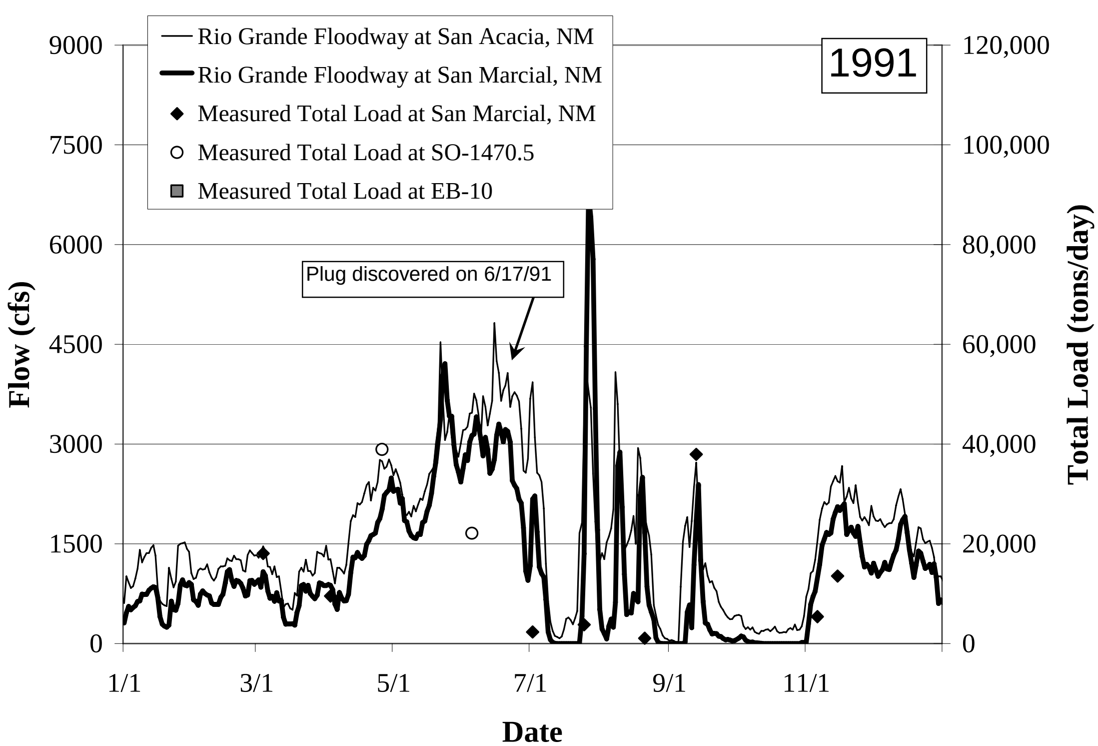


Figure 4.3 Plots of Gaged Flows at San Acacia and San Marcial with Total Loads at San Marcial, SO-1470.5, and EB-10 (1991)

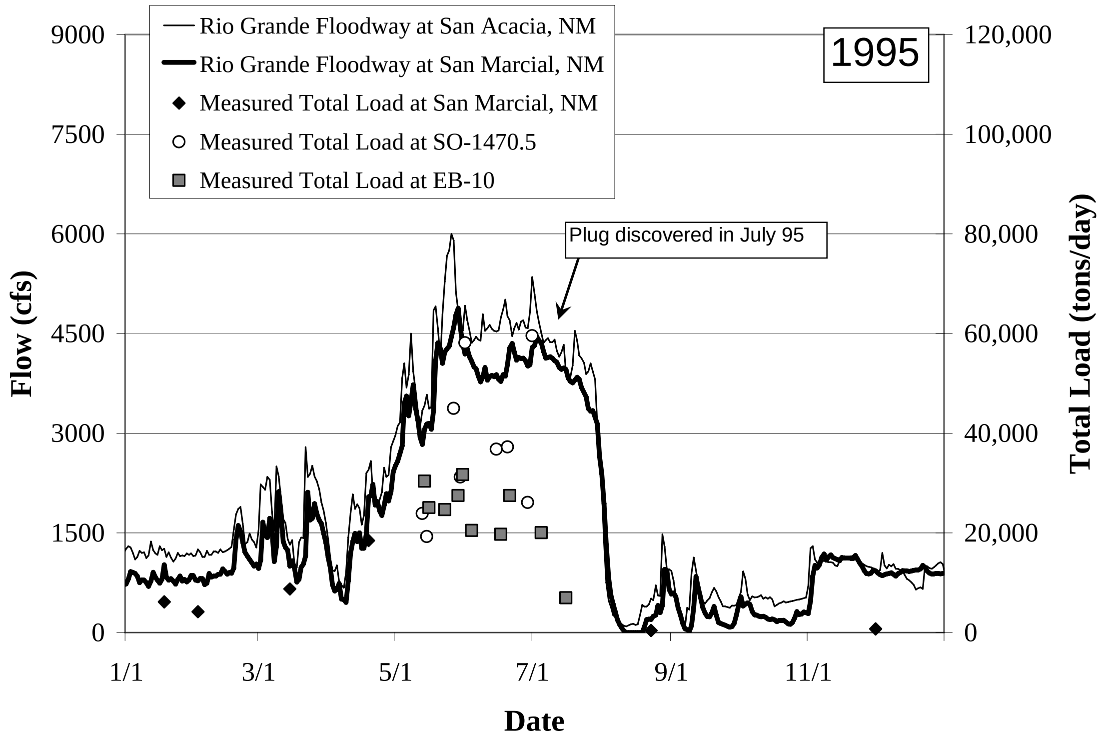


Figure 4.4 Plots of Gaged Flows at San Acacia and San Marcial with Total Loads at San Marcial, SO-1470.5, and EB-10 (1995)

4.2.3 Water Temperature

Water temperature can have an impact on sediment transport capacity in alluvial rivers where the total sediment load is significantly comprised of suspended load (USACE, 1977). As water temperature increases, flow viscosity decreases resulting in a higher sediment fall velocity. The sediment transport rate should decrease for such a scenario. The effect is not as clear when a significant portion of the total sediment load is bedload (USACE, 1977). A significant increase in water temperature may cause deposition in an alluvial river due to a decrease in sediment transport capacity, but this process would not cause the accelerated deposition observed during plug formation in alluvial rivers.

Nordin and Beverage (1965) were unable to identify a quantitative relationship between temperature and sediment transport for the Rio Grande. Water temperature changes along the Middle Rio Grande are seasonal and do not change sufficiently to cause the accelerated deposition recorded in 1991 and 1995 along the Tiffany Junction Reach. Daily fluctuations in water temperature may have a slight effect on the hydraulics, but not sufficient to cause the accelerated deposition that leads to a sediment plug. There are also no consistencies in regards to water temperature for historical cases of sediment plug development in other river systems; therefore, the effect of changes in water temperature on sediment transport capacity is not a key variable affecting sediment plug development.

4.2.4 Roughness

Changes in bedforms can have a significant impact on the hydraulics and sediment transport in an alluvial river. Sediment transport rates along the Middle Rio Grande may increase by 8 to 10 times after a transition from lower regime to upper regime is complete (Culbertson and Dawdy, 1964). If there was a sudden transition to lower regime during 1991 and 1995, that transition may explain a sudden drop in sediment transport capacity, but there is little evidence in the data that such a change in bedforms occurred. Based on the available data (FLO, 1990-1996), it is expected that plane bed was predominant during plug development. Change in bedforms is not a variable affecting sediment plug formation, but the variability of roughness with changes in flow was reviewed to assure such a variation would be appropriately represented in the analysis.

4.2.5 Hyperconcentrations

Hyperconcentrations, or laminated load, pertains to sediment transport when concentrations of sediment in transport affect the fluid properties and ultimately, the sediment transport capacity. The particle fall velocity decreases and sediment essentially remains buoyant. This effect of higher concentrations may explain a sudden variation in sediment transport capacity.

For the Middle Rio Grande, it has been documented that the effect of concentration on fall velocity for concentrations less than about 10,000 ppm is negligible (Nordin and Dempster, 1963). Concentrations along the Middle Rio Grande are usually less than 10,000 ppm. Sediment loads following summer monsoon season runoff events may explain such high concentrations, but sediment plug development is not consistent with individual runoff events. No significant runoff events are evident from the Rio Puerco gage data when the plugs formed (Figures 4.1 and 4.2). Also, sediment loads from the Rio Puerco and Rio Salado are primarily wash load (Baird, 2003).

For other river systems, concentrations are above average when plugs form, but the plugs have not been documented as a mudflow phenomenon. The effects of hyperconcentrations on the incoming sediment load are represented for the analysis as evident in the data, but this effect is not considered to be a key factor affecting plug formation.

4.2.6 Water Losses

Water losses to seepage and evapotranspiration may impact deposition in alluvial rivers. This process causes flow magnitudes to decrease as water is conveyed downstream. The reduction in flow, which can be high during the summer, impacts the hydraulics thus affecting sediment transport and subsequent erosion/deposition. As river flow decreases, the sediment transport capacity drops without a corresponding reduction in sediment load and deposition ensues.

Losses to seepage and evapotranspiration have a clear impact on sediment processes in alluvial rivers, but the impact is too subtle to cause such accelerated deposition observed during plug formation. For the case of the Middle Rio Grande, the Tiffany Junction Reach is actually narrower than other reaches of the river, so losses of main channel flows to evaporation are lower along this reach as opposed to other reaches. If water losses were a significant influence to plug formation, plugs would form in other reaches where water losses are higher than along the Tiffany Junction Reach. Water losses are an issue every year along the Middle Rio Grande and not unique to conditions during 1991 and 1995.

Water losses are not a significant issue for the Yalobusha River in Mississippi or the streams in the Hatchie River Basin in west Tennessee. While water losses are not a predominant process affecting plug development, losses are appropriately represented for computing the hydraulics for the analysis of other processes that are key to plug formation.

4.2.7 Loss of Flow to Overbank Areas

Loss of river flows to overbank areas is a consistent factor for all the river systems where plugs historically occurred. On the Yalobusha River, the main channel conveyance capacity abruptly drops from 20,000 to 2,500 cfs where the sediment plug formed (Simon and Thomas, 2002). The portion of the river above where the plug formed had been channelized. As higher flows reached the end of this channelized reach, a large portion of the flow went overbank and was dispersed across the floodplain. When the plug formed along the Guadalupe River in Texas during 2002, flows went overbank and were diverted through a swale on the inside of the bend just above where the plug occurred. The Corps completed a HEC-RAS study and the results indicated that after river flows exceed 40,000 cfs, flows go overbank through the swale (Gergens, 2003). When the plug formed, river flows peaked at 66,800 cfs and structures located along the swale were damaged. Overbank flows are also common for cases of plug formation in the Hatchie River basin (Diehl, 2000).

The loss of flow to the overbank areas can have a significant effect on sediment transport capacity. Consider a case where the total sediment load rating curve has a power function format (Knighton, 1998):

$$Q_S = coefficient\, Q^{RCEXP} \qquad \text{Equation 4.1}$$

If the rating curve exponent, *RCEXP*, is greater than 1.0, then following a reduction in flow, the sediment transport capacity will drop by a greater percentage than the percentage drop in flow. If the exponent is not significantly greater than 1.0, the vertical distribution of sediment load is another factor that causes a decrease in sediment transport capacity that is disproportionate to the decrease in total sediment load.

4.2.7.1 Vertical Distribution of Sediment Load

If the vertical distribution of the total sediment load is not uniform when flows are lost to the overbank areas, the proportion of the sediment load that is lost to the overbank areas is not equivalent to the proportion of the water that is lost. Essentially, sediment transport capacity is reduced with the loss of flow, but the sediment load is not reduced by the same proportion.

The vertical distribution of total sediment load for most alluvial rivers is non-uniform. For the Rio Grande, sediment sizes that are less than 0.062 mm in diameter are generally uniformly distributed (Nordin and Dempster, 1963), but larger particles follow a predicted non-uniform distribution – particularly if dunes are the predominant bedform. The distribution is more uniform if the bed has "planed out." Data are not available for evaluating the vertical distribution of suspended sediment for the other river systems where plugs developed, but it is expected that the distribution was non-uniform.

4.2.8 Macroforms

Macroforms are common in alluvial rivers and the movement of these bars into a reach with a constriction could explain the development of sediment plugs. Macroforms along the Middle Rio Grande may be ¼ to ½ mile long (Baird, 2003). Such transverse bars move at a rate of 350 feet per day (Culbertson and Scott, 1970). Field personnel do not recollect macroforms moving into the Tiffany Junction Reach during 1991 and 1995 (Rivera, 2003). If a macroform did migrate into the Tiffany Junction Reach, based on the channel morphology, it is expected that it would have caused problems further upstream from where the sediment plugs formed. Such a macroform would have likely caused problems seven miles upstream near rangeline SO-1603.7 where the channel width reduces from approximately 1000 feet to approximately 300 feet and the average bed slope abruptly reduces from 0.0007 to 0.0005. Since macroforms are not identified as a cause for sediment plug development in other river systems, the movement of macroforms is not considered as a factor causing sediment plug development.

The processes and associated parameters that were consistent with periods of historical sediment plug development are delineated in Table 4.2.

Table 4.2 Matrix of Processes and Associated Parameters that were Consistent to Historical Sediment Plug Development

	Incoming Total Load		Sediment Transport Capacity within a Reach					
						Water Losses		
Site	Above Average	Seasonally Variable	Water Temp	Roughness	Hyper-Concentrations	Seepage and Evapotranspiration	to Overbank Areas	Macroforms
Middle Rio Grande	X						X	
Yalobusha River	X						X	
Guadalupe River	X						X	
Hatchie River	X						X	

V. DATA

An expansive database is available for the Tiffany Junction Reach along the Middle Rio Grande that extends from the Highway 380 bridge, south of Socorro New Mexico, downstream past San Marcial, New Mexico. The database includes discharge measurements, bed material samples, suspended sediment samples, and cross section surveys from 1987 to 2002. The information necessary to analyze the 1995 and 1991 conditions are available in addition to data for conditions after the plug developed in 1995. Data are also available for the Yalobusha River system to test the results from the study, but the quantitative information from this river system, when the plug formed, is limited.

5.1 Flow

The most expansive sets of flow data for the Tiffany Junction Reach are the USGS daily flow records (USGS, 1988-2003). The San Marcial gage (ID# 08358400) is located at the lower end of the study reach. This gage is located approximately 1.5 river miles below the location were the sediment plugs formed in 1991 and 1995. The USGS gage at San Acacia (ID# 08354590) is approximately 29 river miles above the upstream end of the study reach. The data from this gage were used to determine the inflows to the study reach. The data for both of these gages are portrayed in two measurement sets: the data for the “floodway” represents the flow in the Rio Grande and data for the “conveyance channel” represents the flow in the Low Flow Conveyance Channel (LFCC) at the gage location.

The 1991 daily flow data from both gages are plotted in Figure 5.1. The plug was *first observed* on June 17, 1991. The data for 1995 are presented in Figure 5.2. The plug was first observed in July of that year.

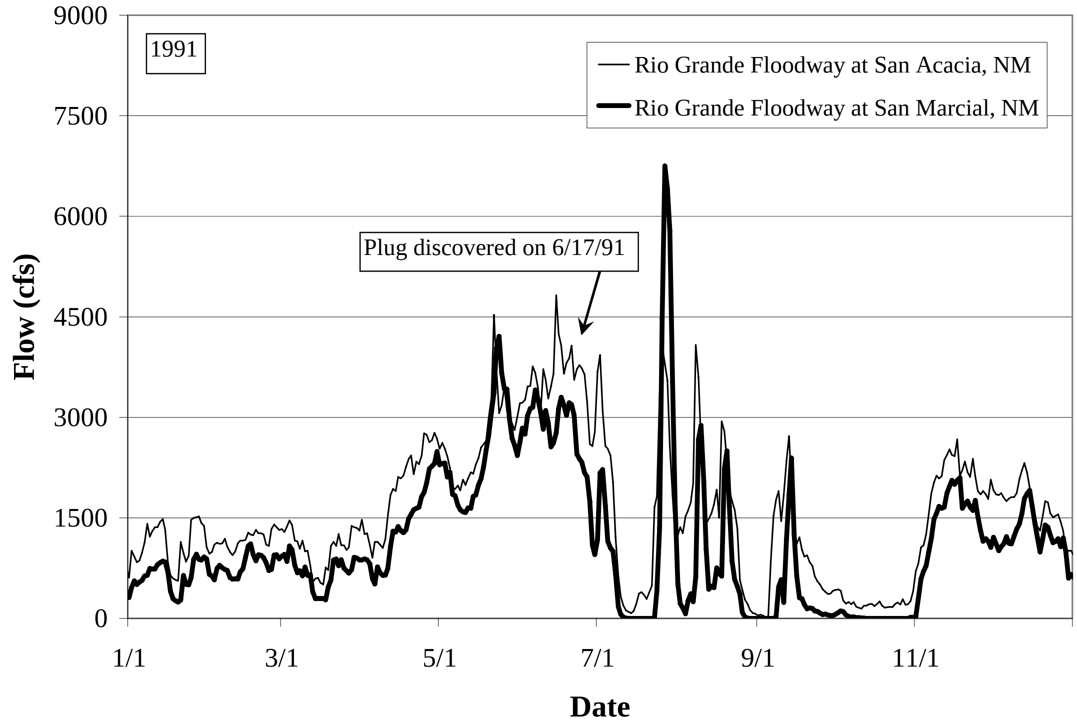


Figure 5.1 USGS Daily Flow Data for San Acacia and San Marcial (1991)

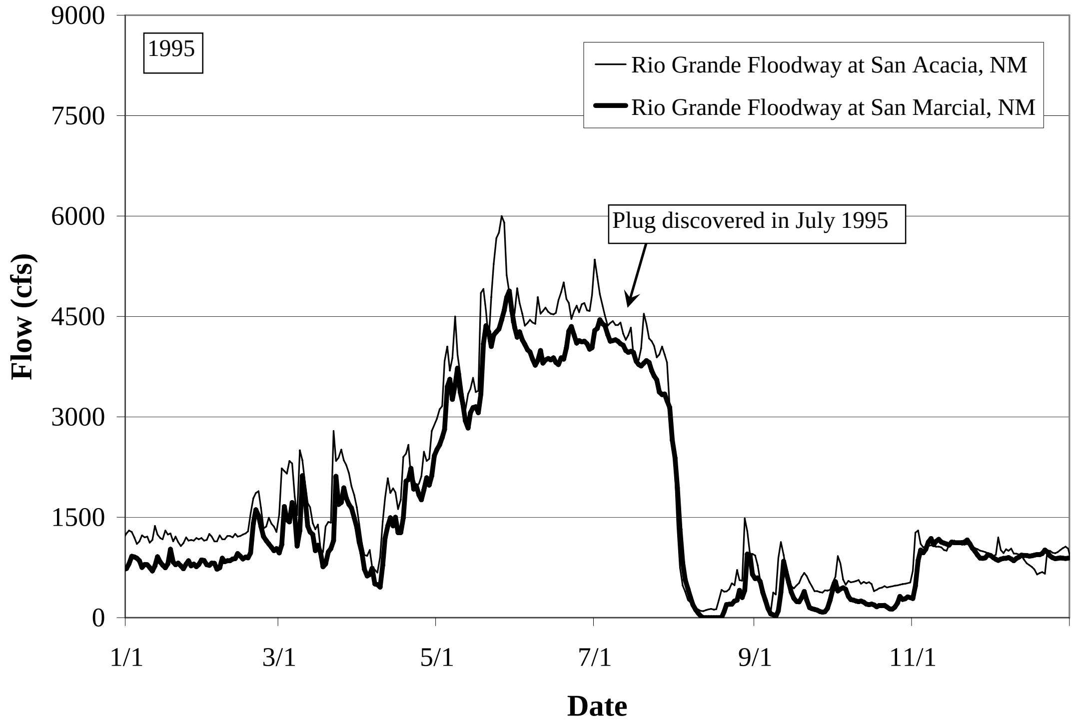


Figure 5.2 USGS Daily Flow Data for San Acacia and San Marcial (1995)

Supplemental flow data are also available from instantaneous measurements made by Reclamation, its contractors, and other agencies (FLO, 1990-1996); however, the USGS daily flow database was the primary source for flowrate information.

5.2 Roughness (Manning n Values)

Manning n values have been calibrated for the Middle Rio Grande and will be expressed as constant values for extended reaches of the river. Also, a single constant roughness value is used for the overbank areas. In order to evaluate alternatives for the Rio Grande and LFCC Modifications DRAFT EIS, a Manning n value of 0.017 is used for the Tiffany Junction Reach (USBR, 2000), and a roughness value of 0.10 is used for the overbanks. Data are also available for the study reach in regards to bedforms and vegetation (FLO, 1990-1996). This information was referenced along with the documents noted in Section 2.3.1 during an attempt to complete further calibration of Manning n values. Manning n values were computed with cross section survey data using reach average slopes and estimated flows to determine whether any variations in roughness with flow could be captured.

5.3 Bed Material

Bed material samples were collected by Reclamation and its contractors at various locations at or near the study reach (FLO, 1990-1996). Included are samples collected throughout the 1990s which provided bed material information for this investigation. Samples were taken regularly at cross section SO-1470.5 which is located immediately above the study reach and at cross section EB-10 which is at the downstream end of the study reach. The data from these samples provided longitudinal (and lateral) variation in the bed material sizes along the study reach. During 1991, samples were taken at numerous cross sections along the Tiffany Junction Reach. The USGS also collected bed material samples at the location of the San Acacia and San Marcial gages (USGS, 1988-2003).

Historical sediment sampling data are available (Nordin and Culbertson, 1961) but are of limited usefulness. Their report indicated that the bed material along the Middle Rio Grande is coarser as you progress upstream (the median grain size increases from 0.25 mm at San Marcial to 0.4 mm below Cochiti Dam), but no trend is noticeable along the 22 mile Tiffany Junction Reach. It has been suggested that the bed material is coarsening over time, but in a recent report it was concluded that there is no evidence of bed coarsening below the San Acacia diversion dam (MEI, 2002).

The median sediment grain size (d_{50}) along the Tiffany Junction Reach is approximately 0.2 to 0.3 mm, and typical values for d_{16} and d_{84} are 0.15 and 0.35 mm, respectively (FLO, 1991-1996). The channel bed along the study reach is comprised of sand sized particles. Since the bed material sediment size is generally uniform along the Tiffany Junction Reach, a single mean sediment size of 0.25 mm is used for analysis. Size gradation plots for selected samples are presented in Figures 5.3 through 5.5.

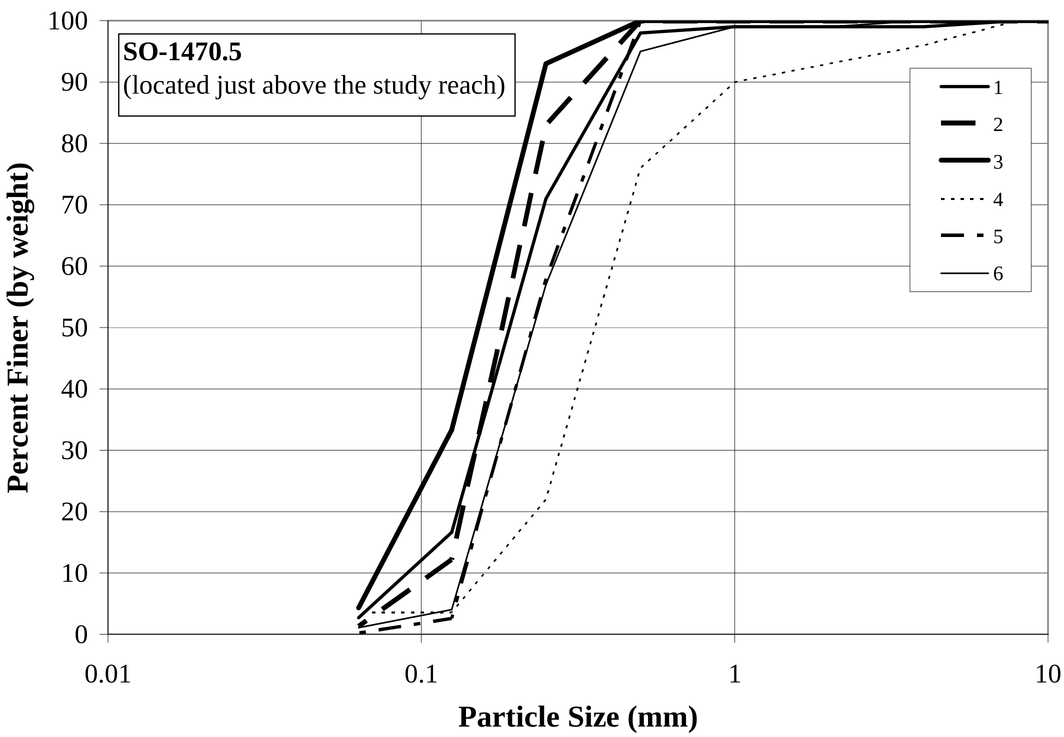


Figure 5.3 Bed Material Size Distribution Plots for SO-1470.5 (Six Samples, 4/26/91)

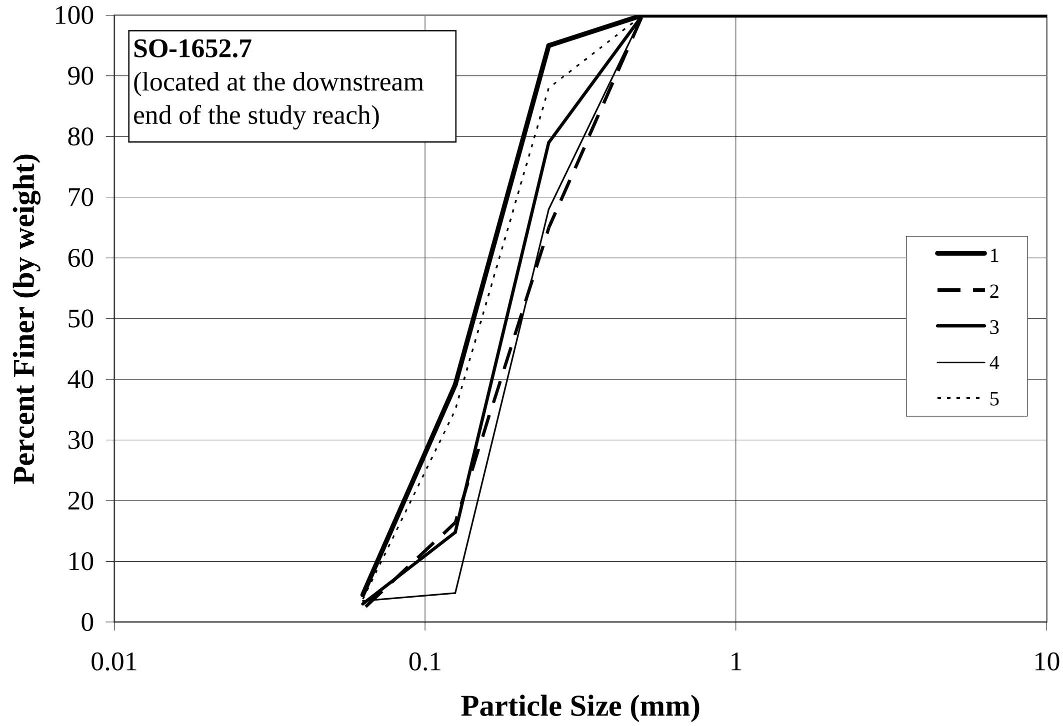


Figure 5.4 Bed Material Size Distribution Plots for SO-1652.7 (Five Samples, 4/28/91)

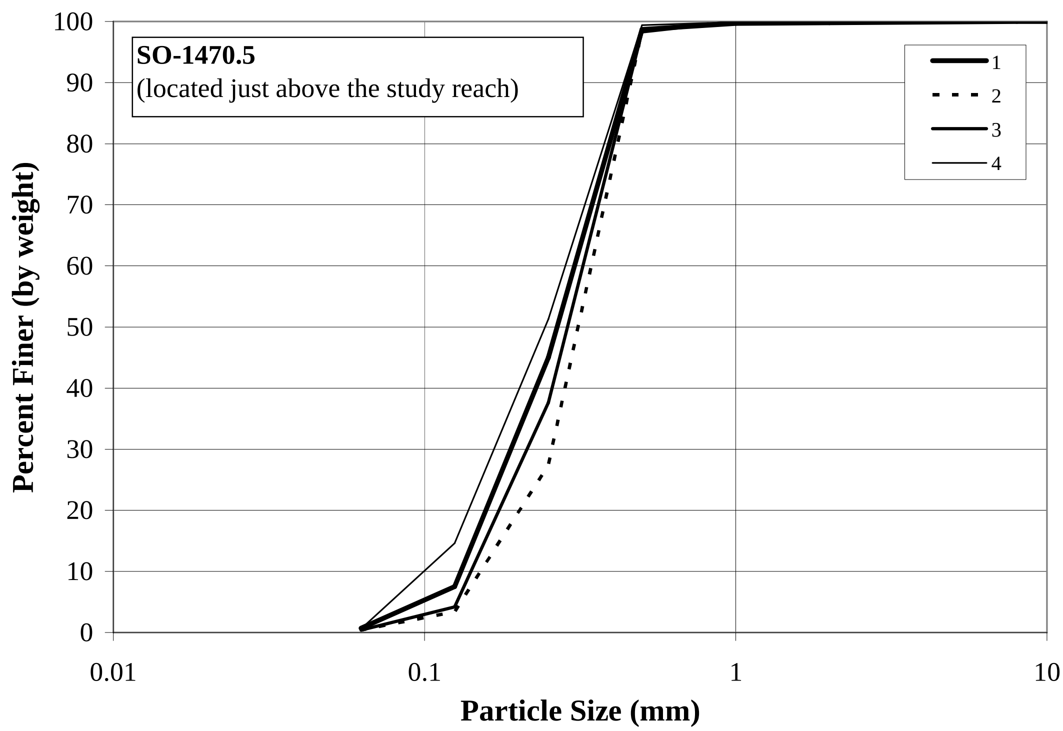


Figure 5.5 Bed Material Size Distribution Plots for SO-1470.5 (Four Samples, 6/15/95)

5.4 Sediment Transport

The USGS collected suspended sediment data at the San Acacia and San Marcial gage locations (USGS, 1988-2003). Reclamation and its contractors also collected data at numerous locations along the Middle Rio Grande including cross section SO-1470.5 which is located immediately above the Tiffany Junction Reach and at EB-10 near the downstream end of the reach (FLO, 1990-1996). Samplers used to collect suspended sediment samples included the DH-48, DH-59, and DH-74. Total sediment load calculations were performed by Reclamation and its contractors using the Modified Einstein Procedure to determine the rate of transport in the “unmeasured zone” (FLO, 1990-1996).

Sediment supply curves were developed with the results from the total sediment load calculations (MEI, 2002). The total sediment load function presented in Figure 5.6 was developed using 67 data points for the total sediment load computed with data collected at random times from 1990 to 1999 at San Marcial (USGS, 1988-2003):

$$TotalLoad\,(tons/day) = 1.4074 * Flow(cfs)^{1.2419} \qquad \text{Equation 5.1}$$

The total sediment load rating curve was used for this study, but some variability in the sediment load, particularly the fine material, may be attributed to the temporary storage of sediment on bars or islands. Finer material settles on islands during receding flows or low flows and is flushed downstream during rising or higher flows (Nordin and

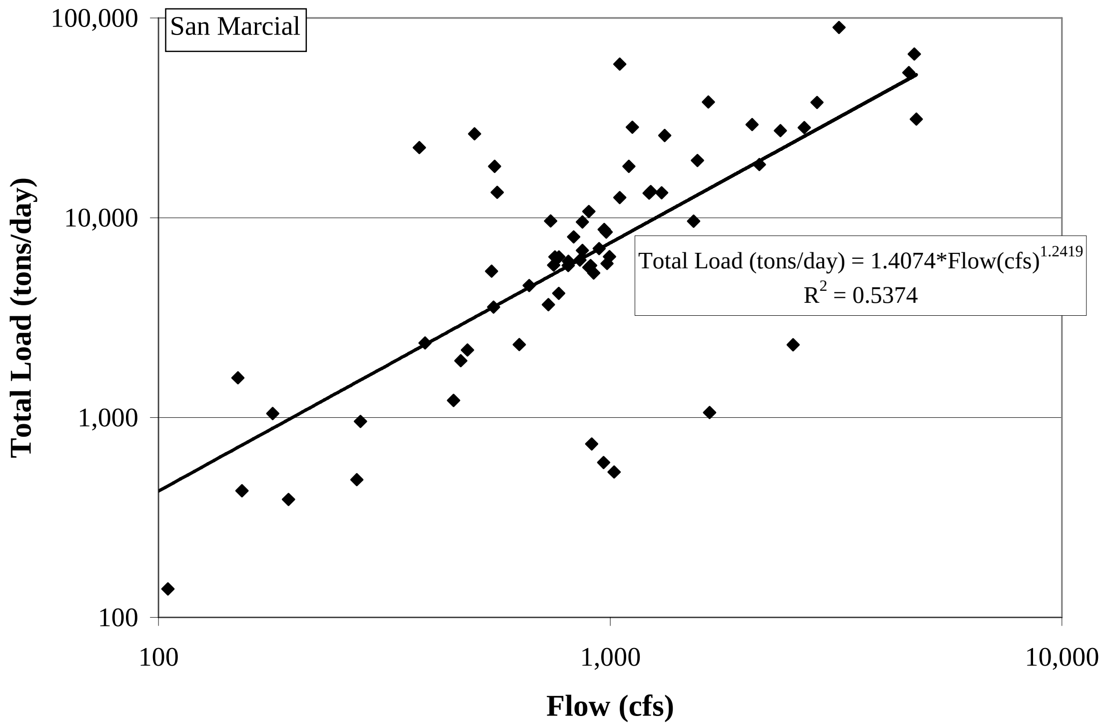


Figure 5.6 Total Sediment Load Rating Curve for San Marcial

Beverage, 1964). The total sediment load data for San Marcial were evaluated to determine seasonal variability in the data; however, no trend was clearly evident.

The vertical distribution of the sediment load in the Rio Grande near Socorro was analyzed by Nordin and Dempster (1963). Several functions were developed for different sediment size classifications (finer material (< 0.0625 mm) is generally uniformly distributed in the water column). Data for a sample cross section are plotted for two other size classifications: 0.125 – 0.25 mm and 0.25 – 0.5 mm (Figure 5.7). These data were utilized to determine a Rouse number of 1.15 to use for the mean sediment size of 0.25 mm.

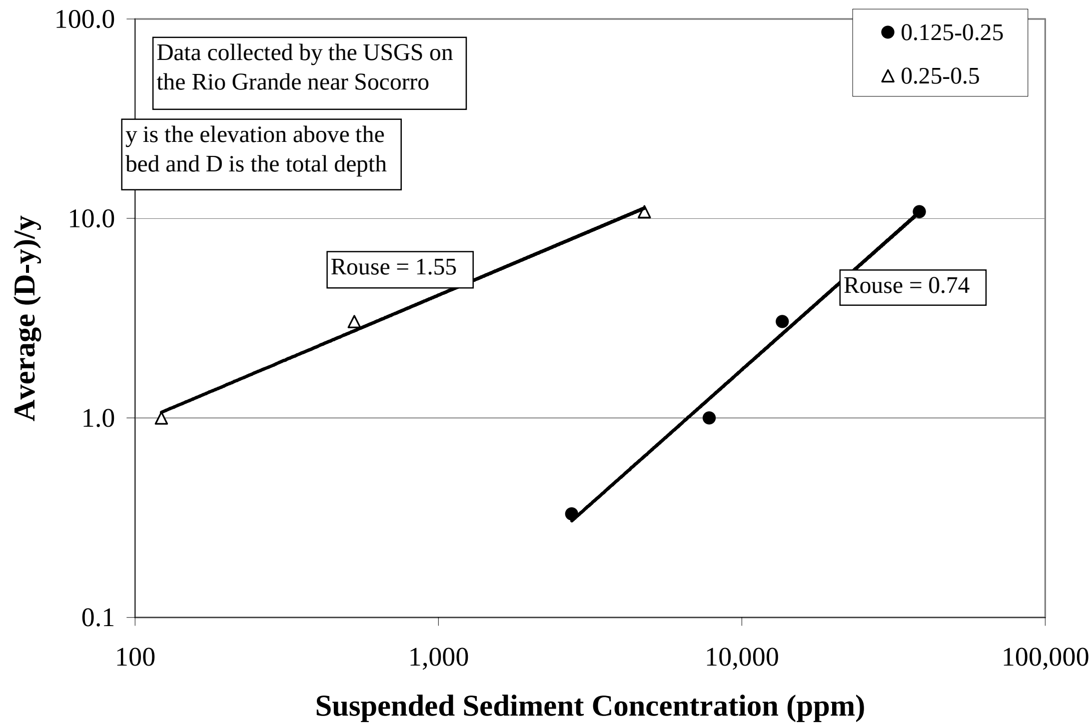


Figure 5.7 Vertical Distribution of Suspended Sediment Concentration

5.5 Cross Section Surveys

Channel cross section survey data from the Tiffany Junction Reach were used to evaluate the performance of the sediment transport and movable bed procedures. Surveys of numerous cross sections were obtained during 1991 and 1995 (FLO, 1990-1996). During 1995, cross sections were surveyed at the exact location of the plug before a pilot channel was dredged. These data, along with testimonial information, provide a baseline of information for evaluating the extent of the sediment plug and timing of its formation.

When data are not available for conditions immediately prior to plug formation in 1995, the information was developed from earlier cross section surveys (FLO, 1990-1996) and a review of general sedimentation trends. The cross section database for conditions prior to the 1991 plug was more extensive as surveys were completed during October of 1990 and April of 1991. Quantitative data are not available in regards to the exact location and extent of the 1991 plug, but the events were well documented by Reclamation (USBR, 1992).

Plots of selected cross section survey data are presented in Figures 5.8 through 5.12. These cross sections are presented to provide the typical channel geometry along the Tiffany Junction Reach. The survey of SO-1673 on 8/5/95 (the solid bold line in Figure 5.11) depicts the channel geometry after the plug formed. The main channel in the middle of the plot is completely plugged with sediment.

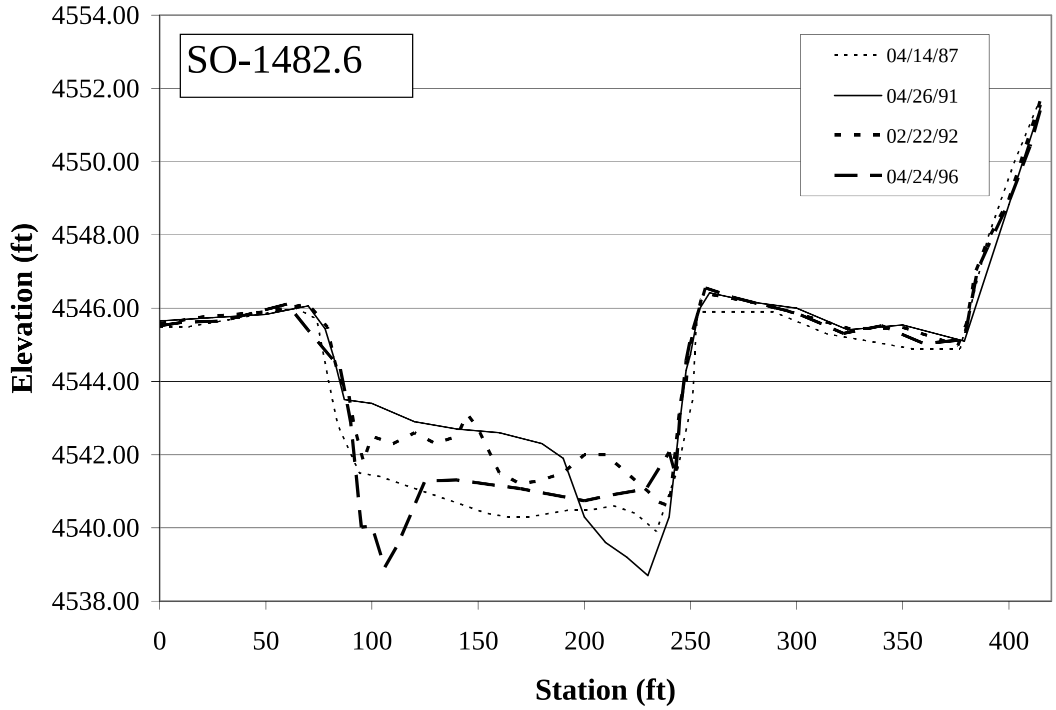


Figure 5.8 Plots of Selected Cross Section Survey Data for SO-1482.6

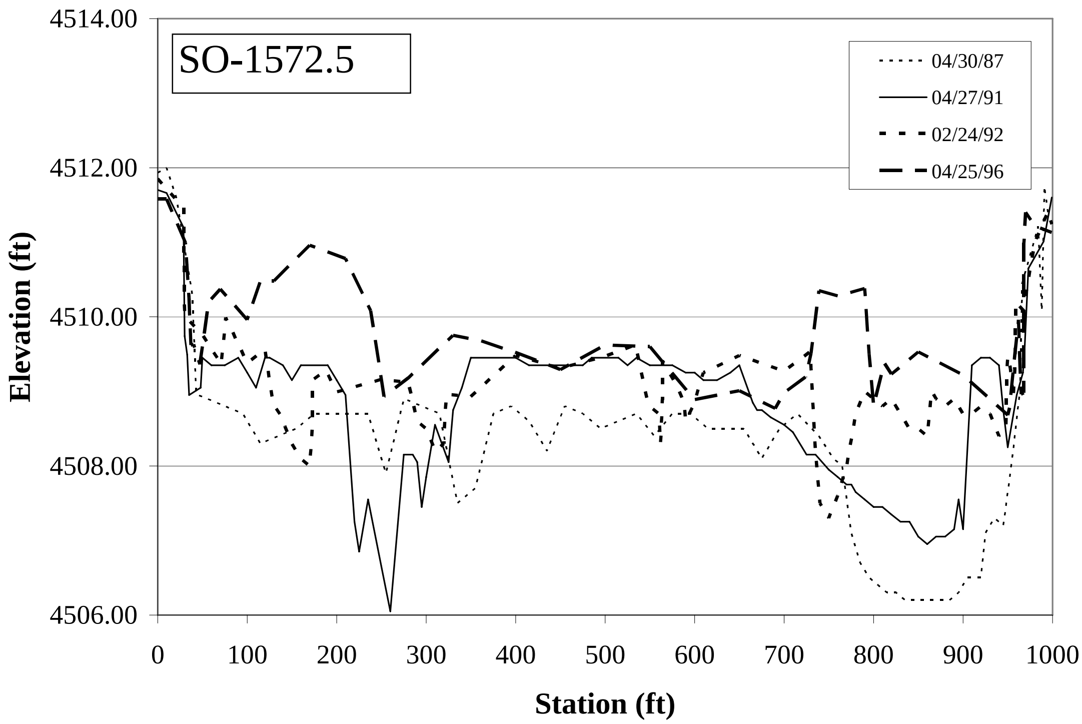


Figure 5.9 Plots of Selected Cross Section Survey Data for SO-1572.5

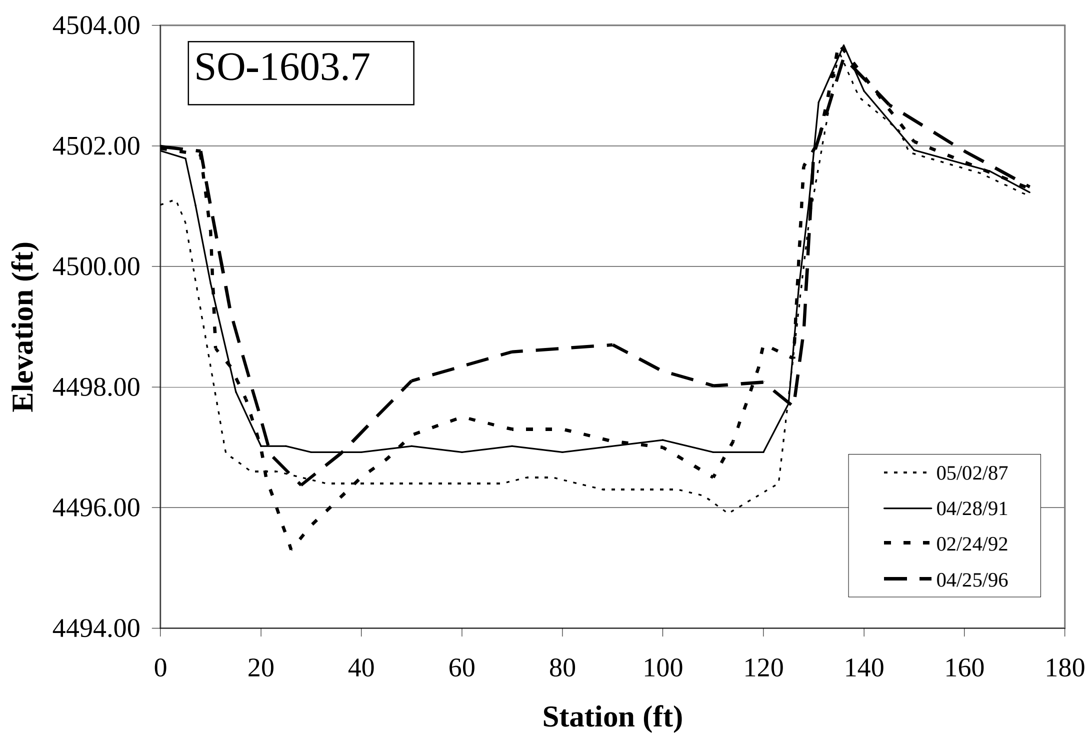


Figure 5.10 Plots of Selected Cross Section Survey Data for SO-1603.7

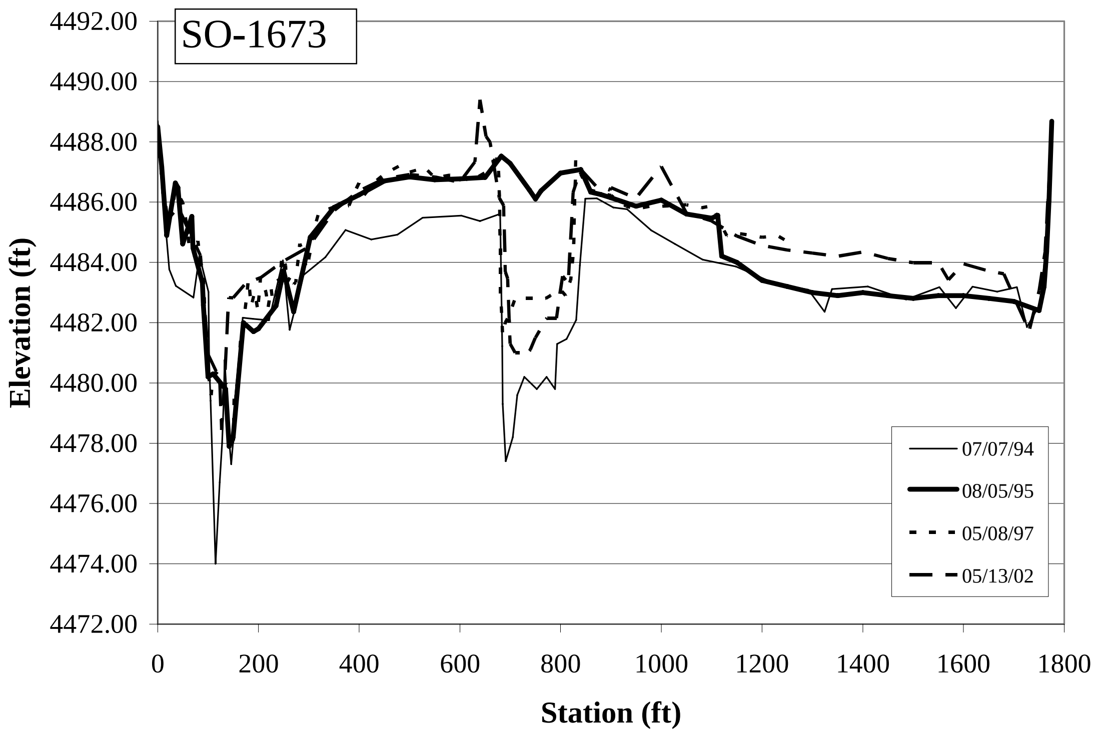


Figure 5.11 Plots of Selected Cross Section Survey Data for SO-1673

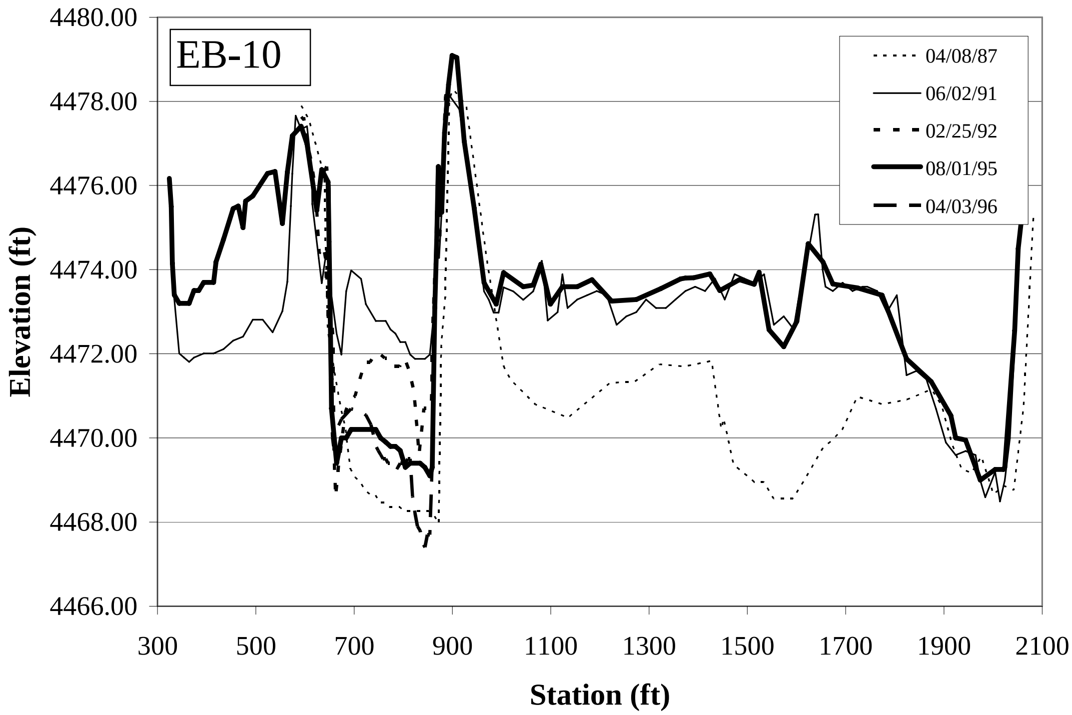


Figure 5.12 Plots of Selected Cross Section Survey Data for EB-10

5.6 Water Surface Elevations

The cross section survey data proved to be most valuable for calibrating and validating the analysis completed for this study in regards to the accelerated deposition associated with plug formation, but the water surface elevations were also referenced to check the hydraulic calculations. Water surface elevation data were collected along the Tiffany Junction Reach at the same times that cross section surveys were completed.

VI. PLUG FORMATION THEORY

Several processes, associated parameters, and site characteristics exist that may influence the development of sediment plugs. After evaluating the available information on historical sediment plug formation, a theory was formulated for the prediction of plug development. 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.

6.1 Processes Related to Plug Formation

For a site that is prone to plug formation due to a constriction, there is a series of processes which ultimately lead to sediment plug formation. Constrictions are local controls or other physical features that significantly reduce the main channel conveyance capacity of an alluvial river. Examples of constrictions include a bend in a river, structure, or debris snag. A constriction may also be a significant and abrupt reduction in the main channel width and/or depth. Processes that lead to sediment plug development are:

1. Daily Total Sediment Load that Exceeds the Historical Average Daily Total Load
2. Abrupt and Significant Loss of Flow to Overbank Areas
3. Non-Uniform Vertical Distribution of the Total Sediment Load
4. Prolonged Higher Discharges

Sediment plugs historically occurred at times when the daily total sediment loads exceeded the historical average daily total sediment load. The higher total sediment loads are usually not atypical but correspond to higher flow conditions. When these higher flows encounter the constriction, water begins to overbank. Based on the sediment rating curve (a power function with an exponent greater than 1.0), with a loss of flow to the overbank areas, there will be a greater percentage reduction in sediment transport capacity, and deposition in the main channel ensues. When flows are lower and entirely conveyed in the main channel, the sediment transport capacity is generally sufficient to transport the incoming total sediment load through the reach. If a considerable portion of the flow is abruptly lost to the overbank areas at a significant constriction, the subsequent deposition becomes accelerated.

The effect that this loss of flow to the overbank areas will have on deposition in the main channel will be most pronounced when the vertical distribution of the total sediment load is non-uniform. If the vertical distribution of sediment is non-uniform, the proportion of the total sediment load that is lost to overbank areas is less than the proportion of the flow that is lost (i.e. the water at the top of the water column is carrying less sediment than at the bottom of the water column). As a result, the sediment transport capacity is reduced but the sediment load decreases by a smaller percentage.

The loss of flow to overbank areas must occur for an extended period (weeks as opposed to hours) for the entire main channel to become completely clogged with sediment (i.e. a sediment plug). Prolonged higher flows result in continued higher sediment input to the reach. In addition, the effect of the reduction in sediment transport capacity that corresponds with the loss of flow to overbank areas becomes more pronounced as this condition continues. If flows return to a level that can be conveyed in the main channel, the loss of sediment transport capacity which coincides with overbank flows is no longer a significant factor. The sediment transport capacity would return to a level that may be sufficient to carry the incoming sediment load or possibly initiate scour. If flows recede in a timely manner, the main channel of the river will not become completely plugged.

6.2 Theory Summary

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 main channel 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 (i.e. near rangeline SO-1683)) 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).

VII. COMPUTER MODEL METHODS

The theory of sediment plug formation discussed in Chapter 6 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.

The hydraulic information is determined by solution of the unsteady flow equations with consideration for the loss of flow to overbank areas and an appropriate representation of channel roughness. To assure all the key processes affecting the focus study reach are represented, losses to seepage and evapotranspiration are also represented. Sediment transport rates are computed using a power function rating curve and the vertical distribution of the total sediment load is determined based on the Rouse Equation. The portion of the total sediment load that is lost to overbank areas is calculated with reference to the water surface elevation, bank elevations, and determined vertical distribution for the total sediment load. Erosion/deposition is then determined assuming an immediate change in bed elevation based on the change in sediment transport capacity between adjacent cross sections.

Within the SPAR model, the solution for the unsteady flow equations and sediment transport computations are uncoupled. Information on the hydraulics is determined for the entire reach for the current computational timestep. Sediment transport rates are calculated based on the determined flowrates which reflect any reduction in flow due to losses to the overbank areas. As water overbanks, flowrates decrease and sediment transport capacity decreases. Before the Exner equation is applied to determine the amount of erosion/deposition along an incremental spatial step, the incoming sediment load to the spatial step is reduced to account for the amount of that sediment which is lost to the overbank areas.

Simulations were completed with a timestep on the order of 30 seconds and cross sections that are 500 feet apart. The Corps' HEC-RAS software was used to develop interpolated cross sections for the input geometry file (USACE HEC, 2002). More details on the methodologies and assumptions used in the SPAR model will be presented.

7.1 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 to assure stability while reducing numerical diffusion (Julien, 2002). Also, extensive analyses were completed for the Tiffany Junction Reach before model calibration to determine the most appropriate representation of roughness and to evaluate water losses to seepage and evapotranspiration.

7.1.1 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 for the effects of flow losses to the overbank areas to be considered. A stage-discharge curve is input for the downstream boundary condition. This curve was determined by regression using 24 data points collected from 1986 through 2002 at rangeline EB-16 along the Rio Grande. An inflow hydrograph is used for the upstream boundary condition. This hydrograph for the flows at the Highway 380 bridge (rangeline SO-1482.6) was developed based on historical flows gaged at San Acacia with consideration for the water losses from San Acacia to the upstream end of the study reach. The loss rate is based on a regression function relating gaged flows at San Marcial to gaged flows at San Acacia (Figure 7.2). 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):

$$C = c\frac{\Delta t}{\Delta x} = \beta V\frac{\Delta t}{\Delta x} \leq 1.0 \qquad \text{Equation 7.1}$$

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 vs. A relationship for a 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 wave celerity during a simulation. Using the highest inflow in the input inflow hydrograph, a corresponding highest average velocity is computed assuming normal depth at the upstream cross section. This average velocity may not represent the highest average velocity that will occur during a simulation due to the variations in the downstream channel geometry. Test runs were completed with the model for the Tiffany Junction Reach to determine an adjustment factor, or ratio, between the highest expected downstream average velocity and the highest average velocity at the upstream cross section. This adjustment factor is then used at the beginning of each model run to estimate the highest expected average velocity based on the input inflow hydrograph. 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.

7.1.2 Roughness

Following an extensive analysis, it was determined that a single Manning n roughness value for the entire Tiffany Junction Reach would be most appropriate for the evaluation of sediment plug formation. Field data indicate that bedforms along the Tiffany Junction Reach are in upper regime above approximately 2000 cfs (FLO, 1990-1996). The sediment plugs that formed in 1991 and 1995 occurred while flowrates were greater than 3000 cfs.

A single Manning n value of 0.017 is used in the SPAR model for the entire Tiffany Junction Reach. The same value was calibrated to match measured deposition/erosion along the Tiffany Junction Reach in the HEC-6T model developed by Reclamation to analyze alternatives for the Rio Grande and LFCC Modifications DRAFT EIS (USBR, 2000). The value of 0.017 is also approximately the same as the values calibrated by FLO Engineering for cross sections at the upstream portion of the Tiffany Junction Reach based on measured and computed water surface elevations. Values from 0.015 to 0.017 were calibrated with data from 1993 and 1994 for flows ranging from 2700 cfs to 5400 cfs (FLO, 1995).

An analysis of the variation of roughness with flow was completed for the Tiffany Junction Reach. Data collected by Reclamation and its contractors at various cross sections were analyzed. The cross section survey data were used with reach average slopes and estimated flowrates to compute Manning n values. Errors in the assumed values for slope and flowrate caused scatter in the computed roughness values, but the average roughness values at each cross section during upper regime conditions are 0.017

(± 0.005). There was no evidence of a relationship between Manning n value and discharge for flowrates greater than 2000 cfs (Figure 7.1 for a sample plot developed with data collected at rangeline SO-1576). It was determined that the variation in computed Manning n values is relatively small during upper regime conditions, and a single value for the entire Tiffany Junction Reach would be appropriate for this study.

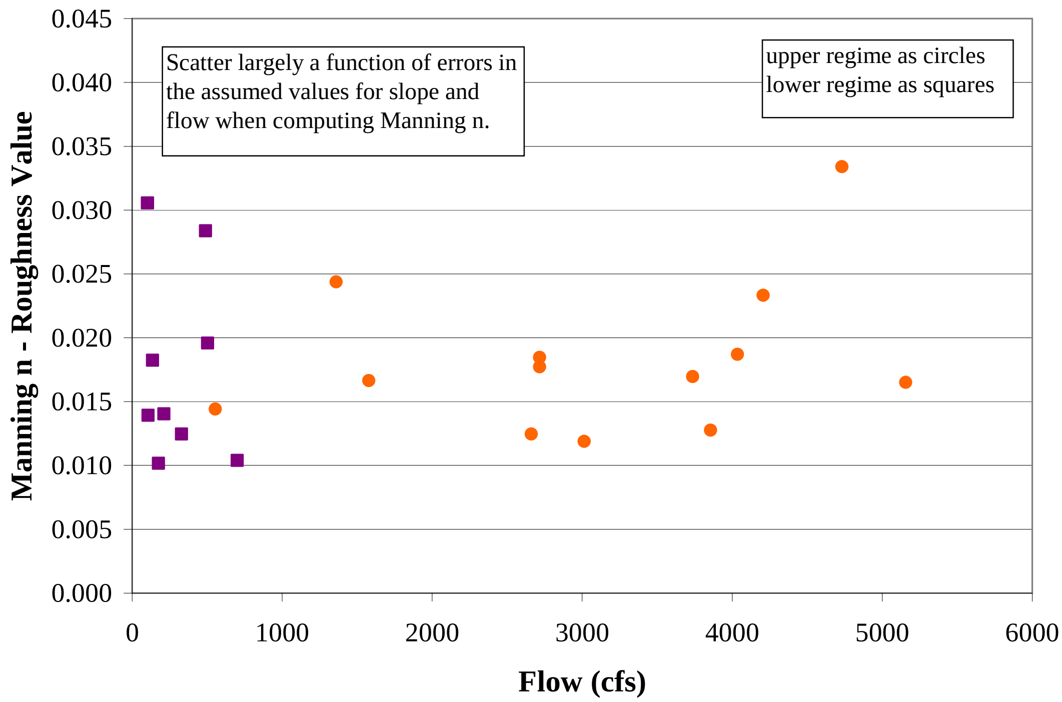


Figure 7.1 Sample Plot of Rough Estimates for Manning n versus Flow (SO-1576)

7.1.3 Losses to Seepage and Evapotranspiration

Water losses to seepage and evapotranspiration are represented specifically for calibration of the SPAR model against plug formation in the Middle Rio Grande. To determine a rate for losses to seepage and evapotranspiration along the Tiffany Junction Reach, a regression equation was developed to relate the gaged flows at San Marcial to the gaged flows at San Acacia (Figure 7.2). Mean daily flow data from 1988 through

2003 were selected such that the data set would be expansive but also representative of conditions during 1991 and 1995 (USGS, 1988-2003). Based on a review of the mean daily data, it was determined that an assumed travel time of one day is appropriate for the analysis at all flows. A loss function was developed to determine the loss per 500 ft incremental spatial step:

$$LossPer500\,ft(cfs) = 0.00028 * FlowAtUpstreamEndof\,500\,ft(cfs) + 0.227$$

Equation 7.2

Losses to seepage and evapotranspiration, along with lateral losses to the overbank areas, are included in the solution of the unsteady flow equations within the SPAR model.

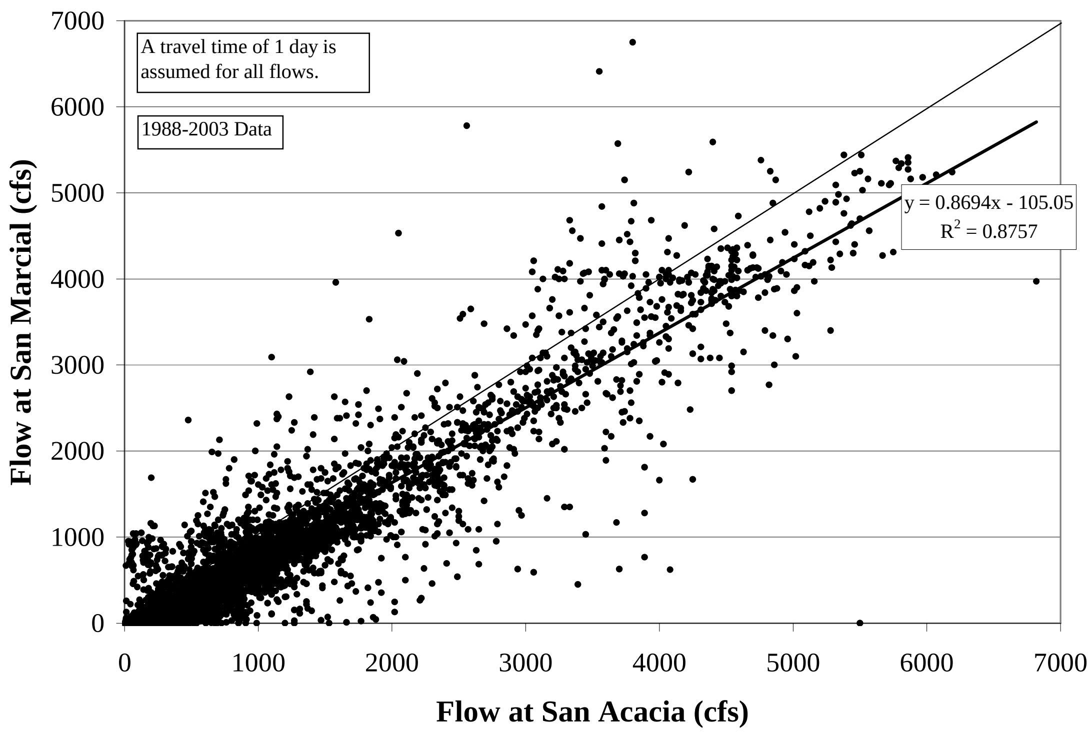


Figure 7.2 Plot of Gaged Flows at San Marcial versus Gaged Flows at San Acacia

7.1.4 Losses to the Overbank Areas

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

$$Q = C * \Delta x * H^{3/2} \qquad \text{Equation 7.3}$$

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, 500 ft. As discussed in Section 8.2, the broad crested weir coefficient is the primary calibration parameter in the model. The elevation of the banks along each 500 ft 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.

For model calibration, the lateral loss of flow is not computed for the entire Tiffany Junction Reach. Sub-reaches where lateral losses occur were isolated based on available inundation mapping from 1992. When the aerial photographs were taken on May 12, 1992, the gaged flow at San Marcial was 5090 cfs. The area of inundation at this flowrate is representative of the approximate maximum extents of overbank flooding that occurred during 1991 and 1995 (the overbank areas are defined as the areas that extend beyond the cross sections as surveyed by Reclamation and its contractors). Minimal flow is lost to overbank areas in the Bosque del Apache National Wildlife Refuge where the main channel is wider (700 to 1300 ft). As a result, lateral losses are not computed in the model for this upper end of the study reach. Any flows that overbank along the upper portion of the reach likely return to the river after a short distance (i.e. the flows going overbank do not serve as a permanent loss from a local reach). If a loss of flow was erroneously computed at this upstream portion of the model, the error would significantly affect the results further downstream. Downstream, the main channel width becomes narrower (150 to 350 feet). In addition, the main channel is slightly perched, so when flows overbank, water is permanently lost from the localized narrower reach.

Flows that are lost to overbank areas along the narrower reach below rangeline SO-1603.7 are forced back to the river above rangeline SO-1701.3 by the mesa on the east side of the river and the railroad to the west of the river. Flows in overbank areas are not modeled, but for calibration of the SPAR model, the flows are added back to the main channel along the reach from rangeline SO-1692 to rangeline SO-1701.3. To assure a smooth transition between the wider reach in the refuge and the narrower reach below SO-1603.7, some of the overbank areas were included as part of the cross sections at rangelines SO-1596.6, SO-1603.7, and SO-1626.

7.2 Sediment Transport

Sediment transport is computed in the SPAR model using a power function rating curve (Figure 5.6). The curve was fit to total sediment loads computed from data collected at the USGS gage at San Marcial (USGS, 1988-2003). Having available data precludes the use of a published sediment transport equation. The available total sediment load data were reviewed to identify whether there are any obvious seasonal trends. While such theories have been offered, trends were not clearly evident based on the available daily total sediment load data.

Bed material samples were collected several times at different locations along the Tiffany Junction Reach (FLO, 1990-1996). These data indicate that the bed material along the Tiffany Junction Reach is nearly uniformly distributed with a median grain size of 0.25 mm. Calculations are completed using the 0.25 mm mean sediment size for the Tiffany Junction Reach.

7.3 Vertical Distribution of Sediment Load

The vertical distribution of the 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):

$$\frac{v_x}{u_*} = \frac{2.3}{\kappa}\log\left(\frac{z}{k_s'}\right) \qquad \text{Equation 7.4}$$

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', of 0.27 ft was chosen based on a historical analysis completed by the USGS (Nordin, 1963). This value is slightly higher than expected for the mean grain size of 0.25 mm; it reflects the presence of small bedforms. At higher flows, bedforms are in upper regime along the study reach and not expected to have a significant impact on the flow.

The vertical distribution of the sediment concentration is computed using the Rouse equation (Equation 2.1). A Rouse number, *Ro*, of 1.15 was determined from data collected by the USGS (Nordin, 1963). Similar values were reported for the Bernalillo Reach of the Middle Rio Grande (Pemberton, 1964). A value for Rouse number was also computed using Equation 2.2 while assuming β_S equal to 1.0, κ equal to 0.4, and a fall velocity of 0.113 ft/s for the mean particle size of 0.25 mm. For a shear velocity equal to 0.25 ft/s which was computed for a slope of 0.0005 and hydraulic radius of 4 ft, the calculated Rouse number is 1.12. The value of 1.15 determined from data collected by the USGS was used for calibration of the SPAR model to conditions in the Middle Rio Grande in 1995.

The concentration, *Ca*, 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. 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 method of bi-sections is used to converge on the correct value for *Ca*. The total sediment load from the power function is divided by the top width and then multiplied by the depth and divided by the hydraulic depth to determine the total sediment load along the vertical at the location of the maximum depth.

7.4 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 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 applying the Exner equation to determine 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 before applying the Exner equation.

7.5 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) as discussed in Section 2.3.3.

Trap efficiency was computed using Equation 2.5 to assure the assumption of immediate erosion/deposition along the incremental spatial step is appropriate. The fall velocity for a particle size of 0.25 mm at a water temperature of 63° F (approximately 17° C) is 0.113 ft/s, and the incremental spatial step is 500 ft. Assuming a mean velocity of 5 ft/s for a hydraulic depth of 3 feet, the trap efficiency computed using Equation 2.5 is 98%. Based on this computation, it was determined that assuming a trap efficiency of 100% is reasonable for this evaluation of plug formation.

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).

VIII. COMPUTER MODEL RESULTS

The SPAR model developed to simulate sediment plug formation was created in FORTRAN using all the methods/procedures presented in Chapter 7. 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.

8.1 Validation of Hydraulics

The solution of the unsteady flow equations in the SPAR model was validated by comparing the results for computed flows and depths to the same results from an unsteady flow simulation completed using HEC-RAS. A simulation was performed with the SPAR model that focused on the hydraulic calculations. The computational timestep was directly input as opposed to being calculated since a computational interval must also be directly input into HEC-RAS. The timestep was set to 30 seconds for both programs.

Input information for both models was derived from the 1995 Tiffany Junction Reach simulation. The cross section data from the most recent surveys prior to development of the 1995 plug were utilized. Many of these surveys were conducted in 1994, with some cross sections surveyed in 1992 or 1993. These cross sections are separated by as little as 2000 feet to as much as 12,000 feet. Cross sections were interpolated for every 500 ft using HEC-RAS and used for both models. The stage-discharge curve developed for the downstream cross section, EB-16, was used as the downstream boundary condition as presented in Figure 8.1.

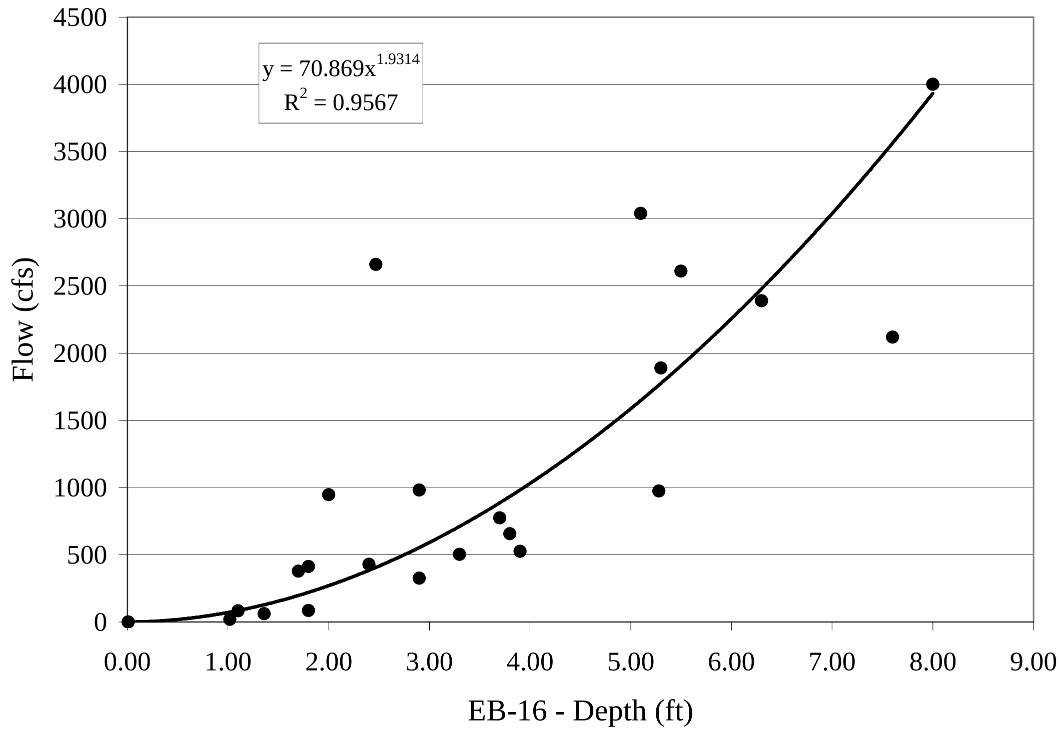


Figure 8.1 Downstream (EB-16) Stage-Discharge Curve for the Tiffany Junction Reach

The hydrograph for 1995 inflows that was developed from USGS gage data was used for the upstream boundary condition (Figure 8.2).

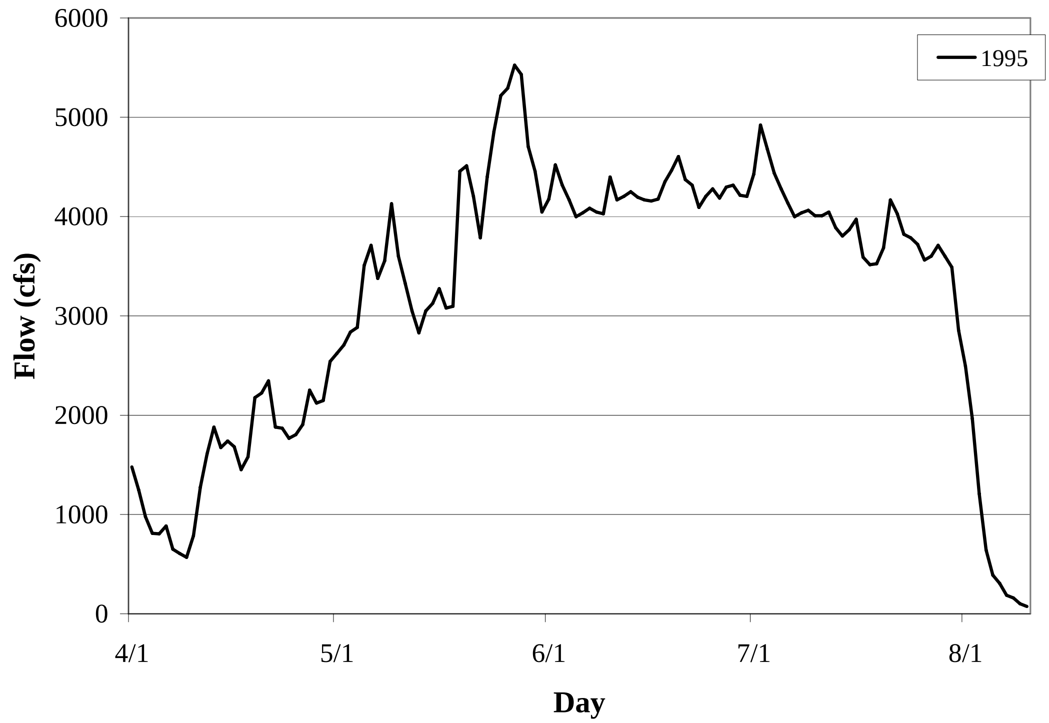


Figure 8.2 132 Day Hydrograph for Inflows to the Tiffany Junction Reach during 1995

Initial depths were input into the SPAR model based on a HEC-RAS steady flow simulation for the initial flow magnitude (the same method is used to determine initial depths for unsteady flow simulation in HEC-RAS). The Manning n roughness coefficient was set to 0.017 in both the SPAR model and HEC-RAS model for the entire reach. Losses to seepage and evapotranspiration were not computed, and no lateral outflows to overbank areas were simulated.

The computed depths between the unsteady flow simulations completed with the SPAR model and HEC-RAS matched within ± 0.2 ft (or 3 to 4% of the total computed depth). Figure 8.3 presents a distribution plot of the percent discrepancies in the daily computed depths between the two programs. The maximum depth deviations between the SPAR model and HEC-RAS model was approximately 0.6 ft. This is attributed to the solution for the downstream boundary condition as opposed to the unsteady flow calculations.

The differences in the daily computed flow rates between the SPAR and HEC-RAS models were within 3 or 4% of the daily computed flow. The unsteady flow equations are solved in HEC-RAS by Gaussian elimination using the skyline storage scheme (USACE HEC, 2002) as opposed to the double sweep method used in the SPAR model. These different methods in conjunction with differences in convergence tolerances influence the discrepancy between the results from the two models.

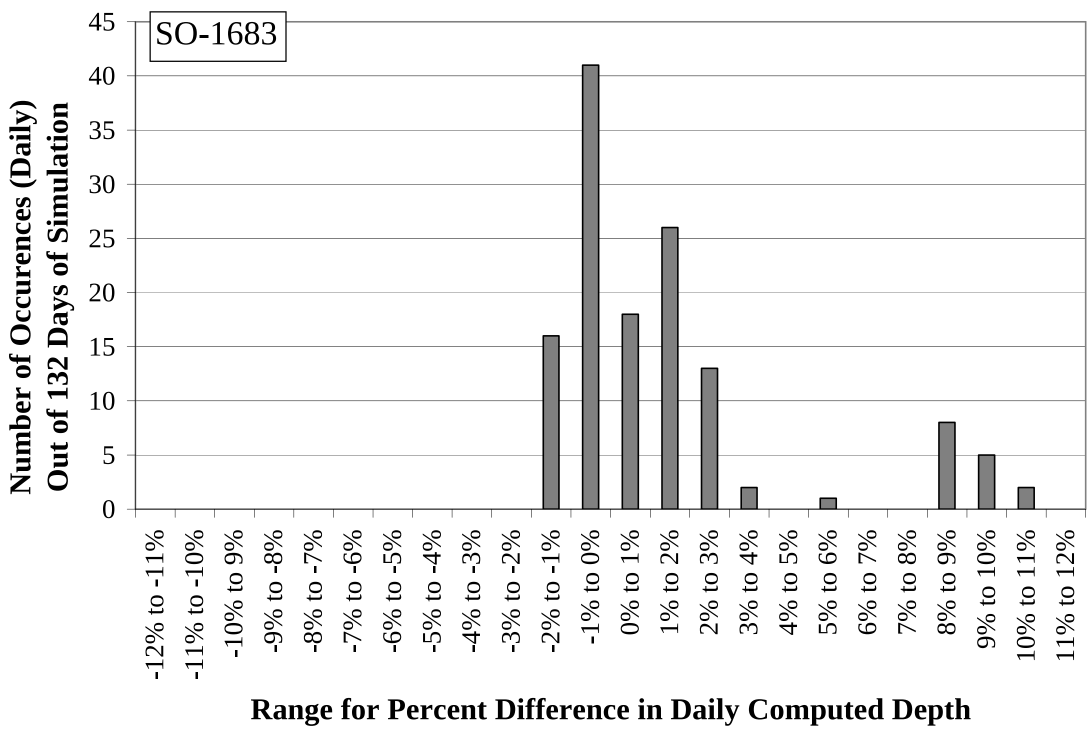


Figure 8.3 Distribution of the Percent Differences in Daily Computed Depths (SO-1683) Four Month Series of Flows from 1995 – Validation of Unsteady Flow Calcs

Another common procedure for checking the solution of the unsteady flow equations is to verify that volume is conserved with reasonable error when comparing the reach inflows and reach outflows from a simulation. The results from the hydraulic calculations completed with the SPAR model were analyzed to check the volume conservation error. Volume is conserved within 2 percent at upstream cross sections, but the error is 8 percent further downstream. The use of a single valued rating curve for a downstream boundary condition can introduce errors in unsteady flow calculations (Cunge *et al.*, 1980), but the results at upstream cross sections are not affected by these errors.

8.2 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 (Figure 5.6), a function for losses to seepage and evapotranspiration (Figure 7.2), a downstream stage discharge curve (Figure 8.1), an inflow hydrograph (Figure 8.2), a constant Manning n roughness value of 0.017 (Refer to Section 7.1.2), a porosity of 0.43 (McWhorter and Sunada, 1977), 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 (Refer to Section 7.3). The same cross section surveys used to validate the solution of the unsteady flow equations 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 as discussed in Section 7.1.4. 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 broad crested weir coefficient used for simulation is 0.5. This value represents a 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.

The main channel of the Middle Rio Grande along the Tiffany Junction Reach is perched above the floodplain due to long-term aggradation of the main channel (Figure 5.11). As a result, the loss of flow to the overbank areas is permanently lost from the local narrower reach (reference water surface elevation data collected by FLO Engineering (1990-1996)). In addition, the water surface in the overbank areas does not back up to the bank elevation of the main channel until the flow becomes significantly higher than what was evident during 1991 and 1995; therefore, an increase in stage in the floodplain would not impact the water surface elevation near the channel banks (or the level of submergence of the broad crested weir).

A comparison of bed elevations predicted with the SPAR model versus bed elevations measured during 1995 is presented in Figure 8.4. Based on testimony and data, the plug extended toward rangeline SO-1626 as of August 5, 1995. Deposition continued through 1996 before a pilot channel was dredged and the plug washed out in 1997. The plug eventually extended to approximately rangeline SO-1613. A plot of predicted deposition in cross section SO-1652.7 is presented in Figure 8.5. The SPAR model was successfully calibrated for plug formation along the Tiffany Junction Reach during 1995.

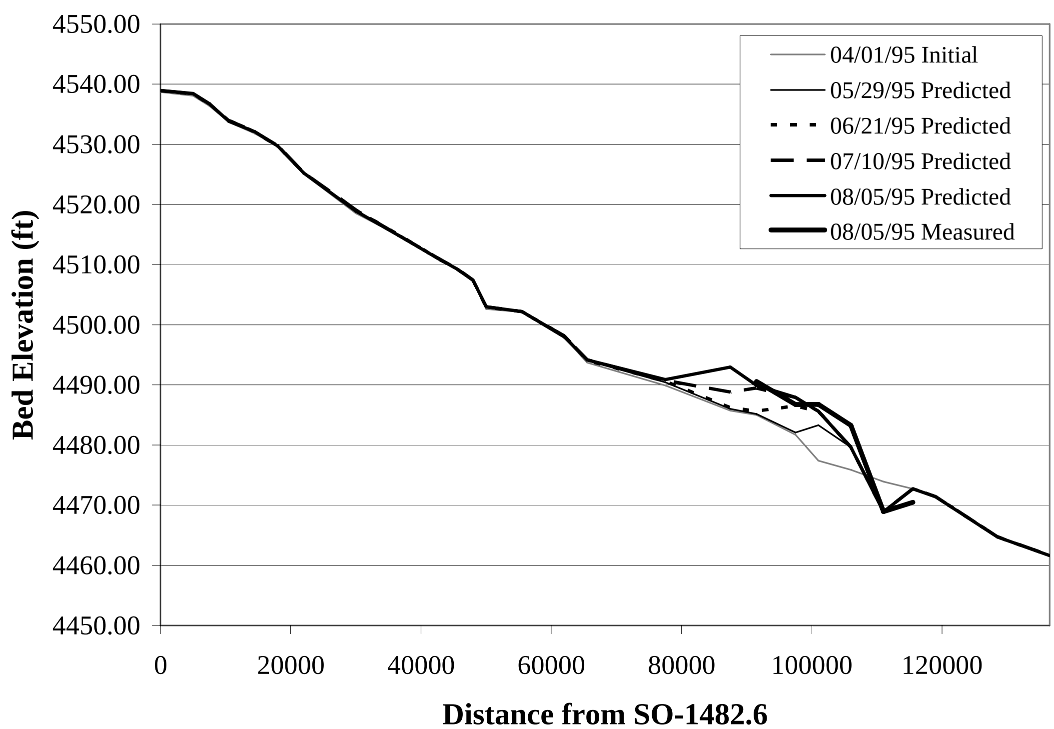


Figure 8.4 Plot of 1995 Initial, Predicted, and Measured Bed Elevations

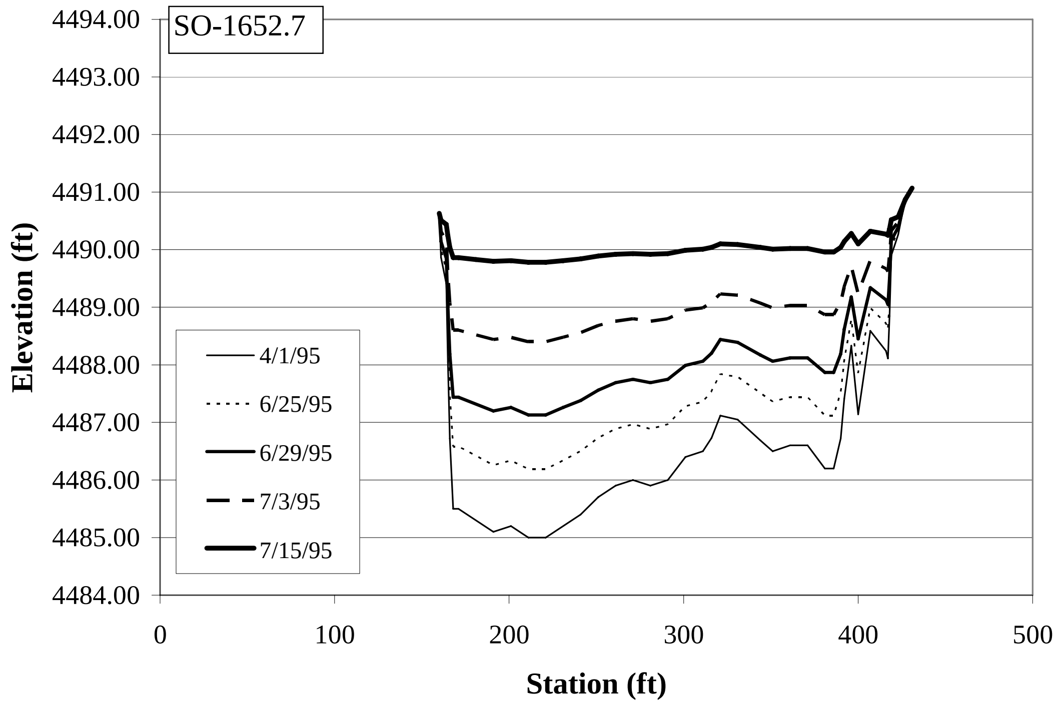


Figure 8.5 Plot of Predicted Deposition during 1995 at Cross Section SO-1652.7

8.3 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 at San Acacia (Figure 8.6).

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). The predicted bed elevations are presented in Figure 8.7.

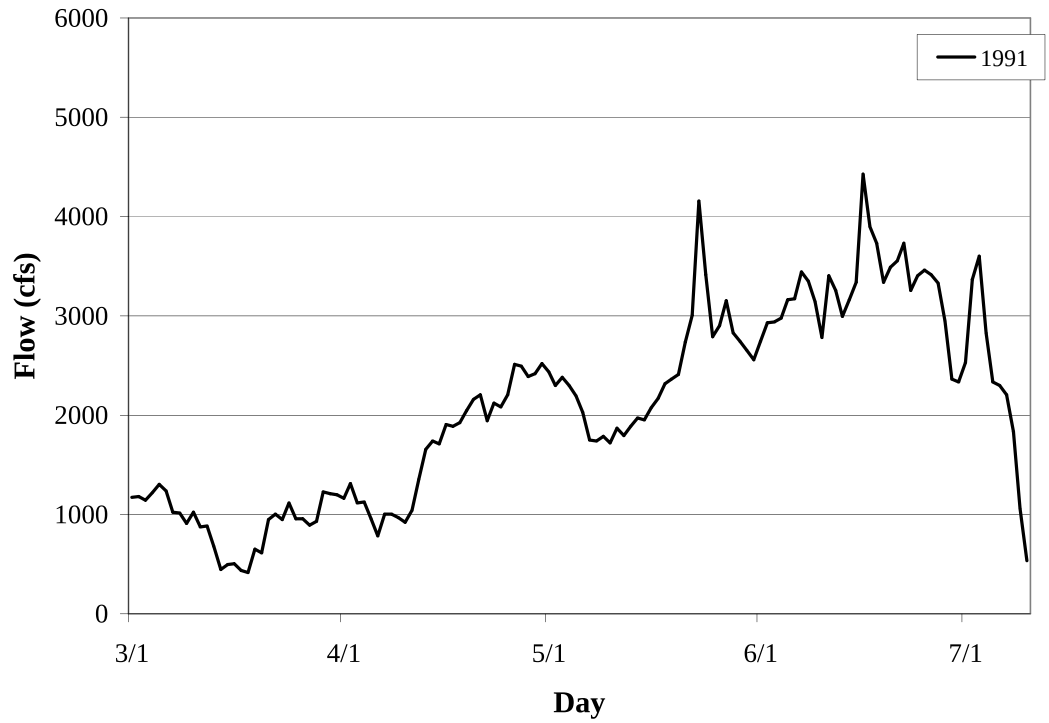


Figure 8.6 132 Day Hydrograph for Inflows to the Tiffany Junction Reach during 1991

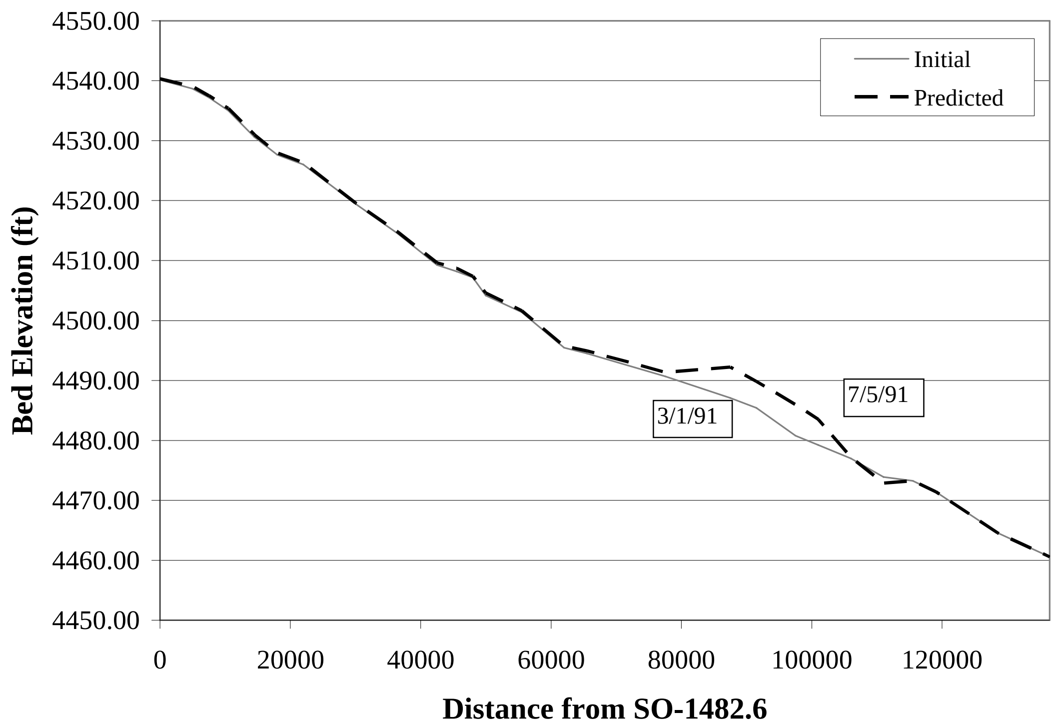


Figure 8.7 Plot of 1991 Initial and Predicted Bed Elevations

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 threshold values of different parameters during plug formation.

IX. CRITERIA FOR PLUG FORMATION

After the SPAR model was calibrated and validated, several random test runs were completed to establish simplified criteria for plug formation. These criteria allow for the prediction of the level at which a plug will form (55% of the main channel plugged, 70% of the main channel plugged, etc.) along with a specified level of confidence. River reaches which are prone to plug formation can be isolated by identifying specific site characteristics. Limitations and boundary conditions associated with the criteria are presented.

9.1 Boundary Conditions

Criteria for plug formation were established solely for analysis of the short term phenomenon of sediment plug formation. Historically, sediment plugs formed in a matter of weeks. The presented criteria should not be used to analyze the response of the Rio Grande to multi-year scenarios; moreover, these criteria were not developed to assess the long term response of the morphology of the river to overbank flows. These criteria should not be used to analyze scenarios where the flows are sufficiently significant to alter the main channel morphology over the short term. For cases that involve significant flood events (flows with a return period greater than 5 years), key variables – that would normally stay constant – could change within the analysis period; thus, the accuracy of the analysis would be affected.

9.1.1 Characteristics of Sites Prone to Sediment Plug Development

Plug formation is dependent upon the presence of a significant and abrupt constriction in the main channel of an alluvial river. Along the Tiffany Junction Reach of the Middle Rio Grande, the main channel conveyance area decreases by approximately 75% from the wider reach of the river in the Bosque del Apache National Wildlife Refuge (2400 ft^2) to the much narrower reach above the Atchison, Topeka, and Santa Fe railroad bridge (600 ft^2). As a result, 25 to 35% of the flow in the Rio Grande is abruptly lost to the overbank areas as the river stage increases with higher releases from Cochiti Dam.

The main channel conveyance area along the Yalobusha River decreased by approximately 60% from the channelized upstream segment of the river to the downstream meandering reach. This scenario was further complicated by the significant reduction in slope (0.0005 to 0.0002) (Shields *et al.*, 2000). For some cases, a debris snag may suddenly cause a reach to be prone to sediment plug development. This is particularly significant for smaller river systems where debris may cause an abrupt reduction in main channel conveyance area, on the order of 50%.

If there is an abrupt and significant reduction in the main channel conveyance area (> 50%) as a result of a bridge, debris snag, backwater effects from a lake, etc., the criteria for sediment plug formation should be checked to determine the thresholds for when a sediment plug will develop.

9.2 Independent Variables

While there are numerous details that affect plug formation, there are five key variables that have the greatest impact on plug development. The first parameter is the quantity of flow lost to the overbank areas as a fraction of the inflow to the focus study reach per longitudinal unit length of river (units of 1/ft):

$$FrOB = \frac{AverageLossToOverbankAreas \Big/ AverageFlowToStudy\,\mathrm{Re}\,ach}{LongitudinalDis\tan ceAtWhichFlowsGoOverbank}$$

Equation 9.1

This parameter represents an abrupt loss of sediment transport capacity associated with a loss of flow due to an abrupt change in the main channel conveyance area, a debris snag, an abrupt change in slope, or some other constriction. Historically, this loss of flow occurs entirely within a few thousand feet longitudinally along a river.

The second parameter is the duration (units of days) that flows are lost to the overbank areas (Equation 9.2). When combined with the fraction of flow lost to the overbank per unit length of river, these two parameters combine to represent the total reduction in sediment transport capacity that corresponds with a loss of flow to the overbank areas.

$$NDAYS = DurationOfOverbankFlows(days)$$ Equation 9.2

The third parameter includes the initial main channel cross section area. It is important because it essentially represents the volume of sediment required for plug formation. When combined with the average total sediment load to the focus study reach, as flows are lost to the overbank areas, this parameter represents the sediment supply available to plug the channel with consideration for the amount of sediment required (units of ft/day). The porosity of the bed material is also represented (Equation 9.3).

$$QSAp0 = \frac{Q_{Savg}}{InitialArea * (1 - p_0)} \qquad \text{Equation 9.3}$$

The fourth parameter is the exponent in the total sediment load power function rating curve (Equation 4.1). As discussed in section 5.9, if the exponent in this power function is greater than 1.0, a percent reduction in flow would yield a greater percent decrease in total sediment load. By including this exponent, *RCEXP*, the disproportionate change in total sediment load is represented. The final parameter is the Rouse number, *Ro*, from Equation 2.1, which accounts for variations in the vertical distribution of the total sediment load.

9.3 Theoretical Derivation of the Independent Variables

The key parameters affecting plug formation represented by the independent variables presented in the previous section can also be theoretically derived from the Exner equation (Equation 2.4 and Equation 9.4) where ∂z_i represents the change in bed elevation resulting from deposition, ultimately leading to a sediment plug:

$$T_{Ei} \frac{\partial Q_{txi}}{\partial x} + (1 - p_0) \frac{W \partial z_i}{\partial t} = 0 \qquad \text{Equation 9.4}$$

A trap efficiency equal to 1, or 100%, can be assumed, and completing the algebra to isolate ∂z_i to one side of the equation yields Equation 9.5:

$$\partial z_i = -\frac{\partial t}{(1 - p_0) W} \frac{\partial Q_{txi}}{\partial x} \qquad \text{Equation 9.5}$$

Total sediment load, Q_{txi}, is a function of flow, Q, based on a power function rating curve (Equation 4.1 and Equation 9.6):

$$Q_{txi} = coefficientQ^{RCEXP}$$ Equation 9.6

Computing the derivative of the total sediment load with respect to flow and multiplying by *Q/Q* yields

$$\frac{\partial Q_{txi}}{\partial Q} = RCEXP * coefQ^{RCEXP-1}\frac{Q}{Q} = RCEXP * \frac{coefQ^{RCEXP}}{Q} = RCEXP * \frac{Q_{txi}}{Q}$$

Equation 9.7

Substituting $RCEXP * \frac{Q_{txi}}{Q}\partial Q$ into Equation 9.5 for ∂Q_{txi} yields

$$\partial z_i = -\frac{\partial t}{(1-p_0)W}\frac{RCEXP * Q_{txi}\frac{\partial Q}{Q}}{\partial x}$$ Equation 9.8

and rearranging the variables yields

$$\partial z_i = \left(-\frac{\partial Q}{Q\partial x}\right)(\partial t)\left(\frac{Q_{txi}}{W(1-p_0)}\right)(RCEXP)$$ Equation 9.9

The variables isolated by the first three sets of parentheses are the same as the three independent variables presented in Equations 9.1 through 9.3, respectively, and RCEXP is the fourth independent variable. This derivation validates the use of these four independent variables to compute the change in bed elevation or deposition associated with plug formation. The Rouse number, *Ro*, is added as a fifth independent variable to capture the effect of the vertical distribution of the total load on the rate of plug formation.

9.4 Quantitative Thresholds

The SPAR model calibrated and validated for the Tiffany Junction Reach of the Middle Rio Grande was used to simulate numerous test cases for different constrictions, specifically represented as reductions in main channel conveyance area and abrupt changes in channel slope. The calibration and validation model runs for the Tiffany Junction Reach, 1991 and 1995, were also included in the matrix. Information about key parameters for all the test cases is presented in Table 9.1.

Table 9.1 Matrix with Information about Key Parameters for Computer Model Test Cases to Evaluate Sediment Plug Formation

Random Test Case Number	Main Channel Cross Section Area	Slope	Rouse Number	Exponent in Total Sediment Load Power Function, RCEXP	Porosity
1	Gradual 80% Reduction	Constant 0.0006	1.15	1.2419	0.43
2	Abrupt 80% Reduction	Constant 0.0002	1.15	1.2419	0.43
3	Gradual 80% Reduction	Constant 0.0008	1.15	1.2419	0.43
4	Gradual 60% Reduction	Constant 0.0010	1.15	1.2419	0.43
5	Abrupt 80% Reduction	Constant 0.0004	1.15	1.2419	0.43
6	Gradual 60% Reduction	Constant 0.0008	1.15	1.2419	0.43
7	Abrupt 60% Reduction	Constant 0.0004	1.15	1.2419	0.43
8	Abrupt 80% Reduction	Constant 0.0006	1.15	1.2419	0.43
9	Abrupt 60% Reduction	Constant 0.0006	1.15	1.2419	0.43
10	Abrupt 80% Reduction	Constant 0.0008	1.15	1.2419	0.43
11	Abrupt 60% Reduction	Constant 0.0008	1.15	1.2419	0.43
12	Abrupt 60% Reduction	Constant 0.0010	1.15	1.2419	0.43
13	Constant	Abrupt 0.0010 to 0.0002	1.15	1.2419	0.43
14	Constant	Abrupt 0.0008 to 0.0002	1.15	1.2419	0.43
15	Abrupt 80% Reduction	Constant 0.0006	0.10	1.2419	0.43
16	Abrupt 80% Reduction	Constant 0.0006	0.30	1.2419	0.43
17	Abrupt 80% Reduction	Constant 0.0006	0.70	1.2419	0.43
18	Abrupt 80% Reduction	Constant 0.0006	1.50	1.2419	0.43
19	Abrupt 80% Reduction	Constant 0.0006	2.00	1.2419	0.43
20	Abrupt 60% Reduction	Constant 0.0008	0.10	1.2419	0.43
21	Abrupt 60% Reduction	Constant 0.0008	0.30	1.2419	0.43
22	Abrupt 60% Reduction	Constant 0.0008	0.70	1.2419	0.43
23	Abrupt 60% Reduction	Constant 0.0008	1.50	1.2419	0.43
24	Abrupt 60% Reduction	Constant 0.0008	2.00	1.2419	0.43
25	Abrupt 80% Reduction	Constant 0.0006	1.15	1.0500	0.43
26	Abrupt 80% Reduction	Constant 0.0006	1.15	1.1000	0.43
27	Abrupt 80% Reduction	Constant 0.0006	1.15	1.1500	0.43
28	Abrupt 80% Reduction	Constant 0.0006	1.15	1.2000	0.43
29	Abrupt 80% Reduction	Constant 0.0006	1.15	1.5000	0.43
30	Abrupt 80% Reduction	Constant 0.0006	1.15	2.0000	0.43

Table 9.1 Matrix with Information about Key Parameters for Computer Model Test Cases to Evaluate Sediment Plug Formation

Random Test Case Number	Main Channel Cross Section Area	Slope	Rouse Number	Exponent in Total Sediment Load Power Function, RCEXP	Porosity
31	Abrupt 80% Reduction	Constant 0.0006	1.15	2.5000	0.43
32	Abrupt 60% Reduction	Constant 0.0008	1.15	1.5000	0.43
33	Abrupt 60% Reduction	Constant 0.0008	1.15	2.0000	0.43
34	Gradual 80% Reduction	Constant 0.0006	1.15	1.1000	0.43
35	Gradual 80% Reduction	Constant 0.0006	1.15	1.1500	0.43
36	Gradual 80% Reduction	Constant 0.0006	1.15	1.2000	0.43
37	Abrupt 80% Reduction	Constant 0.0006	1.15	1.2419	0.25
38	Constant	Abrupt 0.0008 to 0.0002	1.15	1.2419	0.25
39	Gradual 80% Reduction	Constant 0.0006	1.15	1.2419	0.25
40	Abrupt 80% Reduction	Constant 0.0006	1.15	1.2419	0.34
41	Constant	Abrupt 0.0008 to 0.0002	1.15	1.2419	0.34
42	Gradual 80% Reduction	Constant 0.0006	1.15	1.2419	0.34
43	Abrupt 80% Reduction	Constant 0.0006	1.15	1.2419	0.52
44	Constant	Abrupt 0.0008 to 0.0002	1.15	1.2419	0.52
45	Gradual 80% Reduction	Constant 0.0006	1.15	1.2419	0.52
46	Tiffany Junction Reach - 1991		1.15	1.2419	0.43
47	Tiffany Junction Reach - 1995		1.15	1.2419	0.43

Other model simulations were completed where sediment plugs never developed thus precluding the use of the results for evaluating plug formation.

The criteria for plug development are checked with focus on a dimensionless parameter, PLGNUM, which was established as a function of the independent variables discussed in Sections 9.2 and 9.3:

$$PLGNUM = 120 * FrOB(ft^{-1}) * NDAYS(days) * QSAp0(ft/day) * RCEXP * Ro^{1/3}$$

Equation 9.10

Based on the results from the test model runs, the critical threshold values for the PLGNUM parameter were determined for different levels of plug formation. To determine the potential for plug formation for an actual scenario being evaluated, the

PLGNUM parameter can be computed and compared to these critical threshold values which were determined with the calibrated and validated SPAR model.

From the test simulations, values for the independent variables, and PLGNUM, were computed for the time when the channel becomes 55%, 70%, 85%, and 99% plugged. The threshold PLGNUM values for every test case presented in Table 9.1 are plotted in Figures 9.1 through 9.4 for each level of plug formation.

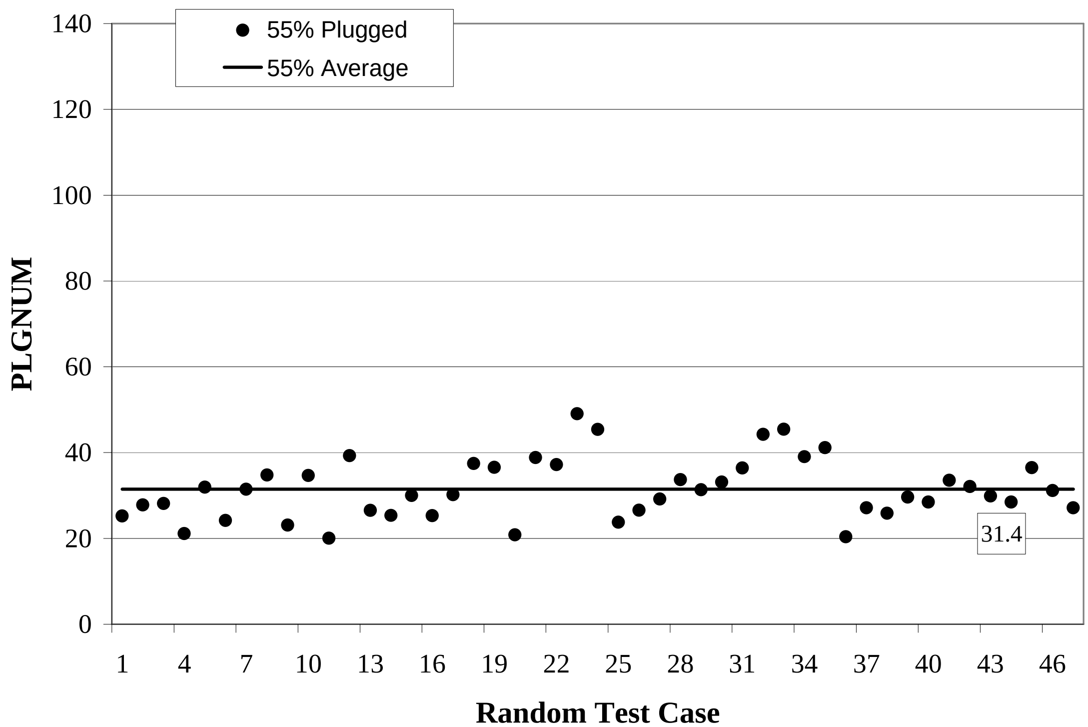


Figure 9.1 Values for PLGNUM for Each Test Case when Channel is 55% Plugged

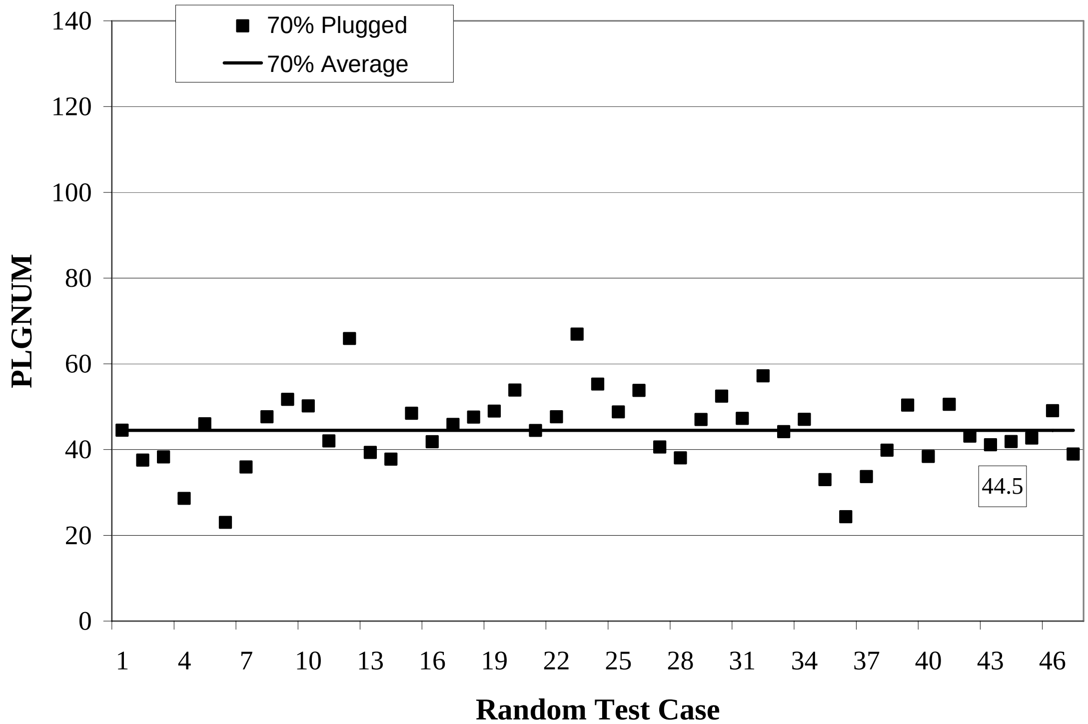


Figure 9.2 Values for PLGNUM for Each Test Case when Channel is 70% Plugged

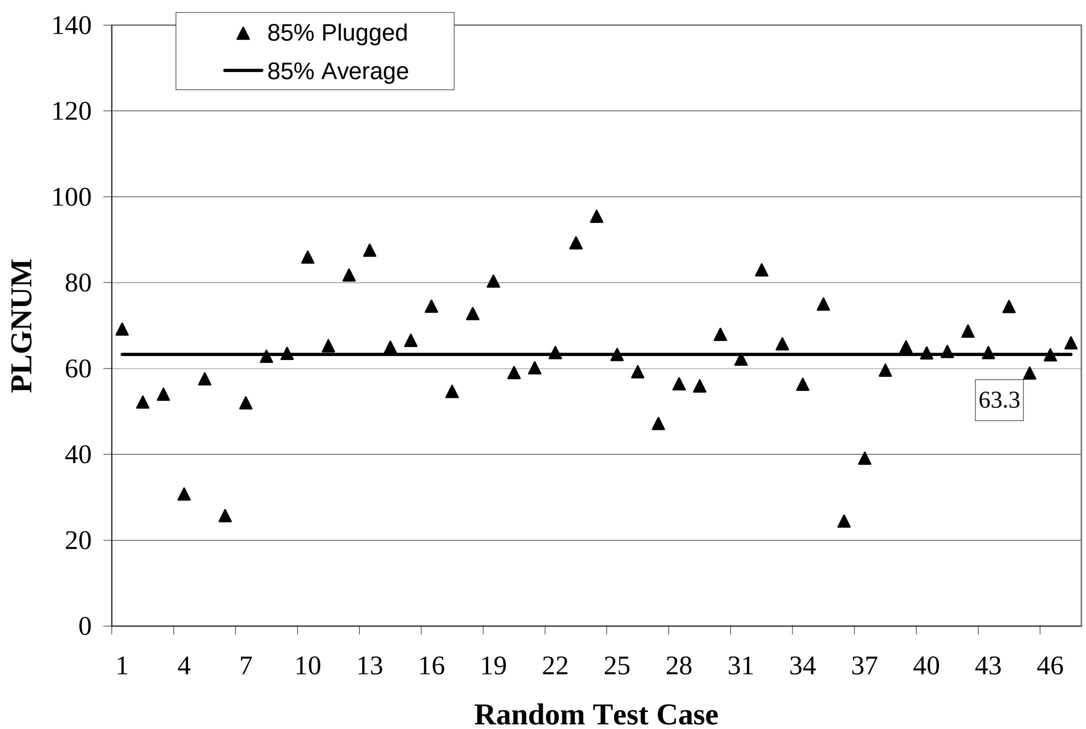


Figure 9.3 Values for PLGNUM for Each Test Case when Channel is 85% Plugged

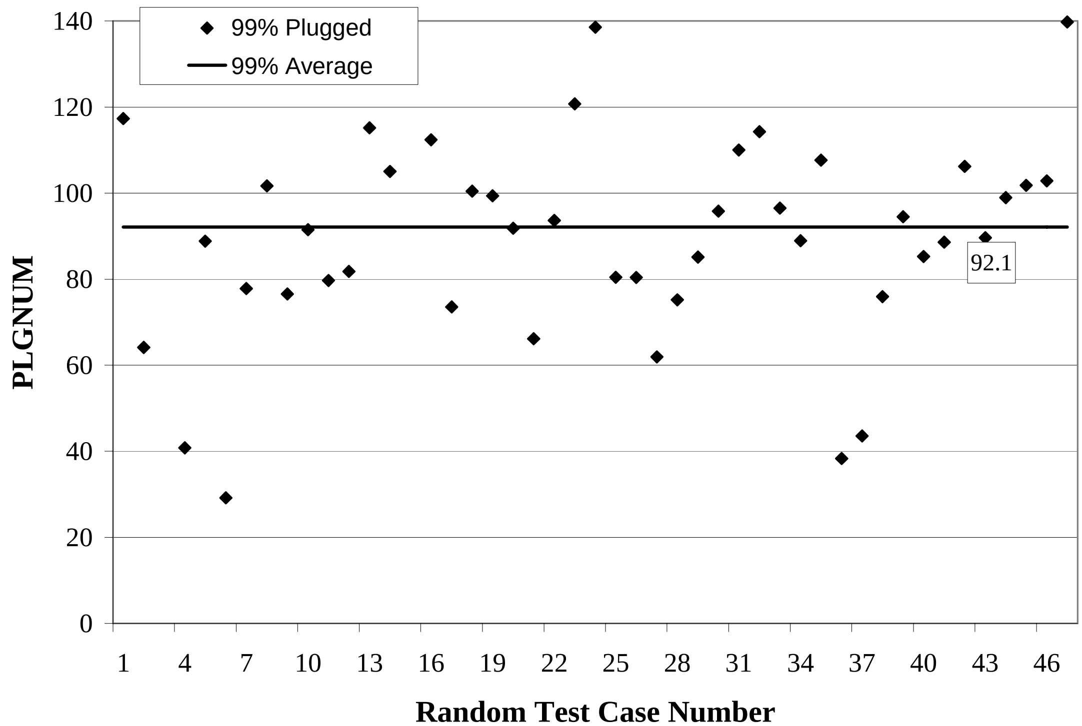


Figure 9.4 Values for PLGNUM for Each Test Case when Channel is 99% Plugged

The scatter in the computed values for PLGNUM allowed for levels of confidence to be computed to correspond with each threshold level of plug formation. After eliminating a few outliers, the confidence level was then plotted versus the value for PLGNUM for each threshold level of plug formation (Figure 9.5).

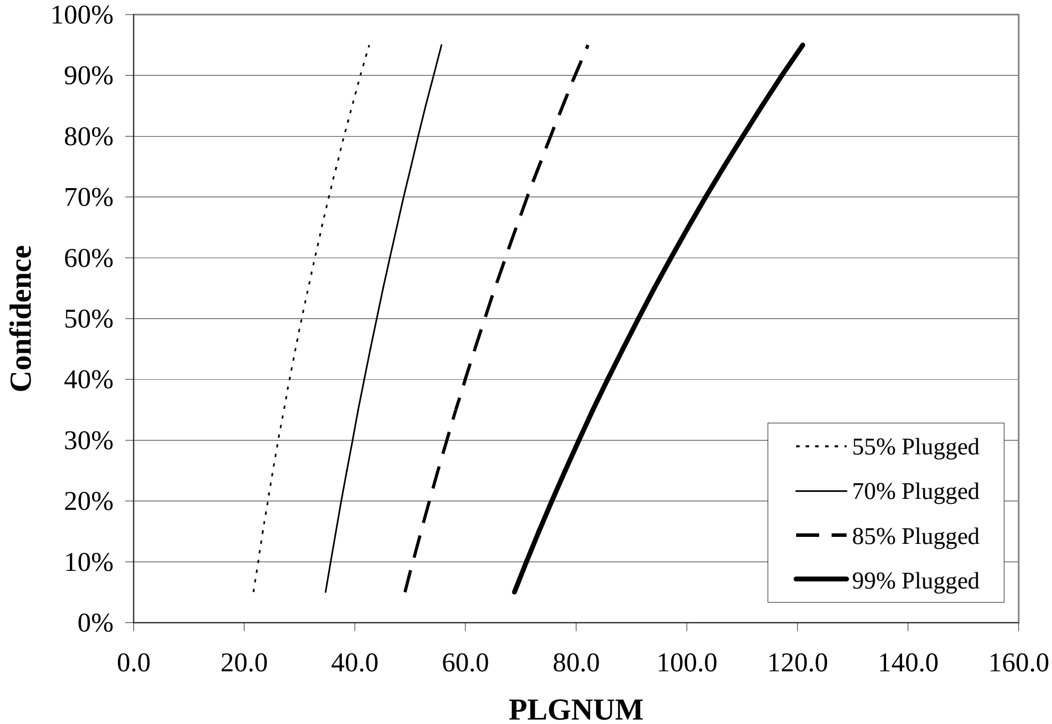


Figure 9.5 Criteria for Plug Formation

The Rouse number, *Ro*, is raised to the 1/3 power based on the model simulations that were completed to assess the sensitivity of the dimensionless PLGNUM parameter to the Rouse number (keeping all other parameters constant). The Rouse number must be small (< 0.50) before it significantly impacts the chance of a plug formation (i.e. if the Rouse number is less than 0.5, the effect of a more uniform vertical distribution for the total sediment load begins to reduce the chances for plug development). The plot in Figure 9.6 depicts the variation of PLGNUM with the Rouse number raised to the 1/3 power versus being included with no exponent (i.e. an exponent equal to 1).

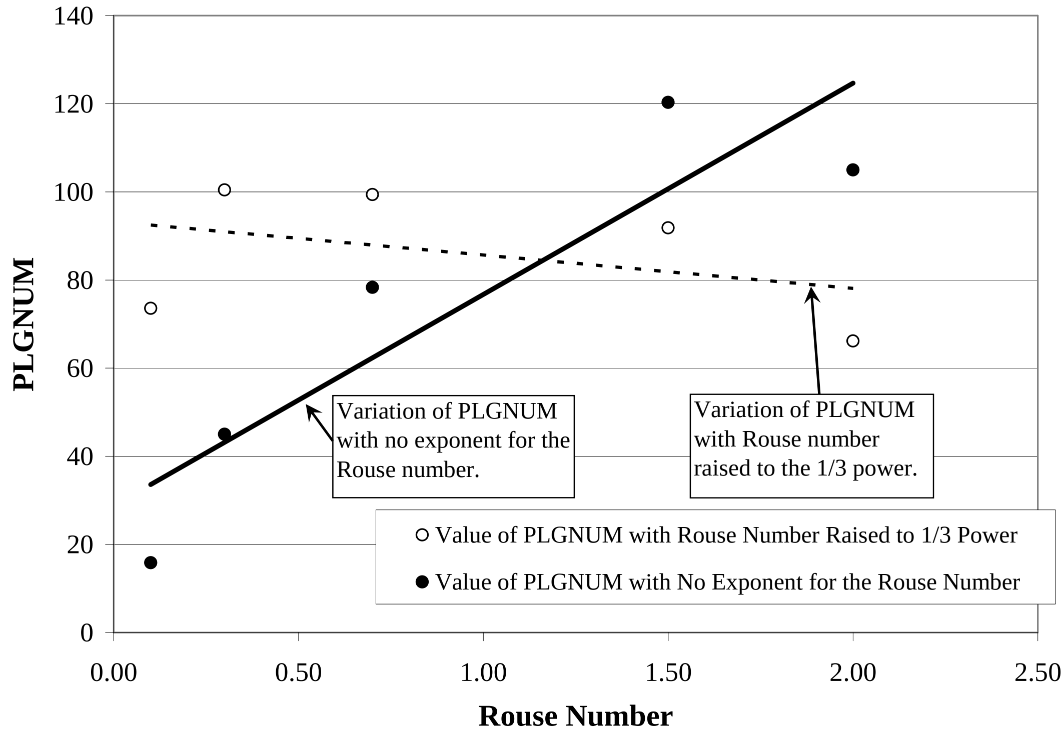


Figure 9.6 Plot of the Variation of PLGNUM with Rouse Number with the Rouse Number Raised to Different Exponents in the Equation for PLGNUM

The following examples demonstrate the use of the criteria for plug formation. Assume a value of 96 is computed for the dimensionless parameter PLGNUM using Equation 9.10 for a scenario along a sample study reach. Based on the criteria presented in Figure 9.5, the channel would become 99% plugged with an associated confidence level of 58%. The criteria from Figure 9.5 are presented in Figure 9.7 with a depiction of this example value of PLGNUM equal to 96.

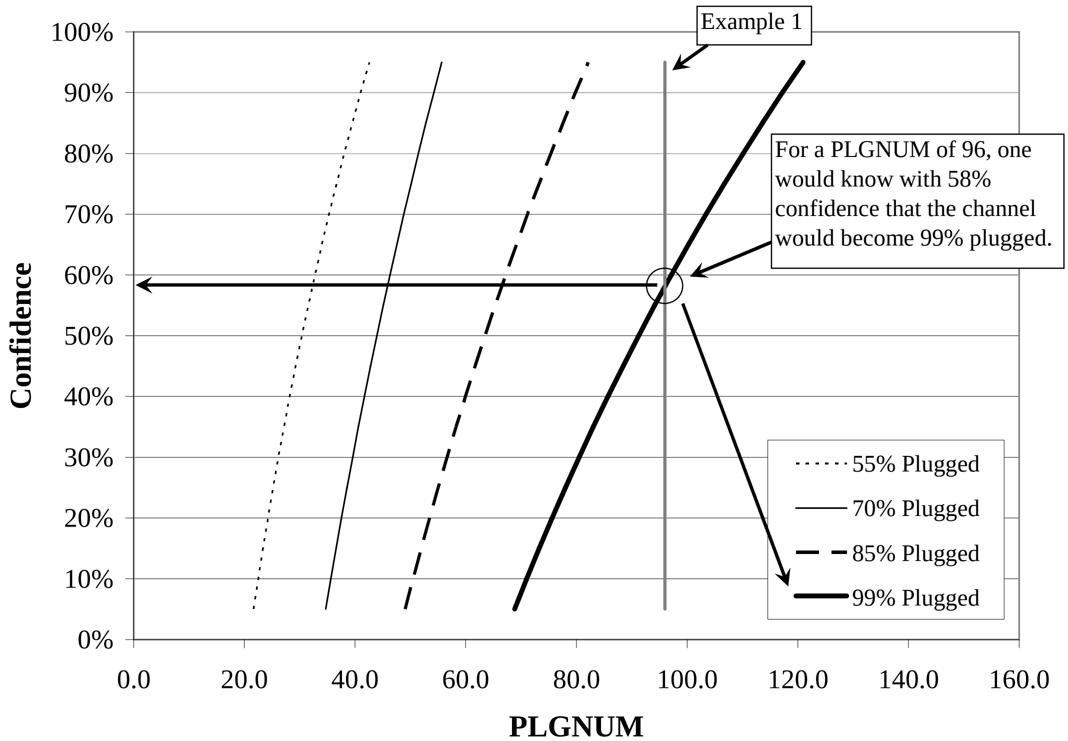


Figure 9.7 Comparison of Value for PLGNUM versus Criteria for Plug Formation – Example 1

If a value of PLGNUM equal to 45 is computed, the confidence level is 54% that the channel would become 70% plugged. The criteria from Figure 9.5 are presented in Figure 9.8 with a depiction of this example computed value of PLGNUM equal to 45.

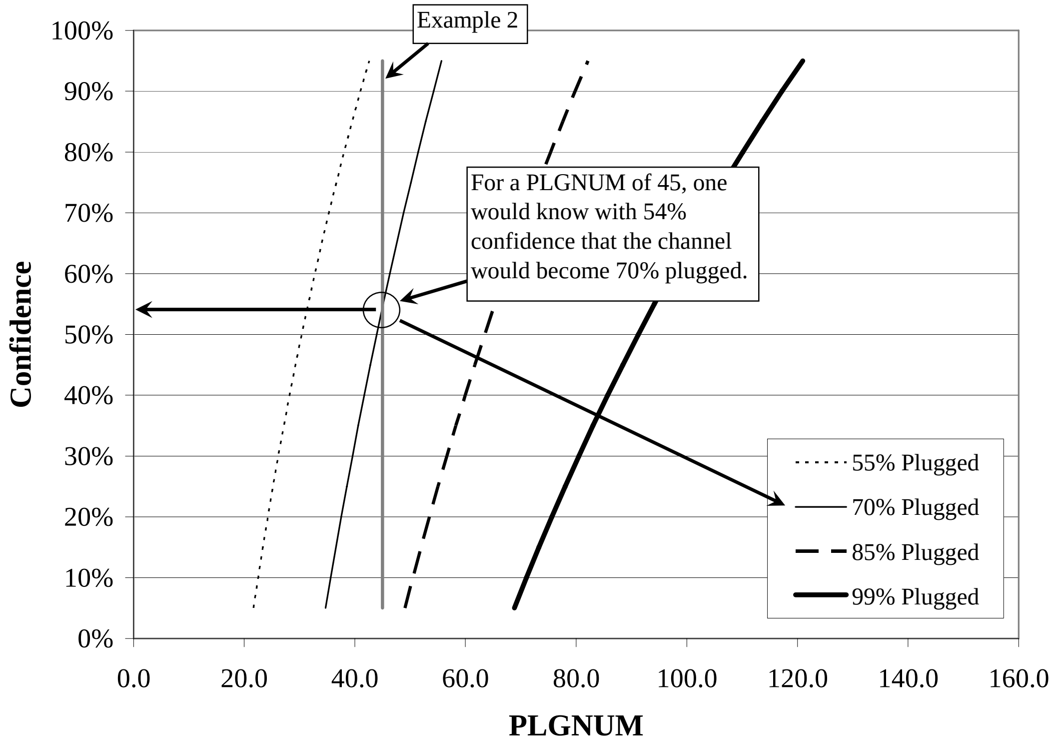


Figure 9.8 Comparison of Value for PLGNUM versus Criteria for Plug Formation – Example 2

After identifying that a segment of an alluvial river is prone to plug formation based on the characteristics discussed in Section 9.1, Equation 9.10 and the criteria for plug formation depicted in Figure 9.5 can be used as a predictive tool to determine at what level a plug will form and a corresponding level of confidence for any specified scenario. The variables in Equation in 9.10 can be adjusted to determine specific critical thresholds for plug formation.

9.5 Criteria Evaluation

In addition to the cases of plug formation along the Rio Grande in 1991 and 1995, the criteria for plug formation were applied and evaluated for two other cases: plug formation on the Yalobusha River in north-central Mississippi and the Tiffany Junction Reach using data from 1994 when a plug did not form (but conditions did not appear to be significantly different from the situation in 1991 and 1995).

9.5.1 Yalobusha River

During 1967, a section of the Yalobusha River was channelized, and that segment of the river had a conveyance capacity of approximately 20,000 cfs (Simon and Thomas, 2002). The downstream meandering reach of the river had a capacity of approximately 2500 cfs; thus, as higher flows reached this meandering section, a significant portion of the flow was abruptly lost to the overbank areas. There was a period during April of 1969 when the flow exceeded 7000 cfs for 3 days and it is believed that this was one of the periods when accelerated deposition occurred which ultimately resulted in a sediment plug (Jones, 1998); therefore,

$$NDAYS = (3)days \, . \qquad \text{Equation 9.11}$$

Based on the information presented in the literature it is estimated that the flows overbanked along a 500 m (or 1640 ft) stretch of the river. With the downstream capacity of 2500 cfs, the fractional loss of flow per unit length of river is computed:

$$FrOB = \frac{\dfrac{7000cfs - 2500cfs}{7000cfs}}{1640\,ft} = 3.96E - 04\,ft^{-1} \qquad \text{Equation 9.12}$$

The mean sediment size along the focus reach of the Yalobusha River is 0.35 mm (Simon and Thomas, 2002), and the corresponding porosity is 0.42 (McWhorter and Sunada, 1977). An initial cross section area for the downstream meandering reach is 1066 ft^2 (Shields *et al.*, 2000). Sediment transport rates had been computed using Yang's equation (Shields *et al.*, 2000). Based on those calculations, an average total sediment load of 30,000 tons/day (360,000 ft^3/day) is estimated for the 3-day 7000 cfs event. An estimate for the third independent variable is computed:

$$QSAp0 = \frac{(360{,}000)\,ft^3/day}{(1066)\,ft^2 * (1-0.42)} = (586)\,ft/day$$

Equation 9.13

For the mean sediment size of 0.35 mm, a Rouse number of 1.20 is estimated, and the exponent for the total sediment load power function is estimated to be 1.50.

The dimensionless value for PLGNUM is computed using Equation 9.10:

$$PLGNUM = 120 * 3.96E-4(ft^{-1}) * 3(days) * 586(ft/day) * 1.50 * (1.20)^{1/3} = 133$$

Equation 9.14

The resulting dimensionless value for PLGNUM is 133. Based on the criteria presented in Figure 9.5, this exceeds the threshold values for plug development. The channel would become 99% plugged with 100% confidence, so the criteria indicate that plug formation would indeed occur along the Yalobusha River. The value for PLGNUM is plotted with the criteria in Figure 9.9. This scenario supports the validation of the criteria for plug formation.

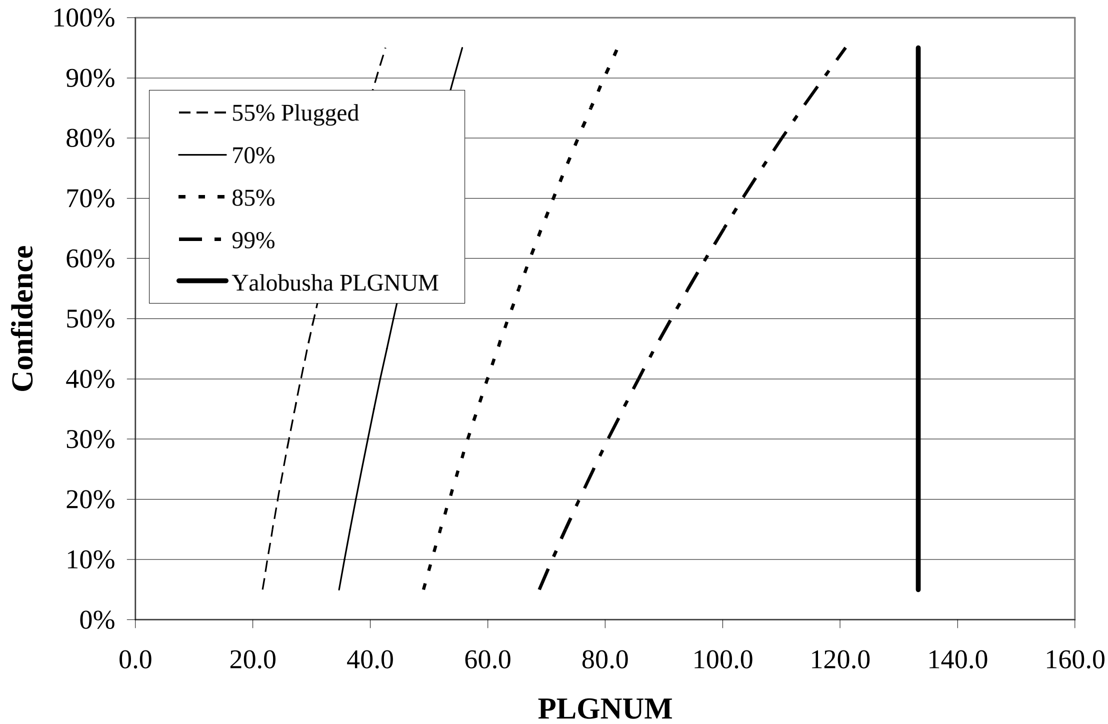


Figure 9.9 Check against Criteria for Plug Formation along the Yalobusha River

9.5.2 Tiffany Junction Reach - 1994

A second test was performed for conditions along the Tiffany Junction Reach in 1994 when a plug did not form although there was a significant release from Cochiti Dam. The conveyance capacity at the critical location for plug formation around rangeline SO-1683 is approximately 3900 cfs. During 1994, the flows gaged at San Marcial exceeded 3900 cfs from May 13th through May 30th.

$$NDAYS = (18)days \qquad \text{Equation 9.15}$$

The average flow during this period was 4500 cfs. It is estimated that a majority of the flow overbanked along a 7000 ft segment of the river from around rangeline SO-1673 toward SO-1683. The fractional loss of flow per unit length of river is computed:

$$FrOB = \frac{\frac{4500cfs - 3900cfs}{4500cfs}}{7000\,ft} = 1.96E - 05\,ft^{-1} \qquad \text{Equation 9.16}$$

The mean sediment size along the Tiffany Junction Reach is 0.25 mm, and the corresponding porosity is 0.43 (McWhorter and Sunada, 1977). The initial average cross section area for the reach from SO-1673 to SO-1683 was 709 ft^2. The average incoming total sediment load for the event based on the rating function for the reach (refer to Equation 4.1) was 48,700 tons/day (589,000 ft^3/day). The independent variable, *QSAp0*, is computed:

$$QSAp0 = \frac{(588{,}900)\,ft^3 / day}{(709)\,ft^2 * (1 - 0.43)} = (1457)\,ft / day \qquad \text{Equation 9.17}$$

As discussed in section 7.3, a Rouse number of 1.15 was determined for the Tiffany Junction Reach. The exponent, *RCEXP*, in the total sediment load power function for the study reach (Equation 4.1) is 1.2419.

The value for PLGNUM is computed:

$$PLGNUM = 120 * 1.96E - 5(ft^{-1}) * 18(days) * 1457(ft / day) * 1.2419 * (1.15)^{1/3} = 80$$

Equation 9.18

The resulting dimensionless value for PLGNUM is 80. Based on the criteria presented in Figure 9.5, the confidence level for the channel to become 99% plugged for a PLGNUM value of 80 is low, 30%; thus, it is not expected that the channel would become completely plugged which matches what occurred in 1994. The value of PLGNUM for this scenario is plotted against the criteria in Figure 9.10. The value does indicate that the channel would be 70% plugged, so the results indicate that there was accelerated deposition during 1994 as a result of the loss of flow to the overbank areas, but the main channel did not become entirely plugged.

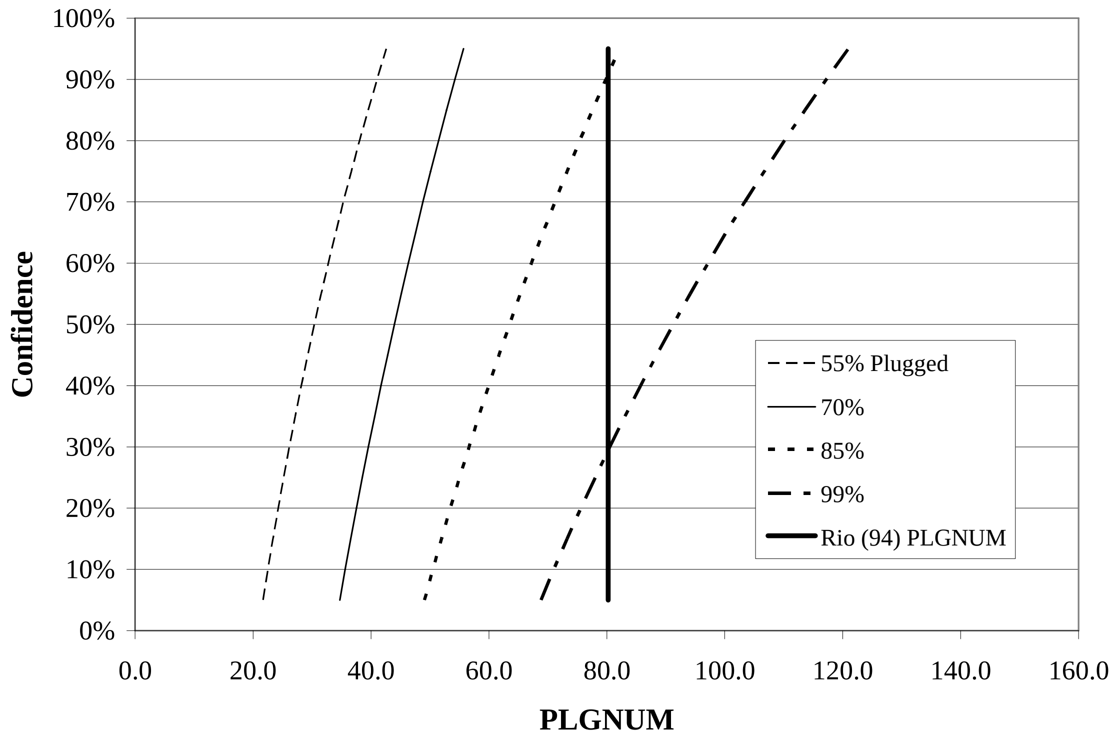


Figure 9.10 Check against Criteria for Plug Formation along the Tiffany Junction Reach (1994)

9.5.3 Tiffany Junction Reach – 1991 and 1995

Data from 1995 and 1991 for the Tiffany Junction Reach were used to calibrate and validate the SPAR model. These data were used again to check the criteria. The values for the dimensionless parameter PLGNUM that were computed using the data for the Tiffany Junction Reach from 1991 and 1995 are 121 and 93, respectively. Based on the criteria, these values confirm that the channel would likely become plugged as occurred in 1991 and 1995. For the situation along the Tiffany Junction Reach, accelerated deposition occurs as soon as flows are lost to the overbank areas. The issue is whether the condition persists long enough for the channel to become *completely* plugged.

9.6 Recommendations for Criteria Application

After a reach has been identified as prone to plug formation, values need to be determined for the independent variables discussed in section 9.2 and 9.3. The key factor affecting the formation of sediment plugs is the loss of flow to overbank areas. If no flows are lost to the overbank areas, the value for the independent variable, *FrOB*, presented in Equation 9.1 is zero; thus, the value for the dimensionless PLGNUM parameter is zero. When checking the criteria, it is important to have an accurate assessment of the flow level at which flows begin to overbank. The initial channel geometry, total sediment load, and Rouse number can be estimated with a reasonable level of accuracy, but the point at which flows overbank is important for determining when the accelerated deposition begins. Also, the threshold flow level at which flows begin to overbank has a significant impact on the number of days that flows are lost to the overbank for a specified inflow hydrograph and the corresponding duration of accelerated deposition.

If resources are available to collect data pertaining to bank elevations and the flow level at which flows are lost to overbank areas, those data would significantly improve the resolution of an analysis against the criteria for plug formation. Any data in regards to the initial main channel conveyance area, total sediment load, and Rouse number (vertical distribution of the total sediment load) would further enhance the accuracy of the results.

X. SUMMARY AND CONCLUSIONS

While there is some understanding about the general issues affecting deposition and erosion in alluvial channels, there is little understanding of the specific processes that affect the development of sediment plugs. Most sediment plug theories discuss a sudden drop in sediment transport capacity or characterize plug development as an effect of flooding. While these and other explanations related to watershed management or other human factors are pertinent, they do not help to identify the specific processes that are occurring when plugs develop.

An investigation was conducted to better understand why, how, where, and when sediment plugs form. A comprehensive literature review was completed and available data were gathered. The literature review included a review of documentation on sediment plugs that developed in different river systems, studies of river mechanics issues for the focus study reach along the Middle Rio Grande, and investigations of processes that may have an effect on sediment plug development. The database for this study includes discharge measurements, bed material samples, suspended sediment samples, and cross section surveys. Site characteristics, processes, and associated parameters that may affect plug formation were identified and evaluated. A theory on how and why plugs develop was formulated based on an evaluation of the available data and literature, a review of consistencies between periods when plugs developed versus periods when plugs did not occur, and a review of consistencies with conditions in different river systems where plugs formed. 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 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. The calibrated and validated model was then used to establish criteria for predicting when plugs will form. Boundary conditions and limitations for the criteria were identified.

The criteria for plug development are checked with focus on a dimensionless parameter, PLGNUM, which was established as a function of independent variables that are directly related to the plug formation theory:

$$PLGNUM = 120 * FrOB(ft^{-1}) * NDAYS(days) * QSAp0(ft/day) * RCEXP * Ro^{1/3}$$

Equation 10.1

Based on the results from several test model runs for plug development, critical threshold values for the PLGNUM parameter were determined for different levels of plug formation (55% of the main channel, 70% of the main channel, etc.) and a corresponding level of confidence (Figure 10.1). To determine the potential for plug formation for an actual scenario being evaluated, the PLGNUM parameter can be computed and compared to these critical threshold values.

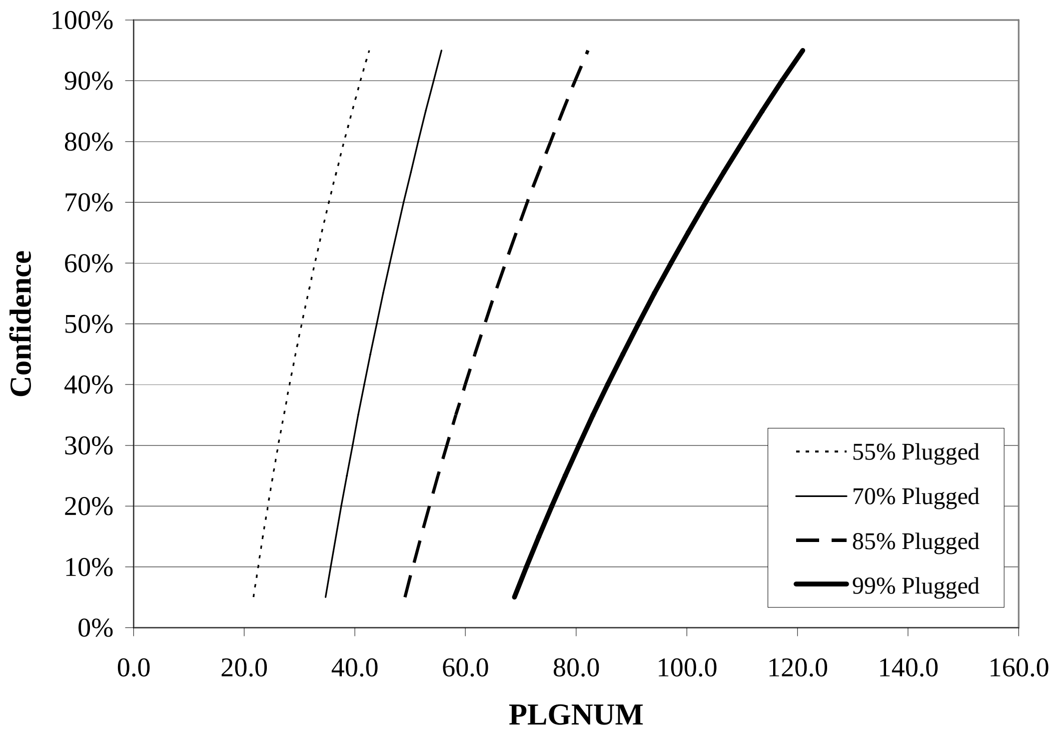


Figure 10.1 Criteria for Plug Formation

The criteria for plug development should be used solely for analysis of the short term phenomenon of sediment plug formation. The criteria should not be used to analyze the response of a river to multi-year scenarios; moreover, these criteria were not developed to assess the long term response of the morphology of an alluvial river to overbank flows. The criteria also should not be referenced for scenarios that involve flows with a return period greater than 5 years which could significantly impact the channel morphology during the period being analyzed.

Site characteristics were identified for locating segments of alluvial rivers where plugs may form. Sediment plugs consistently occur at the location of a constriction where constrictions are local controls or other physical features that significantly and abruptly reduce the main channel conveyance capacity of an alluvial river. Examples of constrictions include a bend in a river, structure, or debris snag. A constriction may also be a significant and abrupt reduction in the main channel width and/or depth. If there is a significant reduction in the main channel conveyance area (> 50%) as a result of a constriction within a few thousand feet longitudinally along an alluvial river, the criteria for sediment plug formation should be checked to determine the thresholds for when a sediment plug will develop.

Based on the developed criteria, for a study reach that has an abrupt constriction (within a 10,000 ft segment) on the order of 50% or greater that forces flow overbank, this loss of flow from the localized reach will cause accelerated deposition in the main channel due to a disproportionate loss of sediment transport capacity versus the loss of total sediment load. Due to the non-uniform vertical distribution of total sediment load, with a 25% loss of flow, the loss to the sediment load may only be a few percent. If the higher flows continue and 25% or more of the flow is lost to the overbanks for approximately 2 weeks or longer, the deposition may cause the main channel to become completely plugged with sediment.

10.1 Recommendations to Improve Analysis Resolution

As a result of this study, engineers not only have a better understanding as to how and why sediment plugs formed along the Tiffany Junction Reach but will be able to better predict when and where a plug will develop. Engineers can use this information to identify sites that are clearly prone to plug formation and ultimately prevent the conditions that might cause a plug to develop. If the criteria are checked and it is identified that a plug may form at a study site of interest, it is recommended that a more thorough and detailed engineering analysis be completed before making any policy decisions.

The resolution of the analyses discussed in this report and the computer model could be improved. As noted in Section 9.6, the most accurate information on bank elevations along the Tiffany Junction Reach should be obtained. This information would improve the analysis results in regards to when flows begin to overbank. A bank elevation profile for the left and right banks of the main channel of the river from rangeline SO-1596.6 to SO-1701.3 would significantly improve the predictive capability for when a plug would form again along the Tiffany Junction Reach.

Additional total sediment load data would certainly improve the resolution of the analyses, and data on the vertical velocity and concentration profiles would also be beneficial. If a situation arose where data could be collected during plug formation, measurements of the loss of flow to the overbank areas would also be very valuable for improving model calibration. Measurements of the flow in the main channel as flows overbank along the Tiffany Junction Reach would provide information as to how much flow is being lost to the overbank areas. Concentration information at the location where these flows overbank would be useful.

Plug formation is also very sensitive to the sediment transport along the study reach. A detailed analysis of sediment transport along the reach and just how the sediment transport capacity changes with varying hydraulic conditions would significantly improve the ability to predict plug formation. Such a detailed analysis may include a review of such factors as the episodic nature of sediment transport, seasonal variation in total sediment load, and the net effect of sediment inputs from arroyos and ephemeral tributaries during the monsoon season. An accurate site specific model, or equation, for predicting sediment transport along the Tiffany Junction Reach would be valuable.

The SPAR model for the Tiffany Junction Reach was used to simulate pre-2005 conditions, and the results indicate that if a prolonged higher release from Cochiti is made as occurred during the early 1990s, plug formation would initiate near SO-1683 as during 1991 and 1995. The channel morphology is the same in that the main channel conveyance area along the reach decreases by approximately 75% from the Bosque toward rangeline SO-1683. In fact, the data collected during August of 2004 indicate that the main channel conveyance capacity at SO-1683 is even less (420 ft^2) than it was during 1995 (680 ft^2) (Tetra Tech, 2004), so the Tiffany Junction Reach is still prone to plug formation as it was during the early 1990s.

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