# REVIEW OF SEDIMENT PLUG FACTORS
# MIDDLE RIO GRANDE, NM

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## NEW MEXICO

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## Foreword and Objective

We appreciate the renewed opportunity to work with the United States Bureau of Reclamation. The objective of this study is to review "all" possible factors involved in the formation of sediment plugs on the Rio Grande. This report aims at providing a digest, rather than an encyclopedic description, on the current knowledge and understanding of plug formation factors. The report is meant to be as brief as technically possible while providing sufficient evidence in support of the conclusions that are drawn. It is clear that this report emerges from numerous contributions prior to this investigation. We would like to acknowledge that the contributions of Craig Boroughs, Kiyoung Park, Ted Bender, Tracy Owen and Chris Shrimpton were most important to define the current state of knowledge described in this report.

## Acknowledgements

We would like to thank the United States Bureau of Reclamation for providing funding for this analysis at the Department of Civil and Environmental Engineering at Colorado State University. We acknowledge and appreciate the most important research contributions of Dr. Kiyoung Park leading to his PhD dissertation on sediment plugs of the Middle Rio Grande. We are highly grateful to Dr. Drew Baird for his most valuable insights on the Rio Grande and for his very thorough review of this report. We also appreciate the valuable input from Jonathan Aubuchon, Nathan Holste and Robert Padilla at the Albuquerque Area Office, as well as the discussion comments from Paula Makar and Yong Lai at the Denver Technical Center.

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# Chapter 1 : Introduction

## 1.1 Sediment Plugs

A sediment plug refers to "aggradation (that may include debris) in a river which completely blocks the original channel and grows upstream by accretion" (Boroughs 2005). Sediment plugs as shown in Figure 1.1a below have formed on the Middle Rio Grande in 1991, 1995, and 2005 in the Elephant Butte reach and in 2008 in the Bosque del Apache reach. The Bosque and the Elephant Butte reaches are illustrated by the green and blue lines respectively in Figure 1.2 below. The Tiffany plugs at the Elephant Butte reach and the Bosque plug at the Bosque reach have required costly dredging, as shown in Figure 1.1b below, to develop a channel and allow water to flow downstream rather than flowing overbank. This impedance has become an interstate and international issue since it prevents water compacts with Texas and Mexico from being fulfilled.

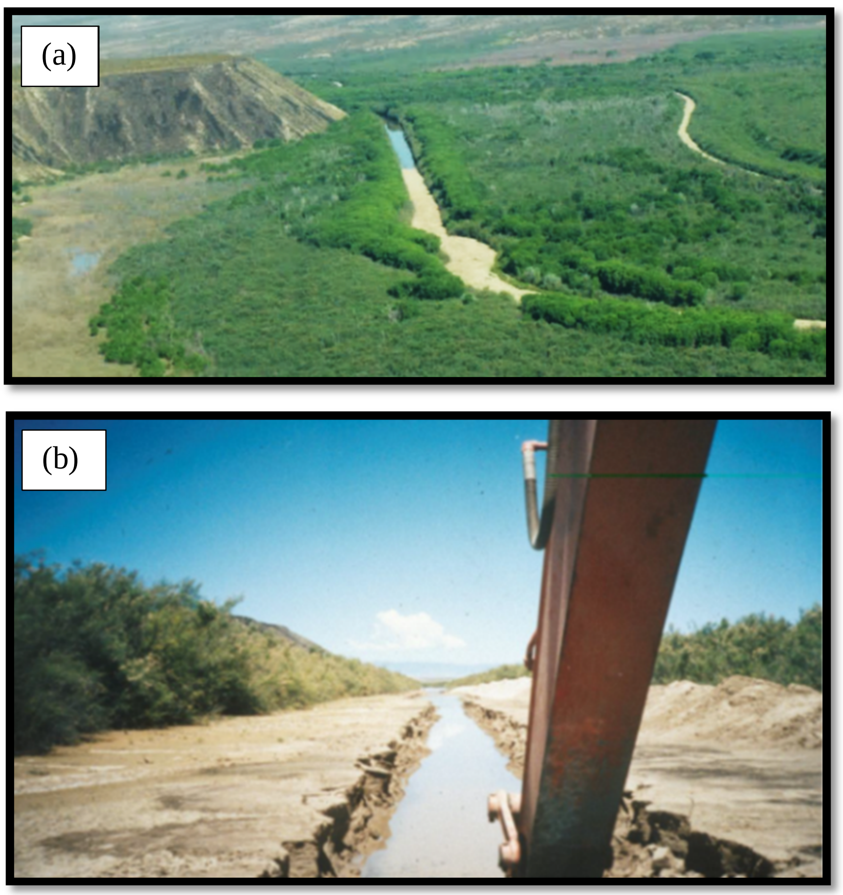



Figure 1.1: a) Photo of 2005 Tiffany plug [Owen et al. 2012]; b) Photo of the dredging of a pilot channel through the 1991 Tiffany plug [Boroughs 2005]

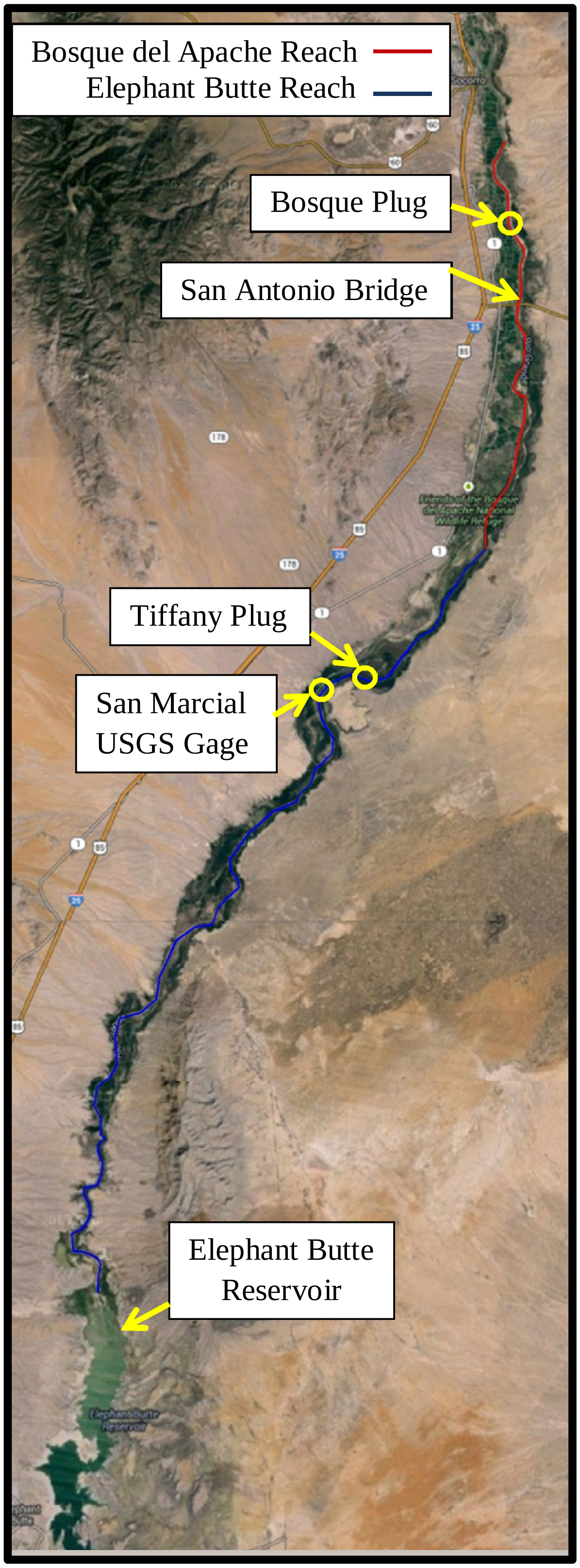



Figure 1.2: Map of Bosque del Apache and Elephant Butte Reaches

## 1.2 Factors

It is important to understand these sediment plugs so that the risk factors associated with their formation can be properly managed. There are several proposed factors to explain the formation of the sediment plugs. These factors include:

(1) Changes in channel slope (Section 2.5)

(2) Local variation in channel width (Sections 2.6 and 3.1.1)

(3) Coarsening of bed material (Section 2.9)

(4) Low bank height (Sections 2.10 and 3.2.1)

(5) Channel perching (Section 2.4 and 3.2.1)

(6) Vertical sediment distribution (Section 3.2.2)

(7) Channel aggradation (Section 2.4-2.6 and 3.3)

(8) Reservoir levels (Section 2.3 and 3.3.1)

(9) Cycles of droughts and floods (Section 3.1.2)

(10) Backwater effects from bridges (Section 2.3 and 3.3.2)

(11) Duration and magnitude of spring runoff (Section 2.7 and Chapter 4)

This assessment will describe the features of the Middle Rio Grande near the site of the sediment plug formation including those factors listed above. The relevance of these features to the formation of the sediment plugs will then be evaluated. The relation between these factors will also be described and illustrated through a flow chart according to the sequence of processes that were likely responsible for the plug formation. Following this evaluation, suggestions for future research will be given that relate to those processes that appear to have significantly contributed to the formation of the sediment plugs. This analysis will utilize the work from past research especially that of Dr. Kiyoung Park, Chris Shrimpton, Tracy Owen, and Dr. Craig Boroughs.

## Chapter 2 : Site Description

The Rio Grande is approximately 1,900 miles long and extends from the Rocky Mountains in southern Colorado to the Gulf of Mexico and flows through New Mexico and along the border of Texas and Mexico (Kammerer 1990). The Middle Rio Grande refers to a one hundred eighty mile long reach of the Rio Grande in New Mexico that extends from the Cochiti Dam to the Elephant Butte Reservoir as shown by the blue region in Figure 2.1 below.


Figure 2.1: Dams and Diversions along the Rio Grande [Abeyta 2009]

The USGS gage #08358400 is located at San Marcial and will be utilized in this assessment. The San Marcial gage is located directly downstream from where the Tiffany plugs occurred and the Bosque plug occurred further upstream from the San Marcial gage as shown in Figure 2.2a below. In addition to the San Marcial gage, the USGS gage #08354900 at San Acacia will also be used and this gage is located further upstream as shown in Figure 2.2b below.

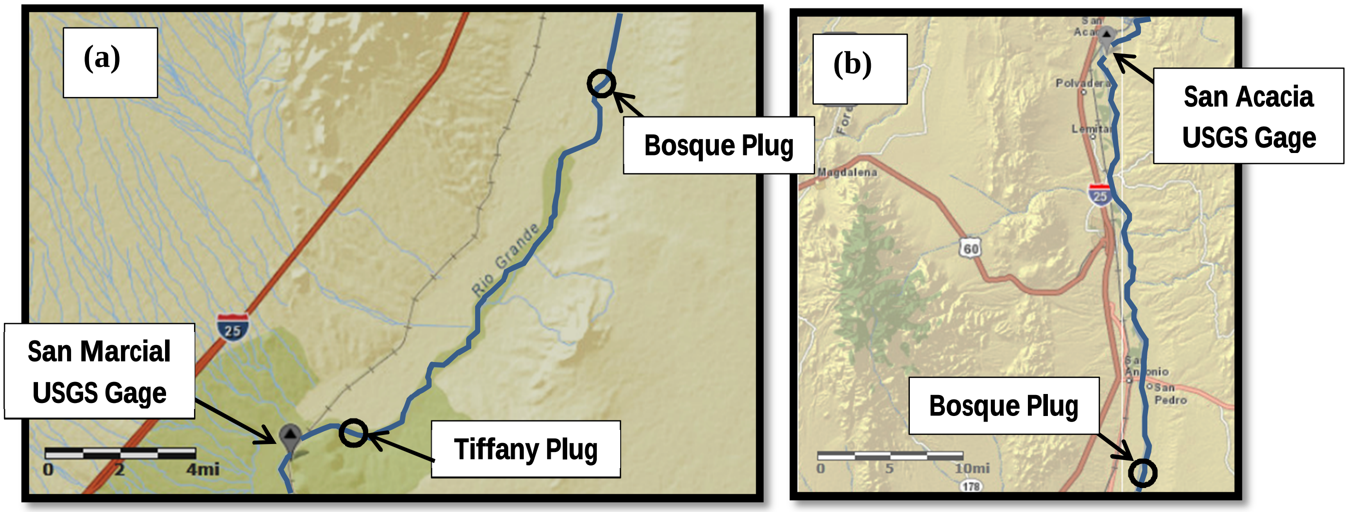



Figure 2.2: a) San Marcial Gage relative to Plug Locations; b) San Acacia Gage relative to Bosque plug [USGS]

## 2.1 Environmental Influence

While investigating the factors related to sediment plug and potential remediation plans it is also important to consider the response of the environment. Figure 2.1 above reveals the extensive human influences on the river which likely contributed to the elimination of over forty percent of the native species on the Middle Rio Grande (Finch et al. 1995). Furthermore there are also endangered and threatened species such as the Rio Grande silvery minnow which is federally and state listed as endangered.

## 2.2 Geometric Factors

This analysis of the Middle Rio Grande will begin by assessing the geometric factors of the river. These factors are important in order to draw conclusions of what factors were likely to have been significant.

### 2.2.1 Perching

A disconnect with the overbank flows from the main channel indicates that the overbank flows cannot immediately return to the channel. In the case of the region where the Bosque and Tiffany plugs formed, this is due to perching of the main channel meaning that the main channel is elevated above the floodplain. It is apparent that this perching exists based on the cross-sectional geometry of the location of the plugs as shown in Figure 2.3a-b below.

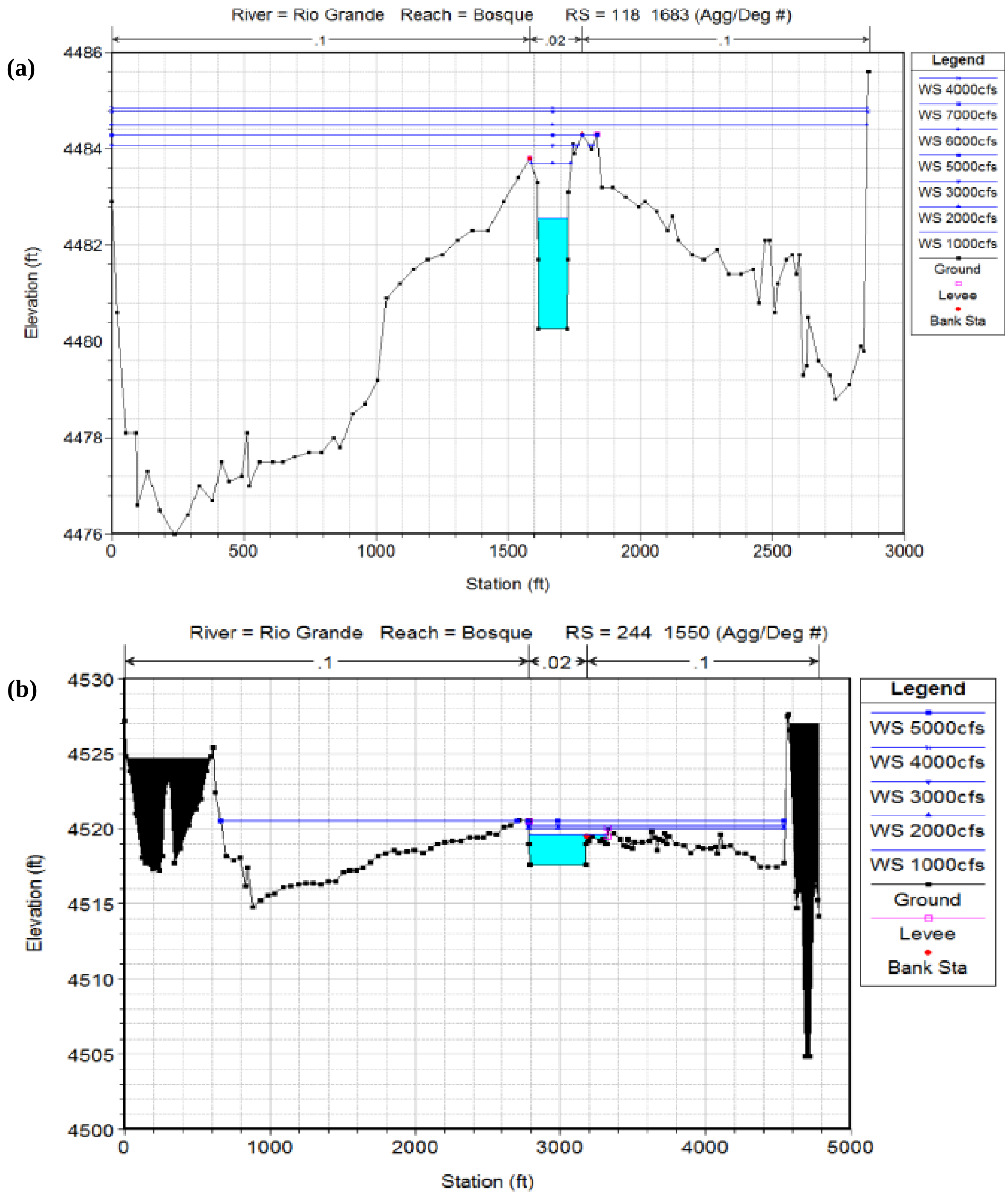



Figure 2.3: Cross sections a) Tiffany plug location [Park 2013]; b) Bosque plug location [Park 2013]

### 2.2.2 Channel Slope

The longitudinal profile of the Middle Rio Grande has varied significantly as shown in Figure 2.4 below. It appears that the downstream profile has been aggrading since 1915 but the upstream profile appears to have remained fairly constant until 1972 when it began degrading. These patterns may be a result of the completion of the Elephant Butte Dam on the downstream end in 1916 and the completion of the Cochiti Dam on the upstream end in 1973. The combination of upstream degradation and downstream aggradation would then lead to a flattening of the channel slope as shown in Figure 2.4 below.

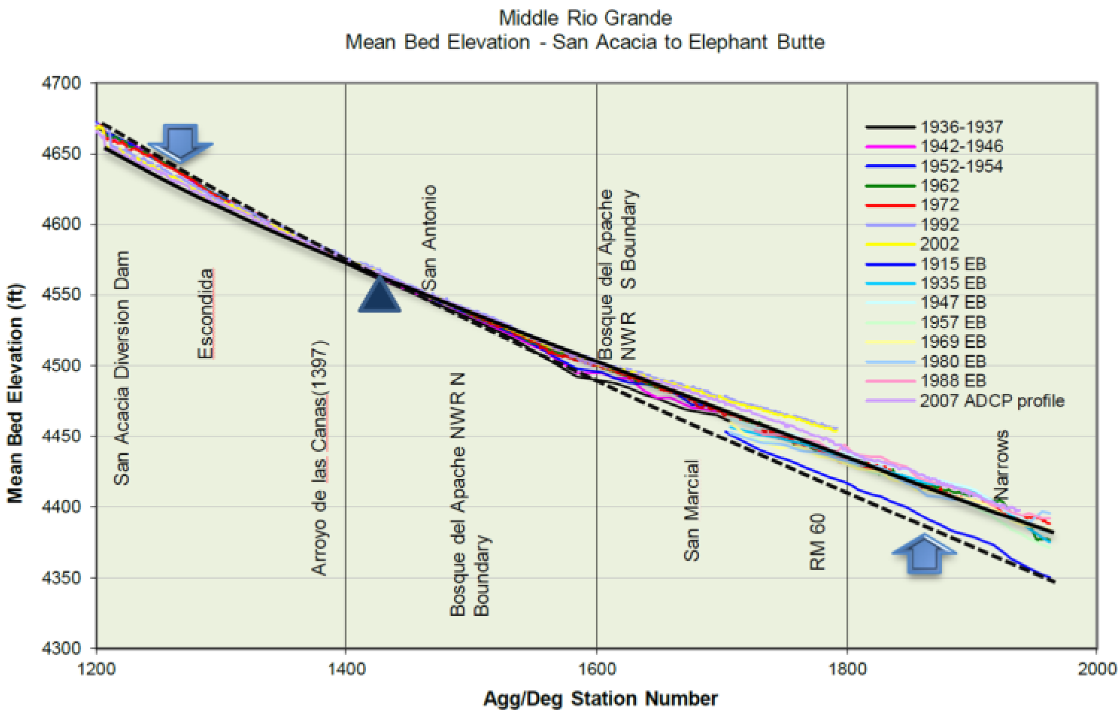



Figure 2.4: Middle Rio Grande Longitudinal Profile [Park 2013]

### 2.2.3 Channel Width

In addition to the declining slope, the width also appears to be decreasing between 1962 and 2009 at the location of the Tiffany plugs and the Bosque plug as shown in Figures 2.5 and 2.6a-b respectively below. Between 1992 and 2002 however, the Tiffany plug width increased while the Bosque plug width decreased as shown in Figure 2.7 below.

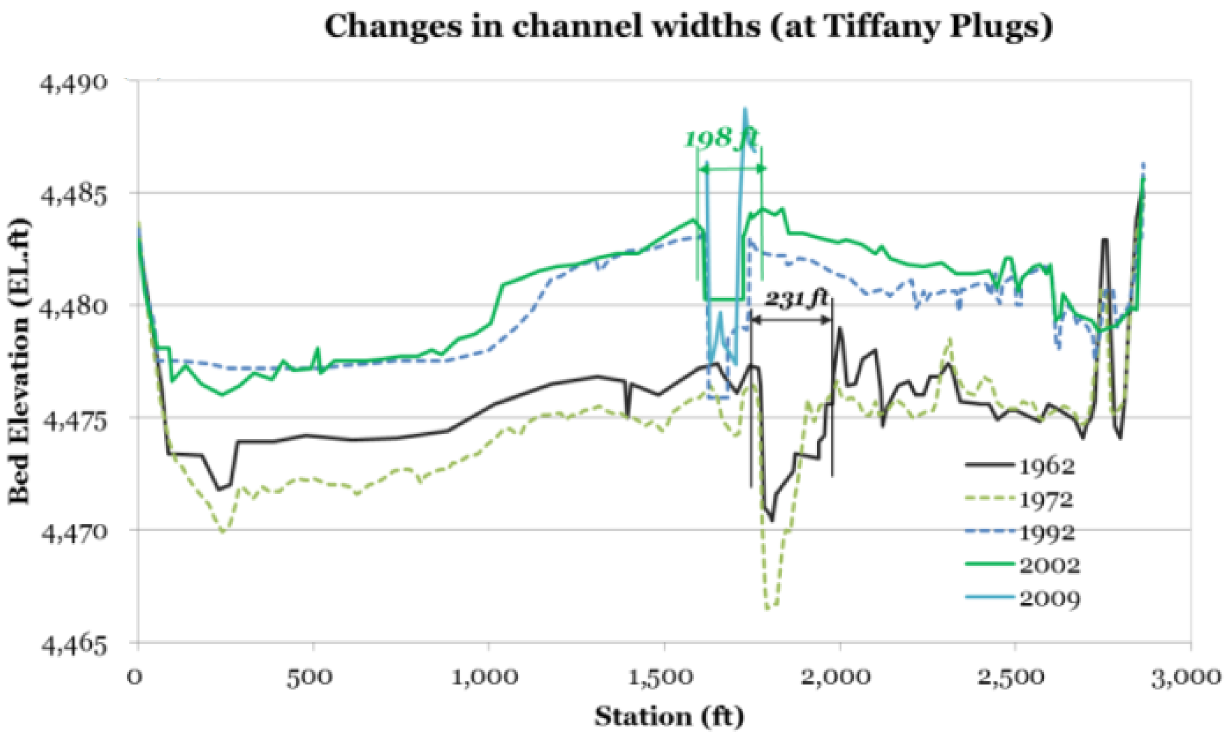



Figure 2.5: Changes in Channel Width at Tiffany Plug Location (Agg/Deg 1683) [Park 2013]

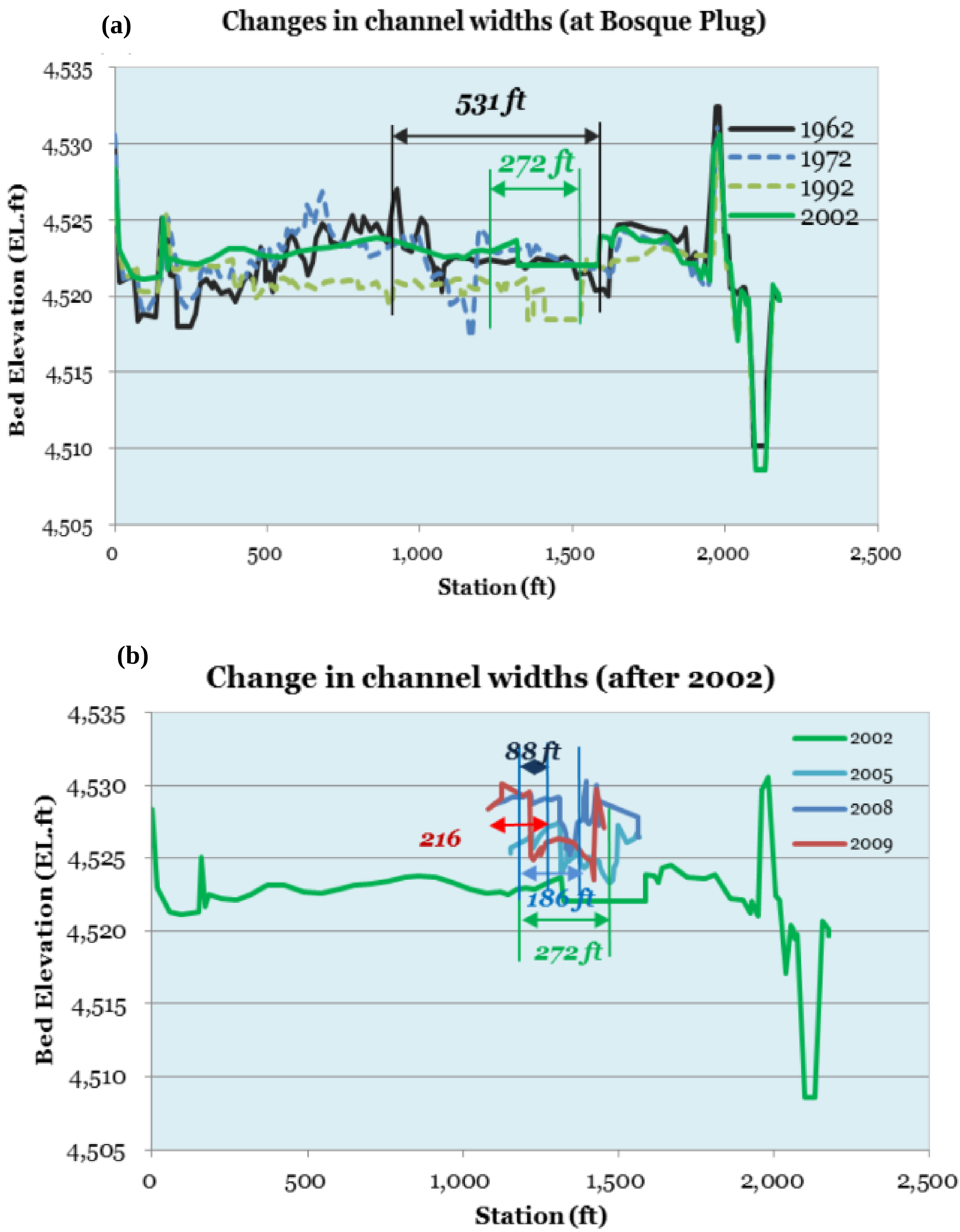



Figure 2.6: Changes in Channel Width at Bosque Plug Location (Agg/Deg 1550) a) 1962-2002 [Park 2013]; b) 2002-2009 [Park 2013]

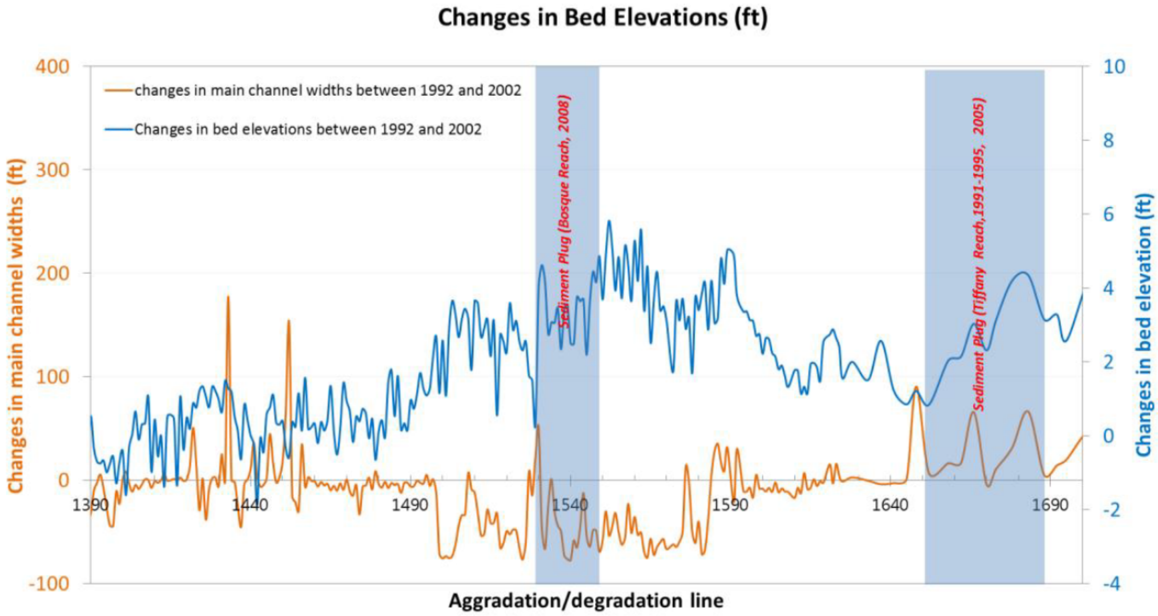



Figure 2.7: Changes in channel width between 1992 and 2002 [Park 2013]

### 2.2.4 Bank Height

The channel depth refers to the height between the main channel bottom and the bank crest. This parameter was computed by assuming rectangular channel geometry and thereby dividing the flow area by the top width of the flow surface. The bank height of the channel of the Middle Rio Grande generally decreased between 1992 and 2002. As shown in Figure 2.8 below, the region where the Tiffany plug formed experienced a decline in the bank height but this decline was greater than the average decline. Also, the bank height where the Bosque plug formed underwent a decline and this decline was more significant than the location where the Tiffany plug formed.

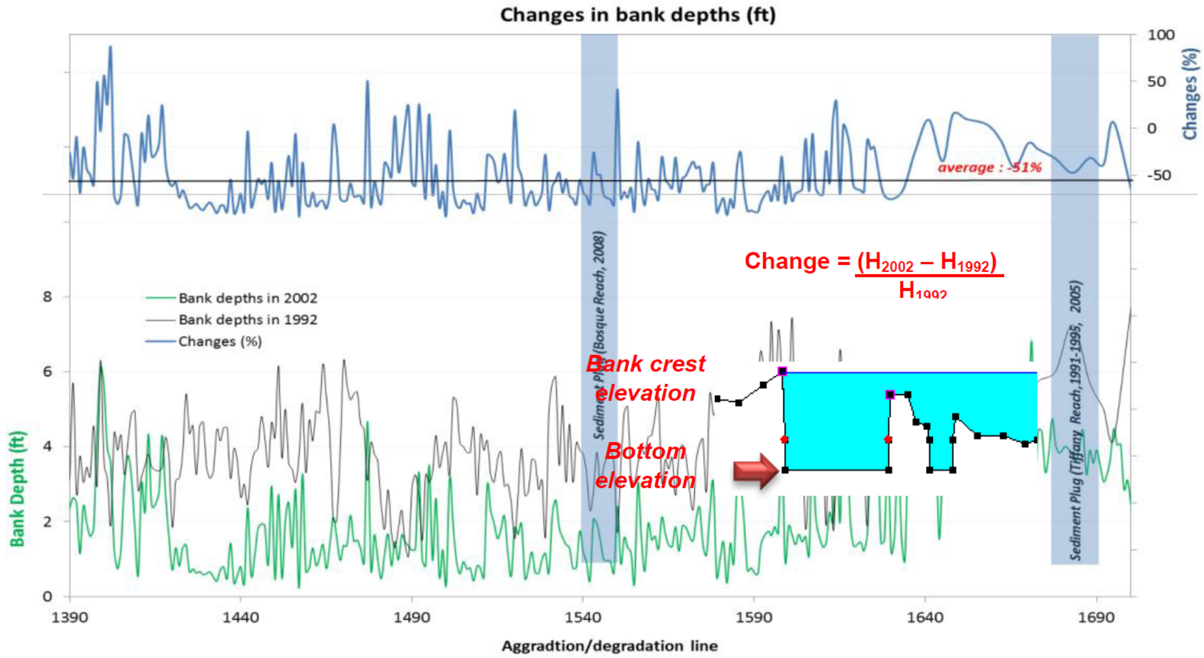



Figure 2.8: Changes in bank height across agg/deg line between 1992 and 2002 [Park 2013]

### 2.2.5 Coarsening of Bed Material

The bed material grain size of the Middle Rio Grande has changed between 1992 and 2002. As shown in Figure 2.9 below, in most regions the bed material has coarsened between 1992 and 2002 such as the location where the Bosque plug formed but the grain size at the Tiffany plug location has remained constant.

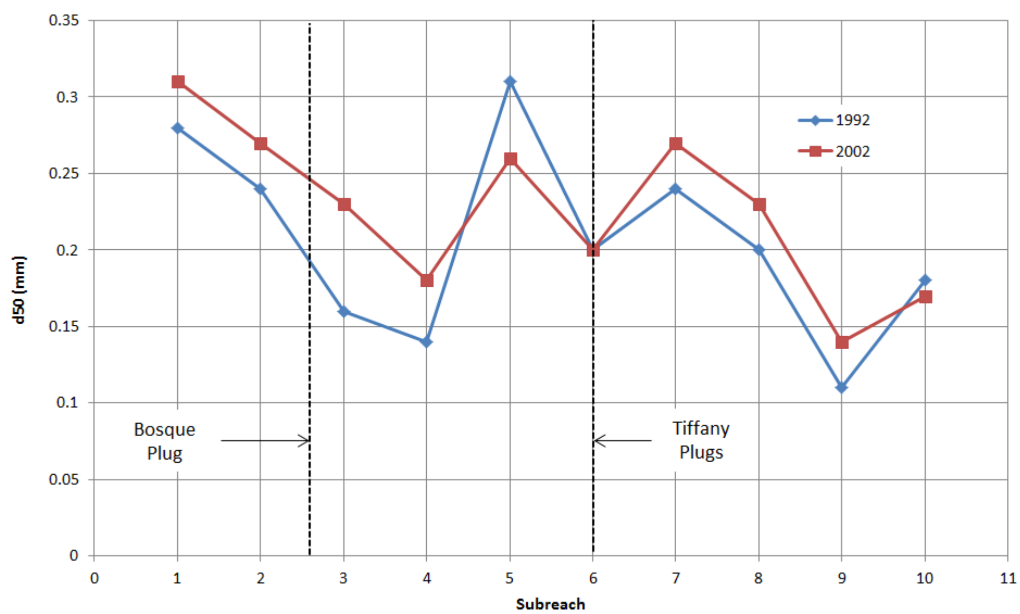



Figure 2.9: Grain size distribution between 1992 and 2002 by subreach [Shrimpton 2012]

### 2.2.6 Vegetation Encroachment

After the water stage has receded during low-flow periods such as from mid-June to the beginning of September in the 2003 hydrograph shown below in Figure 2.10, vegetation has the opportunity to emerge within the floodplain as shown in Figures 2.11a-c below. However, depending on the location and age of the established vegetation, a discharge of relatively large magnitude and long duration will remove this emergent vegetation as shown in Figures 2.11c-e below.

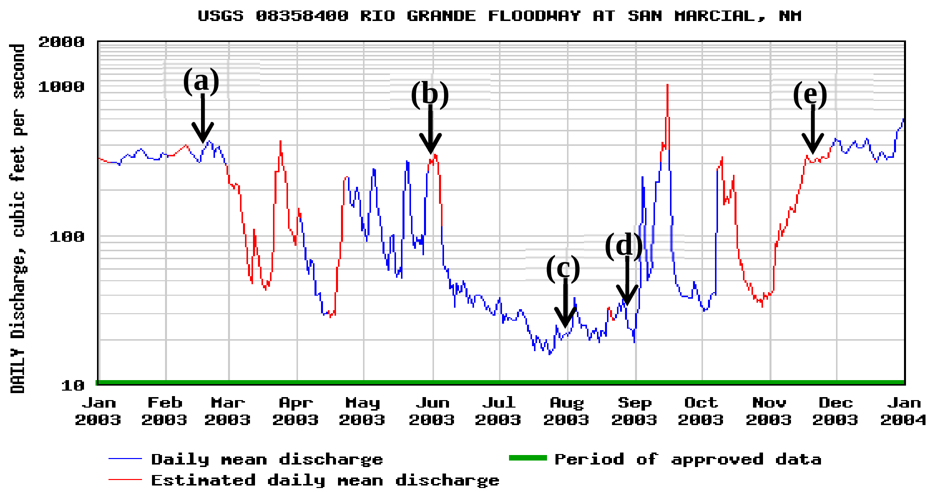



Figure 2.10: 2003 Annual Hydrograph [USGS]


Figure 2.11: Looking downstream from San Marcial a) February 21, 2003 [BOR 2003]; b) May 29, 2003 [BOR 2003]; c) July 28, 2003 [BOR 2003]; d) September 26, 2003 [BOR 2003]; e) November 17, 2003 [BOR 2003]

## 2.3 Flow Data

### 2.3.1 Cochiti Dam

The closure of the Cochiti Dam in 1973 at the upstream end of the Middle Rio Grande has dramatically decreased the sediment load as shown in Figure 2.12 below. In addition, the regulated peak flows also decreased as shown in Table 2.1 below where there is a much greater difference between the regulated and unregulated flows upstream and downstream from Cochiti Dam.

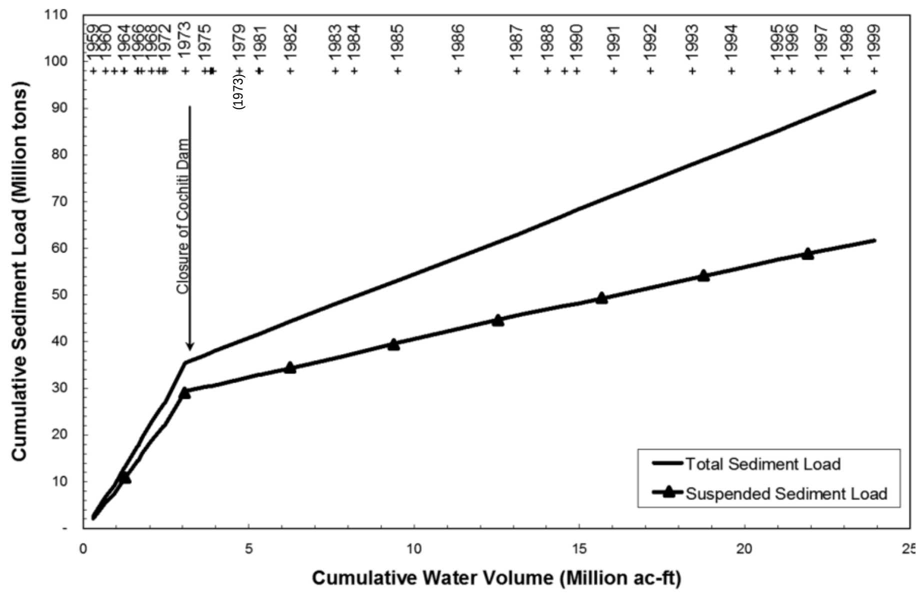



Figure 2.12: Double Mass Curve following the Closure of the Cochiti Dam at the San Acacia Gage [Mussetter et al. 2002]

a) Rio Grande at Otowi Bridge

| Return Period (yr) | Regulated Peak Discharge ($ft^3/s$) | Unregulated Peak Discharge ($ft^3/s$) |
|---|---|---|
| 2 | 8,300 | 10,100 |
| 5 | 12,000 | 14,600 |
| 10 | 14,200 | 17,200 |
| 25 | 16,600 | 20,100 |
| 50 | 18,100 | 22,000 |
| 100 | 19,500 | 23,700 |

b) Rio Grande at San Felipe

| Return Period (yr) | Regulated Peak Discharge ($ft^3/s$) | Unregulated Peak Discharge ($ft^3/s$) |
|---|---|---|
| 2 | 5,600 | 11,700 |
| 5 | 8,600 | 17,500 |
| 10 | 10,000 | 20,900 |
| 25 | 10,000 | 24,700 |
| 50 | 10,000 | 27,100 |
| 100 | 10,000 | 29,300 |

Table 2.1: Return Period of Regulated and Unregulated Flows on the Rio Grande a) Upstream from Cochiti Dam b) Downstream from Cochiti Dam [Write 2010]

### 2.3.2 Backwater

Backwater on the Middle Rio Grande may result from the San Marcial Railroad bridge, bends, or base level changes from the Elephant Butte Reservoir as shown in Figures 2.13a-c respectively below.

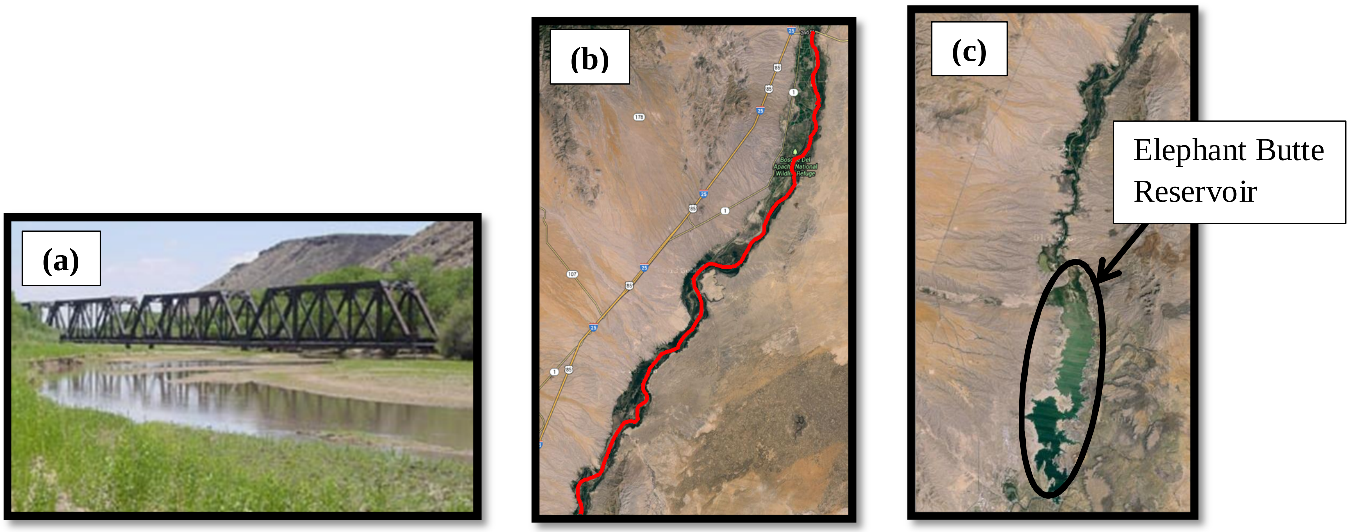



Figure 2.13: Sources of Backwater a) San Marcial Bridge [Dudley, Farrington, & McBride 2003]; b) Bends on the MRG [Google Maps 2013]; c) Elephant Butte Reservoir [Google Maps 2013]

The Tiffany plugs were located approximately thirty-five miles upstream of the Elephant Butte Reservoir and the Bosque Plug was located approximately forty-eight miles upstream of the Elephant Butte Reservoir. Figure 2.14a below demonstrates the temporal significance of reservoir levels and the average bed elevation at San Marcial and Figure 2.14b establishes a temporal significance between the reservoir levels and the average bed elevation at many subreaches including the Tiffany plug location. Figure 2.14a illustrates that the water surface elevation appears to generally be rising while the reservoir was high with dramatic lowering following the Tiffany plugs and the water surface elevation appears to remain relatively constant while the reservoir was low. Figure 2.14b demonstrates that the water surface elevation rose as the reservoir storage increased especially downstream from the San Marcial gage and the water surface elevation fell downstream from the San Marcial gage as the reservoir storage reached a minimum.

(a)

(b)

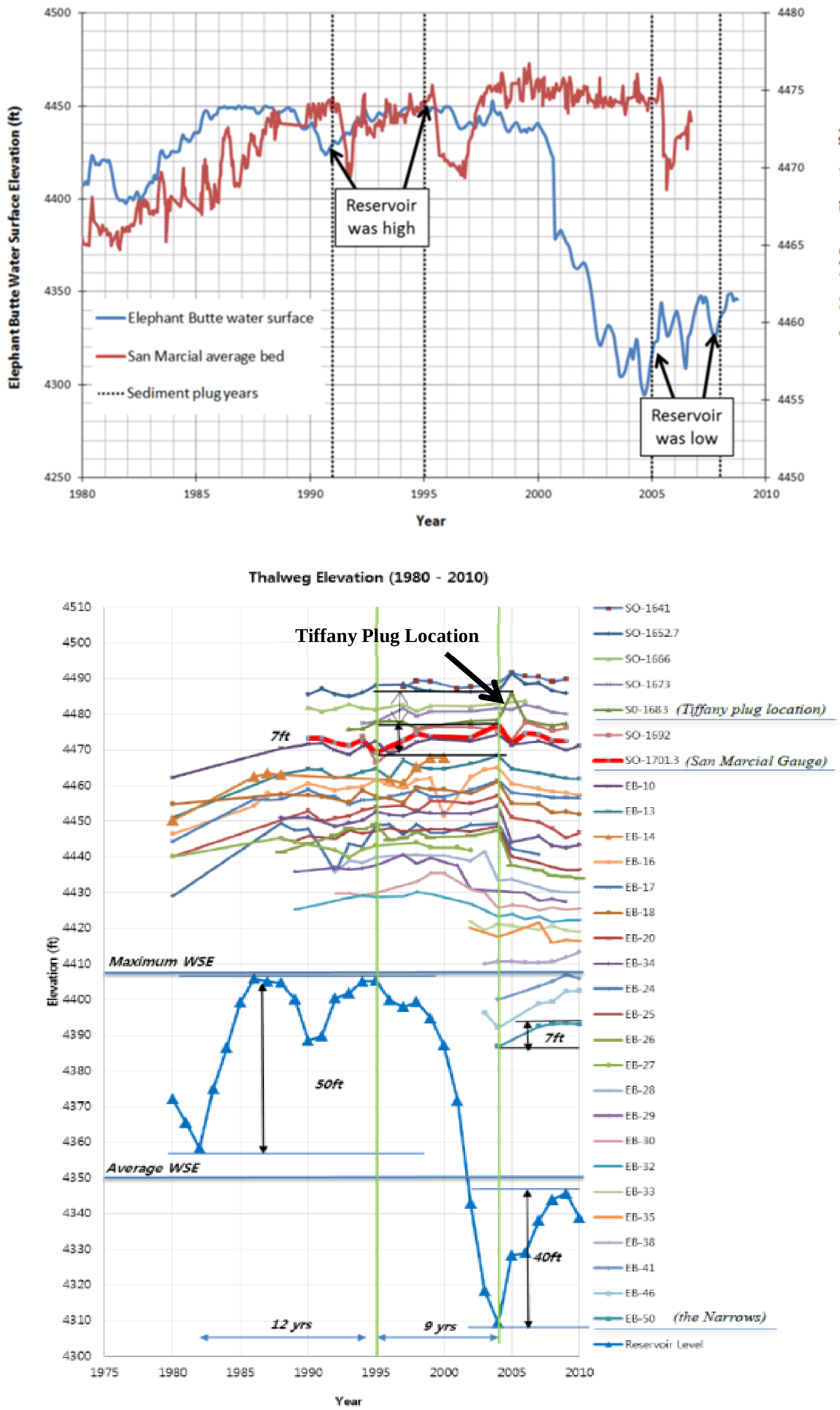



Figure 2.14: a) Reservoir Levels and San Marcial Bed Elevation [Shrimpton 2012]; b) Reservoirs Levels and Bed Elevation of MRG Reaches [Owen et al. 2012]

### 2.3.3 Discharge Peaks

The annual hydrograph in the region typically has two peak discharges associated with the snowmelt peak and the thunderstorm peak. The snowmelt peak typically occurs between May and July while the thunderstorm peak usually takes place between July and September. An annual hydrograph from the San Marcial gaging station that clearly demonstrates these peaks is shown in Figure 2.15 below.

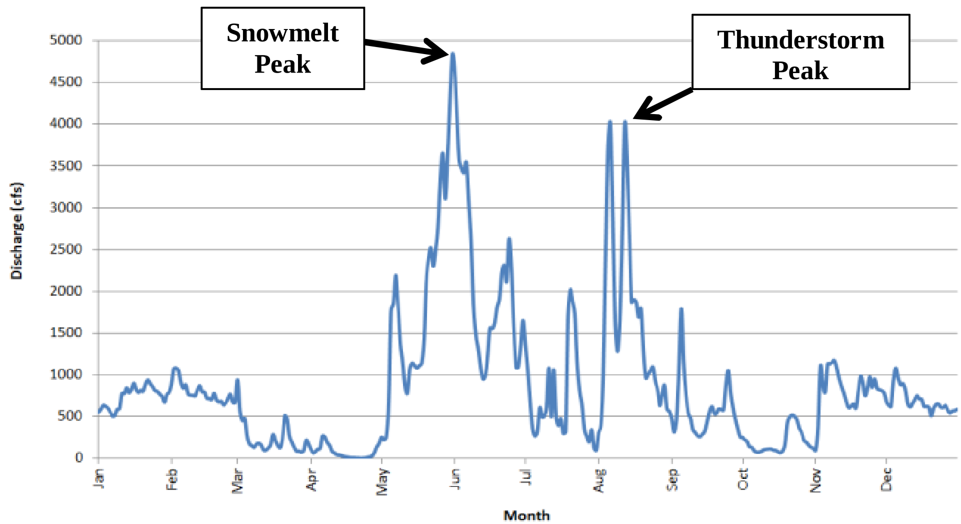



Figure 2.15: 1999 Annual Hydrograph Peaks [Shrimpton 2012]

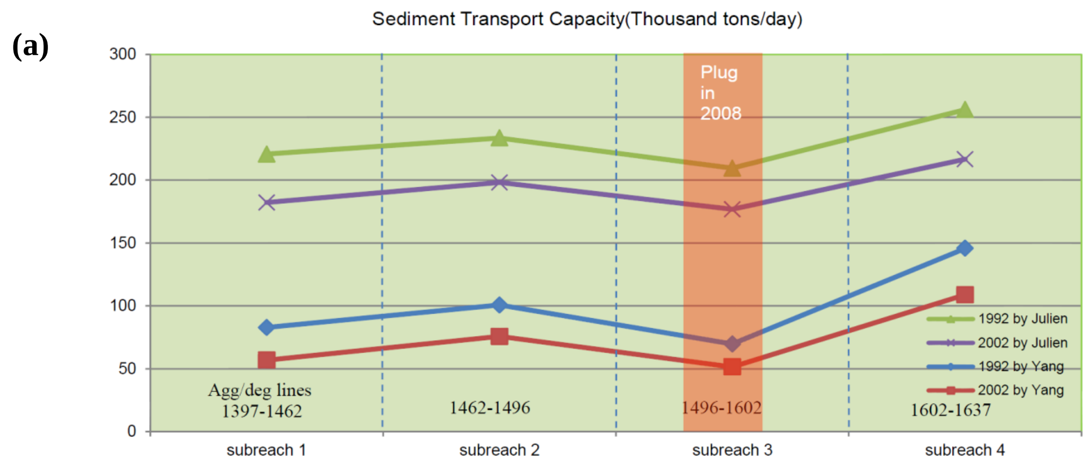
# Chapter 3 : Review of Main Factors

## 3.1 Geometric Factors

Three types of main factors are considered in this chapter: geometric factors (3.1), sedimentation factors (3.2), and backwater factors (3.3). A detailed review of these factors is presented by Park (2013) and a summary of this work is presented here.

The bed material of the Middle Rio Grande is composed of fine particles and has been described as a “shifting sand substratum with low, poorly defined banks” (Lagasse, 1981). This enables both great spatial and temporal variations in the channel geometry.

The channel geometry varies according to the degree of erosion and aggradation. Aggradation can cause upstream slope reduction, and a steeper slope in the aggradation area and downstream. Channel aggradation is a result of lower sediment transport capacity or higher sediment concentration. The sediment transport capacity has been quantified by the Yang and the Julien equation. By comparing the spatial and temporal significance of the sediment transport capacity to the plugs as shown in Figure 3.1a-b below, it is apparent from these equations that the sediment transport capacity was declining at the time leading to the Bosque sediment plug and was relatively low at the location of the plug. This evidence supports the role of the sediment transport capacity to the Bosque plug. Also, near the Tiffany plugs there is evidence that the sediment transport capacity decreased between 1992 and 2002 and especially at the location of the Tiffany plugs. In addition, in 2002 the sediment transport capacity at the Tiffany plug location also appears to be low relative to the other subreaches.



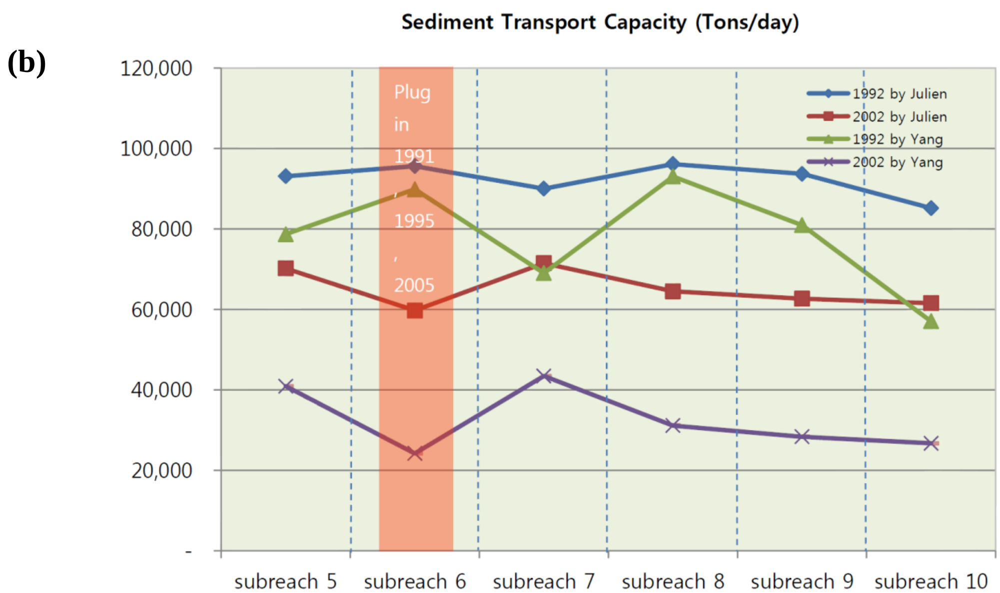




Figure 3.1: Sediment Transport Capacity Profile a) Bosque plug location [Park 2013]; b) Tiffany plug location [Park 2013]

The channel conveyance $(K)$ measures the carrying capacity of the channel and accounts for the channel roughness and the channel geometry as shown in Equation 3.1 below where $\phi = 1.49$ for English units and $1.0$ for metric units, $n$ denotes the Manning roughness coefficient, $A$ denotes the flow area, and $R$ denotes the hydraulic radius. The flow area was computed from the product of the active channel width and the bank height.

$$K = \frac{\phi}{n} A R^{2/3}$$ Equation 3.1

Figure 3.2 below demonstrates that the conveyance at the location of the Bosque plug reduced significantly between 1992 and 2002 while it remained relatively constant at the location of the Tiffany plugs. This time period however may have had more significance at the Bosque plug location than the Tiffany plug as it is the period leading up to the Bosque plug while at the Tiffany plug location it followed the 1991 plug and this period also contained a plug in 1995.

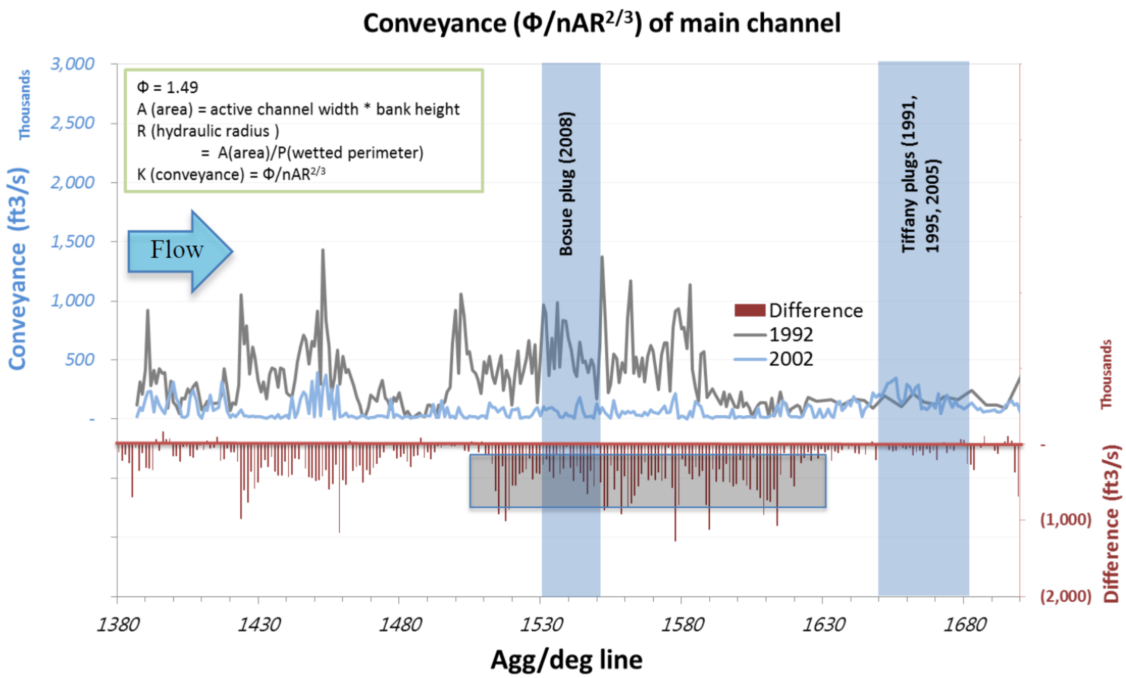



Figure 3.2: Conveyance of the Main Channel from 1992-2002 [Park 2013]

### 3.1.1 Channel Widths

Overall, the average channel width declined by forty percent between 1962 and 2002. According to Figure 2.5 and 2.6a-b, the channel width declined much more significantly at the Bosque plug location than the Tiffany plug location. The width at the location of the Tiffany plug decreased about fourteen percent between 1962 and 2002 while at the Bosque plug location the width decreased about eighty-three percent in the same period.

By reducing the channel width, the flow velocity increases as the flow is constricted and the sediment transport capacity increases. However, as the flow area becomes increasingly reduced the sediment transport capacity can begin to decline if the roughness is higher along the banks than the bed or if the hydraulic radius begins to decline. By applying Julien's and Yang's equations to the reaches where the sediment plugs formed as shown in Figures 3.3a-b and 3.4a-b below, the width at which the plugs formed can be compared to the width of optimal sediment transport capacity. Yang's equation appears to estimate a much lower optimal width than Julien's equation and the sediment transport capacity drops much faster following this width. Nevertheless, there is a consensus that the decline in the channel width as shown in Figures 2.5 and 2.6a-b resulted in a higher sediment transport capacity. This reduction in width between 1962 and 2002 resulted in a ten percent reduction in sediment transport capacity. However, besides producing a higher sediment transport capacity, this decline in channel width would also reduce the magnitude the overbank discharge by reducing the flow area.

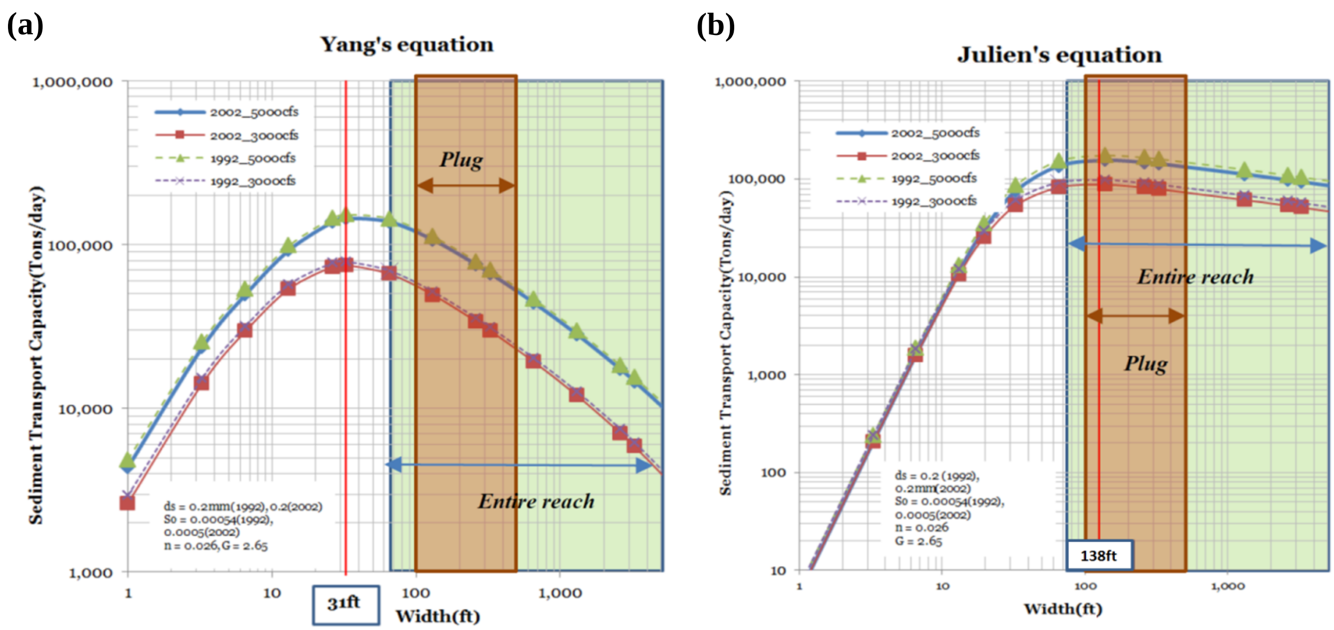



Figure 3.3: Variations in the Sediment Transport Capacity with Width at the Elephant Butte Reach [Park and Julien 2012]

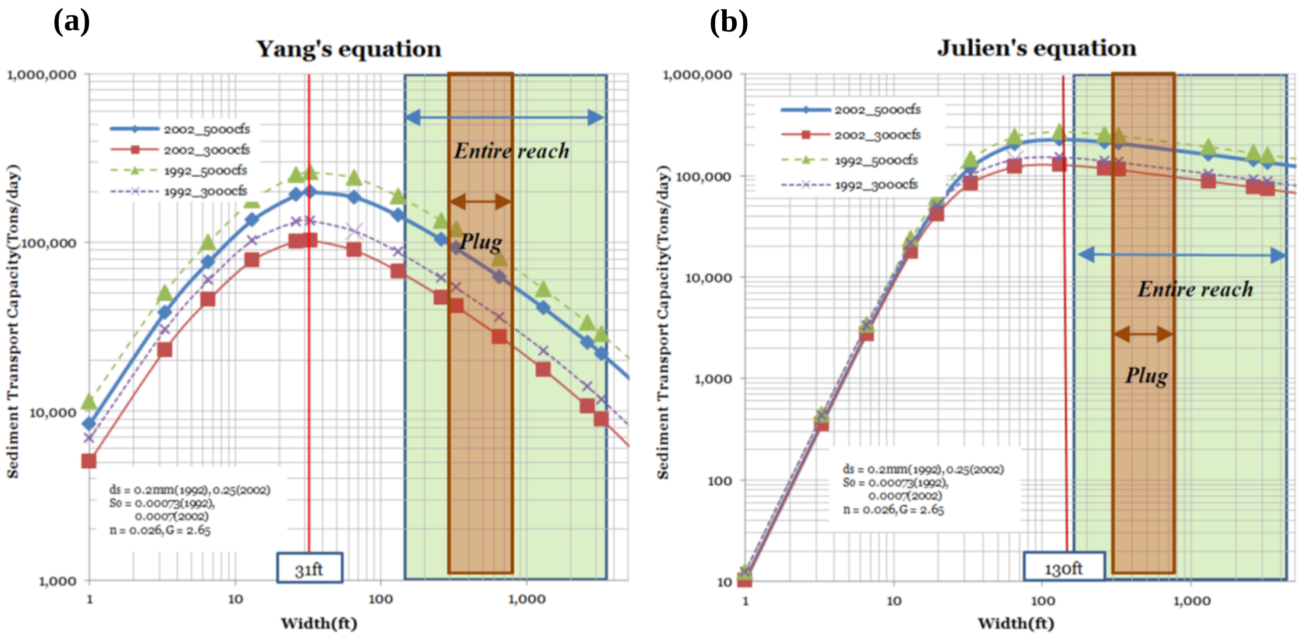



Figure 3.4: Variations in the Sediment Transport Capacity with Width at the Bosque Reach [Park and Julien 2012]

### 3.1.2 Roughness

At a discharge of five thousand cubic feet per second the composite roughness of the main channel and overbank areas increases with channel aggradation, reduced bank height, and increased floodplain flows. Also at this discharge, the roughness of the Middle Rio Grande has risen by approximately fourth-five percent between 1962 and 1972 and approximately fifty percent between 1992 and 2002 as shown in Figure 3.5 below. The roughness due to the coarsening of the bed material as shown in Figure 2.9 caused an insignificant rise in the channel roughness. Figure 3.5 demonstrates that the channel roughness increases substantially as the discharge increases. This is due to the higher roughness on the floodplain and the stage increasing the form roughness. Vegetation encroachment can also increase composite roughness. This vegetation encroachment was likely to have increased during the period of low flow and therefore low stage between 2000 and 2005 as shown by the hydrograph in Figure 3.6a below which would have resulted in significant roughness when the stage increased during the flooding that followed as shown in Figure 3.6b below.

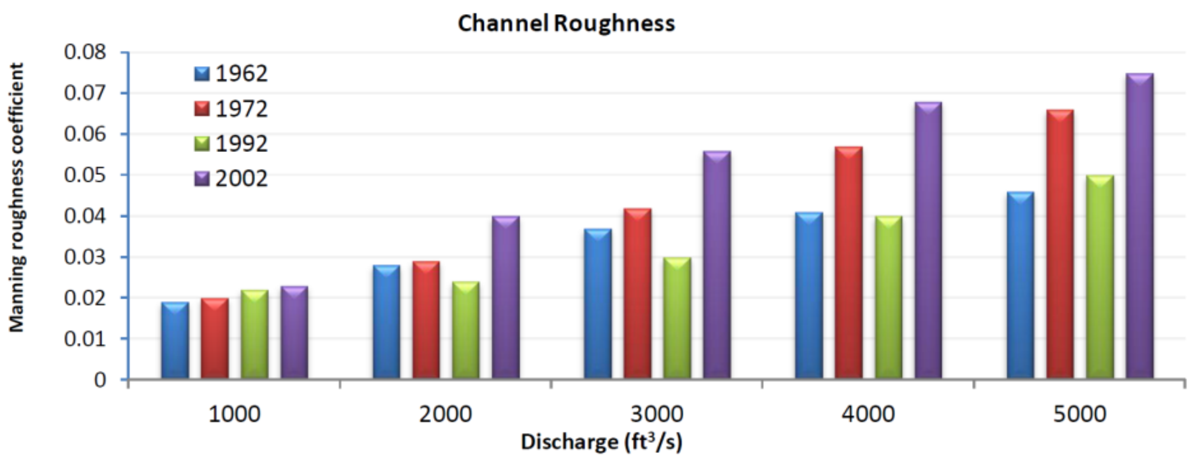
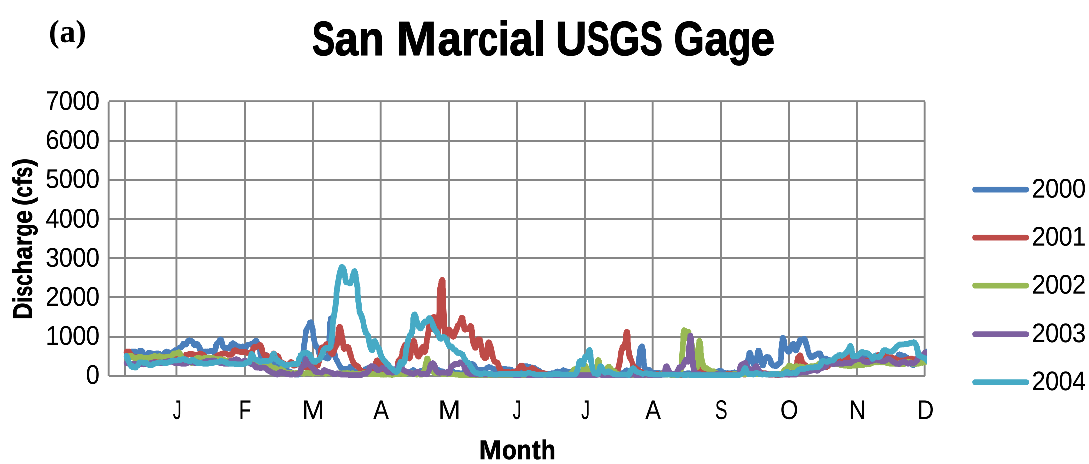



Figure 3.5: Channel Roughness Variations with Time and Discharge [Park 2013]



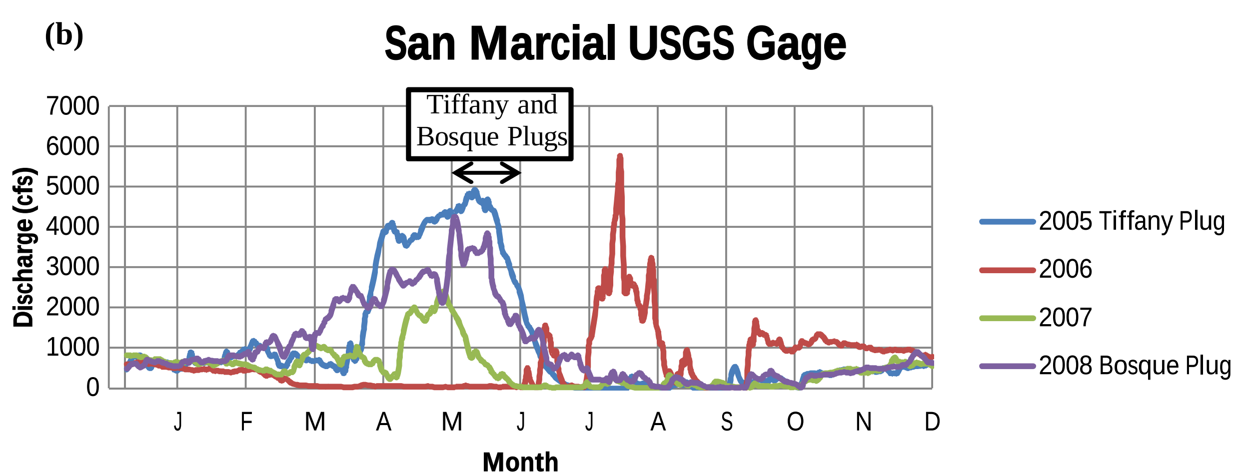




Figure 3.6: Annual Hydrographs a) 2000-2004 Drought [data from USGS]; b) 2005-2008 Flooding [data from USGS]

From Figure 3.7 below, it is apparent that the composite roughness at the location of the Bosque plug increased significantly between 1992 and 2002 while the rise in composite roughness at the location of the Tiffany plugs during this period was relatively minor. In addition, the average sediment transport capacity decreased by forty-five percent. Therefore, despite the ten percent increase in sediment transport capacity during this period due to the reduction in channel width, the overall effect of the geometric factors reduced the sediment transport capacity due to the rise in roughness.

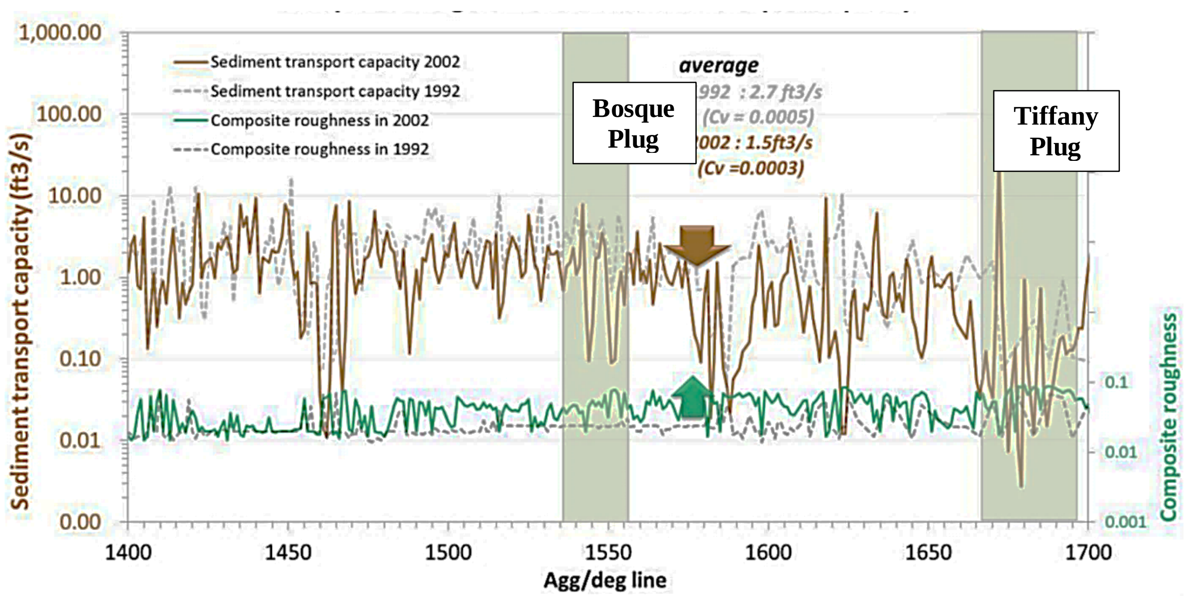



Figure 3.7: Composite Roughness and Sediment Transport Capacity at five thousand cubic feet per second [Park 2013]

## 3.2 Overbank Flows and Concentration Profiles

### 3.2.1 Perching and Overbank Flows

Besides the overbank flows being more prevalent during the spring runoff period, these overbank flows grew more widespread between 1992 and 2002 since the channel flows decreased while the floodplain flows increased as shown in Figure 3.8a-b below These overbank flows resulted in an average loss of thirteen percent of flow between the San Acacia gage and the San Marcial gage during the spring runoff of 1995 prior to the Tiffany plug and an average loss of twenty percent of flow between these gages during the spring runoff of 2008 prior to the Bosque plug. This is likely a result of lower overbank discharge magnitudes and channel perching. Lower overbank discharge magnitudes were a result, in part, of the fifty-one percent decline in bank depth between 1992 and 2002. Channel perching is a consequence of aggradation and levee formation which raises the river's bed elevation above the surrounding floodplain. The perching ratio refers to the ratio of the length of perched subreaches to the total reach length and this ratio increased from thirteen percent to eighty-seven percent in the Bosque and Tiffany areas during this period between 1992 and 2002.

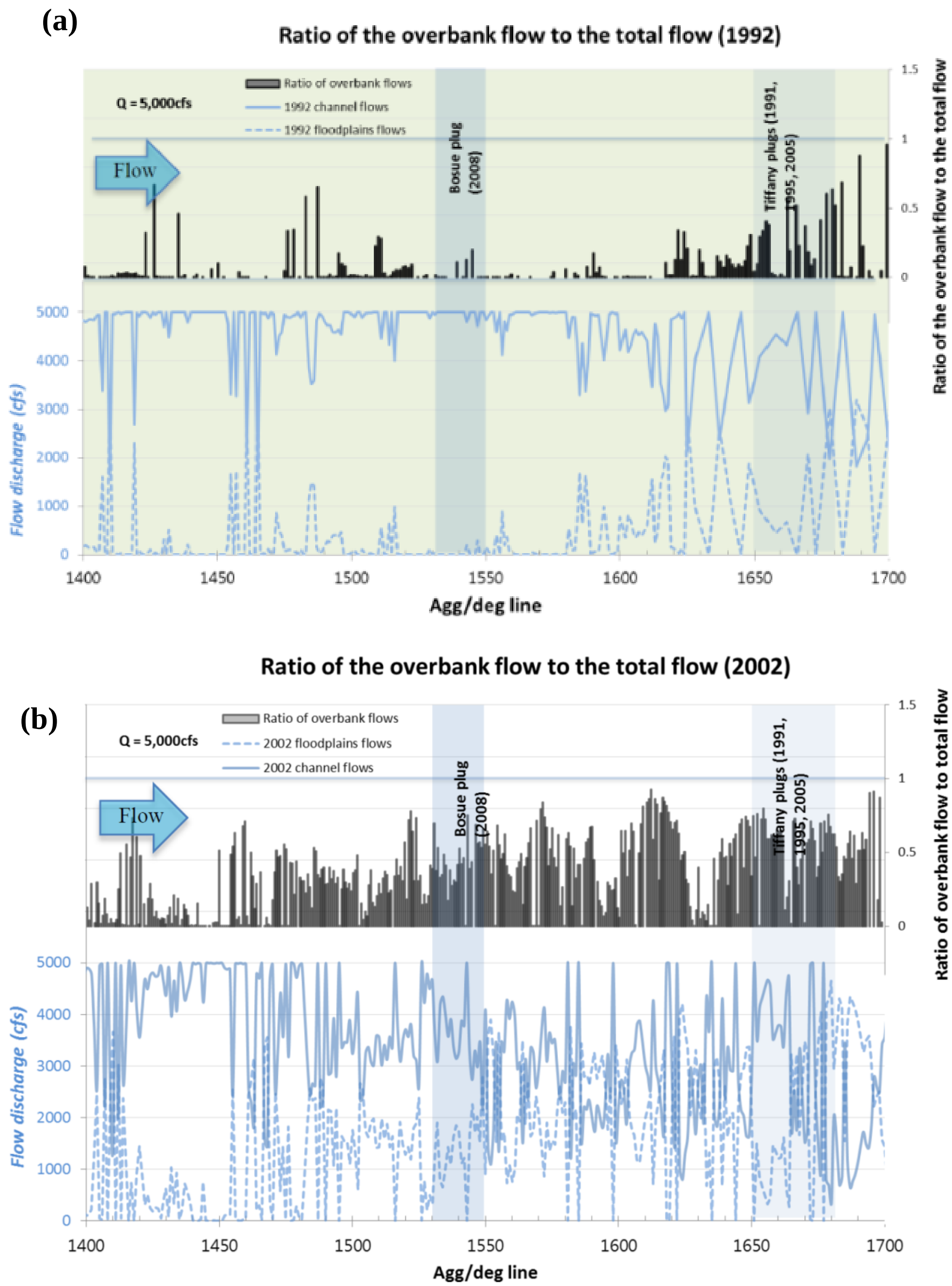



Figure 3.8: Ratio of the Overbank Flow to the Total Flow a) 1992 [Bender 2012]; b) 2002 [Bender 2012]

The location and magnitude of the top five overbank flows in the region of the Bosque plug has varied substantially between 1962 and 2002 as shown in Figure 3.9a below. However in 2002 the top five overbank flows were each of a low magnitude and clustered near the location of the Bosque plug. Figure 3.9b also demonstrates that the bank height is correlated with the magnitude of the overbank flow. This pattern suggests that the overbank flow was a major factor in the formation of the Bosque plug in 2008 and the low bank height was a significant factor to the overbank flow.

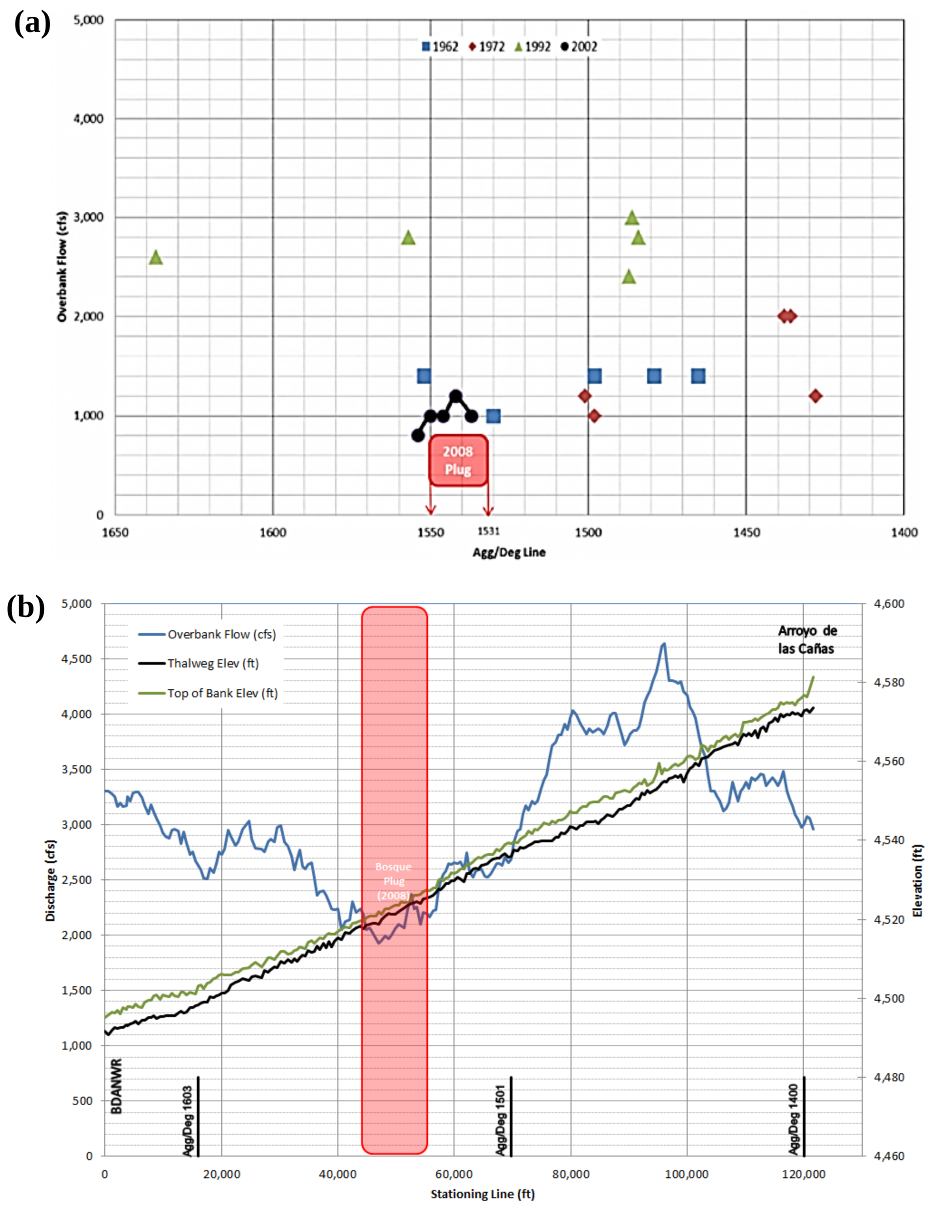



Figure 3.9: a) Variations in locations with lowest overbank flow [Bender 2012]; b) Overbank Discharge and Bank Height in 2002 [Bender 2012]

### 3.2.2 Vertical Sediment Concentration Profiles

The Rouse number $(Ro)$ is a non-dimensional number which represents the ratio of the sediment properties to the hydraulic characteristics of the flow and therefore expresses the sediment concentration profile. A high Rouse number refers to a vertical sediment distribution that concentrates sediment toward the channel bed and is computed according to Equation 3.2 below where $\omega$ denotes the settling velocity, $\beta_s$ denotes the ratio of the sediment to the moment exchange coefficient, $\kappa$ denotes the von Karman constant, and $u_*$ denotes the shear velocity. The Rouse number can then be utilized to compute the sediment concentration profile according to Equation 3.3 where $C_a$ denotes the near-bed sediment concentration, $a$ denotes the thickness of the bed layer, $C$ denotes the concentration at elevation $z$ above the bed layer, and $h$ denotes the flow depth.

$$Ro = \frac{\omega}{\beta_s \kappa u_*} \qquad \text{Equation 3.2}$$

$$C = C_a \left(\frac{h-z}{z}\frac{a}{h-a}\right)^{Ro} \qquad \text{Equation 3.3}$$

Before flowing overbank, the Rouse number at the Bosque plug location varies between approximately 1.2 and 1.8. After flowing overbank the Rouse number at the Bosque plug location varied between approximately 1.2 and 1.6 which corresponds to approximately eighty-five to ninety-two percent of the total load being suspended as shown in Figure 3.10a below. However, once this Rouse number is applied to Equation 3.3 and a sediment concentration profile is obtained as shown in Figure 3.10b below it is clear that the high degree of suspended sediment does not correspond to a uniform distribution of sediment since the sediment concentration at the mid-depth corresponds to only 0.06% of the near-bed sediment concentration. Since the sediment is therefore highly concentrated toward the channel bed, overbank flows will contain an insignificant amount of sediment relative to the amount transported. Also, Figure 3.10b demonstrates that the vertical sediment concentration profile does not vary significantly with respect to the discharge and therefore the sediment will remain highly concentrated toward the bed.

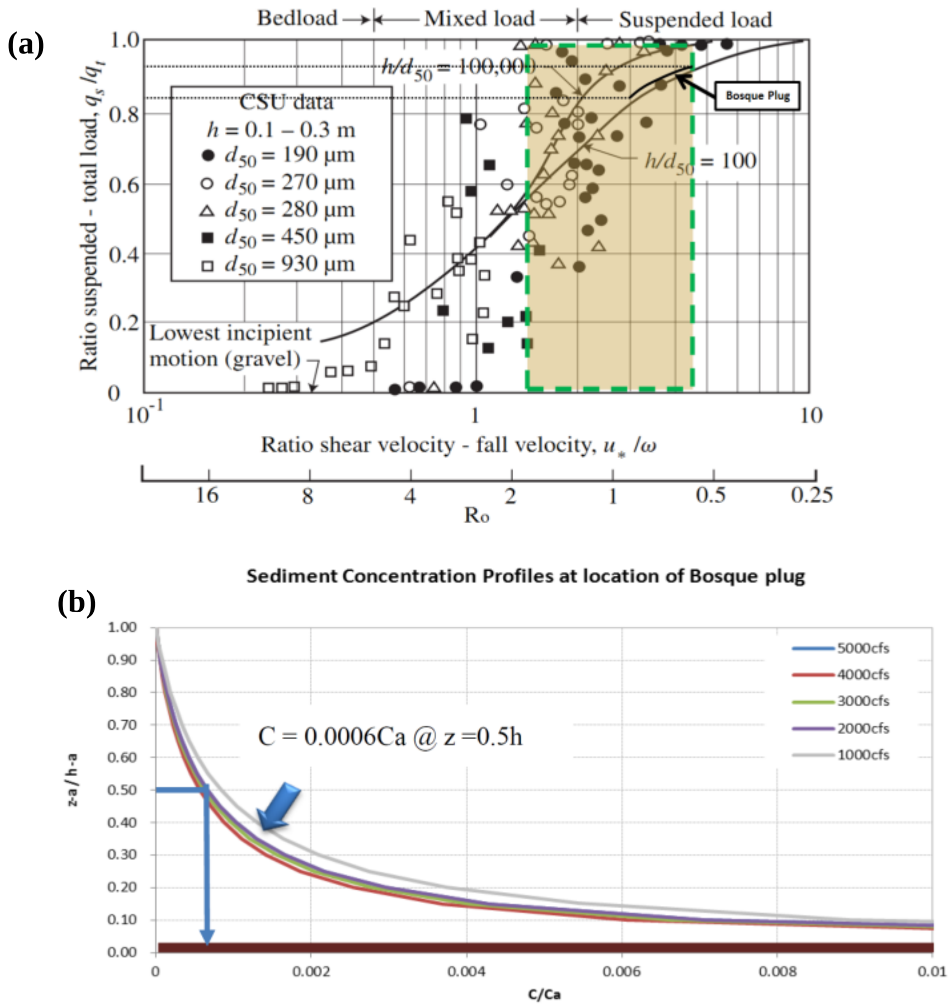



Figure 3.10: Bosque plug location a) Ratio of suspended sediment [Park and Julien 2012]; b) Vertical Sediment Concentration Profile [Park 2013]

At the Tiffany plug location, prior to flowing overbank the Rouse number varies between approximately 0.7 and 2.4 but after flowing overbank the Rouse number varies between approximately 0.7 and 0.8. Also, similarly to the Bosque plug location, the vast majority of the total load is suspended as shown in Figure 3.11a below. Despite this degree of suspended sediment, the sediment concentration at mid-depth is only 0.03% of the sediment concentration near the bed and the vertical sediment concentration profile is fairly independent of the discharge as shown in Figure 3.11b below.

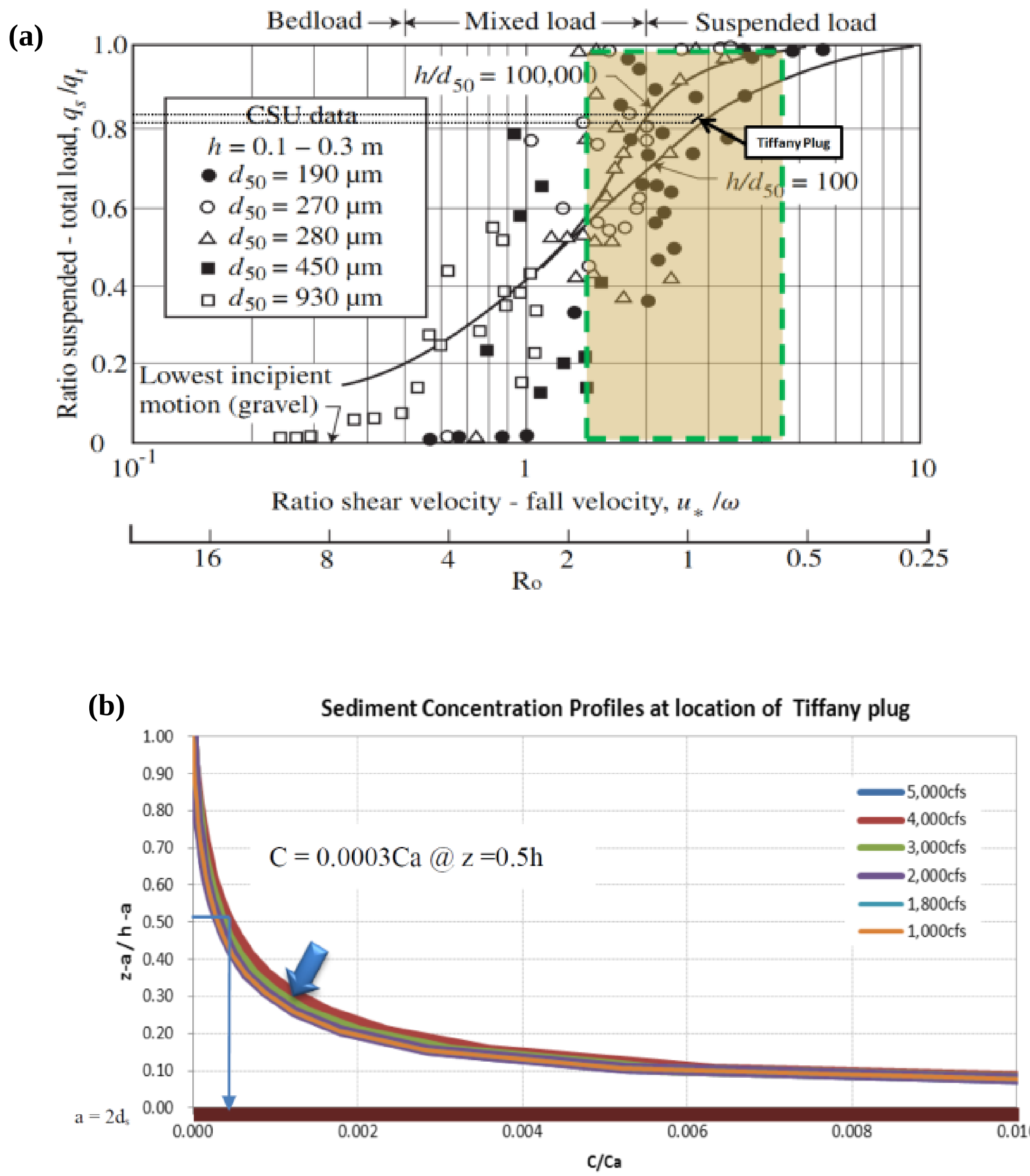



Figure 3.11: Tiffany plug location a) Ratio of Suspended Sediment [Park and Julien 2012]; b) Vertical Sediment Concentration Profile [Park 2013]

By comparing the vertical concentration profiles across various subreaches, it can be determined whether the Rouse number in the regions where the plugs formed was relatively high. It is apparent from Figure 3.12 below that the subreach where the Bosque plug formed (subreach 3) had the highest Rouse number. Overall however, the vertical sediment profiles does not vary significantly between subreaches and with the exception of subreach eight and ten, the Rouse number remains greater than that of the Tiffany plug location.

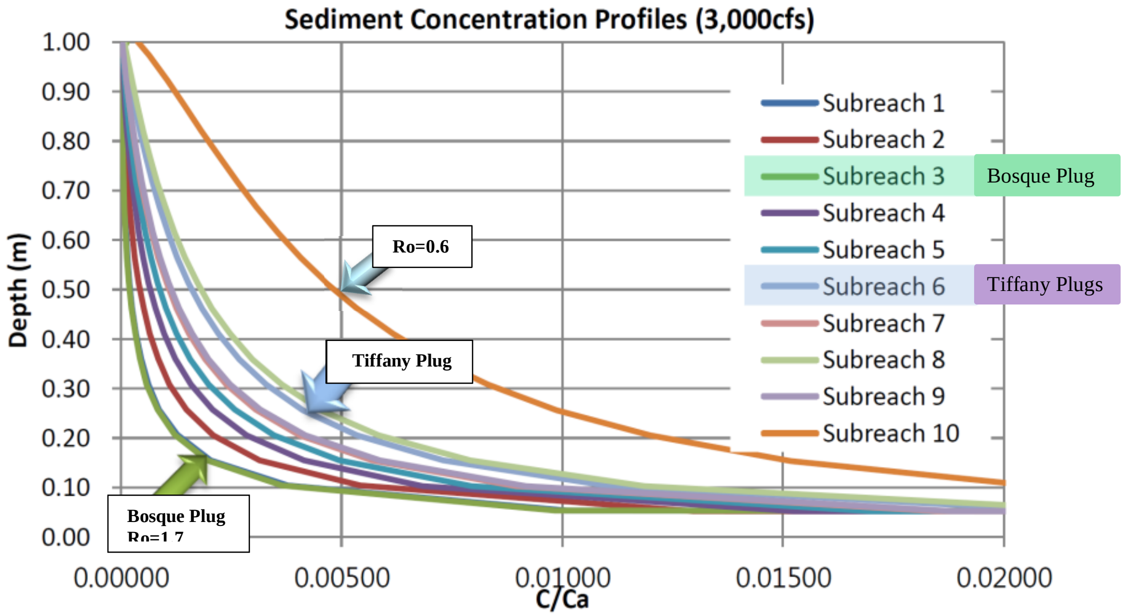



Figure 3.12: Vertical Sediment Concentration by Subreaches in the MRG [Park and Julien 2012]

The Rouse number for the subreaches in Figure 3.12 above varies between 0.6 and 1.7. This sediment distribution can significantly accelerate the rate of aggradation as shown in Figure 3.13 below where $\Delta z$ denotes the change in the bed elevation due to aggraduation. Figure 3.13 simulates sediment plug formation and demonstrates that with a uniform vertical sediment profile it would require ninety-two days for the main channel to completely aggrade while it would only require twenty days with a Rouse number of 1.4. The Rouse number may therefore serve as an accelerating factor to the plug formation and especially since spring runoff duration typically does not exceed the required ninety-two days.

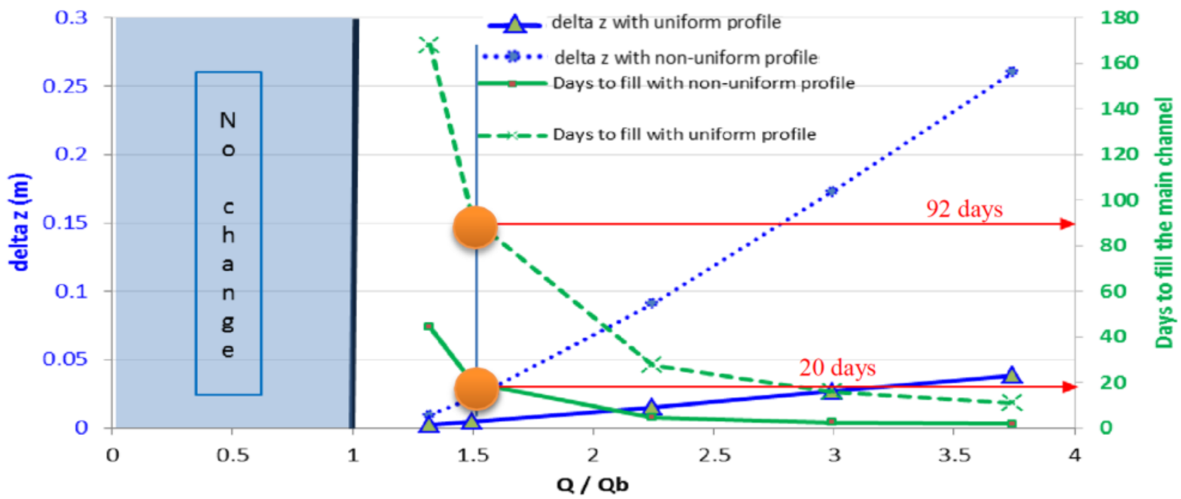



Figure 3.13: Aggradation due to overbank flows with uniform and non-uniform distributions [Park 2013]

## 3.3 Backwater Effects on Bed Aggradation

### 3.3.1 Backwater Effects from Reservoir

When the reservoir level rises, the upstream bed elevation increases. This aggradation can extend as far upstream as the San Antonio Bridge which is located approximately twenty-three miles upstream from the San Marcial gage as shown in Figure 1.2. By comparing the water surface elevation of the reservoir to the plug formation as shown in Figure 2.14a, it is apparent that the 1991 and 1995 Tiffany plugs formed while the reservoir was high due to a period of flooding and the 2005 Tiffany plug as well as the 2008 Bosque plug formed while the reservoir was low due to a drought period between 2000 and 2005.

It is apparent from Figure 2.14b that following the 2005 flooding period and the rise in the reservoir level that the location of the Tiffany plug experienced a significant spike in aggradation while many other locations downstream experienced degradation during this period. This flooding was likely a factor that led to this spike in aggradation during this time following a period of drought and more local factors such as bends and the railroad bridge were probably more influential than the reservoir level since this aggradation appears to have been localized.

By applying Julien's sediment transport capacity equation and Exner's equation, the time required to plug the channel by filling it to seven feet can be determined. This required time assumes that the sediment discharge is a function of the discharge since the discharge magnifies the influence of the backwater. For example, at the Tiffany plug location a discharge of five thousand cubic feet per second corresponds to an aggradation rate of 0.17 centimeters per days and it would therefore require 3.5 years to fill the channel and a discharge of 1,550 cubic feet per second corresponds to an aggradation rate of 0.06 centimeters per day which would require 3,864 days to fill the channel (Park 2013). Therefore, reservoir backwater would likely be associated with long-term plug formation rather than short-term plug formation.

### 3.3.2 Backwater Effects from a Bridge

The backwater from the San Marcial railroad bridge was also simulated and it was demonstrated that at a discharge of five thousand cubic feet per second the bridge would cause the water surface elevation to increase by one foot at Tiffany plug location. Model results show that at a discharge of five thousand cubic feet per second, this backwater would result in an upstream aggradation rate of five centimeters per day and erosion downstream as shown in Figure 3.14 below. This upstream aggradation would be the result of the loss in sediment transport capacity from the resulting backwater and the downstream erosion is a consequence of upstream channel sediment storage causing aggradation.

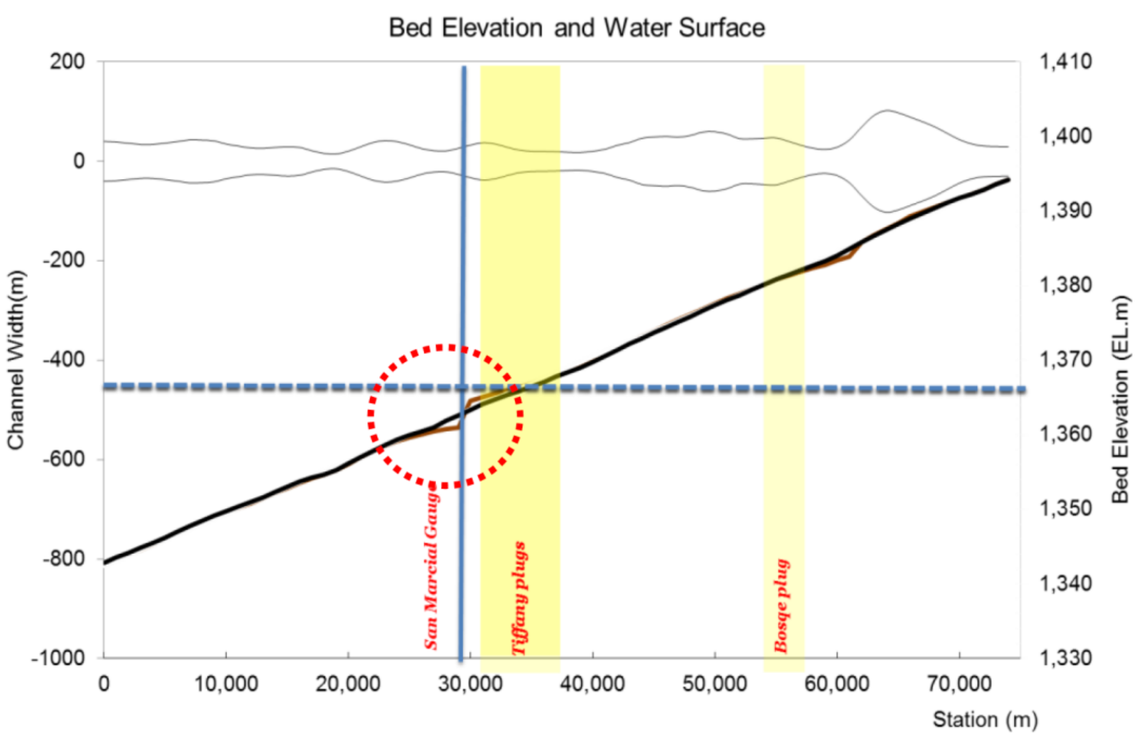



Figure 3.14: Bed Elevation Changes due to the San Marcial Railroad Bridge [Park 2013]

### 3.3.3 Backwater Effects from Sharp Bends

The Tiffany plugs and the Bosque plug occurred directly upstream from bends as shown in Figure 3.15a-b respectively below. The bend located downstream from the Tiffany plugs has a radius of curvature of approximately six thousand feet while the bends located downstream from the Bosque plug have a radius of curvature of approximately nine hundred and three hundred feet as also shown in Figures 3.15a-b respectively below. Sharper bends have a smaller radius of curvature and cause a greater reduction in the flow velocity. Therefore, since the radius of curvature of the bend downstream of the Tiffany plugs is very large, it is not expected that this bend significantly influenced the plug formation. However, since the radius of curvature of the bends downstream of the Bosque plug are quite small, at a discharge of five thousand cubic feet per second these bends can be shown to produce an aggradation rate of five centimeters per day which results in the channel filling to 2.85 feet in approximately seventeen days (Park 2013).

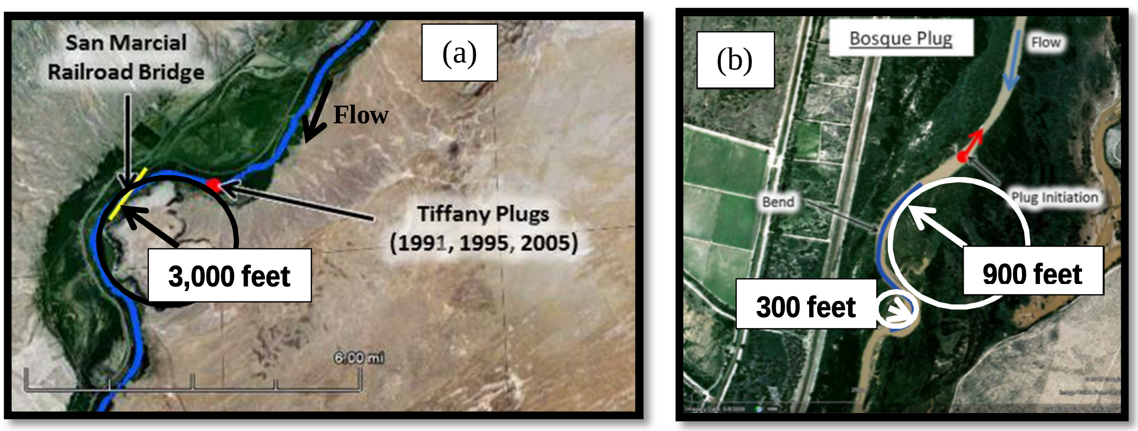



Figure 3.15: Radius of Curvature of the Downstream Bends a) Tiffany Plug Location [adapted from Shrimpton 2012]; b) Bosque Plug Location [adapted from Shrimpton 2012]

## Chapter 4 : Effects of the Duration and Magnitude of Floods

By comparing the discharge at the time of the sediment plugs to the years prior, the correlation between droughts and floods and the sediment plugs can be assessed. According to Figure 4.1a-d below, the 1991 and 2005 Tiffany plugs and the 2008 Bosque plug experienced discharges of high magnitude and long duration relative to the years prior to the flood and the 1995 Tiffany plug experienced a discharge with a relatively long duration relative to the previous years. Therefore, since overbank flows can only occur when the discharge exceeds the overbank discharge magnitude and the duration that these high flows occur correspond to the duration of overbank flows, Figure 4.1a-d supports the likelihood that the overbank flows was a significant factor to the formation of the sediment plugs. In addition, these higher flows would mobilize more sediment which would be required to form a plug. Besides simply high magnitude and long duration discharges contributing to greater overbank flows, plug formation may be promoted by previous years of low magnitude and duration flows. This may be a result of aggradation during low flows which decreases the channel's capacity to convey the subsequent higher flows.

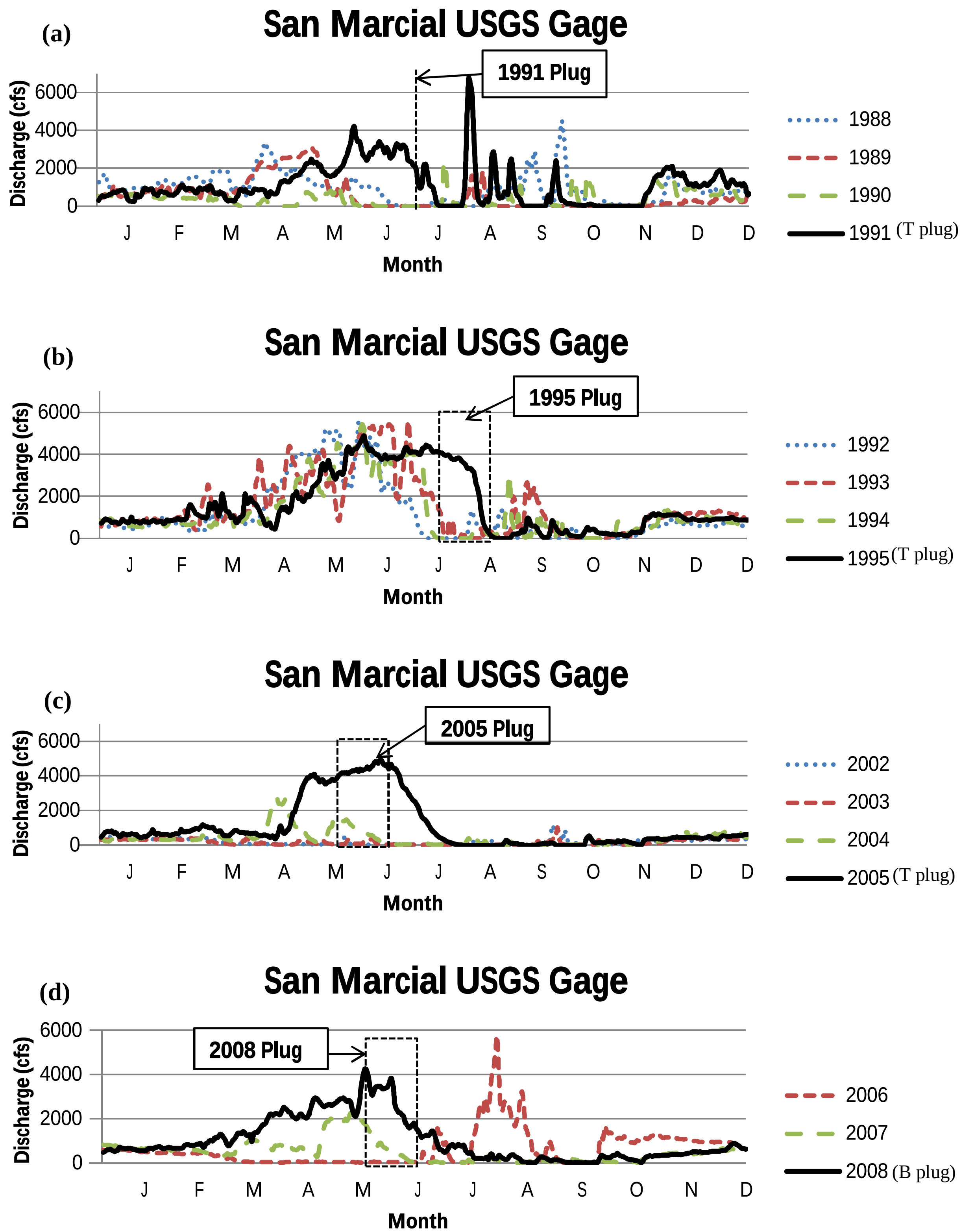



Figure 4.1: Annual Hydrographs during and prior to Plugs a) 1991 Tiffany Plug b) 1995 Tiffany Plug c) 2005 Tiffany Plug d) 2008 Bosque Plug [Rainwater 2013]

Each of the sediment plugs formed during the spring runoff period as opposed to the thunderstorm period. This is potentially due to a higher magnitude and duration of flow or a higher sediment concentration during the spring runoff period. To compare the suspended sediment concentration between the spring runoff and the thunderstorm period and between years when the plugs did and did not occur the average daily suspended sediment concentration can be plotted during the spring runoff period (beginning of May to the end of June) and the thunderstorm period (beginning of July to the end of August) at the San Marcial gage as shown in Figure 4.2 below. It does not appear from Figure 4.2 that it is due to an availability of readily erodible material since there is consistently a higher suspended sediment concentration at the San Marcial gage during the thunderstorm period than the spring runoff period. This suspended sediment concentration is potentially due to the erosion caused by overland flow during a rainstorm event. Besides the suspended sediment concentration being relatively high during the thunderstorm period, it appears to be relatively low during the plug years which suggests that a high suspended sediment concentration was not an important factor in the formation of the plugs.

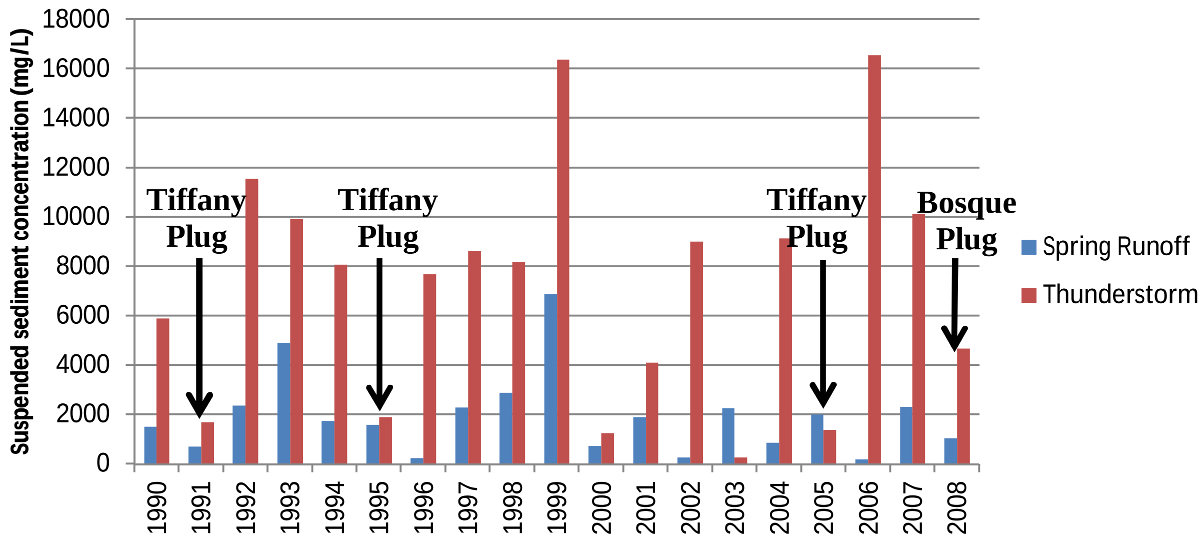


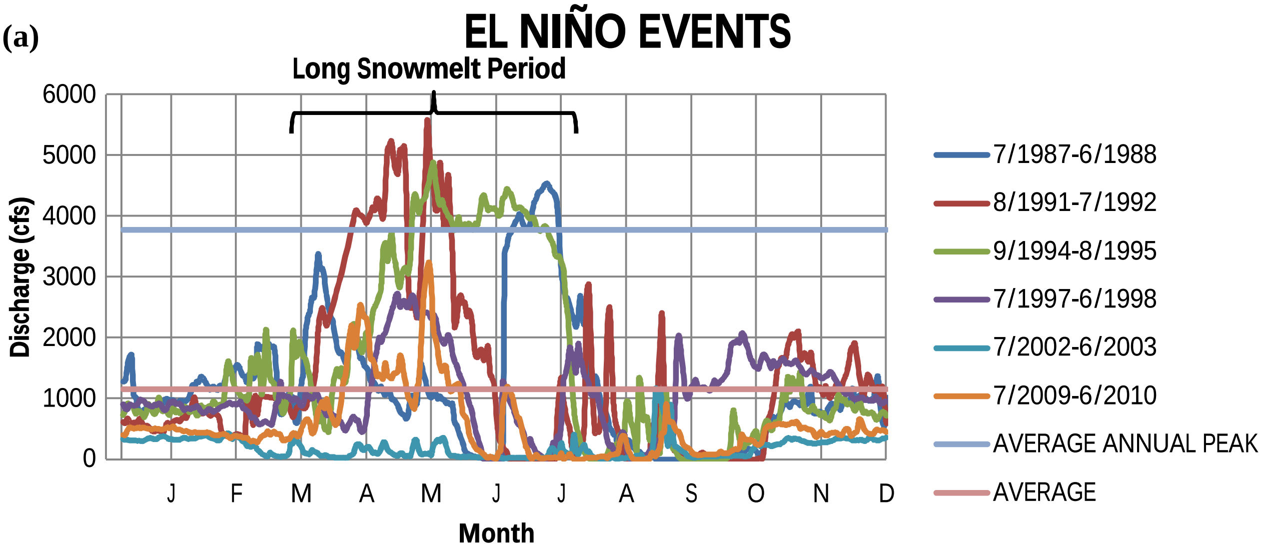

Figure 4.2: Average Suspended Sediment Concentration during the Spring Runoff Period (May-June) and the Thunderstorm Period (July-September) [Rainwater 2013]

Another difference between the spring runoff and the thunderstorm period that may explain the prevalence of sediment plugs during this period is the spring runoff flows typically have a larger magnitude and a longer duration than the thunderstorm peak and therefore the discharge corresponding to overbank flow is exceeded to a higher degree and for a longer period of time.

A spring runoff of a particularly high or low magnitude and duration may be predicted by assessing the impact of the weather patterns known as El Niño and La Niña. El Niño refers to a band of warm water in the Pacific Ocean that develops on the western coast of South America and La Niña refers to a condition of unusually cold water across the equatorial Eastern Central Pacific Ocean (NOAA, 2013). Episodes of El Niño or La Niña conditions can have weather effects in the United States and therefore may impact the spring runoff on the Middle Rio Grande. El Niño conditions generally exhibit greater snowfall across the southern Rockies while La Niña marks a drier period across the Midwestern United States (NWS, 2005). It would therefore be expected that the winter prior to a high spring runoff discharge would be marked by El Niño conditions. The presence of El Niño or La Niña conditions can be quantified by the Oceanic Niño Index (ONI) which measures the difference in the normal sea surface temperature in the east-central Pacific Ocean and therefore a high ONI represents El Niño conditions while a low ONI represents La Niña conditions (Britannica, 2013).

The relationship between the discharge and the ONI can be reviewed by comparing the discharge during El Niño events and La Niña events. If there is a correlation between the ONI and the discharge then it would be expected that the average annual peak discharge and the average discharge of the El Niño events would be greater than the La Niña events. As shown in Figure 4.3a-b below, the El Niño events experienced higher magnitude and duration snowmelt period as well as a greater average discharge and average annual peak but the La Niña period appears to be subjected to a longer and higher magnitude thunderstorm period.

(a)




(b)

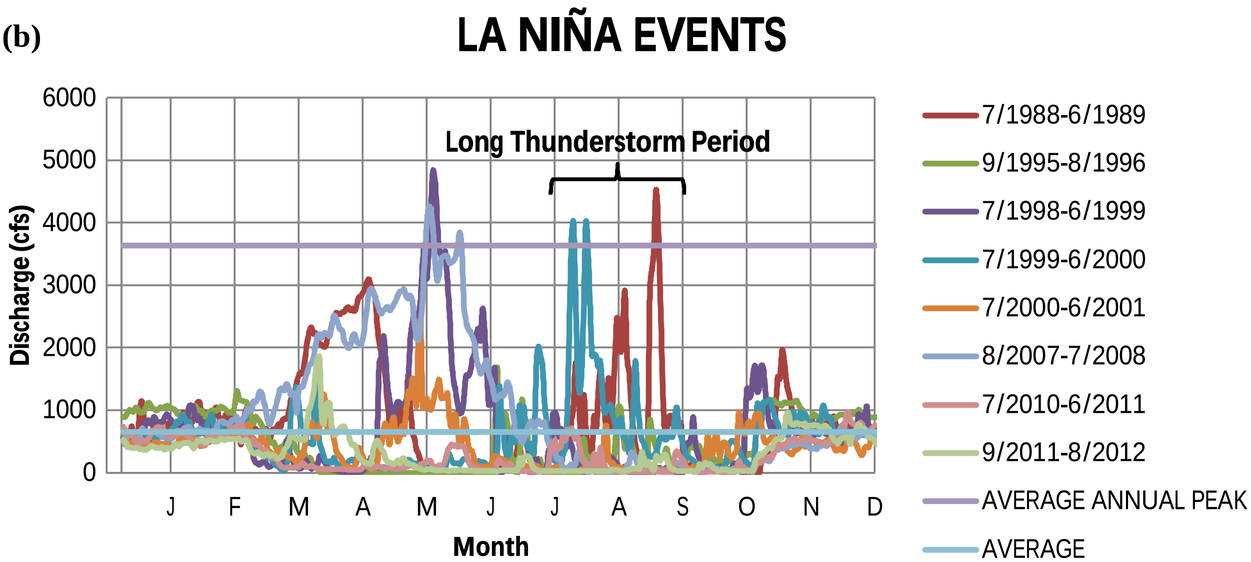



Figure 4.3: Annual Hydrographs a) El Niño Periods b) La Niña Periods [Rainwater 2013]

There is significant spatial and temporal variability in the overbank discharge. The Elephant Butte reach has an overbank discharge of approximately two thousand cubic feet per second while according to Figure 3.9a, in 1992 the Bosque reach had a minimum overbank discharge of approximately two thousand, four hundred cubic feet per second while in 2002 it had a minimum overbank discharge of approximately eight hundred cubic feet per second Therefore it would be noteworthy to assess the influence of the El Niño/La Niña phenomena on the various discharge thresholds. In particular the influence on the duration of magnitudes of discharges in this range can be assessed since it appears from Figure 4.1b that the duration of overbank flows is significant since the years leading up to the 1995 Tiffany plug experienced flooding of comparable magnitudes but shorter durations and thus plugs did not form during these periods. In Figure 4.5 the normal conditions represent periods in which the El Niño index does not exceed 0.5 or fall below -0.5 for more than two months during the year. Therefore, the influence of the El Niño and La Niña periods can be compared individually rather than simply comparing these periods against one another. It appears from Figure 4.5 that the La Niña periods are characterized by a duration of overbank flows that is generally much shorter than the normal conditions and the El Niño periods are characterized by having a longer period of discharge greater than two thousand cubic feet per second than the normal conditions but of comparable periods for discharges greater than three thousand, four thousand, or five thousand cubic feet per second. A possible explanation for the El Niño events having a similar or shorter duration of discharges that are greater than three thousand, four thousand, and five thousand cubic feet per second is due to the presence of dams upstream that prevent large peaks by releasing a greater quantity of water over a longer period of time. Therefore, although the El Niño events typically experience a greater overall discharge during the year, this period is not subjected to longer durations of high discharges. Overall it appears that it is less likely that a relatively long duration of overbank flow will occur during La Niña periods and it is more likely that a relatively long duration of overbank flow will occur during El Niño periods in regions with an overbank discharge of less than approximately three thousand cubic feet per second.

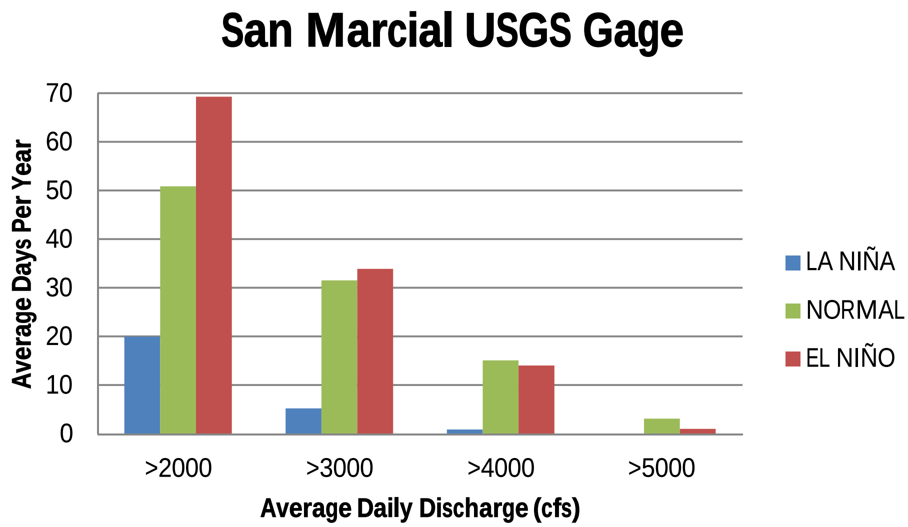



Figure 4.4: Average Days per Year with an Average Discharge beyond a Threshold Magnitude between 1986 and 2012 for La Niña, El Niño, and Normal Conditions [Rainwater 2013]

## Chapter 5 : Description of Plug Formation

The flow chart as shown in Figure 5.1 below illustrates the process that is believed to produce sediment plugs on the Middle Rio Grande. This process has been categorized into four stages to illustrate this process. The first stage is entitled the causing factors since these factors represent the initial circumstances that enable the resulting effects in stage two. The spring runoff duration and sequence however has been separated from the spring runoff magnitude because it is not expected that this factor contributed to the resulting effects. The spring runoff duration and sequence and the resulting effects are expected to be capable of forming a sediment plug, perching, and avulsion but it would require multiple seasons. However, when combined with several accelerating factors, the resulting effects are also expected to be capable of producing a sediment plug within a single season.

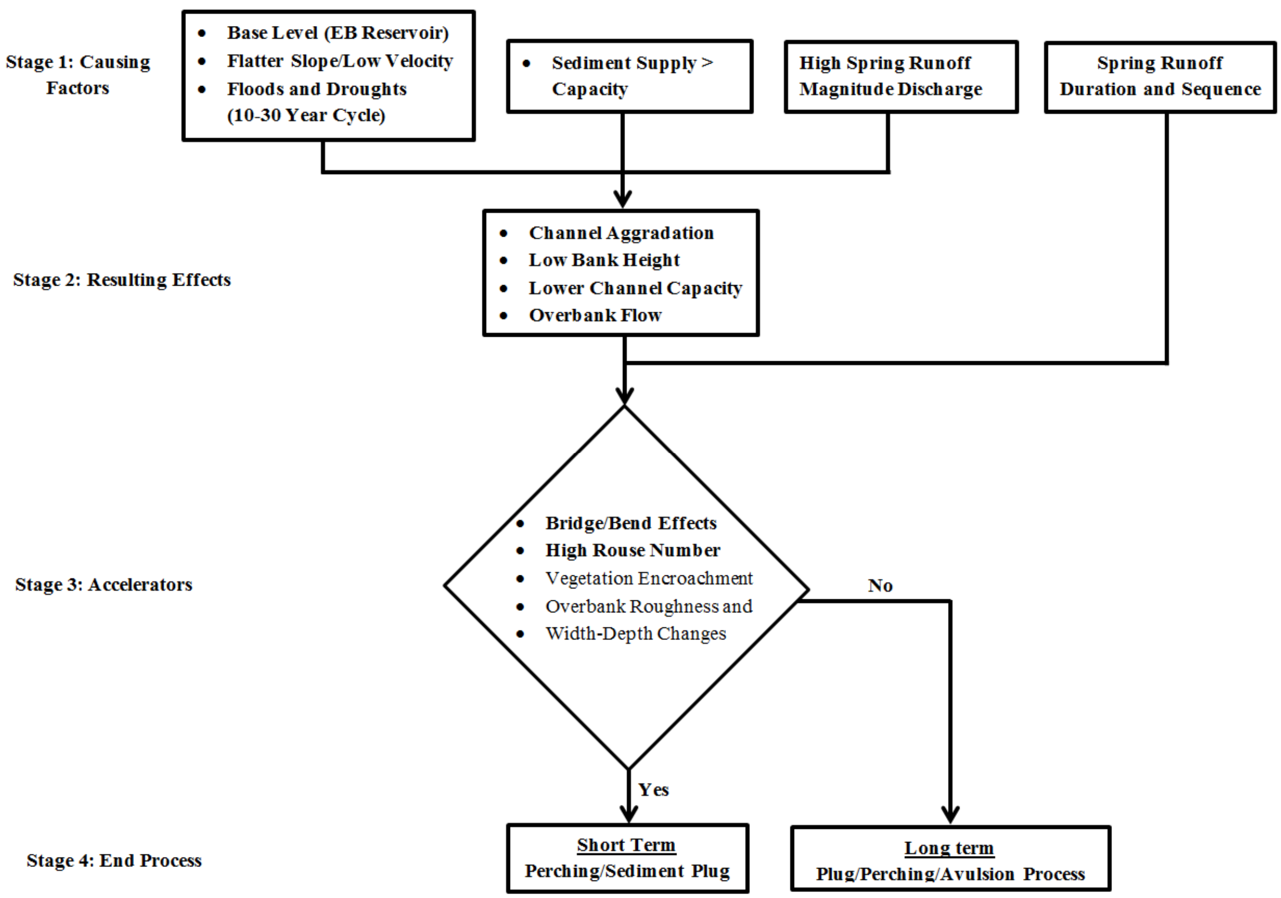



Figure 5.1: Flows Charts a) Sediment Plug Formation b) Avulsion Process

## 5.1 Stage One: Causing Factors

### 5.1.1 Base Level (Elephant Butte Reservoir)

Channel aggradation could be promoted by a high base level of the Elephant Butte Reservoir by lowering the sediment transport capacity. For a given discharge, the sediment transport capacity decreases as the flow area increases and the flow velocity decreases. Therefore, since backwater and therefore flow area increases as the reservoir storage increases, the sediment transport capacity is expected to decreases as the reservoir storage increases. In addition, since the backwater increases upstream as the reservoir storage increases, this aggradation is expected to progress further upstream as the reservoir storage increases.

### 5.1.2 Flatter Slope

A decline in the bed slope is able to lower the sediment transport capacity by decreasing the rate of energy gained from gravity. Therefore by decreasing the bed slope, the sediment transport capacity may reduce which may then result in a fining of the particle size and channel aggradation as illustrated by Lane's balance in Figure 5.2 below and shown by Equation 5.1 below. This reduction is slope may be a consequence of changes in sediment load, particle size, hydrology, or base level changes. The Cochiti dam would be expected to reduce the channel slope by reducing the sediment supply as shown in Figure 2.12 as well as reducing the peak flows as shown in Table 2.1. A reduction in the sediment supply direction downstream from the Cochiti dam would result in degradation since the transport capacity would exceed the sediment supply. This upstream degradation would serve to flatten the channel slope as shown in Figure 5.3 below. The reduction in peak flows could then reduce the sediment transport capacity and potentially lead to greater aggradation further downstream and thereby flatten the slope as shown in Figure 5.3 below. The backwater from the Elephant Butte reservoir would also encourage a region of deposition as described previously and thereby increasing the bed elevation upstream from the dam. Similarly to the reduction in peak flows, this aggradation would serve to reduce the channel slope as shown in Figure 5.3 below.

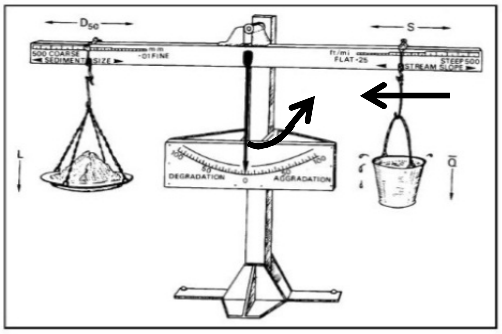


Figure 5.2: Lane's Balance Influence of Slope [Rainwater 2013]

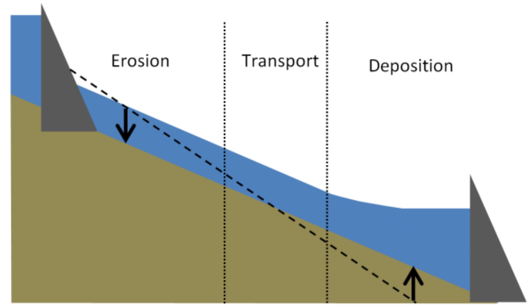



Figure 5.3: Zones of Erosion, Transport, and Deposition [Rainwater 2013]

$$Q_s \cdot D_{50} \,\alpha\, Q_w \cdot S \qquad \text{(Equation 5.1)}$$

### 5.1.3 Floods and Droughts

A process resulting from a cycle of droughts and floods may contribute to channel aggradation because of a low sediment transport capacity during drought periods and then due to overbank flow during flood periods. During drought periods the channel filling with sediment leads to reduced bank height. Then when the next peak flow occurs, more flow goes overbank than otherwise would if there was not a deposition of bed sediments during drought. Evidence of plug formation following periods of drought is shown in Figure 4.1a-d. A process resulting from a cycle of droughts and floods that contributes to low bank height, variations in the channel width, and channel perching is shown in Figure 5.4 below.

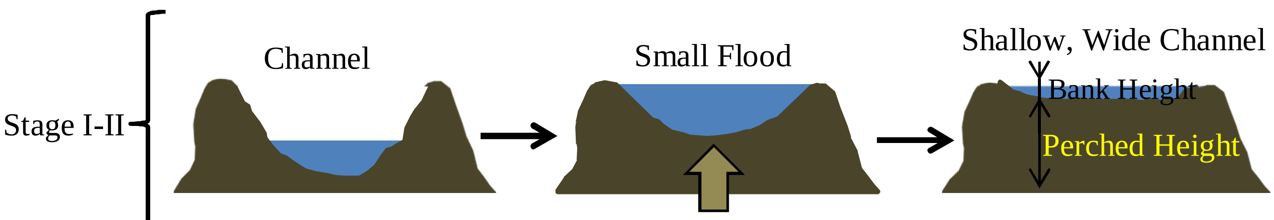



Figure 5.4: Flood and Drought Influence on Channel Geometry [Rainwater 2013]

### 5.1.4 High Sediment Supply and Low Transport Capacity

A high sediment concentration may be a consequence of overbank flow that contains a relatively small amount of sediment and therefore a disproportionately large amount of sediment remains in the channel. Also, a low transport capacity may be a result of a low flow velocity, geometric factors such as a relatively flat slope or a large width-depth ratio, or an increase in the channel roughness. Overbank flow may also contribute to a large width-depth ratio as illustrated in Figure 5.4 as well as a low flow velocity since the flow with the highest velocity is located near the surface of the channel and therefore overbank flow selectively removes the flow with the greatest transport capacity.

### 5.1.5 Spring Runoff Magnitude, Duration, and Sequence

The spring runoff discharge must exceed the overbank discharge in order for overbank flows to occur during this period. In addition to the spring runoff magnitude, a short-term sediment plug formation is dependent on the duration and sequence of the spring runoff. The duration is important because a sediment plug needs a large duration of high volume of sediment to produce aggradation and therefore overbank flows must continue for a significant period of time to produce a plug. Figure 4.1b demonstrates this trend since the years prior to the 1995 Tiffany plug were of a comparable magnitude but the duration was not sufficient for the sediment plug to form. The sequence is a significant factor for a short-term plug since it reduces the conveyance capacity over a short-term scale by increasing the roughness through vegetation encroachment.

## 5.2 Stage Two : Resulting Effects

### 5.2.1 Channel Aggradation

Channel aggradation can potentially result from several of the causing factors. Aggradation is a direct result from the sediment supply exceeding the sediment transport capacity which is promoted by such factors as high reservoir levels, flattening of the longitudinal slope, and periods of drought by reducing the sediment transport capacity.

### 5.2.2 Low Bank Height

The bank height could possibly be reduced by either eroding levees beside a channel or aggrading of the channel bed. According to Figure 2.5, at the Tiffany plug location the channel experienced aggradation which significantly reduced the bank height between 1992 and 2002 but between 2002 and 2009 the bank height increased as the channel degraded. Therefore, the reduction in bank height may have promoted the sediment plugs at the Tiffany plug location due to the causing factors that facilitated channel aggradation. At the Bosque plug location, between 2002 and 2005 the channel aggraded but the banks aggraded more than the channel which resulting in an increase in bank height and the bank height did not change significantly between 2005 and 2008 as shown in Figure 2.6. Therefore, the bank height was not likely a factor that led to plug formation.

### 5.2.3 Lower Channel Capacity

The channel conveyance capacity is a function of the channel roughness, flow area, and hydraulic radius as shown in Equation 3.1. The channel conveyance capacity is reduced as a result of channel aggradation on the channel bed to raise the bed elevation or on the channel banks to reduce the channel width without increasing the bank height. Also, assuming the channel width exceeds the channel depth, the hydraulic radius decreases as the wetted perimeter associated with a given flow area discharge increases. Therefore, as the channel bed aggrades, the width tends to increase and the hydraulic radius would decrease. A lower hydraulic radius would then indicate a lower conveyance capacity. In summary, the channel conveyance capacity tends to decrease due to the effects of the causing factors such as floods and droughts and those that lead to channel aggradation.

### 5.2.4 Overbank Flow

Overbank flows are promoted by a lower flow area, lower flow velocity, or higher discharge. A lower flow area may occur as a result of those factors discussed in the previous section. A lower flow velocity for a given discharge may result from a flatter slope or high channel roughness which may be a result of cycles of floods and droughts as discussed previously. A higher discharge may occur as a result of a high spring runoff magnitude and this discharge is sustained through a spring discharge with a long duration.

## 5.3 Stage Three : Accelerators

Simulations performed by (Park, 2013) demonstrate that it requires a timespan of many years for the channel to aggrade sufficiently to produce a sediment plug. However, there are several factors that may act as accelerators in order to produce rapid aggradation that is capable of producing a sediment plug within a single spring runoff season. These accelerating factors include: bridge/bend effects, a high Rouse number, overbank roughness, vegetation encroachment, and width-to-depth ratio changes.

### 5.3.1Bridge/Bend Effects

Bridges and bends have a tendency to create backwater as shown in Figure 5.5 below which can lead to greater aggradation and overbank flows as well as a higher Rouse number. Bridges can create backwater by confining the flow area and thereby raising the stage associated with a given discharge. Bends also have the ability to create backwater by reducing the flow energy and thereby the flow velocity which also raises the stage associated with a given discharge. This backwater accelerates aggradation by reducing the sediment transport capacity since flow with a higher velocity has a higher sediment transport capacity than a lower velocity flow for a given discharge. This backwater also accelerates overbank flows by increasing the stage associated with a given discharge. The Rouse number increases as a result of backwater by reducing the shear velocity as shown in Equation 3.2.

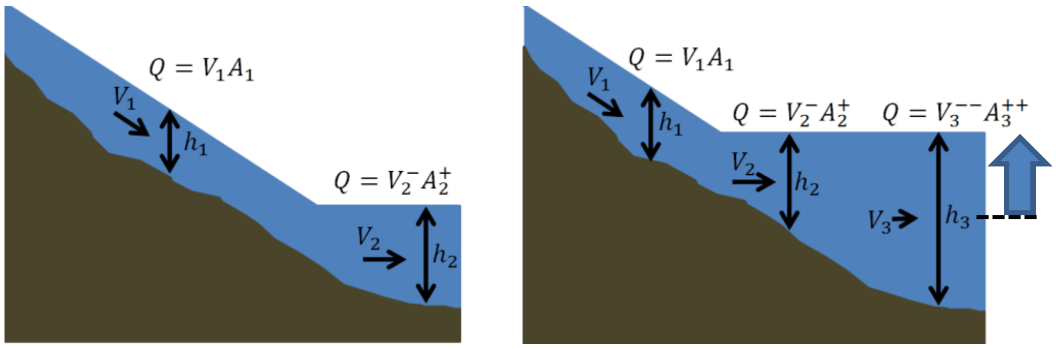



Figure 5.5: Influence of Local Backwater on Flow Velocity [Rainwater 2013]

### 5.3.2 High Rouse Number

A high Rouse number is associated with higher rates of aggradation especially when accompanied by overbank flows. Since the Rouse number is expressed by the ratio of the fall velocity and the shear velocity it is affected by the particle size, the hydraulic radius, and the energy gradient. The hydraulic radius is then, in turn, affected by the discharge, flow velocity, and channel geometry and assuming steady, uniform flow the energy gradient is equivalent to the channel's longitudinal gradient. The discharge and local factors however, do not appear to have significantly affected the Rouse number since the Rouse number remained relatively constant regardless of the subreach as shown in Figure 3.12 and regardless of the discharge at the Bosque or the Tiffany plug locations as shown in Figures 3.10b and 3.11b respectively.

A mechanism that could increase the sediment concentration in the main channel may derive from overbank flows and a low bank height as shown in Figure 5.6 a-c below. Figure 5.6a shows the channel with perched banks and sediment concentrated towards the bed. Then as illustrated in Figure 5.6b, when the channel experiences a high discharge whose flows overtop the banks, the flows lost represent the highest velocity and the lowest sediment concentration. The overall sediment concentration of the main channel therefore increases and it is hypothesized that the velocity profile decreases. Also, the velocity profile decreases due to aggradation which reduces the hydraulic radius as well as the upstream slope. This reduction in flow velocity would then decrease the shear velocity which increases the Rouse number. This combination of higher sediment concentration and lower flow velocity to maintain this sediment in suspension leads to channel aggradation as shown in Figure 5.6c below.

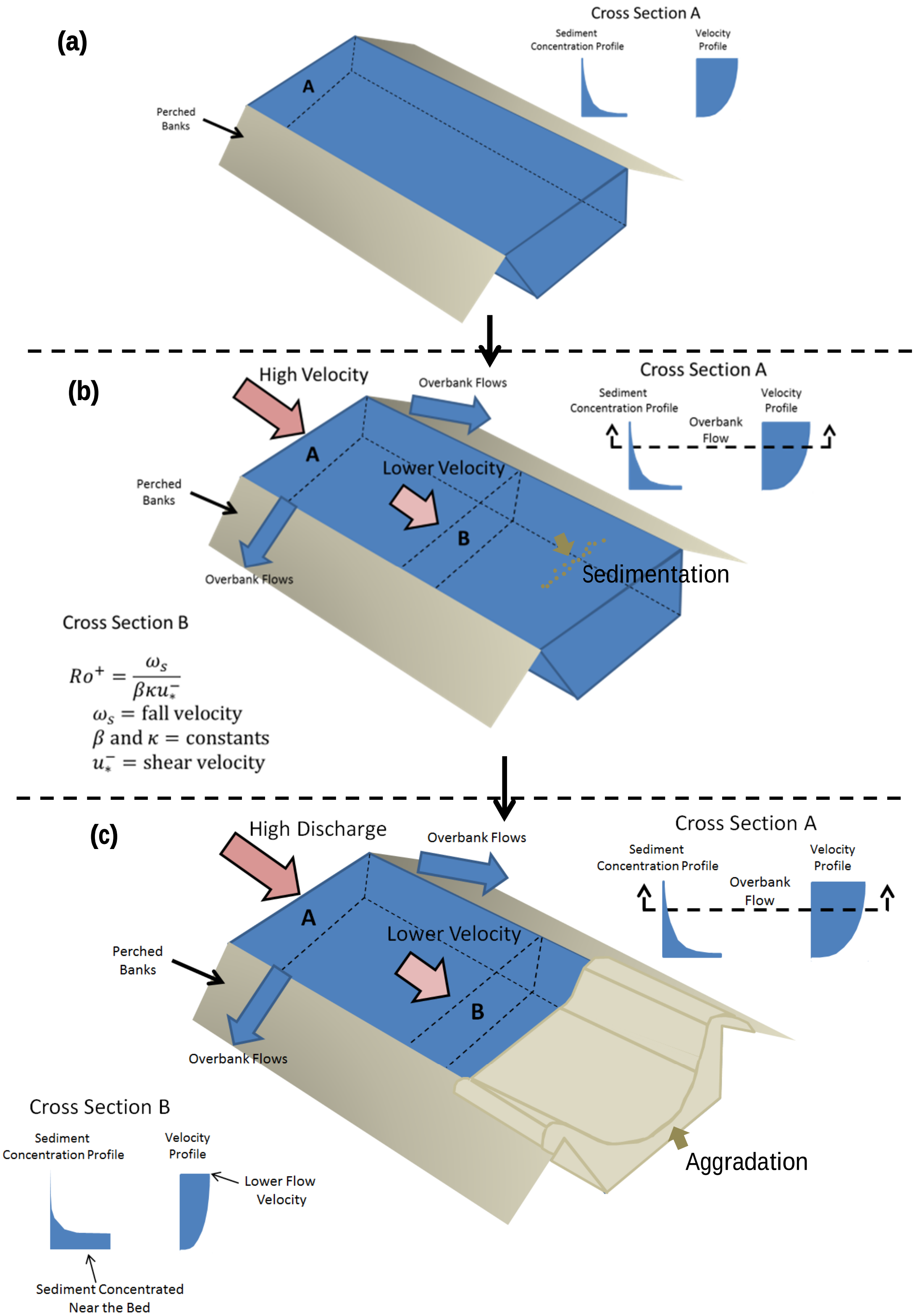



Figure 5.6: Channel Aggradation due to Overbank Flow [adapted from Rainwater 2013]

### 5.3.3 Vegetation Encroachment and Overbank Roughness

As the flow reaches overbank it can encounters additional roughness as shown in Figure 3.5. Vegetation encroachment is likely associated with cycles of droughts and floods since it is during periods of drought that vegetation can enter the floodplain as shown in Figure 2.10 and Figure 2.11. Following these periods of drought, the flow's stage will increase and this vegetation will provide additional roughness to the flow. Sources of overbank roughness may also derive from form roughness, coarser sediment, and vegetation and other debris. This roughness could then accelerate the formation of a sediment plug by promoting channel aggradation by reducing the sediment transport capacity, reducing the channel conveyance capacity, and lowering the overbank discharge magnitude by lowering the flow velocity.

### 5.3.4 Width-Depth Changes

Changes in the width-to-depth ratio derives from aggradation or degradation taking place either on the channel bed or the channel banks as well as changes in the stage of the flow. By assuming constant roughness along the channel bed and banks, a larger width-to-depth ratio generally has greater roughness than a narrower width due to a lower hydraulic radius. Based on Figure 2.5 and Figure 2.6 it appears that the width-to-depth ratio was increasing leading up to the 1991 and 1995 Tiffany plugs since the depth is decreasing but this ratio appears to be decreasing leading up to the 2005 Tiffany plug as the depth increases and the 2008 Bosque plug as the width decreases. Since the width-to-depth ratio was increasing leading up to the 1991 and 1995 Tiffany plugs the channel roughness was likely increasing during this period. This roughness may have accelerated plug formation by reducing the sediment transport capacity which would promote channel aggradation and reduce the flow velocity which would lower the channel conveyance capacity and increase the likelihood of overbank flows. The declining width leading up to the Bosque plug however may indicate that the decreasing flow area have been a more significant factor than the roughness. Spatial variations in the width and depth would also lower the sediment transport capacity by dissipating energy as the channel contracts and expands.

## 5.4 Stage Four: End Process

### 5.4.1 Avulsion Process

Since the avulsion process is based on a longer-term development, the accelerating factors are usually present for an avulsion to occur. The factors associated with stage one and stage two are sufficient to produce perching and a sediment plug.

Through overbank flow, sediment settles on the banks of the channel forming levees as shown in Figure 5.7a-d below as well as perching by settling on the channel bed as shown in Figure 5.8a-c below. This levee formation and perching are then likely to have been significant factors that facilitated sediment plug formation. An avulsion refers to the process of flows from a river leaving the previous channel and forming a new channel. After the formation of a sediment plug, the water from the channel is forced to flow overbank. If the channel is perched than this overbank flow will not return since the overbank region is lower than the channel. Then after sufficient water has flowed overbank, it can begin to form a new channel and thereby completing this process of avulsion as shown in Figures 5.8 a-d and 5.9a-c below.

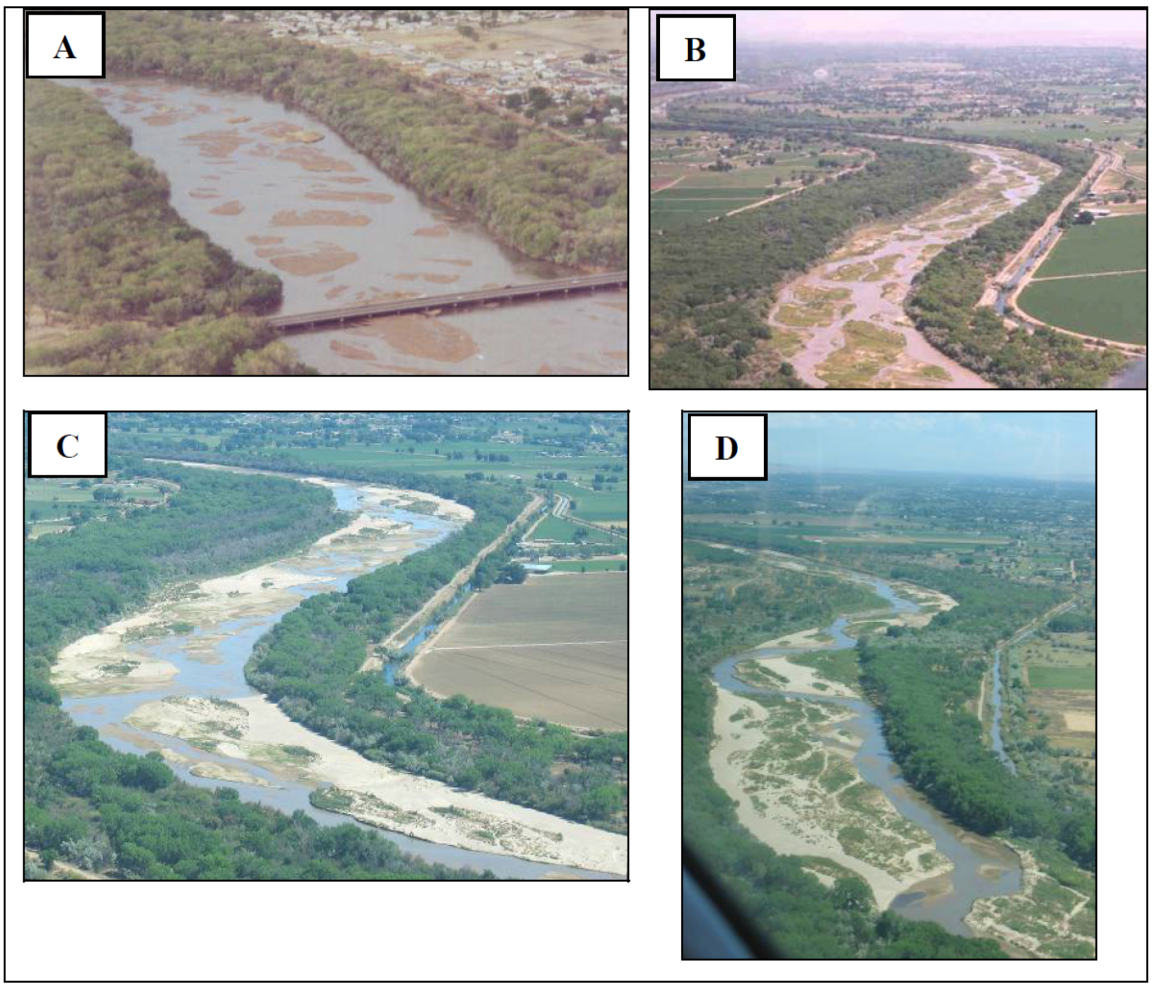



Figure 5.7: Formation of Levees on the Middle Rio Grande near Belen, New Mexico where A) 2000, B) 2002, C) 2005, and D) 2006 [Massong, T., Makar, P., and Bauer, T. 2010]

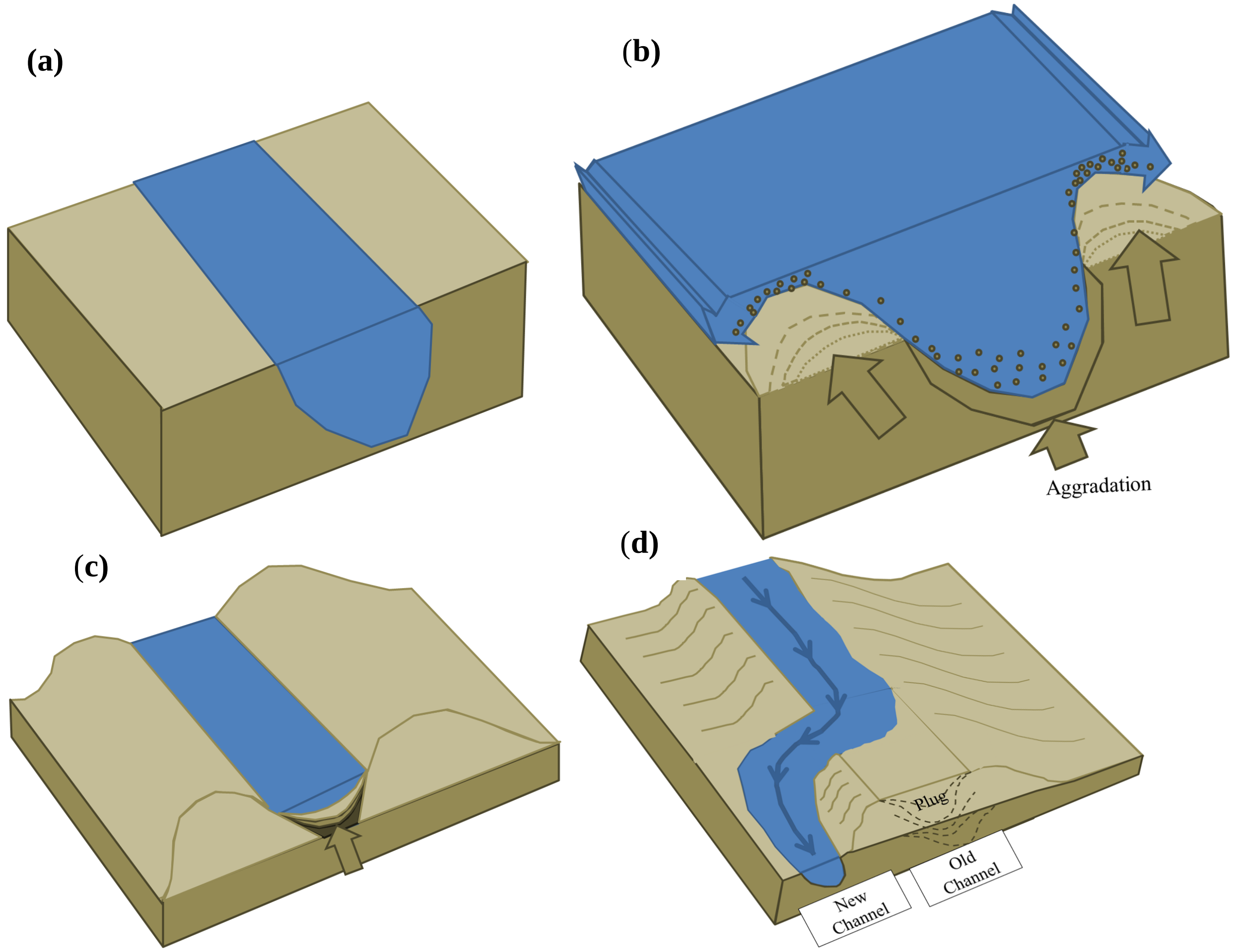



Figure 5.8: Formation of Natural Levees, Perching, and Avulsion [Rainwater 2013]

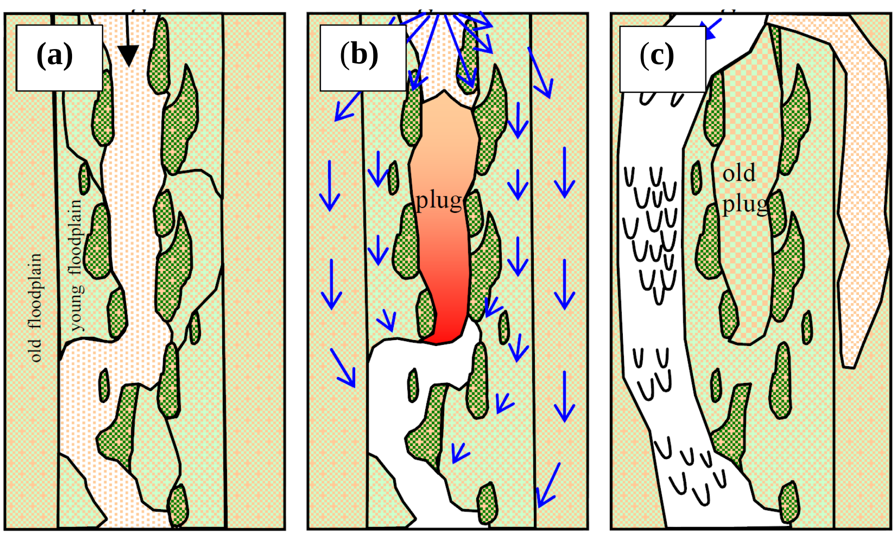



Figure 5.9: Formation of a plug and avulsion upstream from a sharp bend [Massong, T., Makar, P., and Bauer, T. 2010]

### 5.4.2 Sediment Plug Formation

Prior to the formation of a short-term plug there are several accelerating factors which enables the plugs to form during a single flood season. The backwater effects from bends would have significantly accelerated the Bosque plug while the backwater effects from the San Marcial bridge would have significantly accelerated the Tiffany plugs. Also, a high Rouse number accelerates the sediment plug formation by decreasing the amount of sediment relatively to the water that is lost overbank and thereby increasing the amount of sediment near the bed which cannot be transported by the decreased main channel flow volume. This accelerates the process of more flow going overbank which incrementally increased sediment near the bed. This process progresses until a plug is formed. Other accelerating factors that increase roughness include vegetation encroachment and width-depth ratio changes.

Vegetation is able to enter the floodplain during drought periods when the flow stage has receded as shown in Figure 2.12a-c above. Then during flood periods when the water's stage has increased, this vegetation is able to significantly increase the channel roughness as shown in Figure 3.5.

Width-depth ratio changes can also accelerate sediment plug formation since the hydraulic radius decreases as the width-depth ratio increases. Assuming a greater flow width than flow depth, a lower hydraulic radius is associated with a higher wetted perimeter for a given flow area. Therefore, assuming constant channel roughness along the channel banks and bed and since a larger wetted perimeter is associated with higher channel roughness, it can be inferred that as the channel width increases, the channel roughness can be expected to increase and the sediment transport capacity can be expected to decreases.

With the exception of a high Rouse number, the accelerating factors increase the stage associated with a given discharge. This increases the likelihood of overbank flows which when associated with a high Rouse number accelerates aggradation by enabling a much greater proportion of water to be lost overbank relatively to the concentration of sediment in the channel. These factors then allow the plug to form over the course of a single season when present.

## Chapter 6 : Summary and Conclusions

The following chapter summarizes the conclusions from this analysis and is taken from “Mechanisms of Sediment Plug Formation in the Middle Rio Grande, New Mexico” by Dr. Kiyoung Park.

◦***Geometric factors : channel width and roughness***

Between 1962 and 2002 the average channel width narrowed significantly and especially at the Bosque plug region which continued to narrow until the plug formed at this location in 2008. The width at the Tiffany plug location however, narrowed less than the average change of the channel. This reduction in width resulted in a higher sediment transport capacity as well as a lower threshold for overbank flow.

The average channel roughness increased during this period between 1962 and 2002. Between 1992 and 2002 this rise was particularly apparent at the Bosque plug location. This rise in roughness caused a dramatic decline in sediment transport that outweighed the increase due to the channel narrowing. Therefore, the net effect of channel narrowing and greater roughness was channel aggradation and a lower threshold for overbank flows.

◦***Sedimentation factors: overbank flows and sediment concentration profiles***

The cross section of the Bosque plug is wide and lies within a wide floodplain while the cross section at the Tiffany plug location is narrow and perched and lies within an even wider floodplain. These conditions promote significant losses of flow especially at the Tiffany plug location. In addition, between 1992 and 2002 the perching ratio increased and the bank height lowered which supported greater overbank flows which increased water losses.

When the sediment concentration profile focuses sediment toward the channel bed it can significantly accelerate aggradation as a result of overbank flows. Between 1992 and 2002 it is believed that this sediment became increasingly concentrated toward the channel bed as the particle size coarsened which increased the fall velocity and the as the width-to-depth ratio increased which decreased the shear velocity as the hydraulic radius decreased.

◦***Analysis of the most important factors***

Backwater effect from the reservoir has influenced on the upstream channel elevation on a long-term basis, providing the basic condition with sediment plug formation. Under the influence of low reservoir stage, occurrence of a sediment plug is less likely. Channel narrowing and higher roughness promote overbank flows and induce loss of water to overbank areas, thus these two factors can be categorized as temporal factors. These overbank flows, when coupled with a sediment profile that is concentrated toward the channel bed, is capable of forming a sediment plug within weeks which supports the overbanks flows and sediment concentration profile being the most significant factors.

Local backwater effects from the railroad bridge and sharp bends justify the location of the plugs upstream from these obstructions. Therefore the backwater from these features can be classified as local triggering factors.

Perching, overbank flows, and the sediment concentration profile are likely the most significant factors related to the sediment plug formation. Local backwater effects from the bridges and sharp bends were also assessed to be important factors. However, without the temporal changes of channel widths and roughness, the occurrence probability of a sediment plug will decrease significantly.

These factors may also be classified according to their importance at each plug location. The Tiffany plugs were likely to have been more affected by backwater effect from the reservoir and railroad bridge since these plugs were closer to these obstructions. In contrast, the Bosque plug was likely more influenced by the channel narrowing and capacity, roughness, and sharp bends. The sediment concentration profile and overbank flows however, were likely to have been significant at both plug locations.

Water temperature, coarsening of bed materials, and tributary sediment inflows also can be categorized as possible factors, but there was no significant proof from given data and documentation.

Therefore, a sediment plug may be expected when the reservoir stage is high, where backwater effect from bridge or sharp bends exist, and especially if channel narrowing and increases in roughness proceed.

| Possible causing factors | | Significance | Location (Tiffany:T, Bosque:B) | Duration of Influence | Level of condition (Conditional: C, Acceleratior : A) | Remarks (Aggradation rate[1]) *(numerical simulation)* |
|---|---|---|---|---|---|---|
| Geometric factors | Channel widths | Medium | B | Long | C | Less than 0.01cm/day |
| | Roughness | Medium | B | Long | C | Less than 0.1cm/day |
| Sedimentation factors | Perching/overbank flows | High | T, B | Short | A | 0.6cm/day *(0.3cm/day)* |
| | Concentration profiles | High | T, B | Short | A | 2cm/day *(1.5cm/day)* |
| Backwater effect factors | reservoir | Medium | T, B | Long | C | 0.06cm/day *(0.06cm/day)* |
| | bridge | High | T | Short | C, A | 5cm/day *(3cm/day)* |
| | sharp bends | High | B | Short | C, A | 4cm/day *(1.3cm/day)* |
| Other factors | Water temperature | Low | T, B | Long | A | - |
| | Particle coarsening | Low | T, B | Long | A | |
| | Tributary inflows | Low | T, B | Short | A | |

* flow discharge : 44m$^3$/s for backwater from reservoir, 141 m$^3$/s for backwater from bridge and sharp bends, 57 m$^3$/s for overbank flows /concentration profiles, 49 ~ 137 m$^3$/s for numerical simulation

Table 6.1 : Significance of causing factors [Park 2013]

The prevalence of the sediment plugs during spring runoff periods suggests that factors associated with this phase were critical to the formation of the plugs. Based on Figure 4.2 it appears unlikely that the spring runoff is associated with a high sediment concentration and therefore this was not likely to have been a critical factor to the sediment plug formation. The spring runoff period in this region however is generally associated with longer duration of high magnitude flows and higher magnitude flows that any other point of the year. Therefore it is likely that overbank flows were a critical factor to the formation of a plug. The duration of these overbank flows is likely to be shorter during the La Niña weather phenomena and in regions with an overbank flow of less than approximately three thousand cubic feet per second the duration of overbank flows is likely to be longer during the El Niño weather phenomena.

## 6.1 Suggestion for Future Research

A few suggestions for future research are proposed in this section.

1) The flow conditions at the San Marcial Bridge should be examined during flood conditions. Does the bridge opening cause backwater? What discharge will cause pressure flow? What is the effect of the pier angle and pier scour on the conveyance capacity of the bridge? These

are important unsolved questions that may have an impact on plug formation in the Tiffany area.

2) As a maintenance practice, the areas where sharp bends may develop should be located during the aerial surveys conducted by Reclamation. These sharp bends may be trigger plugs to form at unwanted locations, e.g. the Bosque del Apache.
3) Perhaps one of the most important aspects that would require further research is the overall effect of Elephant Butte Reservoir on the upstream backwater extent and delta development. As shown on Figure 2-14, the river response to reservoir changes depends on the location upstream of EB Reservoir. The lower reaches near the reservoir respond rapidly to reservoir elevation changes. However, the riverbed elevation changes observed farther upstream are observed to be opposite to the reservoir elevation changes. For instance, the river bed near San Marcial did continue to aggrade long after the reservoir reached very low levels, and this could be an important factor in the timing of sediment plugs. This is a complex problem and should be the topic for a PhD dissertation study at CSU.
4) Physical modeling is also recommendable to fine tune and quantify our understanding of plug formation. Focus could be on the mechanics of backwater and sedimentation upstream of bridge contractions. To subject the understanding we gained from field conditions to a thorough laboratory test could bring the question of plug formation to a full closure. Some of the interesting aspects to be investigated in the lab would be the effect of bridge crossings, cross section openings, pier skewness, effects of sharp bends and vegetation on the floodplain. Finally the effect of levee height may also be explores for better understanding of sediment plugs in relation to avulsions.
5) Since historic sediment plugs only occurred during snowmelt floods, further study to understand why a sediment plug did not occur during the monsoon season may prove to be useful. The influence of tributary sediment inflow and possible arroyo plug formation caused by large sediment loads in steep tributaries depositing in milder valley areas could be investigated.
6) Detailed numerical models (2-D or 3-D) numerical modeling may be helpful for detailed studies of levee flows. A better understanding of vegetation roughness may also be useful in the future.

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