REVIEW OF SEDIMENT PLUG FACTORS
MIDDLE RIO GRANDE, NM

PLAN B TECHNICAL REPORT

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PREPARED BY:

JONATHAN S. RAINWATER

COLORADO STATE UNIVERSITY

ENGINEERING RESEARCH CENTER

DEPARTMENT OF CIVIL ENGINEERING

FORT COLLINS, COLORADO 80523

Acknowledgements

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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 River in 1991, 1995, and 2005 in the Elephant Butte reach and in 2008 in the Bosque reach. 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.

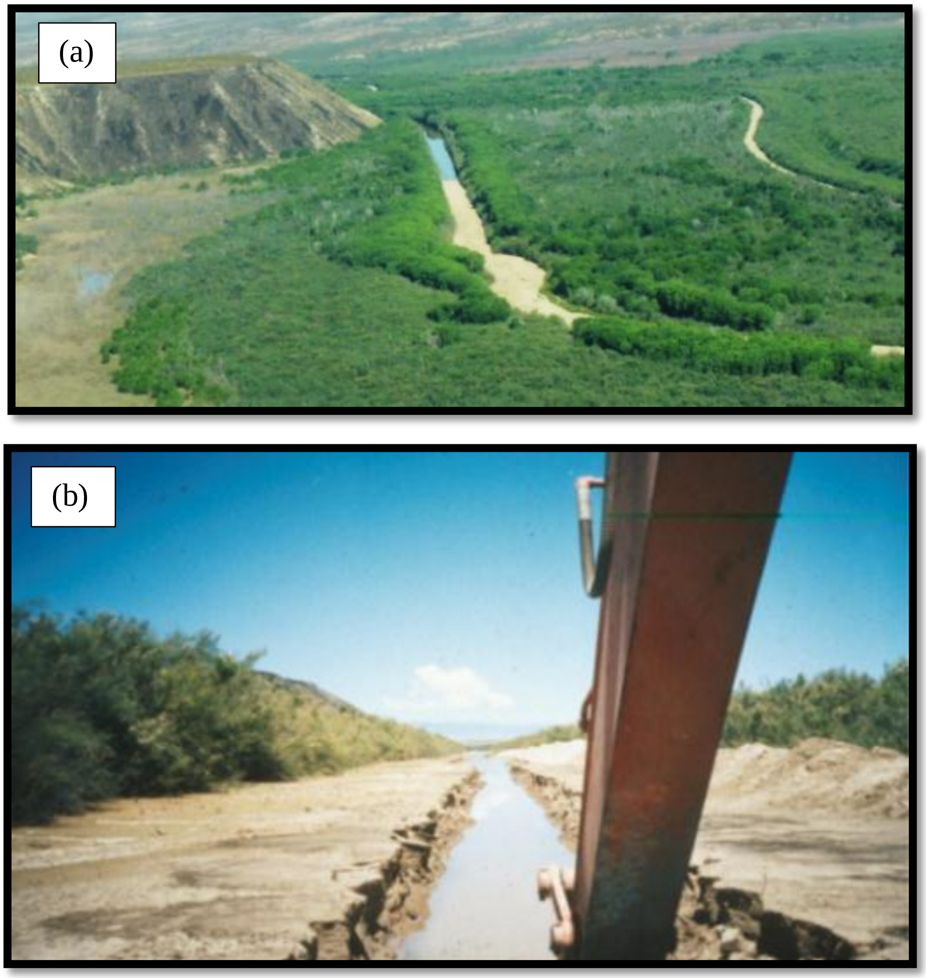


Figure 1.1: a) Photo of 2005 Tiffany plug [Owen et al. 2012]; b) Photo of the dredging of a pilot channel through the 1991 Tiffany plug [Boroughs 2005]

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 involve inspecting the relevance of the aforementioned factors to the sediment plugs and investigating the processes associated with them. Since the Bosque plug and the Tiffany plugs formed in separate locations, we will assess the relevance of these factors in each location individually since the mechanisms responsible may differ.

Chapter 2 : Site Description

The Rio Grande River 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 River refers to a one hundred eighty mile long reach of the Rio Grande River 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.

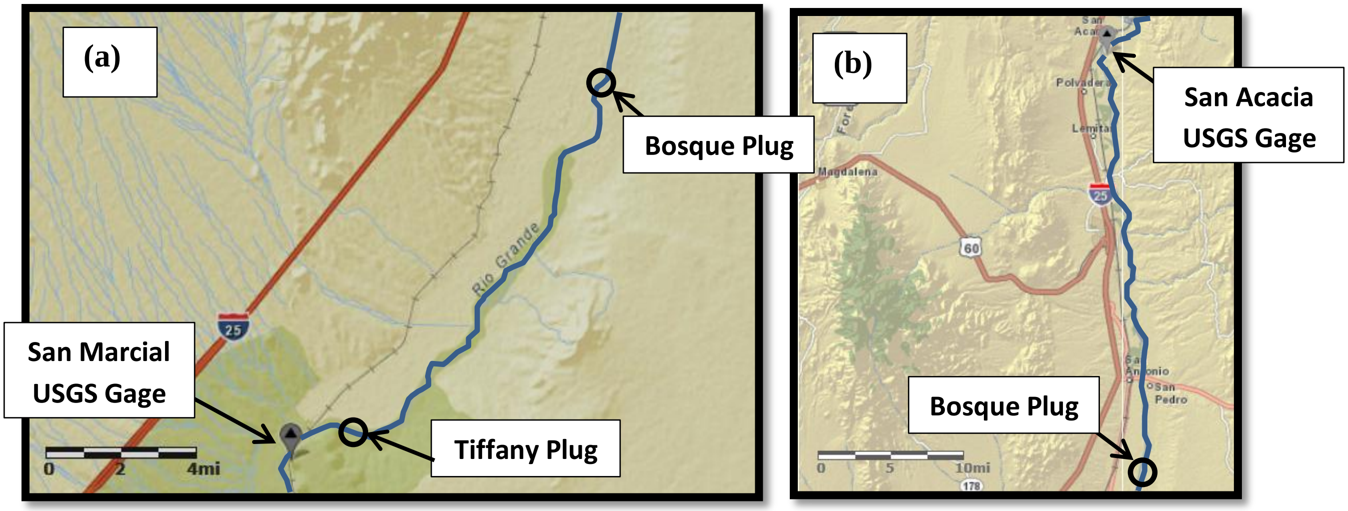


Figure 2.2: a) San Marcial Gage relative to Plug Locations; b) San Acacia Gage relative to Bosque plug [USGS]

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 River (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.

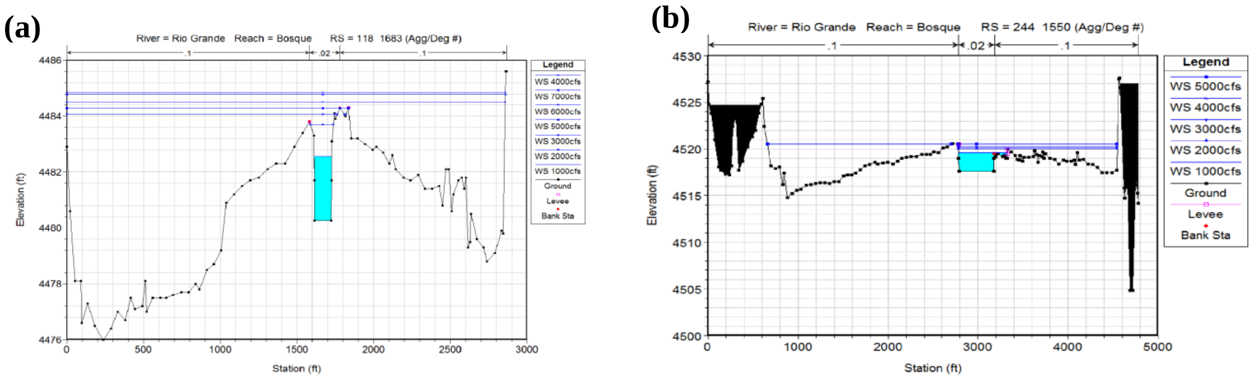


Figure 2.3: Cross sections a) Tiffany plug location [Park 2013]; b) Bosque plug location [Park 2013]

2.2.2 Channel Slope

The channel slope has varied considerably and has decreased overall by degrading upstream while aggrading downstream as shown in Figure 2.4 below. This reduction in the channel slope would result in a decline in the sediment transport capacity.

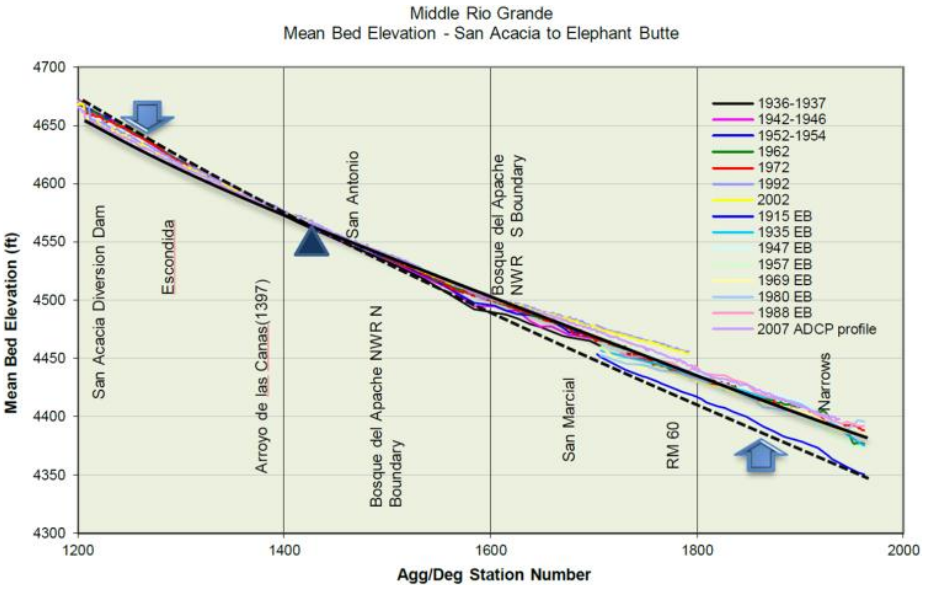


Figure 2.4: MRG Longitudinal Profile [Park 2013]

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.

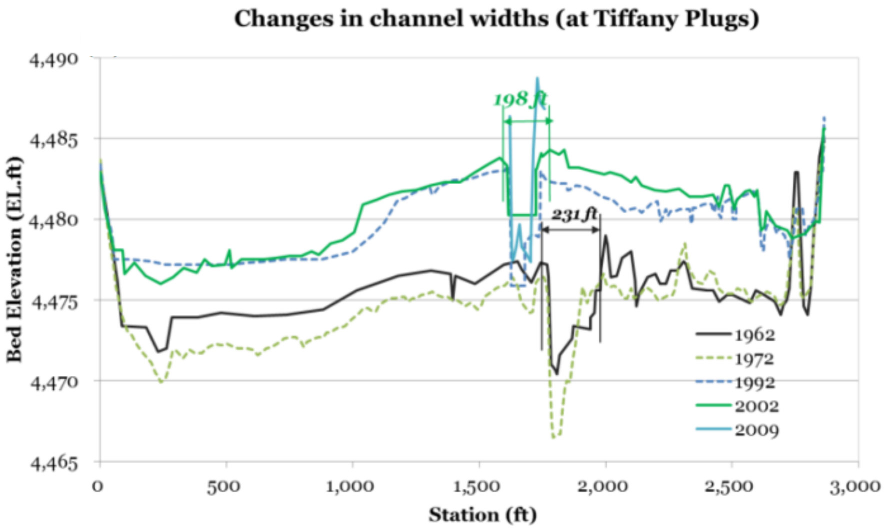


Figure 2.5: Changes in Channel Width at Tiffany Plug Location [Park 2013]

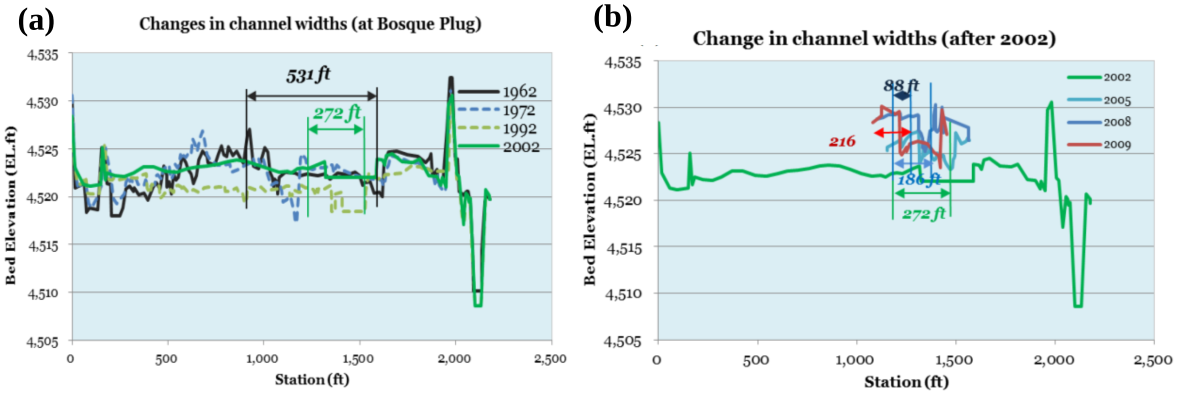


Figure 2.6: Changes in Channel Width at Bosque Plug Location a) 1962-2002 [Park 2013]; b) 2002-2009 [Park 2013]

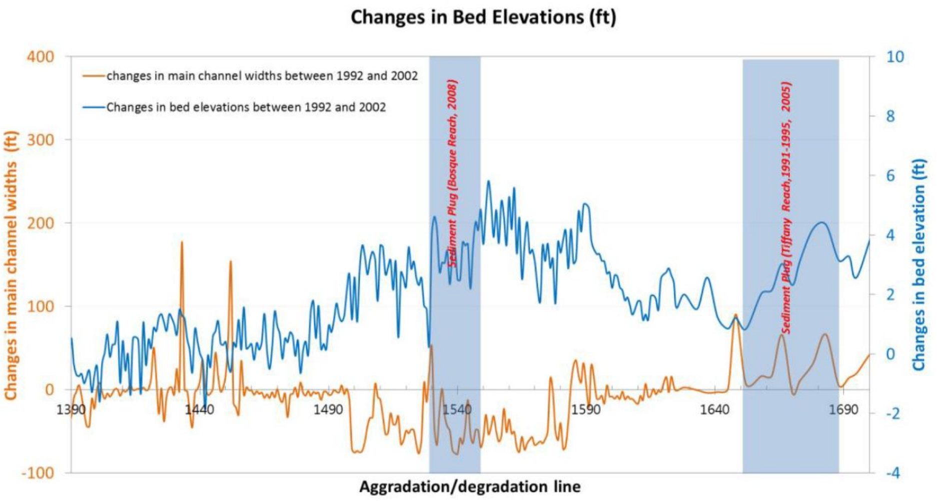


Figure 2.7: Changes in channel width between 1992 and 2002 [Park 2013]

2.2.4 Bank Height

The 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.

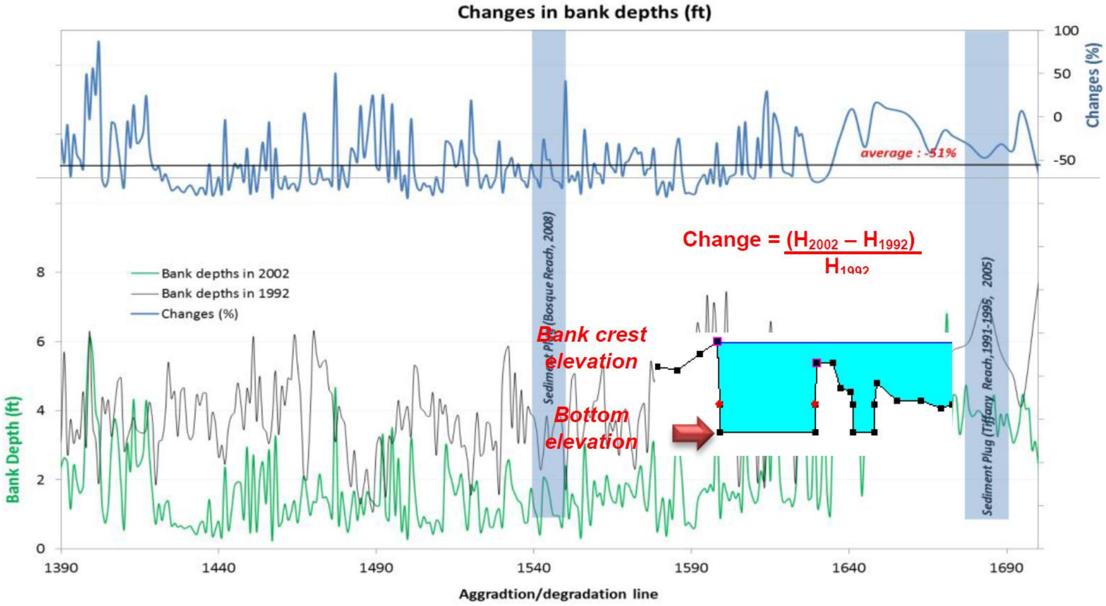


Figure 2.8: Changes in bank depths across agg/deg line between 1992 and 2002 [Park 2013]

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.

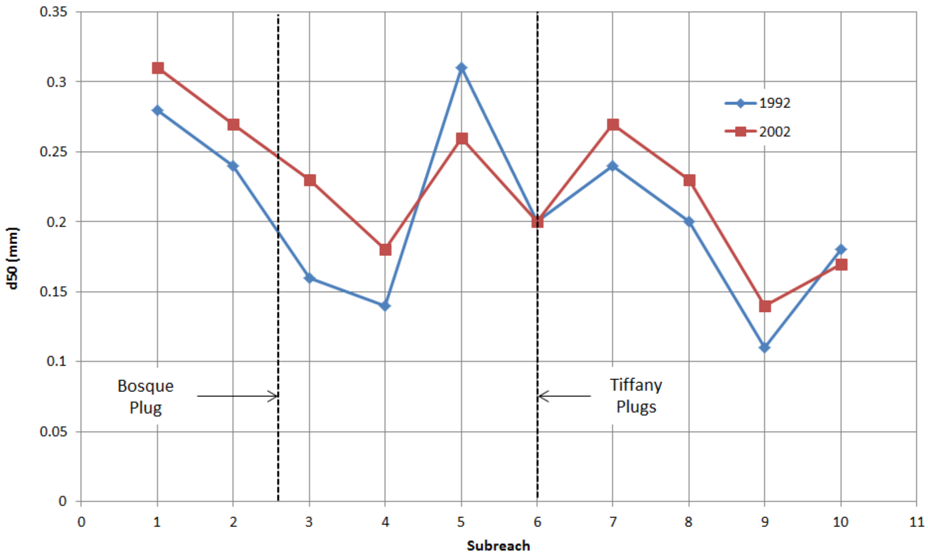


Figure 2.9: Grain size distribution between 1992 and 2002 by subreach [Shrimpton 2012]

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 grow within the floodplain as shown in Figures 2.11a-c below. However, if this vegetation is met by flooding with a sufficiently large magnitude and long duration it will remove this vegetation such as shown in Figures 2.11c-e below.

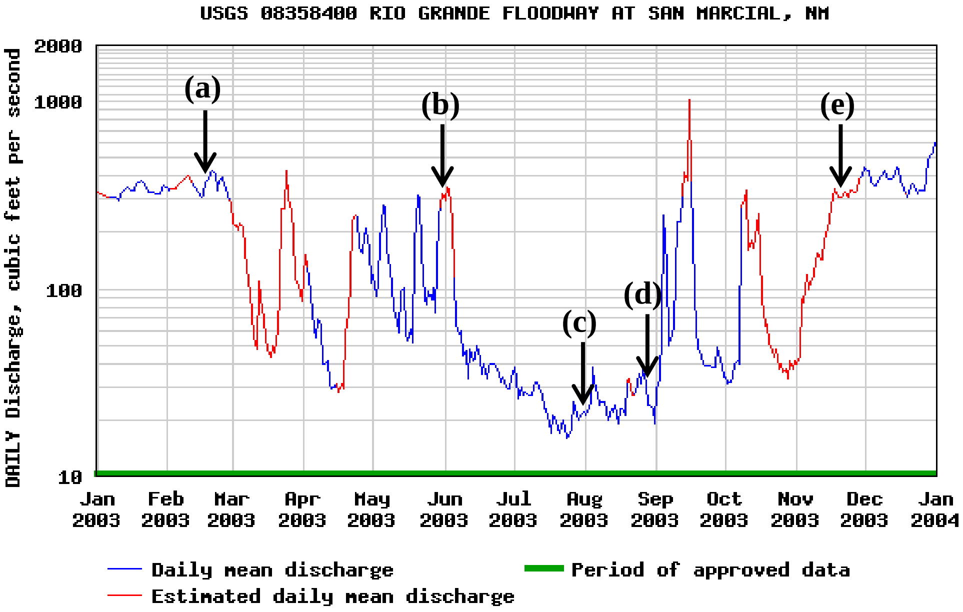


Figure 2.10: 2003 Annual Hydrograph [USGS]

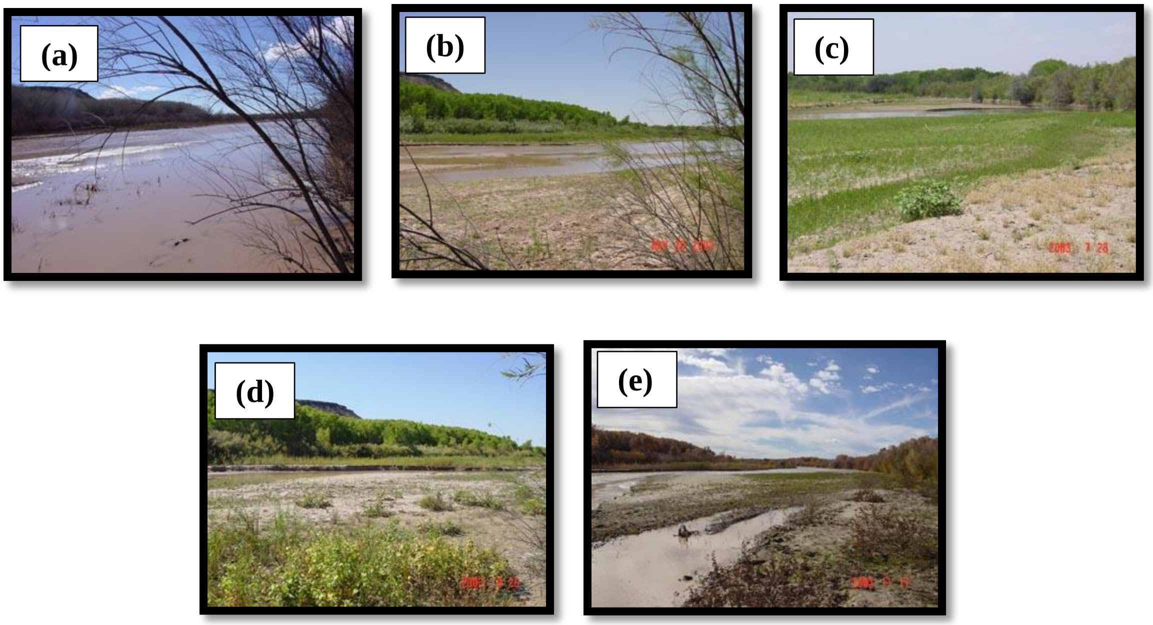


Figure 2.11: Looking downstream from San Marcial a) February 21, 2003 [BOR 2003]; b) May 29, 2003 [BOR 2003]; c) July 28, 2003 [BOR 2003]; d) September 26, 2003 [BOR 2003]; e) November 17, 2003 [BOR 2003]

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 while the peak flows also decreased as shown in Table 2.1 below.

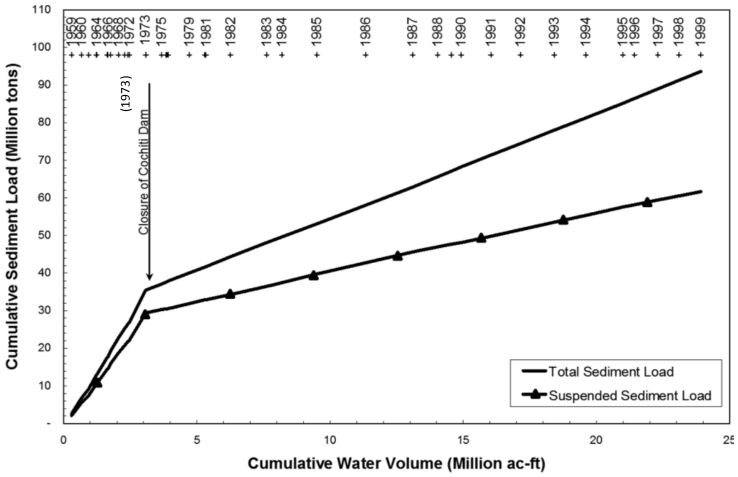
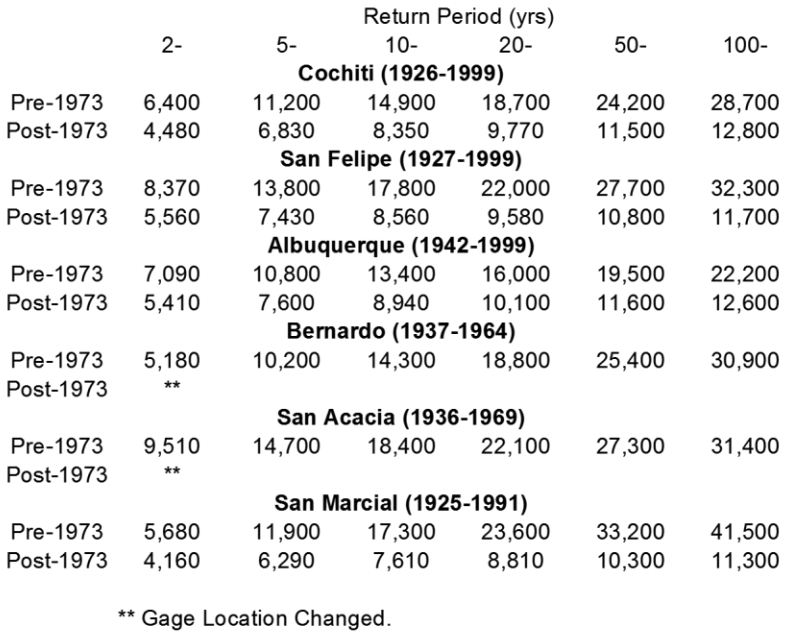


Figure 2.12: Double Mass Curve following the Closure of the Cochiti Dam at the San Acacia Gage [Mussetter et al. 2002]



	Return Period (yrs)					
	2-	5-	10-	20-	50-	100-
			Cochiti (1926-1999)			
Pre-1973	6,400	11,200	14,900	18,700	24,200	28,700
Post-1973	4,480	6,830	8,350	9,770	11,500	12,800
			San Felipe (1927-1999)			
Pre-1973	8,370	13,800	17,800	22,000	27,700	32,300
Post-1973	5,560	7,430	8,560	9,580	10,800	11,700
			Albuquerque (1942-1999)			
Pre-1973	7,090	10,800	13,400	16,000	19,500	22,200
Post-1973	5,410	7,600	8,940	10,100	11,600	12,600
			Bernardo (1937-1964)			
Pre-1973	5,180	10,200	14,300	18,800	25,400	30,900
Post-1973	**					
			San Acacia (1936-1969)			
Pre-1973	9,510	14,700	18,400	22,100	27,300	31,400
Post-1973	**					
			San Marcial (1925-1991)			
Pre-1973	5,680	11,900	17,300	23,600	33,200	41,500
Post-1973	4,160	6,290	7,610	8,810	10,300	11,300

** Gage Location Changed.

Table 2.1: Return Period following the Closure of the Cochiti Dam [Mussetter et al. 2002]

2.3.2 Backwater

Backwater on the Middle Rio Grande River 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.

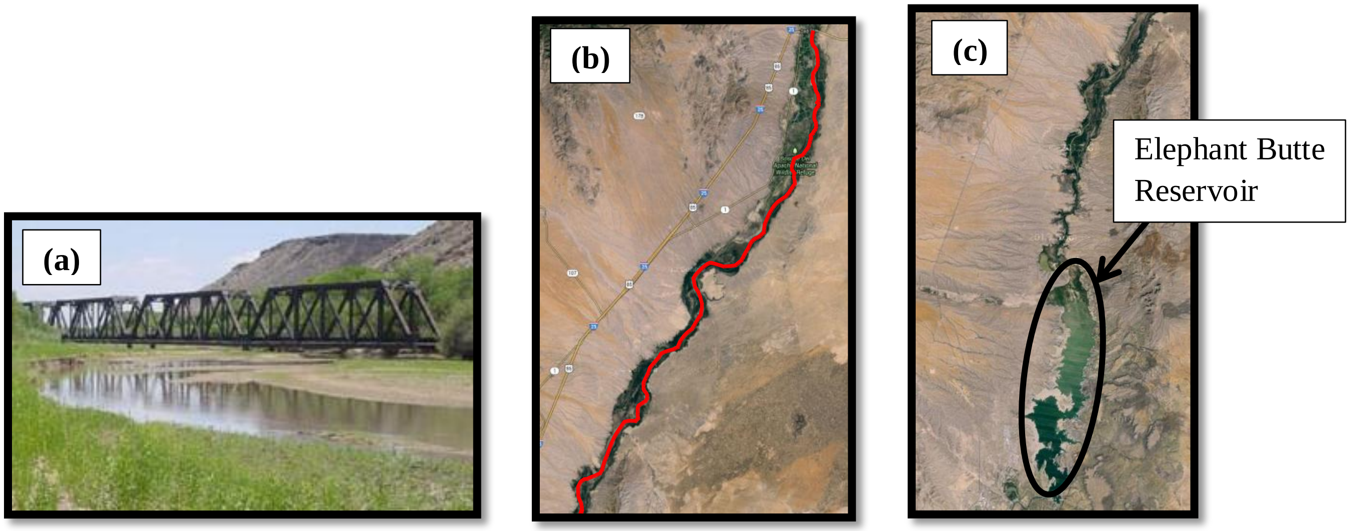


Figure 2.13: Sources of Backwater a) San Marcial Bridge [Dudley, Farrington, & McBride 2003]; b) Bends on the MRG [Google Maps 2013]; c) Elephant Butte Reservoir [Google Maps 2013]

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.

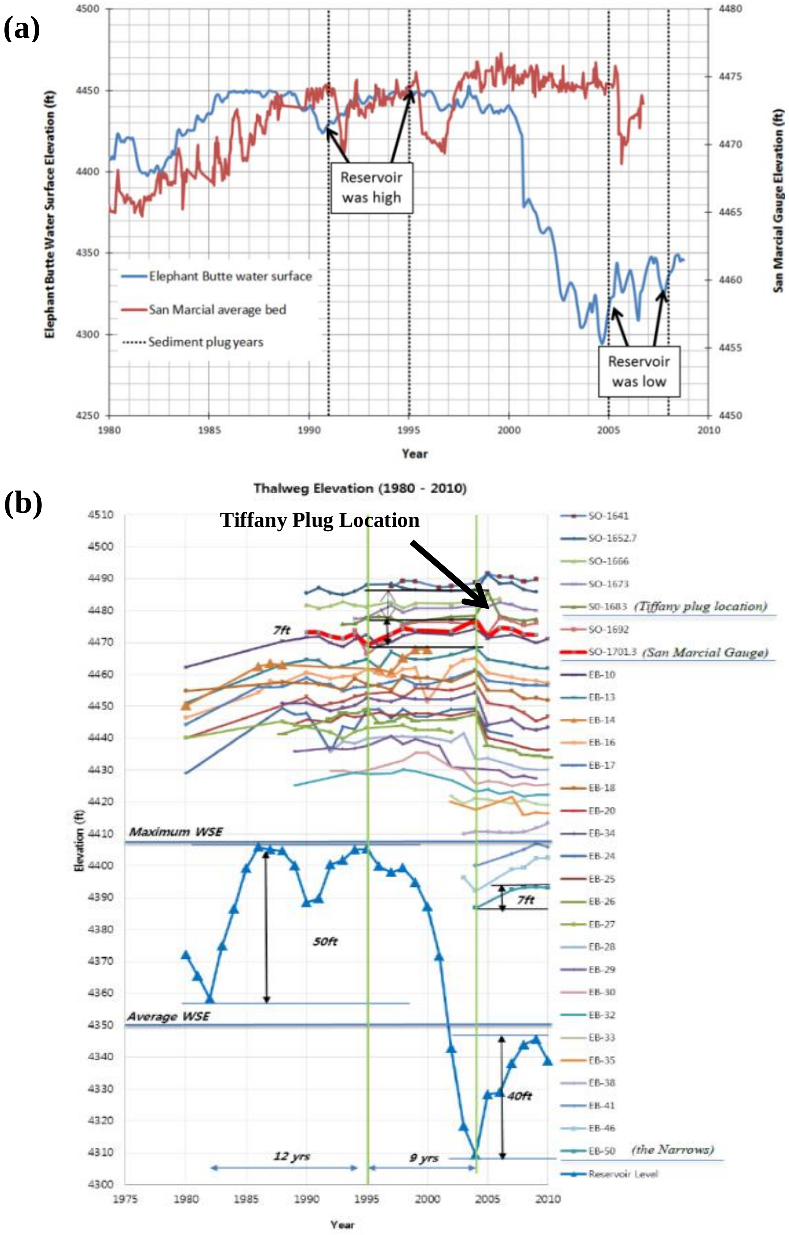


Figure 2.14: a) Reservoir Levels and San Marcial Bed Elevation [Shrimpton 2012]; b) Reservoirs Levels and Bed Elevation of MRG Reaches [Owen et al. 2012]

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.

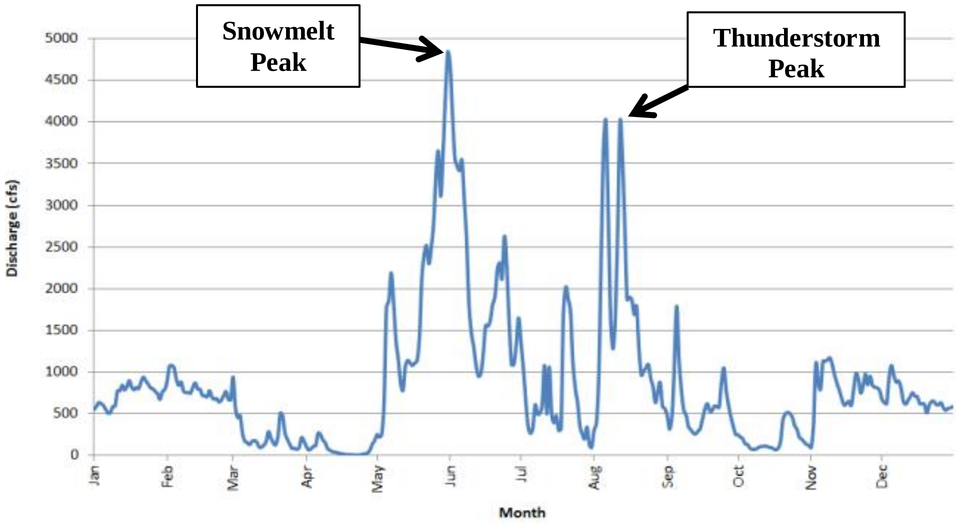


Figure 2.13: Annual Hydrograph Peaks [Shrimpton 2012]

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 River 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 is necessary for the variations in geometric factors such as the reduction of width and slope. Channel aggradation is a result of either or a combination of lower sediment transport capacity and 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, we can see that there is a consensus 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 a consensus 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.

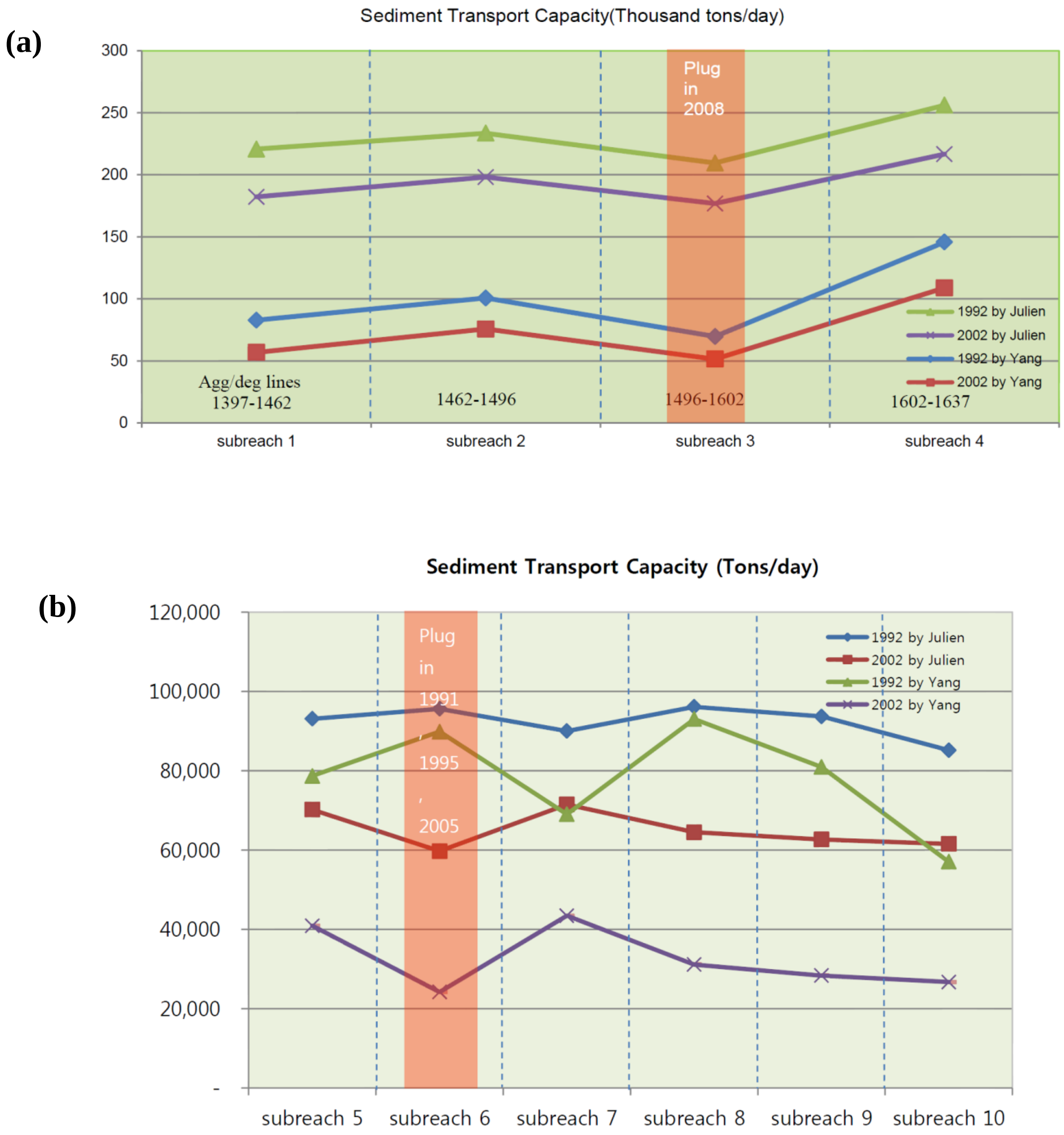


Figure 3.1: Sediment Transport Capacity Profile a) Bosque plug location [Park 2013]; b) Tiffany plug location [Park 2013]

The channel conveyance measures the carrying capacity of the channel and accounts for the channel roughness and the channel geometry. 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.

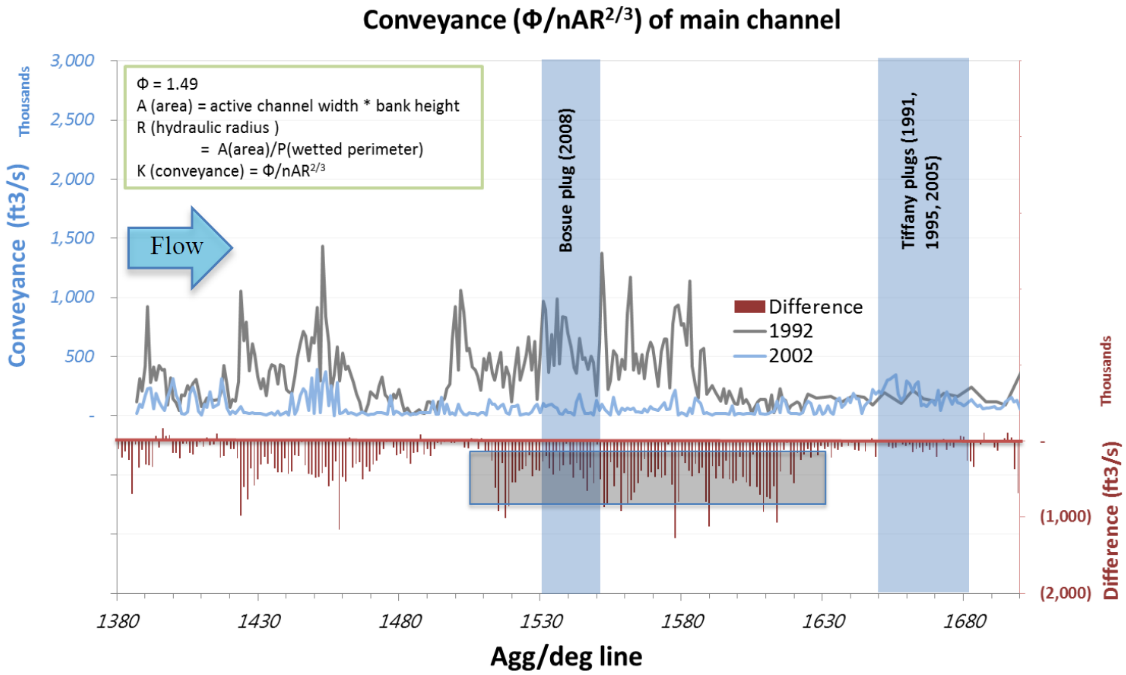


Figure 3.2: Conveyance of the Main Channel from 1992-2002 [Park 2013]

3.1.1 Channel Widths

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, we can compare the width at which the plugs formed 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.

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. However, besides producing a higher sediment transport capacity, this decline in channel width would have also produced a smaller flow area which would therefore decrease the magnitude of the overbank discharge.

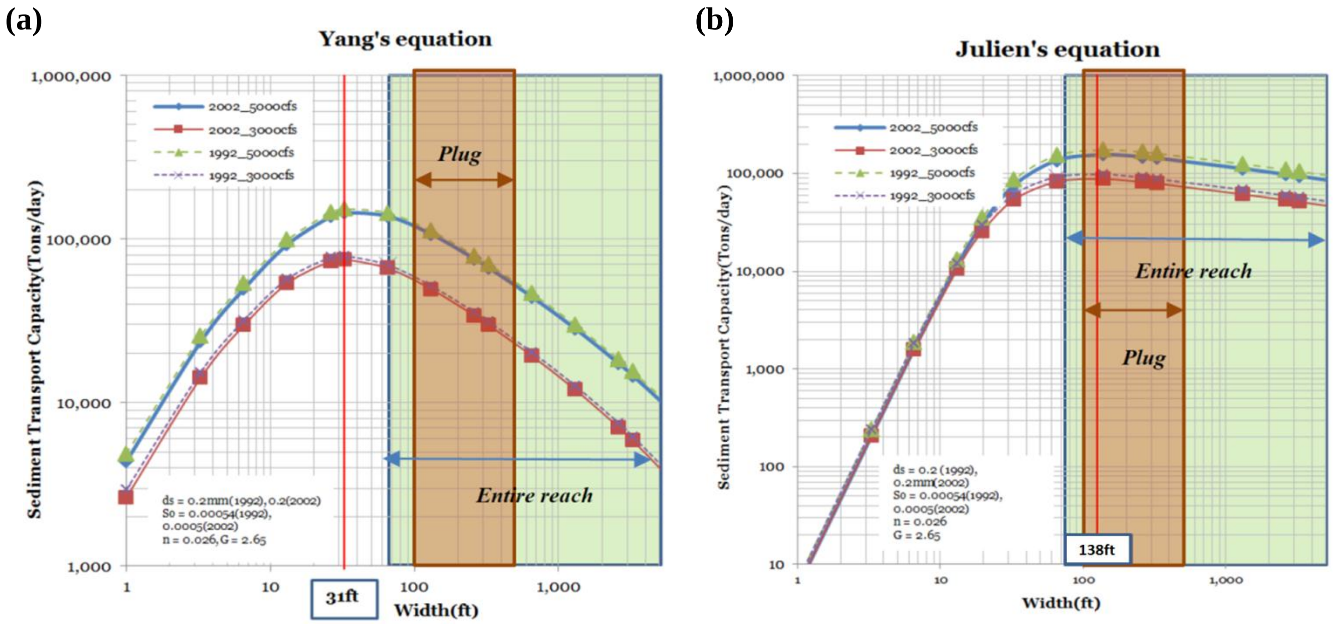


Figure 3.3: Variations in the Sediment Transport Capacity with Width at the Elephant Butte Reach [Park 2012]

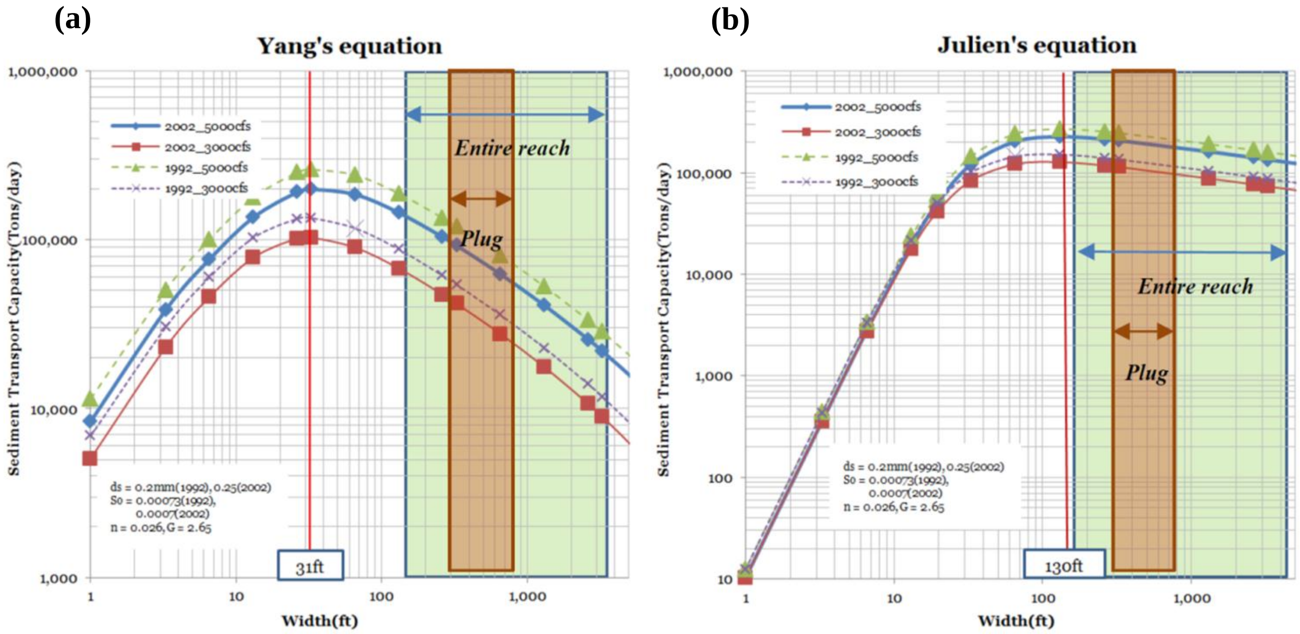


Figure 3.4: Variations in the Sediment Transport Capacity with Width at the Bosque Reach [Park 2012]

3.1.2 Roughness

The roughness of the Middle Rio Grande has risen between 1962 and 1972 and again between 1992 and 2002 as shown in Figure 3.5 below where the channel roughness is compared at different periods and across a range of discharges. 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. This higher roughness on the floodplain likely stems from vegetation encroachment. This vegetation encroachment was likely to have been quite significant 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.

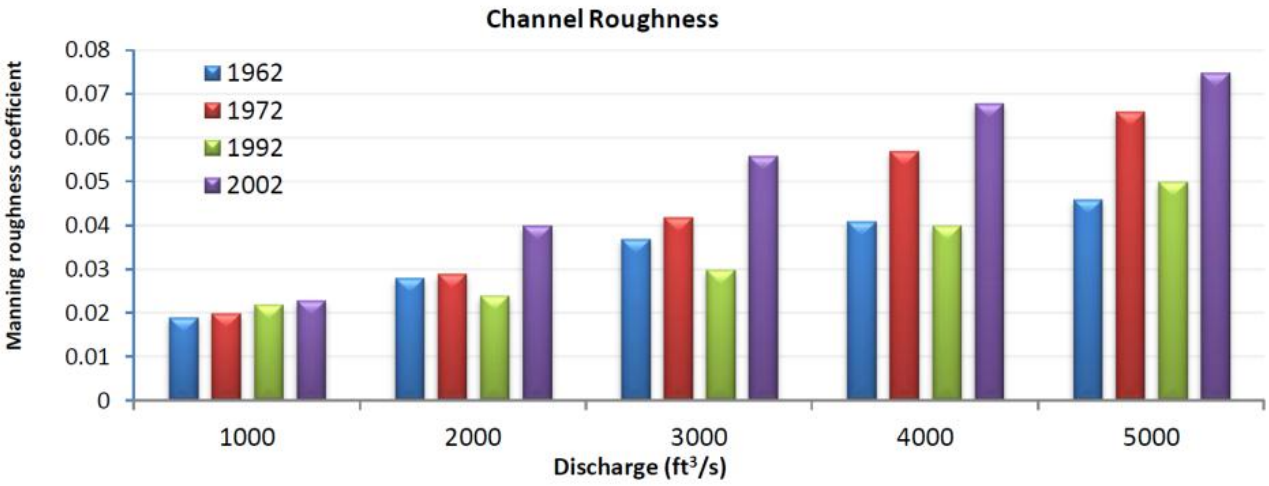


Figure 3.5: Channel Roughness Variations with Time and Discharge [Park 2013]

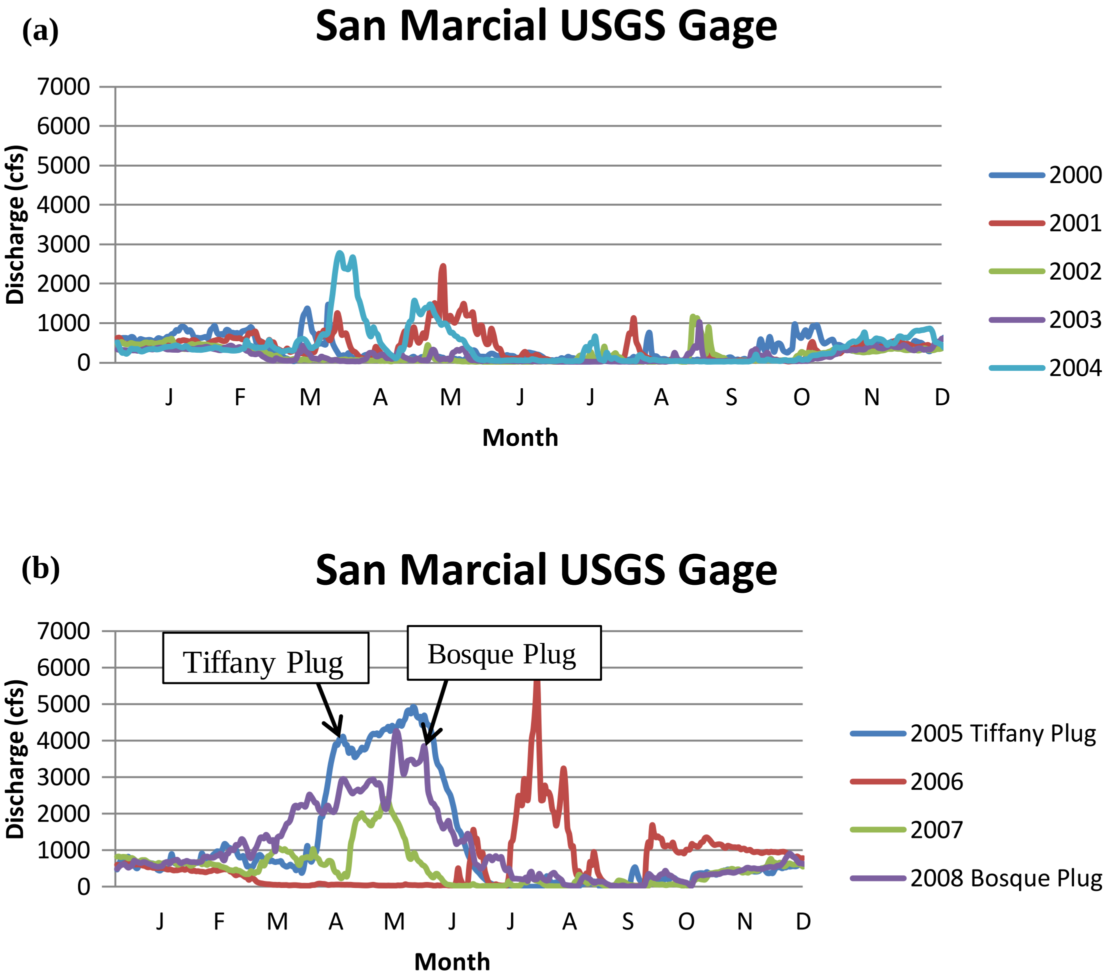


Figure 3.6: Annual Hydrographs a) 2000-2004 Drought [data from USGS]; b) 2005-2008 Flooding [data from USGS]

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 sediment transport capacity at both locations appears to decline significantly during this period.

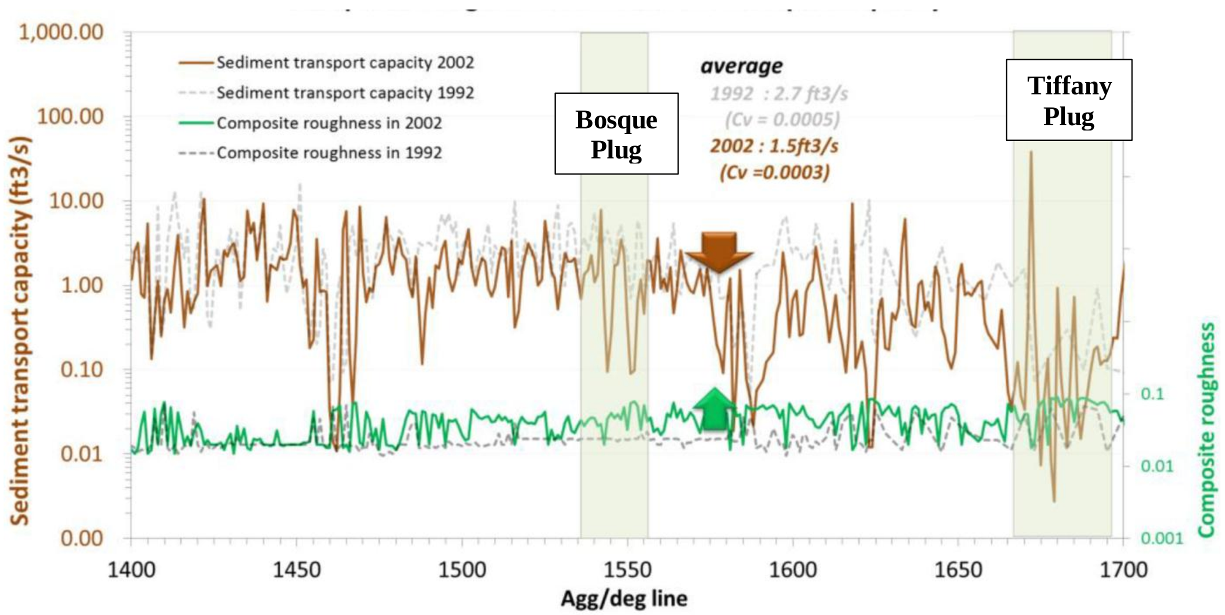


Figure 3.7: Composite Roughness and Sediment Transport Capacity [Park 2013]

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 as shown in Figure 3.8a-b below since the channel flows decreased while the floodplain flows increased. This is likely a result of lower overbank discharge magnitudes and channel perching. 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 during this period between 1992 and 2002.

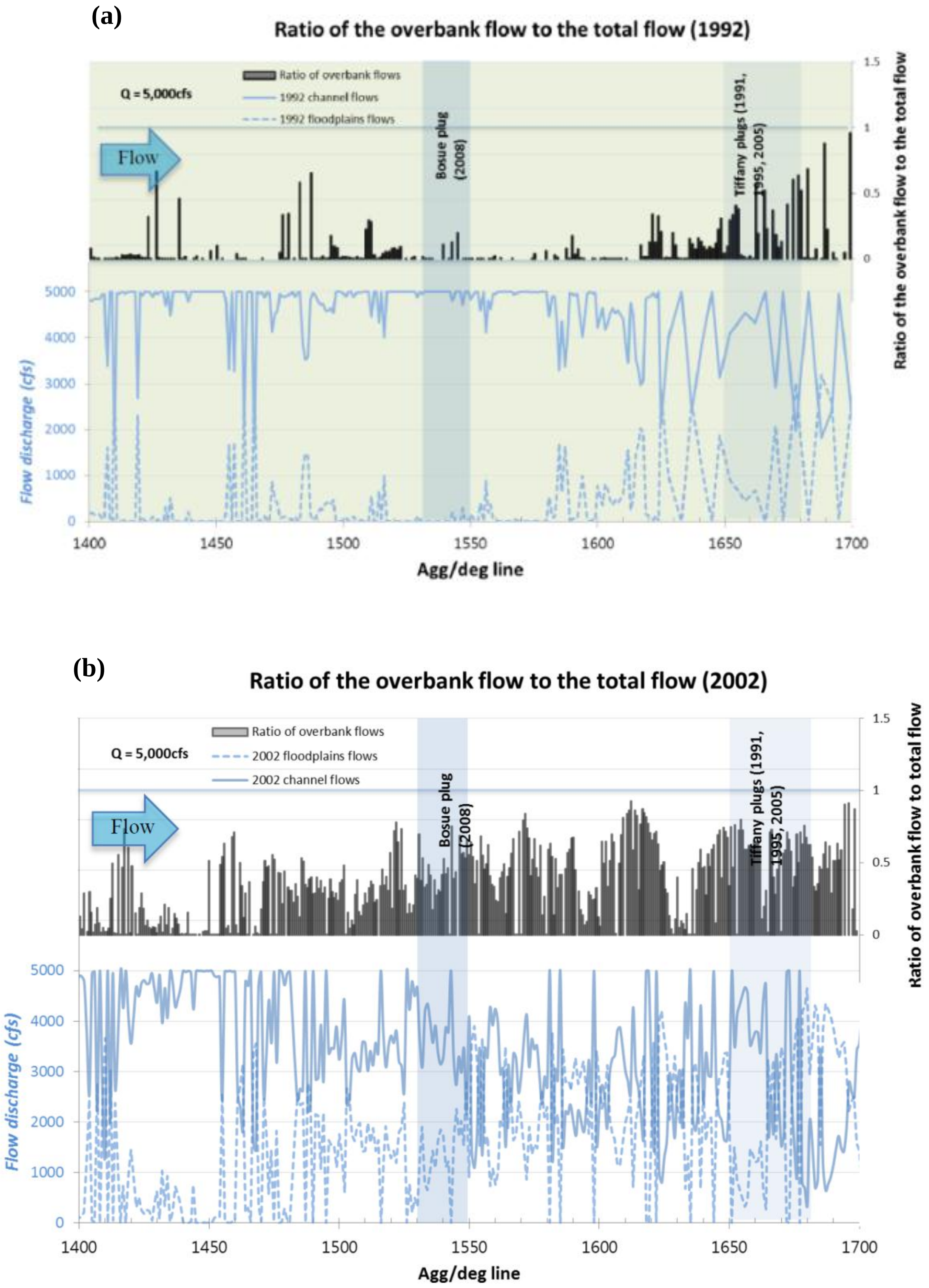


Figure 3.8: Ratio of the Overbank Flow to the Total Flow a) 1992 [Park 2013]; b) 2002 [Park 2013]

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.

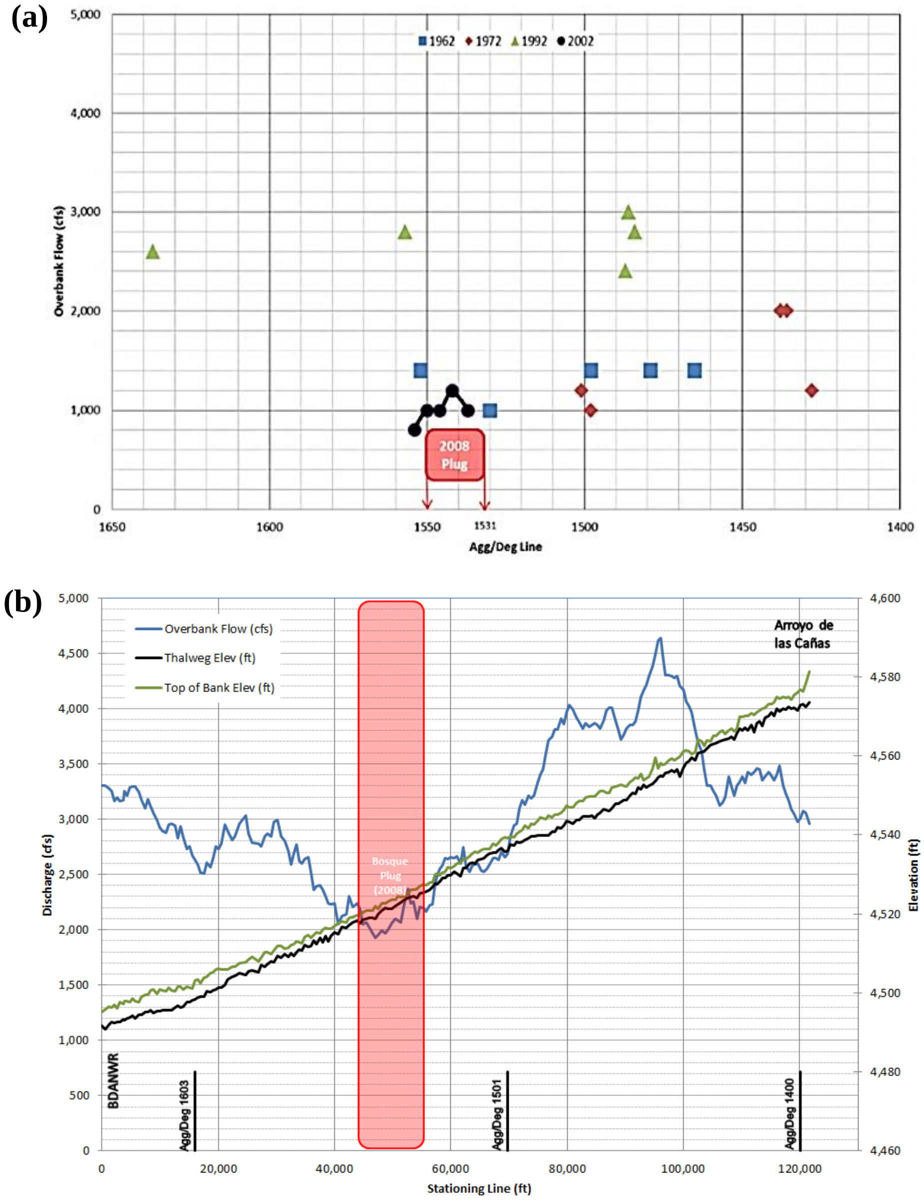


Figure 3.9: a) Variations in locations with lowest overbank flow [Shrimpton 2012]; b) Overbank Discharge and Bank Height in 2002 [Shrimpton 2012]

3.2.2 Vertical Sediment Concentration Profiles

A high Rouse number refers to a vertical sediment distribution that concentrates sediment toward the channel bed. After flowing overbank the Rouse number at the Bosque plug location varied between approximately 1.1 and 1.5 which corresponds to approximately eighty-five to ninety-two percent of the total load being suspended as shown in Figure 3.10a below. This high degree of suspended sediment however does not correspond to a uniform distribution of sediment as shown in Figure 3.10b below in which it is demonstrated that the sediment concentration at the mid-depth corresponds to only 0.06% of the near-bed sediment concentration. Also, Figure 3.10b demonstrates that the vertical sediment concentration profile does not vary significantly with respect to the discharge and therefore the Rouse number will remain high despite a high discharge.

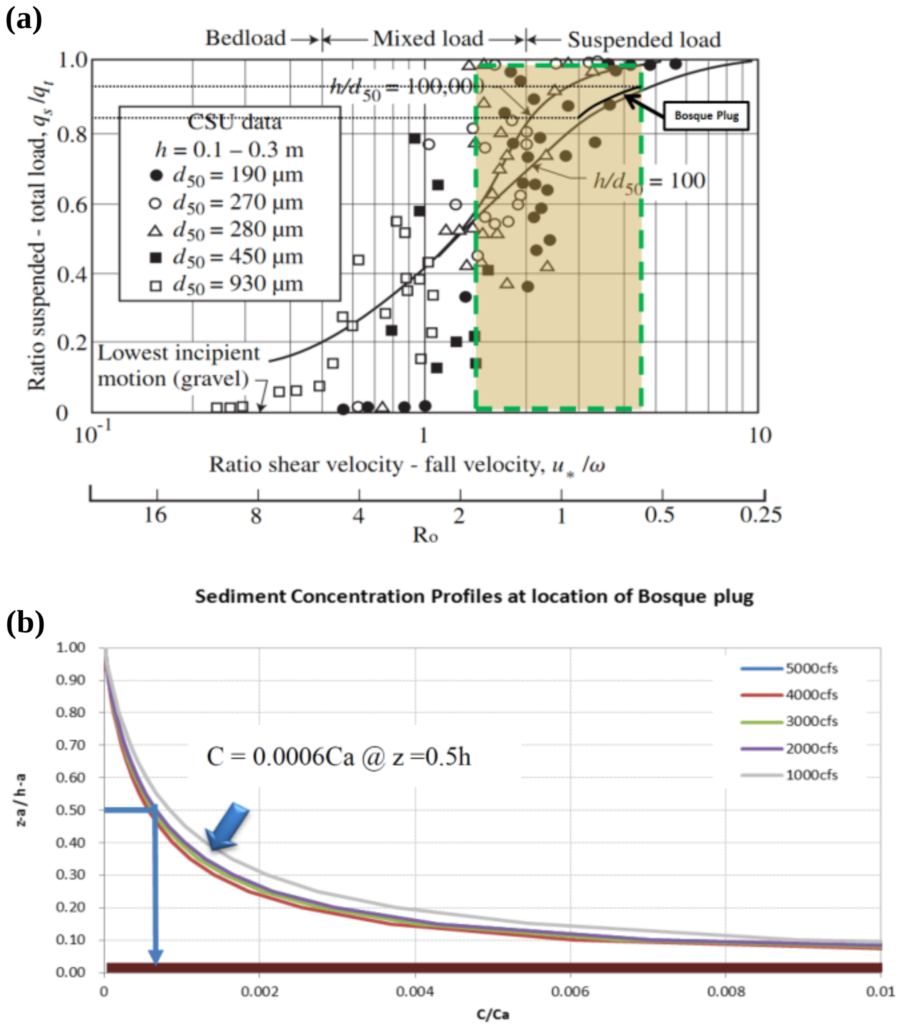


Figure 3.10: Bosque plug location a) Ratio of suspended sediment [Park 2012]; b) Vertical Sediment Concentration Profile [Park 2013]

The Rouse number at the Tiffany plug location is approximately 1.0 following flowing overbank. 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.

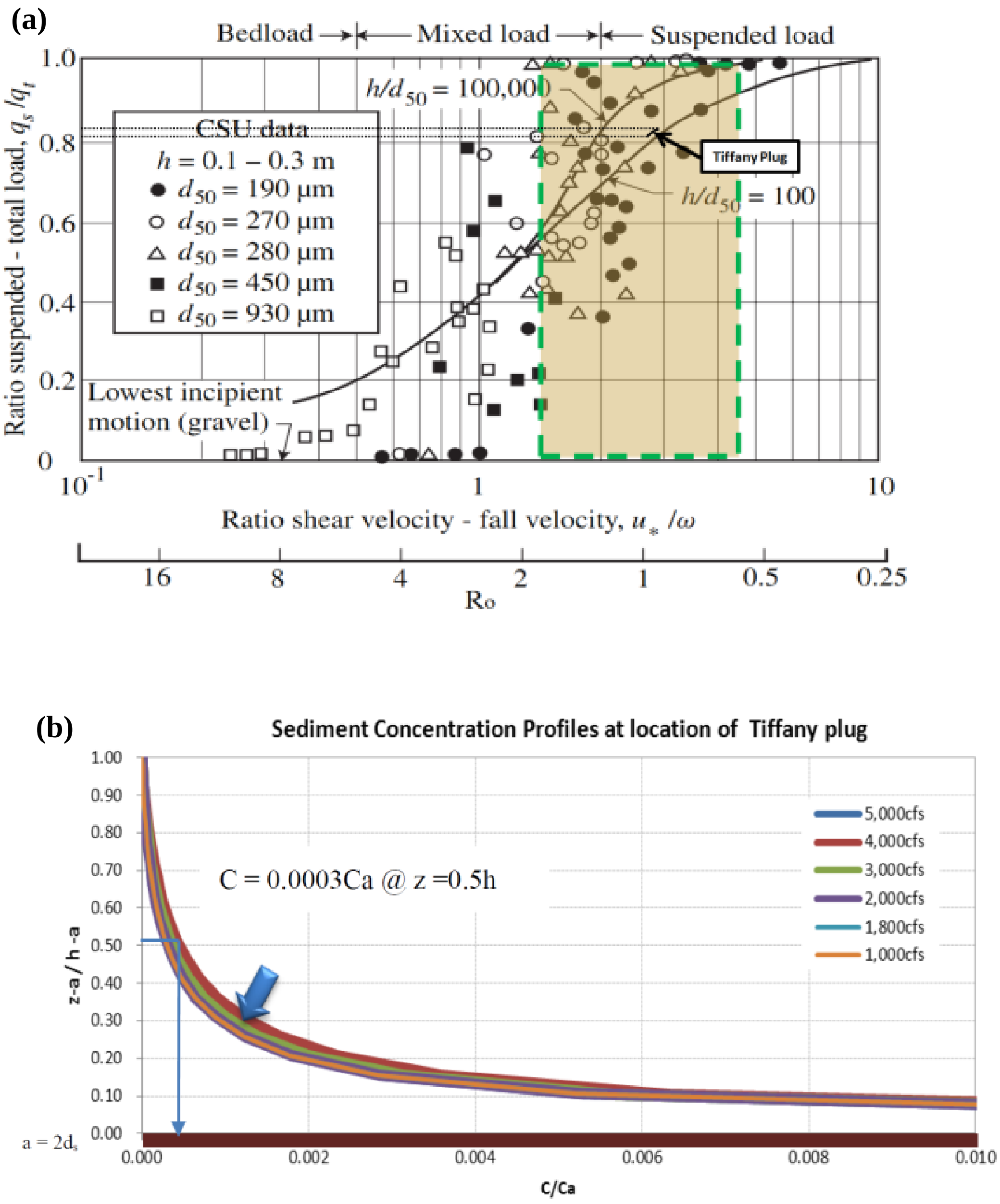


Figure 3.11: Tiffany plug location a) Ratio of Suspended Sediment [Park 2012]; b) Vertical Sediment Concentration Profile [Park 2013]

By comparing the vertical concentration profiles across various subreaches we can determine 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 do not vary significantly between subreaches as the Rouse number remains large.

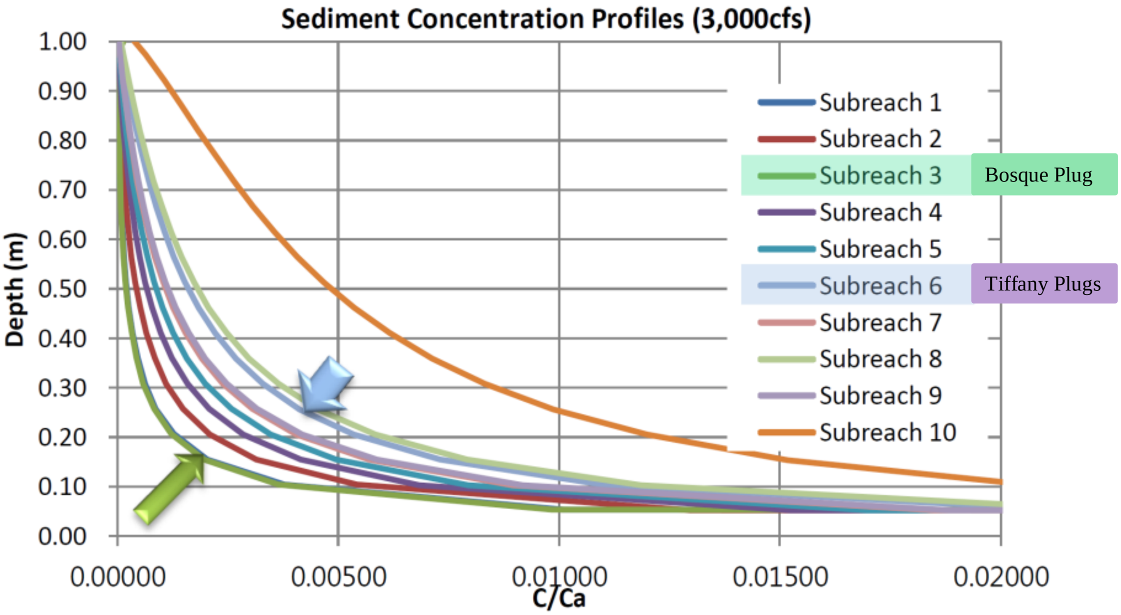


Figure 3.12: Vertical Sediment Concentration by Subreaches in the MRG [Park 2012]

The Rouse number for the subreaches in Figure 3.12 above varies between 0.7 and 1.4. This sediment distribution can significantly accelerate the rate of aggradation as shown in Figure 3.13 below which 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.

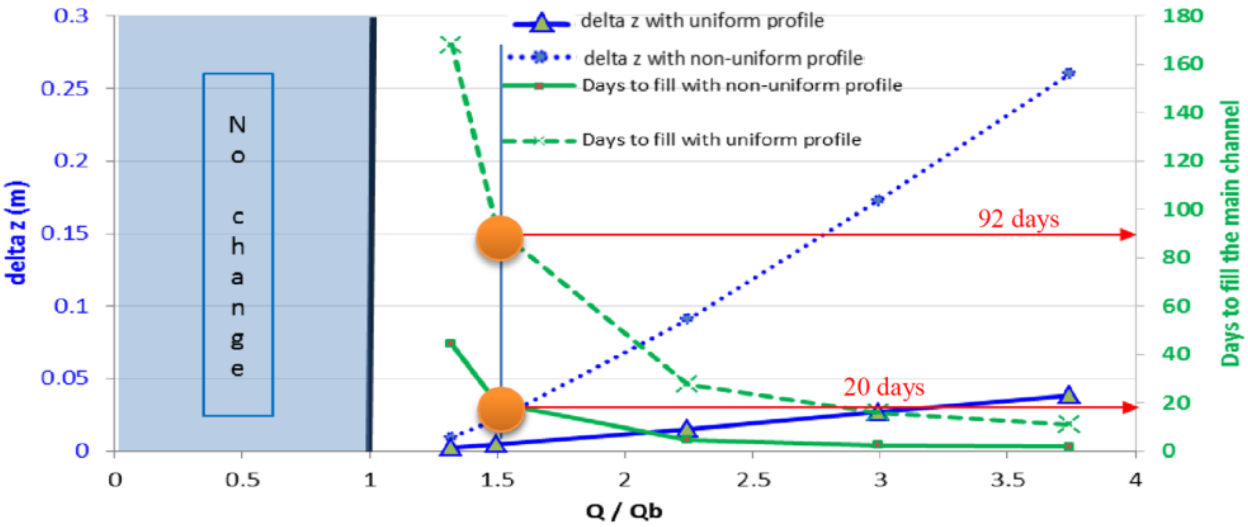


Figure 3.13: Aggradation due to overbank flows with uniform and non-uniform distributions [Park 2013]

3.3 Backwater Effects on Bed Aggradation

3.3.1 Backwater Effects from Reservoir

If the reservoir levels were directly responsible for the sediment plug formation then it would be expected that these sediment plugs would develop when the reservoir base level was high because by increasing the flow area, the flow velocity decreases which would decrease the sediment transport capacity. By comparing the water surface elevation of the reservoir to the plug formation as shown in Figure 2.14a, we can see 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 spike was therefore likely a result of flooding 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 (Park 2013). Since the Bosque plug formed further upstream than the Tiffany plug it would require a greater amount of time for the reservoir to cause a plug to form at this location. These long periods of time demonstrate that the reservoir is unlikely to have caused the plug at either the Tiffany or the Bosque plug locations.

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 one foot of backwater at the Tiffany plug location. 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 the loss of sediment concentration from the upstream aggradation.

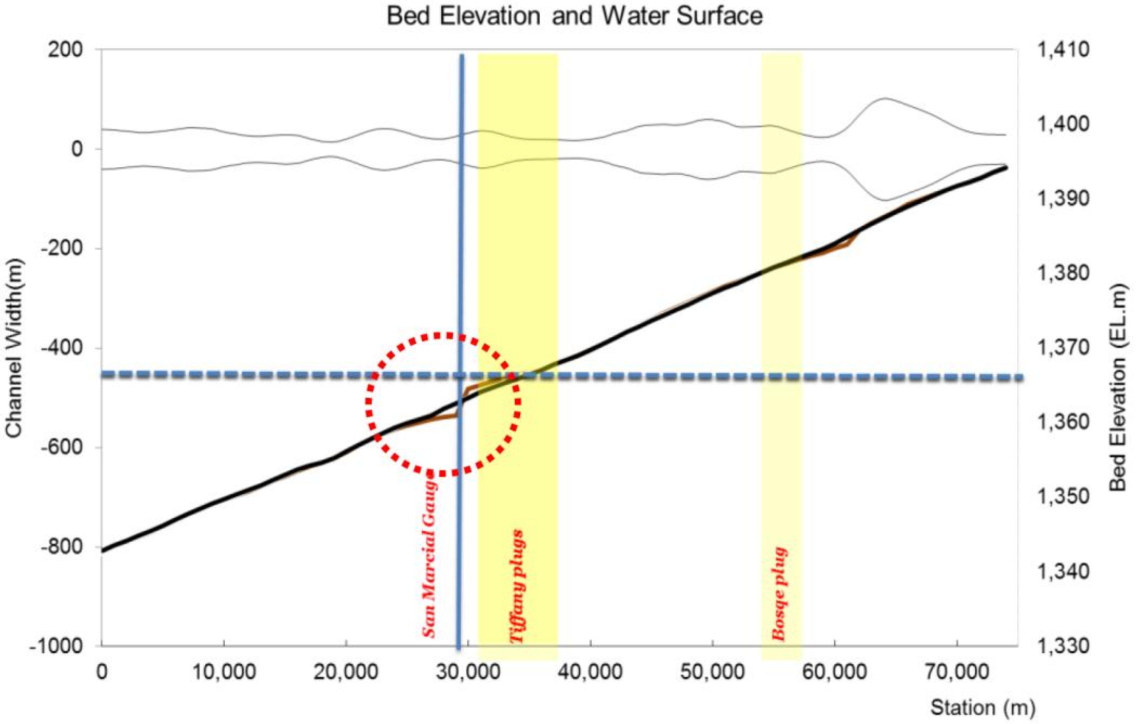


Figure 3.14: Bed Elevation Changes due to the San Marcial Railroad Bridge [Park 2013]

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, 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).

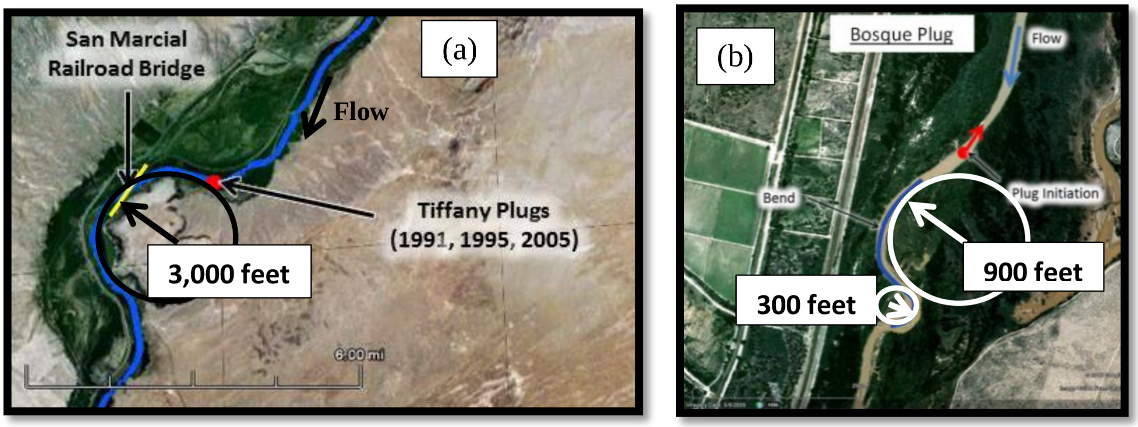


Figure 3.15: Radius of Curvature of the Downstream Bends a) Tiffany Plug Location [adapted from Shrimpton 2012]; b) Bosque Plug Location [adapted from Shrimpton 2012]

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 we can assess whether there is a correlation between droughts and floods and the sediment plugs. 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.

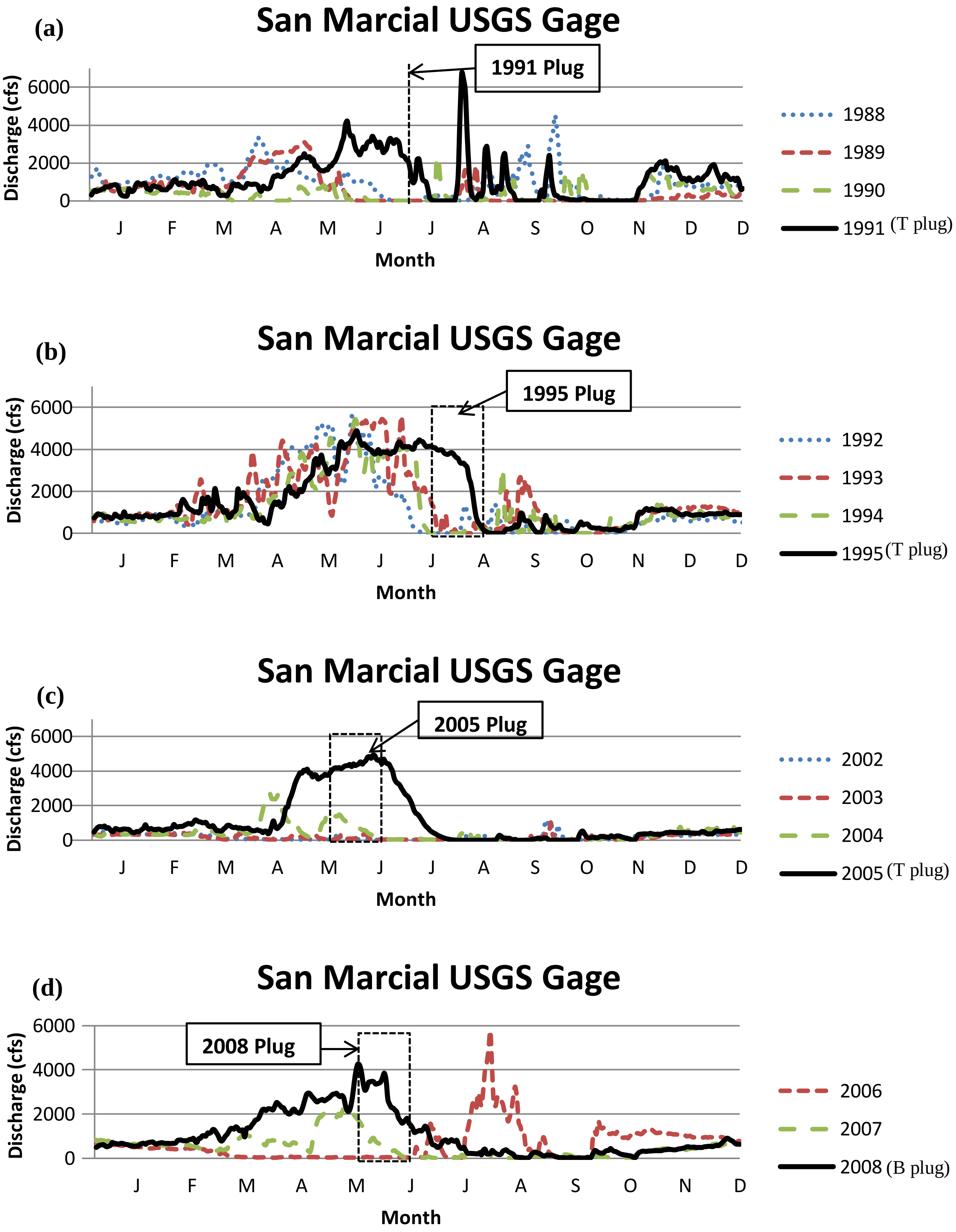


Figure 4.1: Annual Hydrographs during and prior to Plugs a) 1991 Tiffany Plug b) 1995 Tiffany Plug c) 2005 Tiffany Plug d) 2008 Bosque Plug [Data obtained from USGS]

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 we can graph the average daily suspended sediment concentration 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.

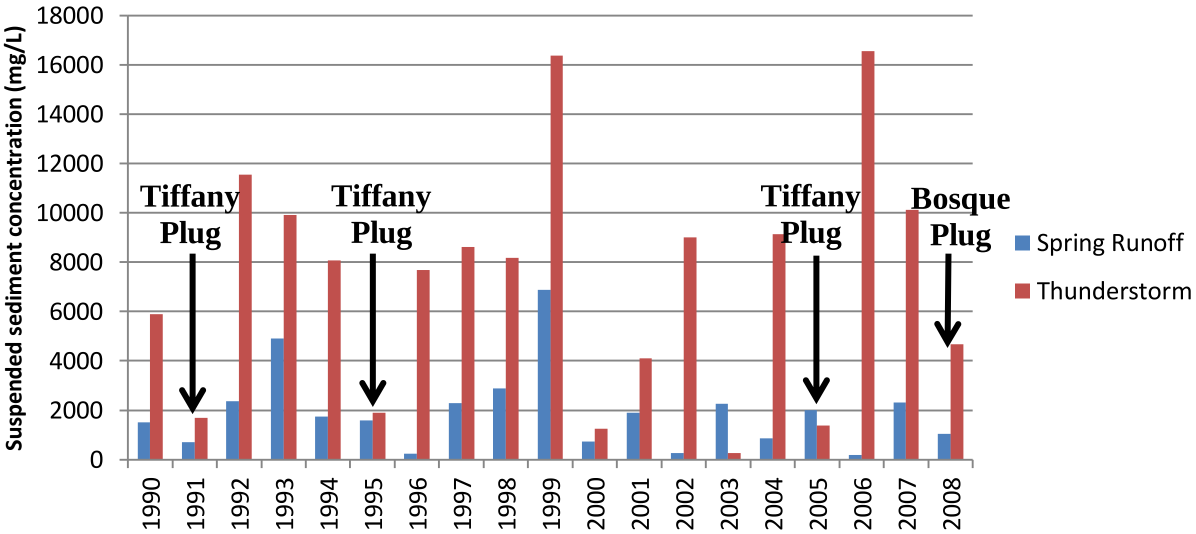


Figure 4.2: Average Suspended Sediment Concentration during the Spring Runoff Period (May-June) and the Thunderstorm Period (July-September) [Data obtained from USGS]

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. This difference in discharge may be increased by the banks which serve to reduce the discharge in the channel during the thunderstorm period by blocking the overland flow from entering the channel since it is perched above the floodplain.

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). It is clear from Figures 4.3a, b, and e below that the Tiffany plugs appear to have formed following a winter with a relatively high ONI while the Bosque plug did not and despite exceptions such as in 2003, Figures 4.3a-f appears to support a somewhat weak correlation between the Oceanic Niño Index and the discharge.

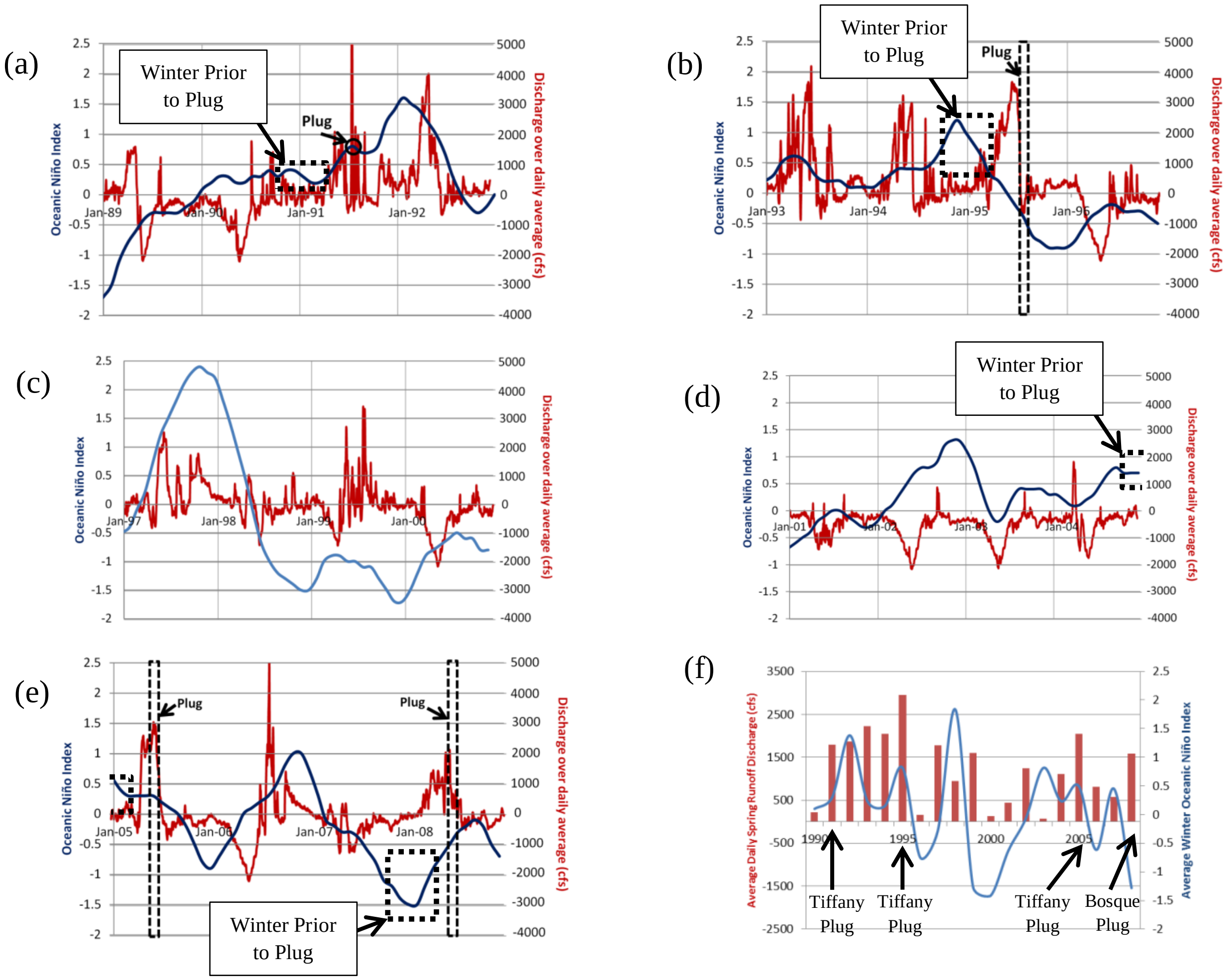


Figure 4.3: Relation between discharge and the ONI a) 1989-1993 b) 1993-1997 c) 1997-2001 d) 2001-2005 e) 2005-2009 f) Average Winter ONI and Average Spring Runoff [Data obtained from USGS]

To further assess this relationship between the discharge and the El Niño/La Niña phenomena we will compare the discharge during the periods when we would expect a rise or a decline. 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 4.4a-b below, the El Niño events experienced a greater average discharge and a greater average annual peak than the La Niña events but the La Niña period appears to be subjected to a loner and higher magnitude thunderstorm period. In addition, it appears that the El Niño period is marked by a longer snowmelt period while the La Niña period is marked by a longer thunderstorm period.

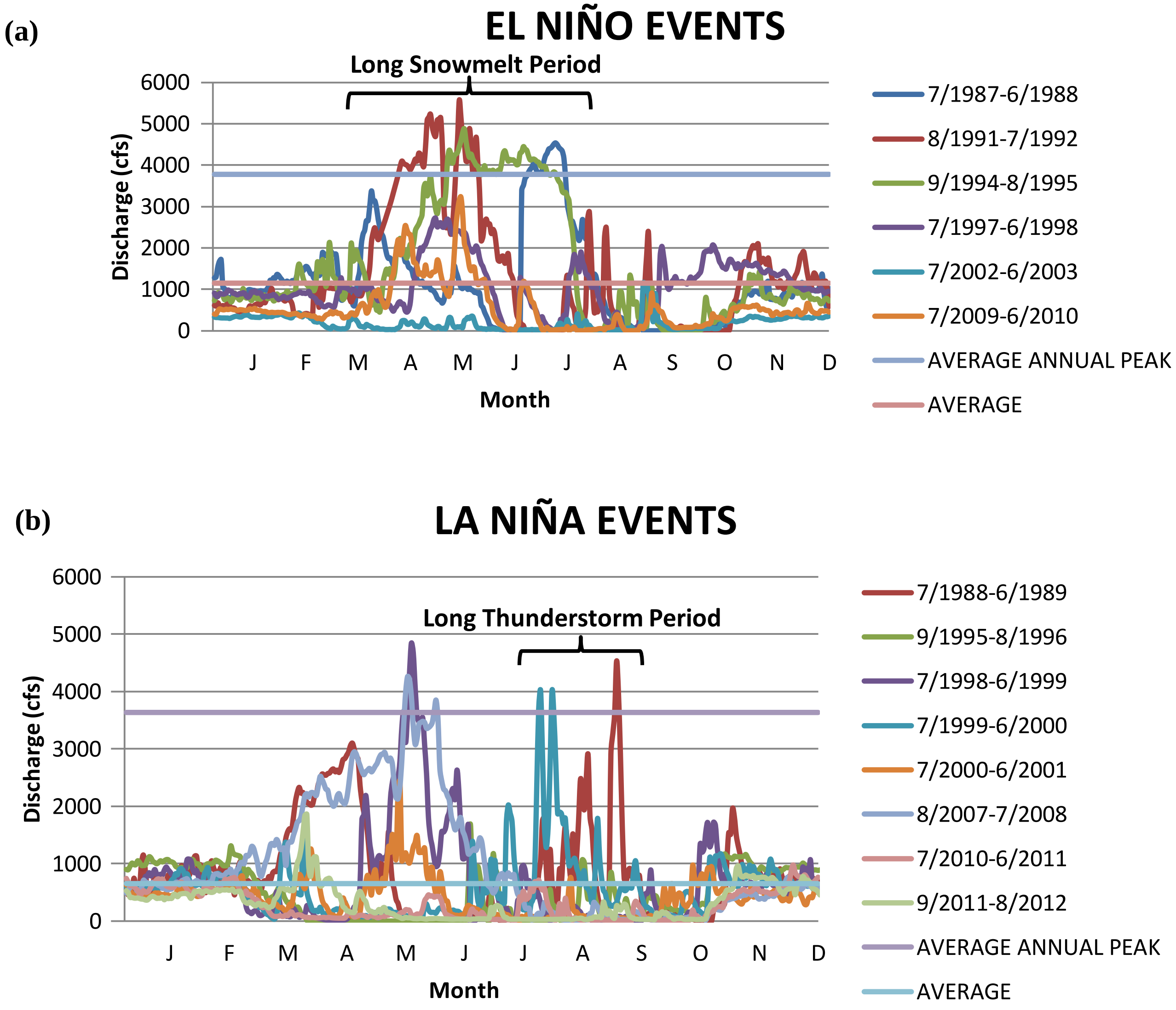


Figure 4.4: Annual Hydrographs a) El Niño Periods b) La Niña Periods [Data obtained from USGS]

There is significant spatial and temporal variability in the overbank discharge. The Elephant Butte reach has an overbank discharge of two thousand cubic feet per second while the Bosque reach has an overbank discharge of five thousand cubic feet per second. The overbank discharge at the time and location of the Bosque sediment plug however was much less than five thousand cubic feet per second as shown in Figure 3.9a above. Therefore it would be noteworthy to assess the influence of the El Niño/La Niña phenomena on the discharges in this range. In particular we will assess their influence on the duration of magnitudes of discharges in this range since from Figure 4.1b it appears 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 appears to avoid extremes and therefore we can assess the influence of the El Niño and La Niña periods individually rather than simply comparing these periods. 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.

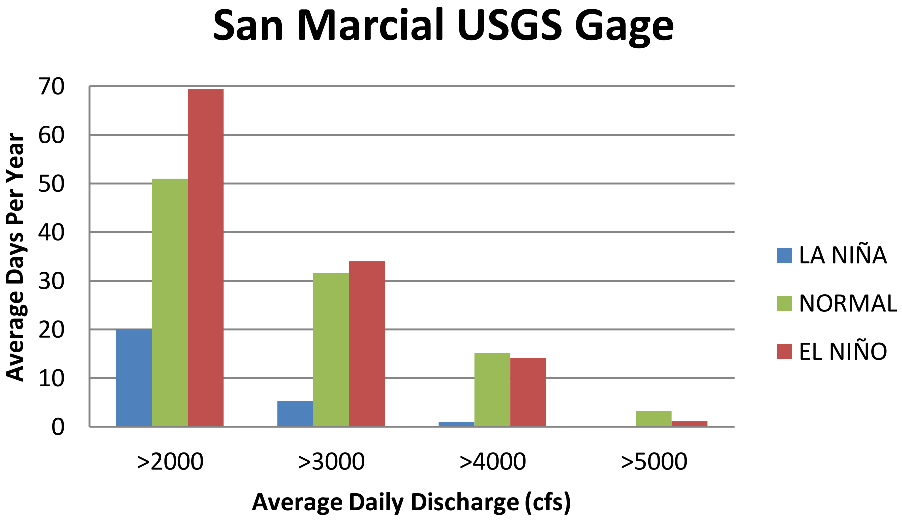
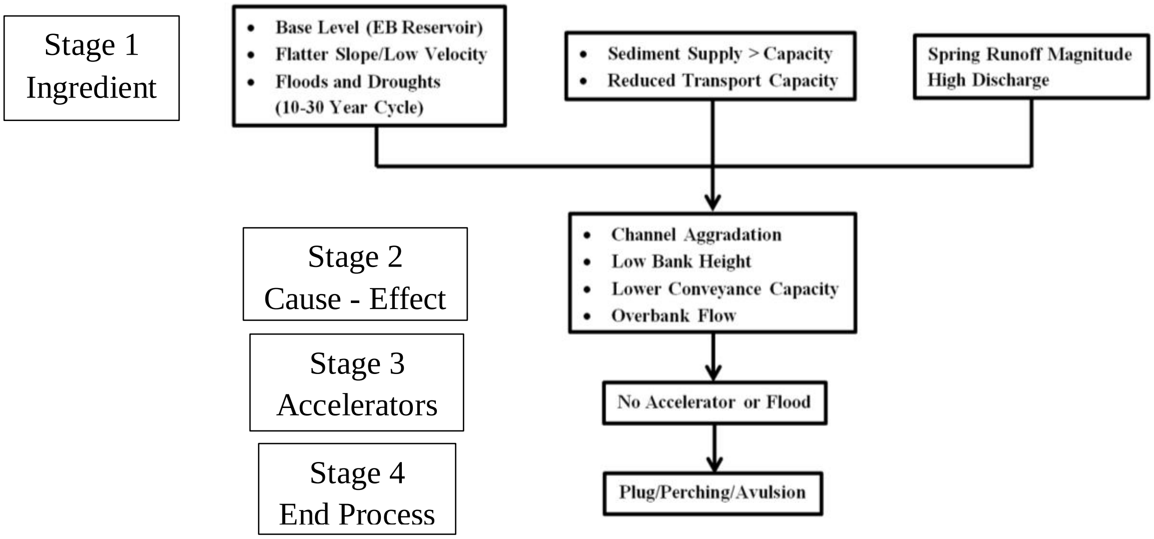


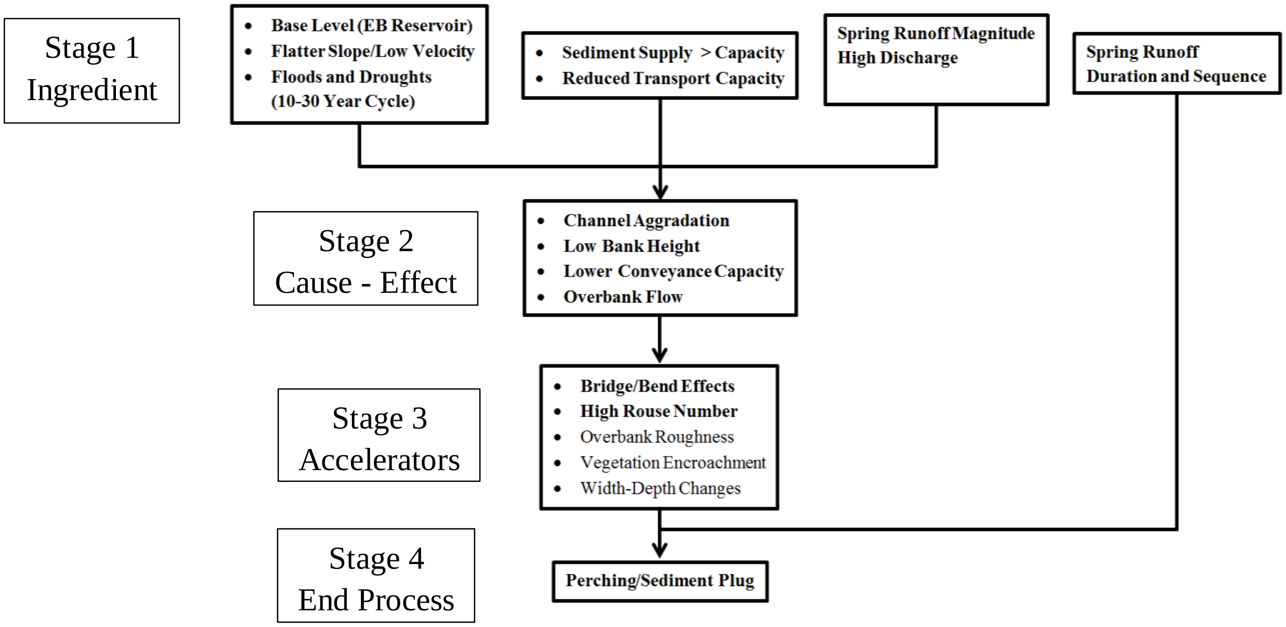
Figure 4.5: Average Days per Year with an Average Discharge beyond a Threshold Magnitude during La Niña, El Niño, and Normal Conditions [Data obtained from USGS]

Chapter 5 : Description of Plug Formation

Sediment plugs are a result of a combination of several factors and the cause/effect relationships between them. There is a sediment plug formation process which involves a short-term development due to several accelerating factors as shown in Figure 5.1a and a longer-term avulsion process as shown in Figure 5.1b.



(a) **Avulsion Process (Long Term)**



(b) **Sediment Plug Formation (Short Term)**

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

5.1 Stage One: Ingredients

5.1.1 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, channel aggradation may result 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 the Cochiti dam upstream and the Elephant Butte dam downstream. The Cochiti dam would reduce the sediment supply which would encourage erosion directly downstream of the dam and it would reduce the peak flows which would create a region of deposition further downstream. The backwater from the Elephant Butte dam would also encourage a region of deposition by reducing the sediment transport capacity upstream. These factors may result in zones of erosion, transport, and deposition downstream from the dam as shown in Figure 5.3 below.

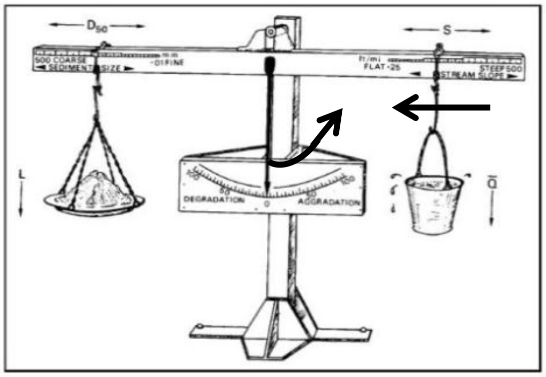


Figure 5.2: Lane's Balance Influence of Slope

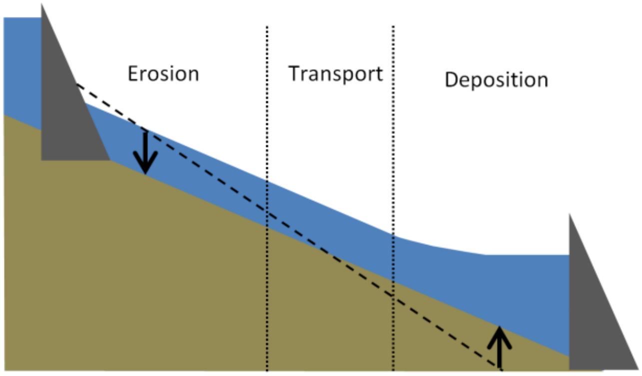


Figure 5.3: Zones of Erosion, Transport, and Deposition

$$Q_s^- \cdot D_{50}\ \alpha\ Q_w \cdot S^-$$

(Equation 5.1)

5.1.2 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. Evidence of plug formation following periods of drought is shown in Figure 4.1a-d. The cycle of floods and droughts may lead to overbank flows by decreasing the magnitude of overbank flow and enhancing the influence of overbank flow by contributing to channel perching. The magnitude of overbank flow can be decreased by reducing the flow area as the bank height is lowered, creating variations in the channel width, and allowing for vegetation to encroach into the floodplain. 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.

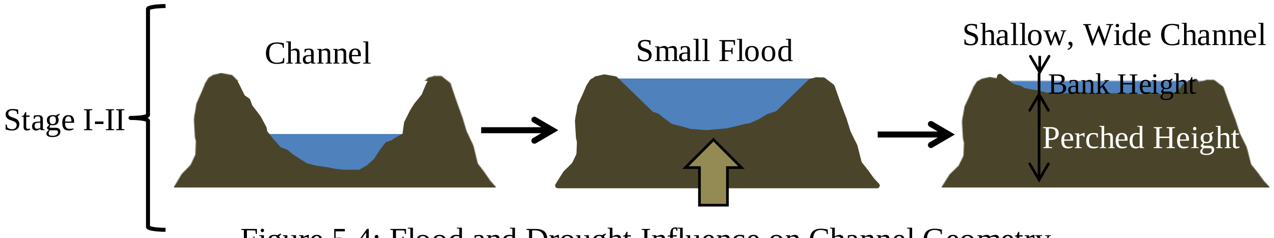


Figure 5.4: Flood and Drought Influence on Channel Geometry

5.1.2 High Sediment Supply and Low Transport Capacity

A high sediment supply 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.

5.1.3 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 relies on the duration and sequence of the spring runoff. The duration is important because a sediment plug is a product of excessive 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 and by producing an inefficient channel geometry.

5.2 Stage Two : Cause-Effect

The “ingredients” from stage one are factors that can result in stage two features. By a process of floods and droughts and by increasing the sediment supply beyond the sediment transport capacity or reducing the sediment transport capacity beyond the sediment supply such as from a flatter slope or reservoir backwater, channel aggradation will develop which can lower the bank height and thereby lowering the channel conveyance capacity. A lower channel conveyance capacity will lower the discharge required to achieve overbank flow by increasing the stage of a given discharge.

5.3 Stage Three : Accelerators

Simulations performed by Dr. Kiyoung Park demonstrate that it requires a timespan of several years to aggrade the channel 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 season. These accelerating factors include: bridge/bend effects, a high Rouse number, overbank roughness, vegetation encroachment, and width-to-depth ratio changes.

Lower sediment transport capacity and therefore channel aggradation may be the result of a lower flow velocity due to a greater flow area from backwater effects as shown in Figure 5.5 below. Backwater effects may result from obstacles such as bridges or bends.

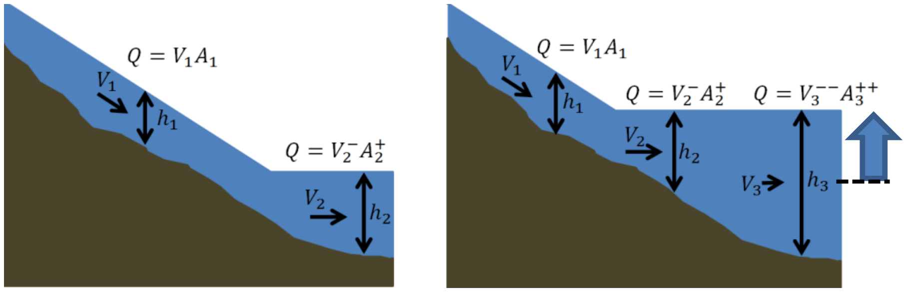


Figure 5.4: Backwater Influence on Flow Velocity

Besides lowering the sediment transport capacity, a lower flow velocity may also contribute to overbank flows and a higher Rouse number. This impact on the Rouse number however does not appear to have been significant 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 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 channel therefore increases and the velocity profile decreases. Also, since the channel is perched, the overbank flows are disconnected from the main channel and do not immediately return and since the high velocity flows are lost overbank, the shear velocity decreases 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.

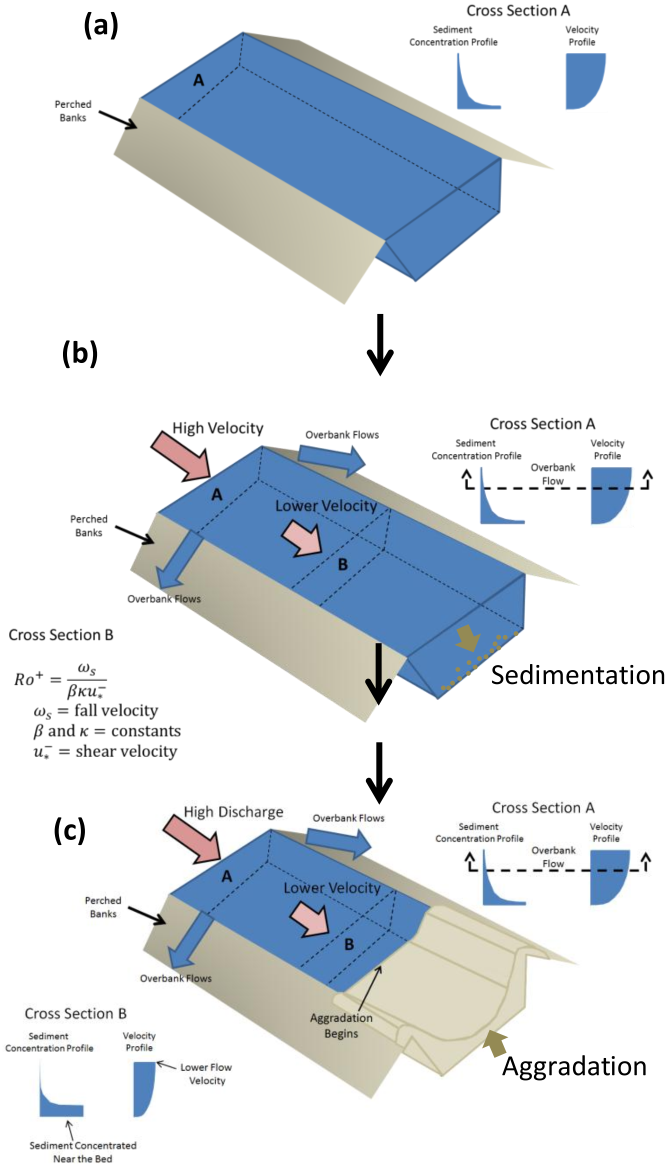


Figure 5.5: Channel Aggradation due to Overbank Flow

Besides floods and droughts producing a wider channel, this process also invariably leads to variations in the channel width as additional factors influence the degree of erosion and sedimentation. These variations may also lower the sediment transport capacity by dissipating energy as the channel contracts and expands as well as raising the sediment concentration due to overbank flows.

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 not relevant. 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 perching then enables the sediment plugs to form since the overbank flows cannot immediately return to the channel. An avulsion refers to the flows from a river forming a new channel and thereby leaving the previous channel. After the formation of a sediment plug, the water from the channel is forced to flow overbank. If the channel is perched then once this water has flowed overbank then it will not return since it will have reached a lower elevation than the channel. Then after an adequate amount of 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.

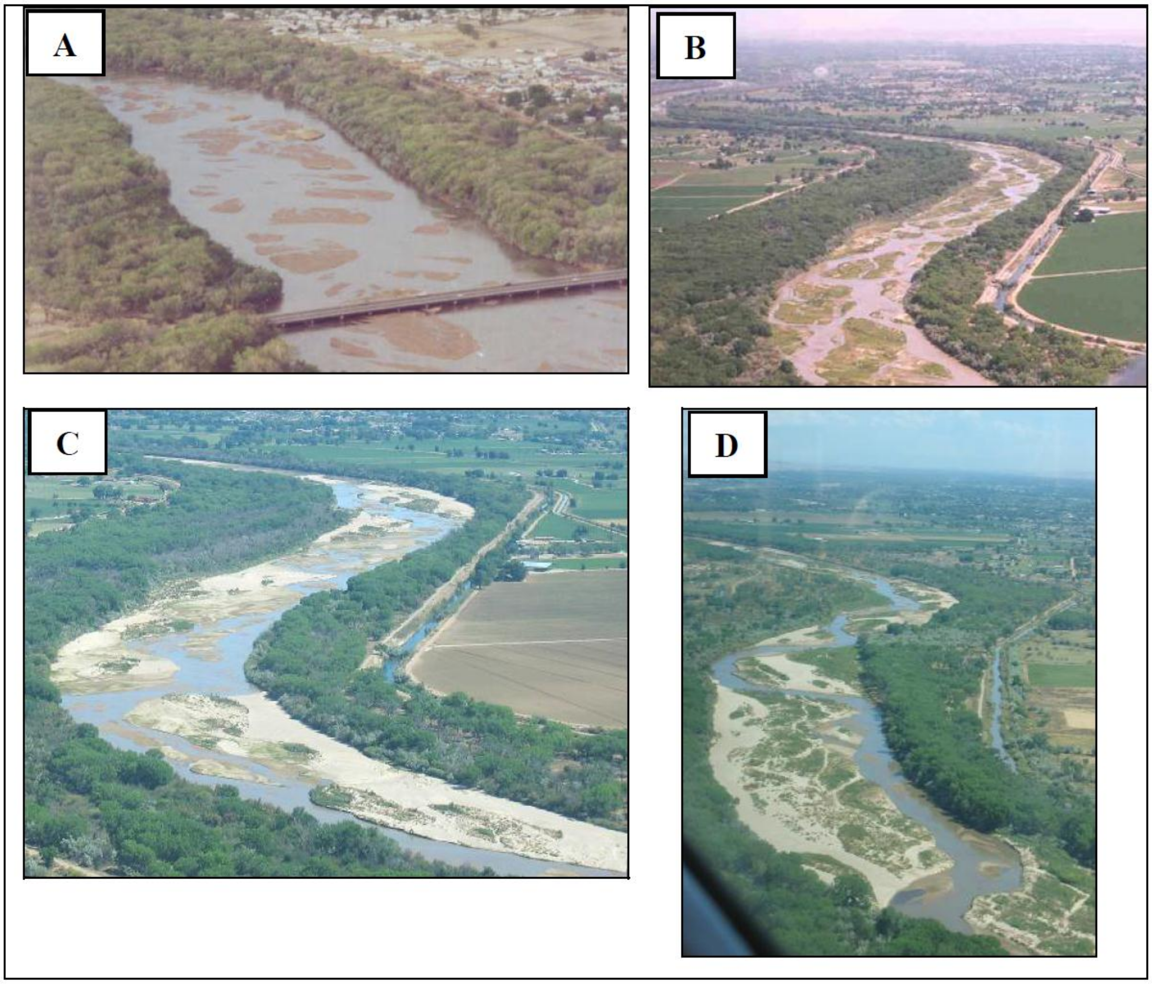


Figure 5.6: Formation of Levees on the Middle Rio Grande near Belen, New Mexico where A) 2000, B) 2002, C) 2005, and D) 2006 [Massong, T., Makar, P., and Bauer, T. 2010]

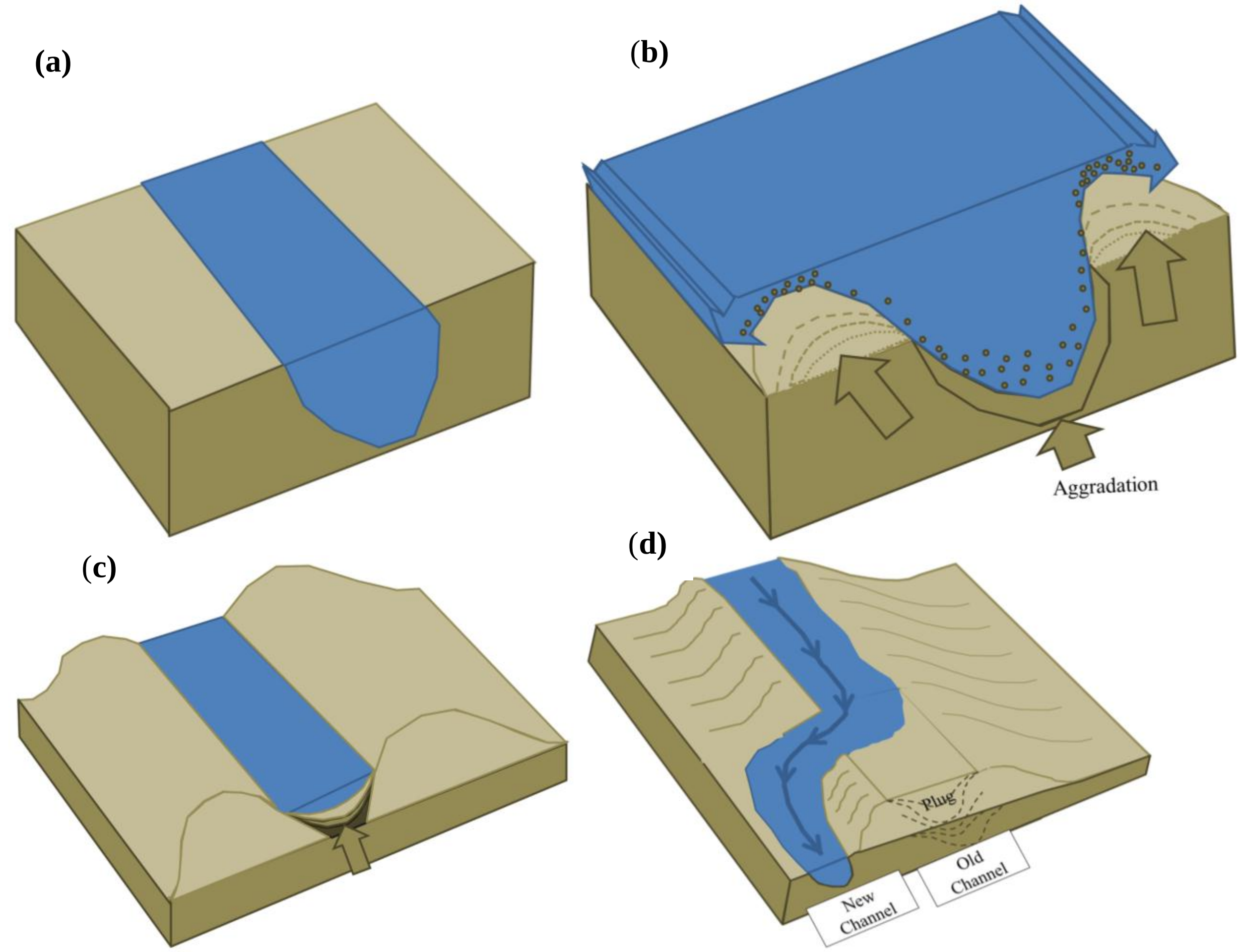


Figure 5.8: Formation of Natural Levees, Perching, and Avulsion

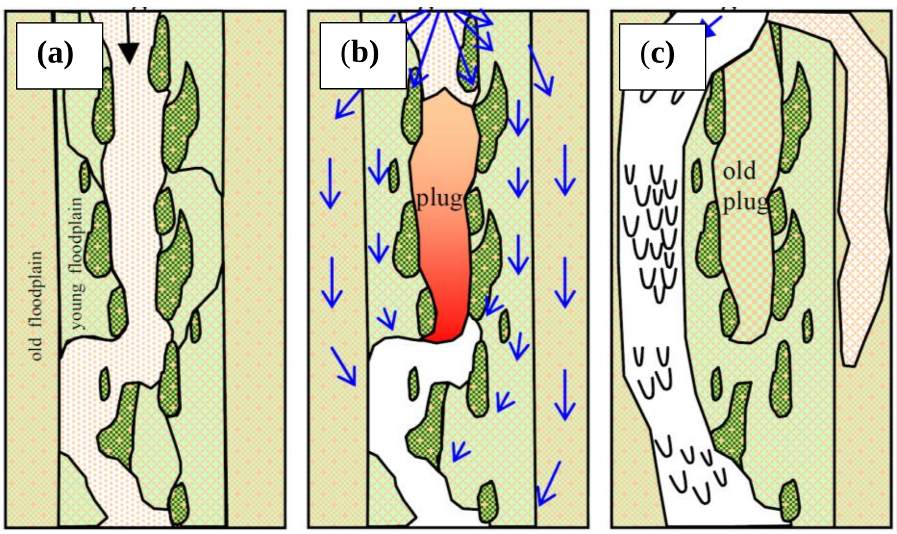


Figure 5.9: Formation of a plug and avulsion upstream from a sharp bend [Massong, T., Makar, P., and Bauer, T. 2010]

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 rate of aggradation and the likelihood of a sediment plug. Other accelerating factors are associated with periods of floods and droughts such as overbank roughness including 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 and then during flood periods when the flood 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 this process by reducing the flow area as the flow depth decreases and by reducing the sediment transport capacity as the width-to-depth ratio increases.

The overbank flows necessary for perching and the sediment plug formation are increased due to accelerating factors which raise the stage for a corresponding discharge and enables a much greater proportion of clean water to flow overbank than sediment. 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*

The channel has narrowed 40% between 1962 and 2002 and channel capacity has decreased over time (77% at Bosque plug area). The channel narrowing and vegetation encroachment toward the main channel caused the 50% increase of the representative composite roughness between 1992 and 2002 at 5,000cfs discharge. Accordingly sediment transport capacity has decreased 45%. The historic sediment plugs occurred at the sub-reaches 3 and 6 had lower transport capacity compared with adjacent sub-reaches. The decrease of channel width (40% over 40 years) does not cause significant increase of sediment transport capacity (0.6-0.2= 1.1, 10% increase over 40 years), while the increase of roughness (50%) causes considerable loss of sediment transport capacity (45%). Therefore geometric factors induce more overbank flows and channel bed aggradation.

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

While the cross-section of the Bosque plug was wide with a relatively wide floodplain, the Tiffany plug cross-section was narrow and perched with a considerably wider floodplain, causing significant loss of flow and sediment. The perching ratio has increased (13% →87%) and bank depth has decreased 51% between 1992 and 2002. The perching and lower bank depth facilitated more overbank flows and 13 ~ 20% loss of water between the San Acacia gauge and the San Marcial gauge.

Sediment concentration profile can be determined by the Rouse equation. Over time, particle size has coarsened (0.2mm → 0.25mm) and the width/depth ratio has increased (129 → 229) between 1992 and 2002. Accordingly, the Rouse number has increased and sediment concentration profile became more concentrated near the bed. The Rouse number ranged from 0.6 to 1.7 from 1992 to 2002. The high Rouse number (Ro >1.4) and near-bed sediment concentration profile accelerate the aggradation rates (4 ~ 7 times faster) than for uniform-concentration profiles. In order to fill the main channel, about 3 months is needed when the overbank flows is considered only. However, the high near-bed concentration shortens the plug formation time to 20 days. Since snowmelt floods more than bankfull discharges last less than 2 months, the acceleration factors are essential for sediment plug to form.

◦*Analysis of the most important factors*

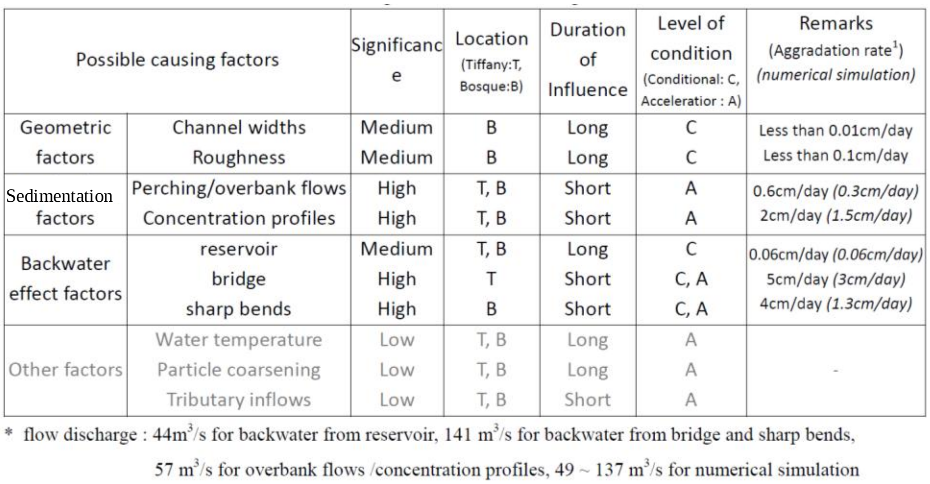
The base level of the Elephant Butte Reservoir has influenced the upstream channel bed elevation over time and therefore provides the basic condition for a sediment plug. Backwater effects from the reservoir can fill the reservoir by aggrading seven feet over the 25.5 mile long channel in roughly ten years with an average flow discharge of 1,550 cubic feet per second. By lowering the reservoir level, the channel capacity increases which then decreases the backwater effect and reduces the likelihood of a sediment plug.

Besides the reservoir, the backwater effect from the railroad bridge and sharp bends explain why the historic sediment plugs formed at particular areas, therefore these two parameters can be classified as local triggering factors. The San Marcia railroad bridge pier contraction and congested abutments generate about one foot high backwater which propagates to the Tiffany plug area (1.6 miles upstream). The upstream channel bed around the San Marcial Railroad Bridge (Agg/deg 1702) has aggraded consistently (12 feet increase between 1979 and 1987) and this is likely influenced by the backwater from the bridge and with some lag time by the backwater from the reservoir levels.

Unlike the Tiffany plug area which experienced significant backwater from the railroad bridge, the Bosque plug was influenced by sharp bends which caused 1.6 feet of backwater which propagates roughly one mile upstream. This backwater can therefore influence the channel aggradation since the Bosque plug was located 0.6 miles upstream from the sharp bends and it was estimated to only require seventeen days for the main channel to fill the 2.85 foot height of the channel.

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 (1% decrease per year). Owing to the increase of overbank flows, sediment concentration profiles speed up the main channel aggradation, causing a sediment plug to form within a matter of weeks, thus these two factors are the most significant factors (1.3ft / 20 days= 2 cm / day).

In a view point of significance, perching/overbank flow and sediment concentration profile can be considered as the primary causing factors of sediment plugs, followed by the backwater effects from bridge and sharp bends. Without the temporal changes of channel widths and roughness, the occurrence probability of a sediment plug will decrease significantly. On the other hand, causal factors can be divided into two groups depending on the plug location. The Tiffany plugs have been more affected by the backwater effect from the reservoir and railroad bridge, while the Bosque plug was more influenced by the decrease of channel width/channel capacity, roughness, and sharp bends. Sediment concentration profiles and overbank flows were commonly significant at both plug locations. As shown in Table 6.1,when the reservoir level is high for a long period of time and a long and high snowmelt flood occurs, a new sediment plug may form around the historic sediment plug location(aggradation rate $\Delta z > 2 \sim 5 \text{cm} / \text{day}$).Water temperature, coarsening of bed material, and tributary sediment inflows also can be categorized as possible factors, but there was no significant proof from the given data and documentation.



Possible causing factors		Significance	Location (Tiffany:T, Bosque:B)	Duration of Influence	Level of condition (Conditional: C, Accelerator : 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

Future research concerning the conditions of the San Marcial Bridge such as the pier angle and pier scour as well as its conveyance capacity and nearby cross-sectional changes particularly during floods would be useful to further assess the significance of this sediment plug formation factor.

Physical modeling is also recommendable to deeply understand the mechanics of backwater and sedimentation behind the bridge piers. In addition to the bridge piers and abutments, bridge girders also augment the backwater effect at high flow discharge. The submerging effect due to bridge girders cause more extensive flooded areas. Also, sharp bends were observed after 2006 but the reason for their formation downstream from the Bosque plug is not fully understood. Monitoring and understanding the process of sharp bend development also helps to understand the mechanics of the Bosque plug formation.

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 tributary sediment inflow in the previous years may present a factor for this pattern. Data gathering from five arroyos in the study area would be required for this study to lead to meaningful conclusions.

Backwater effects from the reservoir, bridge, and sharp bends was roughly simulated to estimate the time to influence upstream channel bed elevation. The relationship between reservoir levels and upstream channel aggradation/degradation is valuable to establish standard dam operating procedures to prevent the Tiffany plug formation. Investigation of how the backwater effect responds to the channel bed elevation through physical and (2-D or 3-D) numerical modeling will assist in the determination of the increase of water depth and its effect on the channel sedimentation. Since the existing bridge backwater equation was roughly developed based on a fixed-bed channel, a mobile-bed equation also needs to be investigated.

Vegetation encroachment has been significant over time. In addition to the vegetation encroachment in terms of vegetated area, vegetation density also needs to be studied to accurately estimate the resistance to flow. Increases in roughness due to channel planform also deserve to investigate for obtaining accurate total roughness. Roughness coefficients in accordance with local vegetation conditions need to be studied in further research, since the overbank flow is a primary factor in sediment plug formation and roughness is a key factor that causes the overbank flow.

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