CHANNEL CHANGES ON THE MIDDLE RIO GRANDE

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ABSTRACT

The Middle Rio Grande (MRG) has changed dramatically over the last century as a result of both natural and human-caused alterations in the watershed and channel. The observed channel morphology is constantly changing as the MRG seeks to balance the movement of sediment (sediment supply) with the energy available from the flow of water (sediment transport capacity) (Schumm et al., 1984). An imbalance between sediment transport capacity and sediment supply is a key cause of most channel and flood plain adjustments (Lane, 1955; Schumm, 1977) and this condition has been observed on the Middle Rio Grande. Factors affecting the imbalance between sediment transport capacity and sediment supply have been categorized as drivers of adjustment and controls on adjustment.

Important drivers on the MRG include flow frequency, magnitude and duration; and sediment supply. Controls on recent channel adjustments on the MRG include bank stability, bed stability, base level, flood plain lateral confinement, and flood plain connectivity. The influence of drivers and controls along the MRG is variable, but commonalities have been identified. It is the commonalities in the river's responses to drivers and controls present that help identify and separate the MRG into reaches with similar trends. The relationship between sediment transport capacity and sediment supply is fundamental to anticipating future changes in reach trends and the direction of river responses. Observed reach-based trends include Channel Narrowing, Vegetation Encroachment, Degradation, Increased Bank Height, Bank Erosion, Coarsening of Bed Material, Aggradation, Channel Plugging with Sediment, and Perched Channel Conditions.

CHANNEL CHANGE FACTORS

The Middle Rio Grande (MRG) between Cochiti Lake and Elephant Butte Reservoir (Figure 1) has changed dramatically over the last century as a result of both natural and human-caused alterations in the watershed and channel. The channel conditions of a river result from geomorphic processes and the natural and anthropogenic influences on those processes. "Because alluvial channels are open systems with mobile and deformable boundaries, they have the ability to self regulate to the imposed flow and sediment load" (Goudie, 2004). The observed channel morphology of a channel changes over time because rivers seek to balance the movement of sediment (sediment supply) with the energy available from the flow of water (sediment transport capacity) (Schumm et al., 1984). It is the imbalance between sediment transport capacity and sediment supply which is a key cause of most channel and flood plain adjustments (Lane, 1955 and Schumm, 1977).

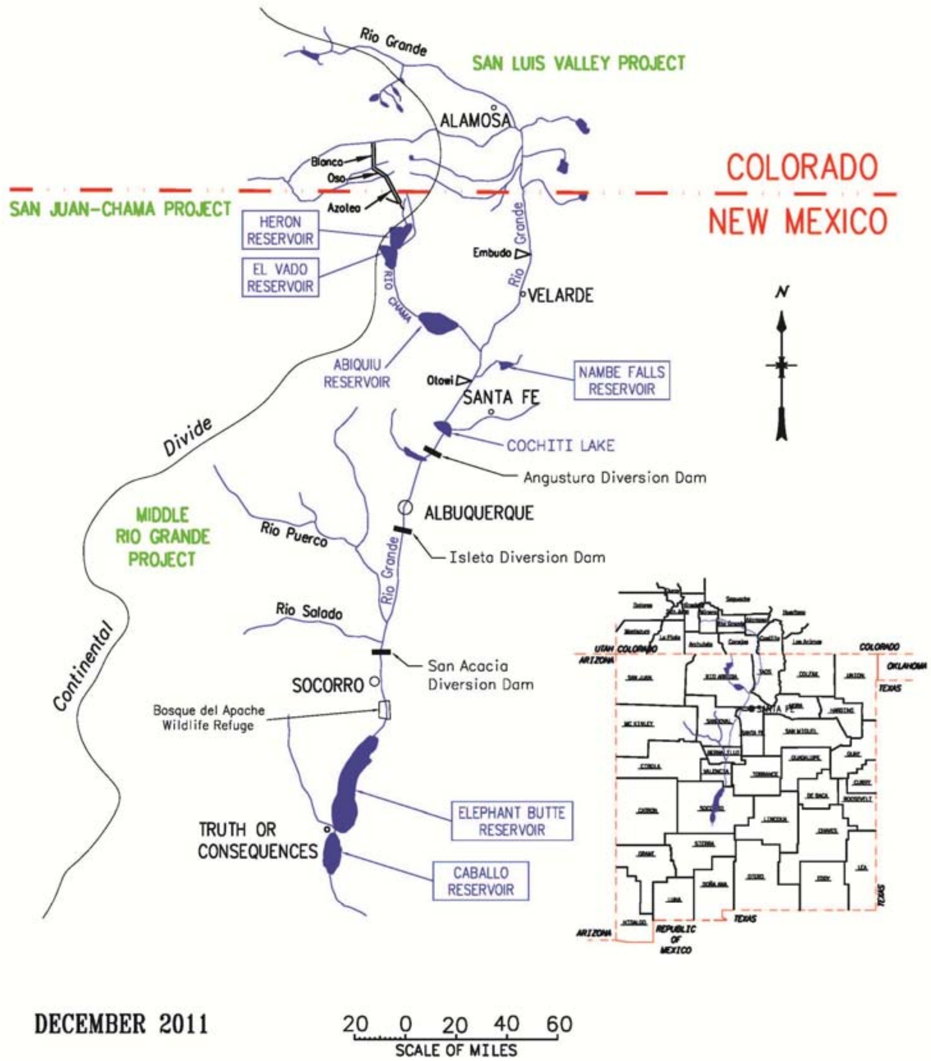
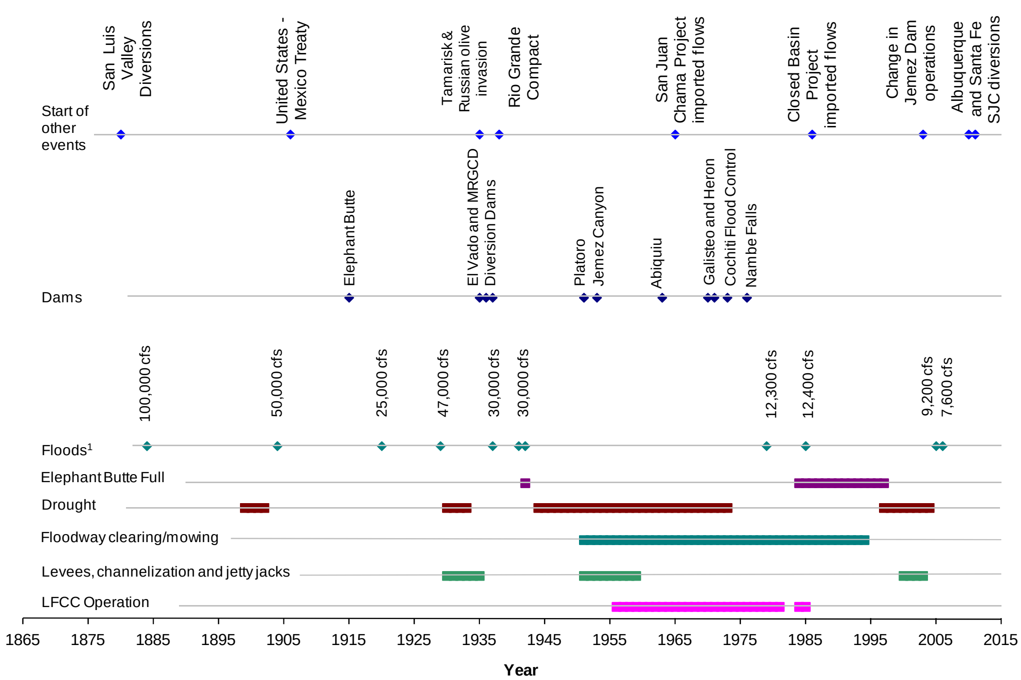


Figure 1. Location map (Cord Everetts, pers. com. January 2012)

Factors affecting the imbalance between sediment transport capacity and sediment supply can be categorized as drivers of adjustment and controls on adjustment. Important drivers on the MRG include flow frequency, magnitude and duration; and sediment supply. Water management on the Rio Grande has decreased stream flow variability and increased median stream flow occurrence for subsequent water years. Flood and sediment control dams have decreased the magnitude of the flood peak discharge and the volume of sediment delivered to the channel downstream of each facility. Upstream reservoir storage has also provided increased low flows to meet water user needs. In addition, changes in the frequency and intensity of precipitation patterns in the southwest have occurred.

Controls on recent channel adjustments on the Middle Rio Grande include bank stability, bed stability, base level, flood plain lateral confinement, and flood plain connectivity. Bank stability can be affected by natural (e.g., riparian vegetation) or mechanical (e.g., riprap) means. Similarly, bed stability can arise from channel armoring through bed material coarsening or from constructed cross channel features. An example of a base level control is a change in pool elevation of a reservoir, resulting in an upstream channel response, such as channel degradation or aggradation. Levees and geologic outcrops can create lateral confinement of the flood plain and limit channel migration. A well-connected flood plain dissipates the energy of flood flows, reducing the sediment transport capacity.

Figure 2 is a timeline of many of the significant events influencing the Middle Rio Grande. Large scale channelization and irrigation projects began in the 1930s with the initial levee, diversion dam and El Vado reservoir construction. The results of the comprehensive plan for the Middle Rio Grande Project were significant, which included channel rectification and maintenance, reservoir construction, rehabilitation of the MRGCD infrastructure, and other collateral improvements. The initial work on the Project, in the 1950s and 1960s, consisted primarily of river channelization, levee improvements, construction of the LFCC between San Acacia Diversion Dam and Elephant Butte Reservoir, and construction or rehabilitation of Platoro, El Vado, Jemez Canyon, Angostura, Isleta, and San Acacia Dams. Earlier dam construction includes Elephant Butte (1916) and Caballo (1938) dams; later dam construction includes Cochiti (1975) and Galisteo (1970) Dams. There are also several diversion dams present between Velarde and Otowi gage.



[1] Floods are measured at various gauges

Figure 2. Timeline of many significant events on the Middle Rio Grande

Agriculture (including irrigation infrastructure) is present near much of the river as are populated areas (both cities and Pueblos) which were originally located to be near water. Several bank protection projects have been constructed to protect these locations and/or the levees that shield them. These include placement of Kellner jetty jacks, riprap, and most recently using techniques such as bioengineered banklines, flow redirection, and grade control.

REACH-BASED TRENDS

Current and historical geomorphic trends are observable adjustments of the river's self-regulating response to move towards the condition of balance between sediment transport capacity and sediment supply. The influence of drivers and controls along the MRG is variable, but commonalities have been identified. It is the commonalities in the river's responses to drivers and controls present that help identify and separate the MRG into reaches with similar trends. Several major current trends have been observed on the MRG, although not all on every reach. These trends and their applicability to the MRG are discussed in the sections below. The relationship between sediment transport capacity and sediment supply is also identified for each trend. This relationship is fundamental to anticipating future changes in reach trends and the direction of river responses.

Channel Narrowing *(sediment transport capacity can be either greater or less than sediment supply).*

Based on historical accounts and survey data, the MRG has narrowed significantly over the last century (Makar 2010). The channel narrowing that has occurred since 1949 is likely the result of some combination of decreased peak flows, increased low flow duration, decreased sediment supply, increased bank stability, increased flood plain lateral confinement, and decreased flood plain connectivity. The particular combination is dependent on reach-specific conditions.

When sediment transport capacity is greater than sediment supply, bed degradation or channel incision can occur. More bed degradation occurs in the channel thalweg (deepest area of the channel) than in shallower areas resulting in channel narrowing. For the case where the sediment transport capacity is less than the sediment supply, channel narrowing can occur as a result of sediment deposition in the form of medial or bank-attached bars during high flows (lateral accretion). When subsequent flows are lower, these bars may not remobilize and so result in channel narrowing.

Vegetation Encroachment *(sediment transport capacity can be either greater or less than sediment supply)***.**

Significant vegetation encroachment into the active channel has occurred historically (Scurlock, 1998; Lagasse, 1980; Makar et. al., 2006) and again during the recent drought cycle (Figure 3). This is likely the result of decreased peak flows and increased low flow magnitude and duration. Increased low flows provide water more consistently and encourage vegetation growth near the channel. At the same time, the decreased peak flows have insufficient shear stresses to uproot the established vegetation. Existing hydrology and flood control operations for safe channel capacity make an event large enough to destabilize the current vegetation extremely unlikely on the MRG. Thus, it is likely that on a reach scale, bank erosion and subsequent bank migration will be restricted, provided the bed elevation does not degrade below the root zone of established riparian vegetation. The planform change from a fairly wide and braided active channel to a much narrower single thread as seen in Figure 3 is occurring with similar encroachment in many reaches.

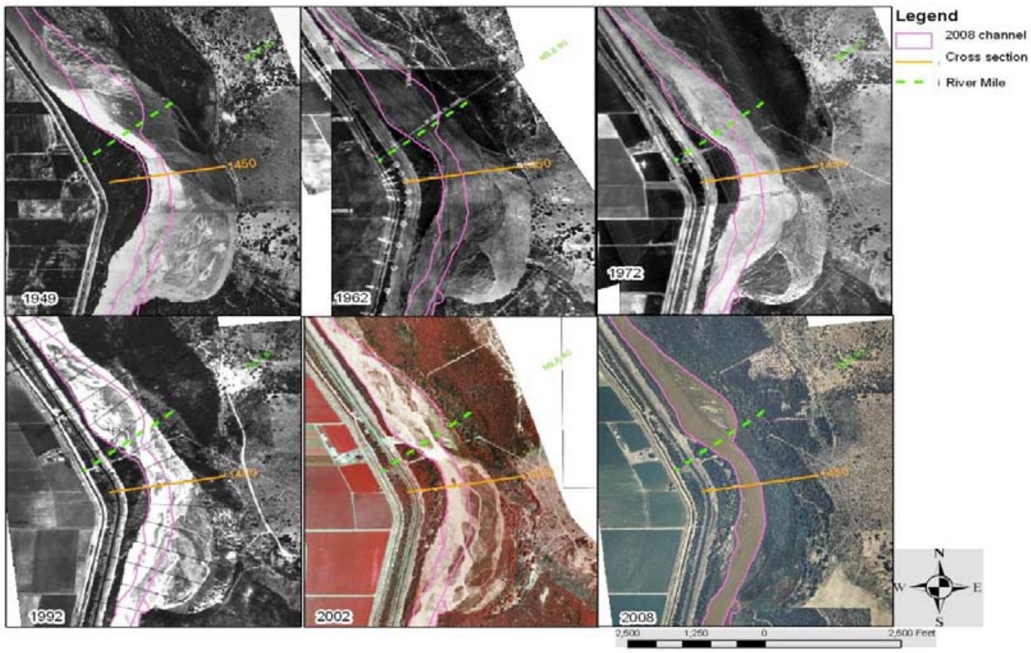


Figure 3. Channel location/planform changes over time, just upstream of Highway 380 Bridge, San Antonio, New Mexico.

Conditions where the sediment transport capacity is greater than the sediment supply can lead to bed degradation or channel incision, as described above in the section on channel narrowing. The channel incises more along the thalweg than in other portions of the river bed; therefore, adjoining, higher areas of the river bed are inundated and mobilized less frequently, which creates a condition conducive to vegetation growth. This vegetation growth then reduces the width of the active channel. Conditions in which the sediment transport capacity is less than the sediment supply can result in sediment deposition. These deposits can become vegetated if they are not remobilized, thereby narrowing the channel.

Increased Bank Height *(sediment transport capacity can be either greater or less than sediment supply):*

The increase in bank height that has occurred is likely the result of some combination of decreased sediment supply, increased bank stability, low bed stability, lowered base level (e.g. Elephant Butte reservoir pool elevation), increased flood plain lateral confinement, and flood plain connectivity (lower velocities in flood plain

cause sediment to settle and result in vertical accretion in flood plain). The particular combination is dependent on reach-specific conditions.
If the sediment transport capacity is greater than the sediment supply, bank height increases can occur as a consequence of channel degradation or incision. When sediment transport capacity is less than sediment supply, bank height can increase due to sediment deposition in the flood plain (vertical accretion); however, if there is channel aggradation, the resulting bank height change may be smaller due to sediment accumulation in the river bed. Vertical accretion also occurs in over bank areas in reaches where the sediment transport capacity is greater than the supply during bank overtopping flow events. This is primarily due to the lower sediment transport capacity of the flood plain when flows go over bank. An example of vertical accretion on the MRG is the observation of surface deposits during the high flows in the spring of 2005 on vegetated bars and islands within the Albuquerque area (Meyer and Hepler, 2007). Similarly, after the 2005 spring runoff ended, field observations indicated significant vertical accretion occurred on the bars, islands and flood plains in the Isleta to Rio Puerco reach, especially near areas of flowing water (Bauer, 2009). The higher features subsequently require larger-magnitude runoff events to inundate.

Bank Erosion *(sediment transport capacity is greater than sediment supply)***.**

The bank erosion that has occurred is likely the result of some combination of decreased sediment supply, low bank stability, lowered base level (e.g. Elephant Butte reservoir pool elevation), increased flood plain lateral confinement, and decreased flood plain connectivity. The last three all contribute to higher flow energy which adds to the river's ability to self adjust through bank erosion. The particular combination of factors contributing to bank erosion is dependent on reach-specific conditions. Bed material coarsening (discussed below) can make the bed more resistant to erosion than the banks. When the bank stability is less than the bed stability, the channel responds to unmet sediment transport capacity by bank erosion and lengthening of the channel, thereby increasing sinuosity. An overly-lengthened channel may reduce sinuosity when a more hydraulically efficient cutoff channel develops and straightens that bend. It should be noted, however, that on the reach scale, the MRG is generally classified as having low sinuosity.

Vegetation can make the banks more erosion resistant than the bed, and may make the channel narrower. When sediment supply is less than capacity, this can contribute to channel bed degradation or incision, which can lead to taller banks that are often less stable, again resulting in bank erosion. At present, the bank heights in several reaches of the MRG are generally tall enough for the river's thalweg to intersect the banks beneath the root zone of the riparian vegetation, creating conditions in which the banks are more easily eroded. This coupled with a single-channel planform and a thalweg that alternates between the banks has led to the development of a series of migrating bends in those reaches. Figure 4 shows a bend that initially formed in 1998/1999 as a small bank line erosion spot with rapid growth in 2004-2006. In 2006, a cutoff channel begins to form which evolves to take more flow than the channel along the outside bank line and by 2008, the cutoff channel has captured all non-channel forming flow and the outside boundary begins stabilizing.

Massong et.al (2010) presents a planform evolution model that describes these changes.

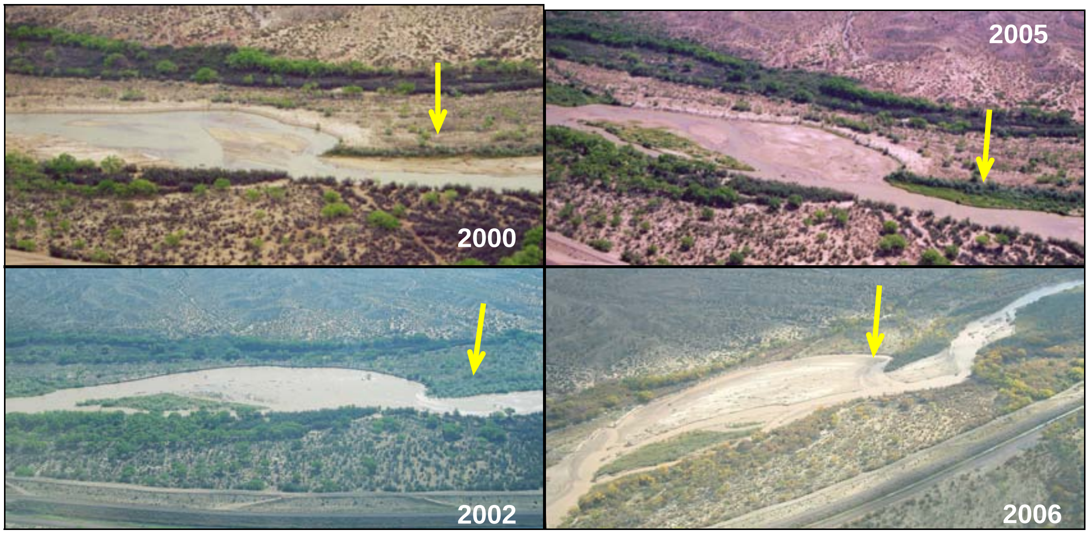


Figure 4. Laterally migrating bend located about six miles downstream from San Acacia diversion dam. Yellow arrow identifies the same location.

Bed Material Coarsening *(sediment transport capacity is greater than sediment supply).*

As the channel bed degrades or incises, bed sediment of finer sizes, which are more easily transported, are removed from the bed while coarser sizes remain. Figure 5 presents the median size of the bed material over time in the MRG and shows the coarsening trend. Coarsening bed material is likely the result of some combination of decreased sediment supply, increased bank stability, low bed stability, availability of coarser material in the channel bed and banks, lowered base level (e.g. Elephant Butte reservoir pool elevation), increased flood-plain lateral confinement, and decreased flood-plain connectivity. The last three of these factors all contribute to higher flow energy, which adds to the river's ability to move bed material. Under these conditions, the bed materials coarsen further, since the amount of energy to move a particle is proportional to its size. The particular combination of factors contributing to coarsening of bed material is dependent on reach-specific conditions. Bauer (2009) documents a significant coarsening of the bed material beginning in the 1980s just downstream of Cochiti Dam that extends to San Acacia Dam over time. The coarsening downstream of San Acacia is most likely the result of changes in both quantity and size fractions of tributary sediment loads.

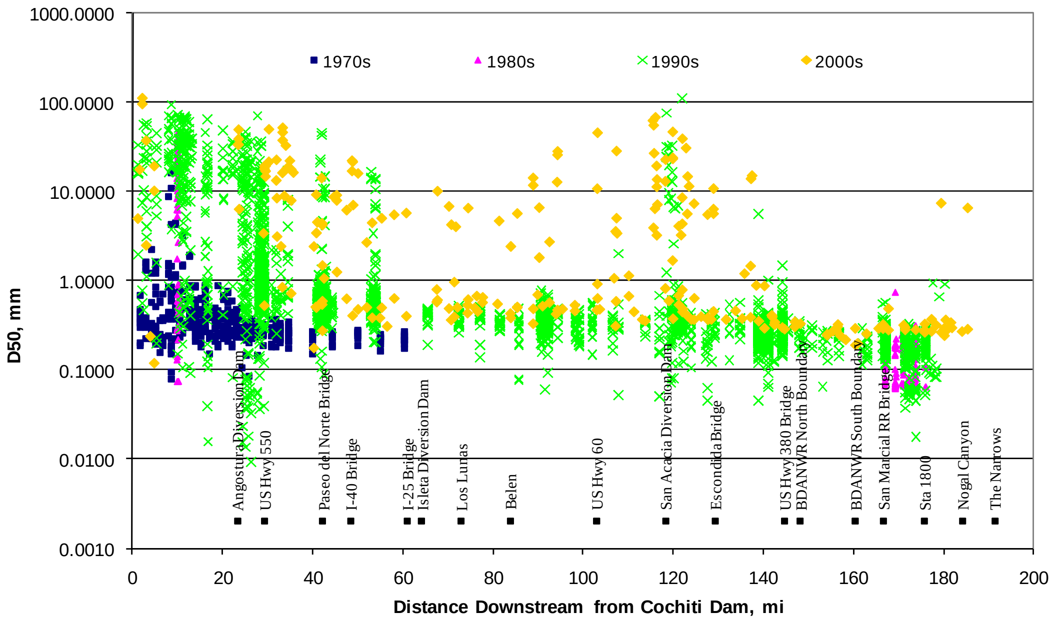


Figure 5. Median bed material size on the MRG over time (Bauer, 2009)

Channel Bed Degradation *(sediment transport capacity is greater than sediment supply).*

When banks are more resistant than the bed, the river seeks to increase its sediment supply by transporting additional sediment from the bed. The incision that has occurred is likely the result of some combination of decreased sediment supply, increased bank stability, low bed stability, lowered base level (e.g. Elephant Butte reservoir pool elevation), increased flood plain lateral confinement, and decreased flood plain connectivity. The last three factors all contribute to higher flow energy, which adds to the river's ability to self-adjust through channel bed degradation. The particular combination of factors is dependent on reach-specific conditions.

Incision on the MRG between Cochiti and Isleta has been impacted most strongly by construction of Cochiti and Jemez Canyon Dams and these effects appear to be continuing to extend downstream. Figure 6 shows general degradation after 1972 upstream of Arroyo de la Parida. The lack of upstream sediment supply exacerbated the combined effects from the placed jetty fields of the more efficient channel and the reduction of bank material as a sediment source and resulted in significant degradation of the river channel and disconnection from the adjacent flood plain. Another example of this trend in the lower reaches of the MRG occurred as a result of the Elephant Butte Reservoir pool lowering. The low elevation of Elephant Butte reservoir is one of the causes of erosion of the upstream channel and delta deposits that has led to channel degradation from the southern BDANWR to the pool. This effect has been exacerbated by the very low sediment supply downstream of plugs and channel fill. Due to these changes, the channel has become disconnected from the surrounding flood plain in some areas. The extent (depth and length) of degradation depends on the extent of the base level lowering, the duration that the reservoir pool is lower, and the reduction in upstream sediment supply. The incision throughout the MRG also has the effect of lowering the water table in the vicinity of the active channel, which diminishes the ability of the river to recharge perennial and ephemeral wetland areas.

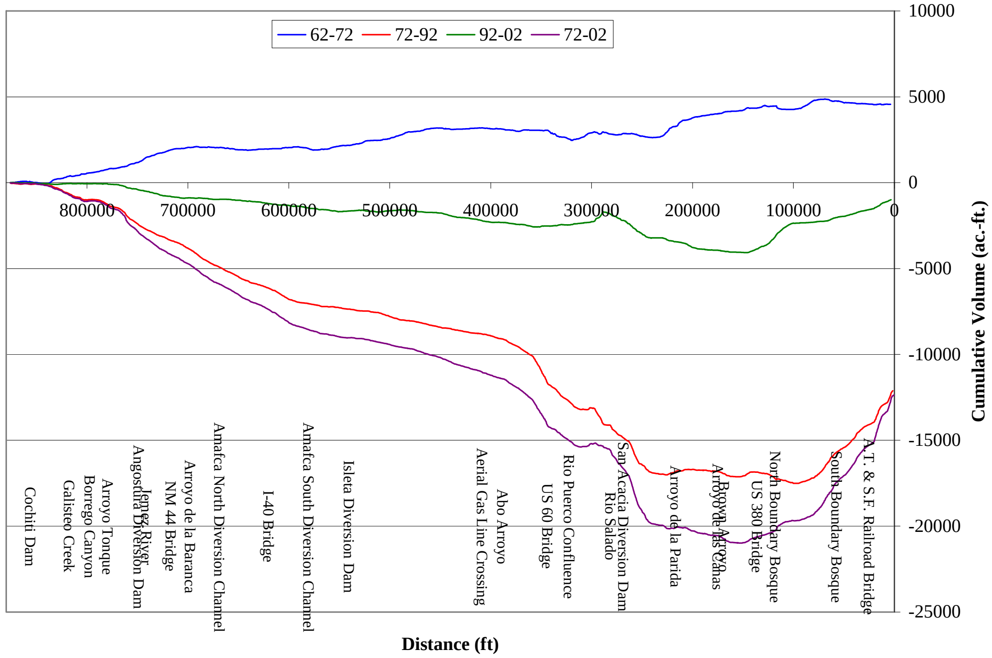


Figure 6. Single mass curve of change in channel sediment volume

Aggradation *(sediment transport capacity is less than sediment supply).*

Aggradation is likely the result of some combination of high sediment supply, low transport capacity, increased bank stability, higher base level (e.g. Elephant Butte reservoir pool elevation rising which causes flatter slopes and increased flow resistance upstream, which tend to decrease the channel's sediment transport capacity), increased flood plain lateral confinement (which causes increased aggradation, due to limitation of the available area for deposition), and increased flood plain connectivity. The particular combination of factors contributing to aggradation is dependent on reach-specific conditions.

When sediment deposition occurs, it can raise the bed elevation in both the main channel and the adjoining riparian zone. The extents and amounts are dependent upon the magnitude of the sediment transport imbalance; the greater the imbalance, the greater the deposition. The aggradation rate in the San Marcial area has been historically greater than any other reach. From 1900 to 1937, the riverbed aggraded more than 16 feet at the San Marcial railroad bridge. It has aggraded almost 13 more feet through 1999 (Makar, 2009). The railroad bridge has been raised three times for a total of 22 feet (Van Citters, 2000). Prior to 2005, the average bankfull discharge throughout the San Antonio to RM 78 reach of the MRG was approximately 3,000 cfs; in 2008 field observation indicated the area from approximately RM 84 to 81 had a bankfull discharge of less than 1,000 cfs, indicating that this reach experienced substantial channel filling in that time period. Figure 6 shows general aggradation for the entire reach between 1962 and 1972 and for all time periods from San Antonio at the US 380 Bridge and downstream. This subreach is strongly influenced by the elevation of Elephant Butte Reservoir (Elephant Butte Dam was closed in 1916) as well as sediment and water discharge magnitude, duration, and frequency (Levish, 2010). During wetter periods with a full reservoir, these reaches continue to experience high levels of aggradation, alternating with degradation influenced by recession of the reservoir during drier periods and lower incoming sediment load.

Channel Plugging with Sediment *(sediment transport capacity is less than sediment supply).*

Channel plugging is likely the result of some combination of high sediment supply, channel aggradation, lateral constraints restricting channel location (e.g. preventing avulsions) and flood plain (e.g. levees), higher base level (e.g. Elephant Butte reservoir pool elevation), and increased flood-plain connectivity. A higher base level and an increase in flood plain connectivity can reduce the sediment transport capacity of the river, which over time builds conditions that support the formation of sediment plugs. The particular combination of factors that lead to plugs is dependent on reach-specific conditions.

As sediment deposits in the main channel, flow from the top of the water column can go over bank at lower discharges. Because there is a lower concentration of sediment being transported at the top of the column, the over bank flow removes a higher percentage of water volume than sediment load. As a result, the main channel sediment transport capacity is reduced but the sediment supply decreases by a smaller percentage. This results in additional deposition in the main channel. Continued over bank flows with sediment accumulation in the main channel further reduces main channel flow capacity. This process can continue until sediment completely fills the main channel (Boroughs et al., 2011).

Perched Channel Conditions *(sediment transport capacity is less than sediment supply).*

Perched channel conditions, where the river channel is higher than adjoining riparian areas in the floodway or land outside the levee, are likely the result of some combination of increased bank and bed stability, higher base level (e.g. Elephant Butte reservoir pool elevation), and increased floodway lateral confinement.

As a riverbed raises and sediment-laden waters flow over bank into the riparian zone, flow velocity decreases, which causes sediment deposition, which in turn raises the river bank height. Continued bed raising and over bank deposition results in a channel bed, bordered by natural levees, which is higher than the adjoining areas between levees or geologic formations. If sediment deposition continues unevenly across the floodway, and is more pronounced in the main channel and immediately adjoining flood plain areas, flood plain areas further away from the main channel may become significantly lower than the main channel area. This condition is known as a perched channel (Figure 7).

A river corridor can also become higher than land areas outside the levee when sediment deposition occurs across the restricted flood plain. The historic valley flood plain accessible by the MRG has been significantly reduced by levees paralleling much of the river. Subsequent aggradation between the levees has rendered that area higher than the adjoining valley for most of the MRG between Angostura Diversion Dam and Elephant Butte Dam. This process is most pronounced on the Rio Grande downstream of San Antonio. Perched channel conditions can be a factor in channel plugging.

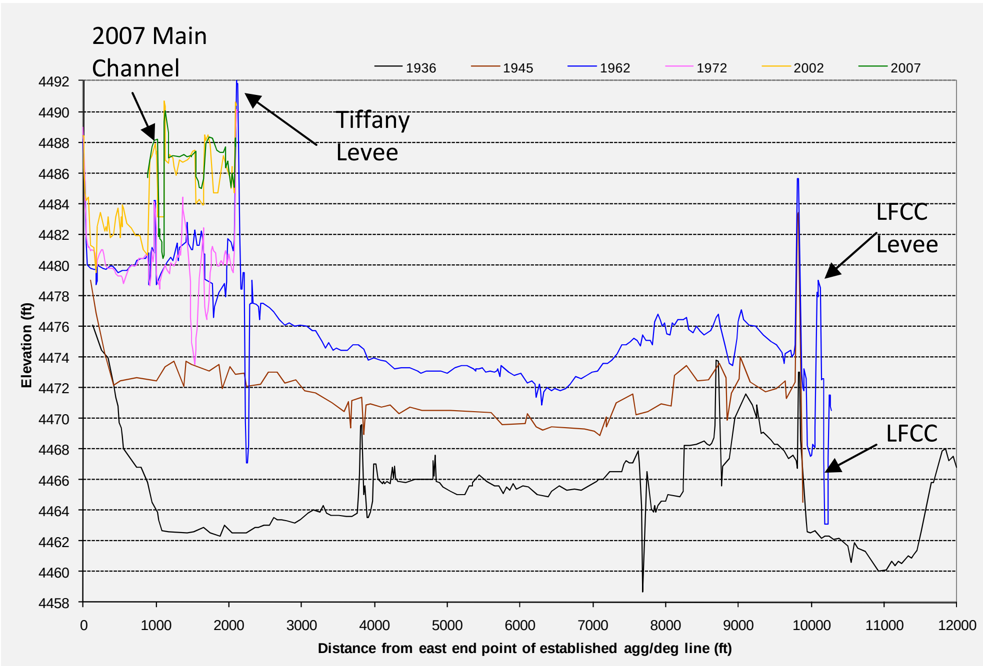


Figure 7. Cross section 1670 over time (approximately 6.5 miles downstream of the South Boundary of the Bosque del Apache National Wildlife Refuge)

Increased Channel Uniformity *(sediment transport capacity can be either greater or lesser than sediment supply).*

On a reach scale in the MRG, morphological features (width, depth, velocity, flood plain connection, backwater features, etc.) that were once significantly variable are becoming more uniform. This increase in channel uniformity results primarily from the decreased variability in flows, sediment supply, and lateral bank stabilization. The decreased flow variability is a result of flow control, which causes lower peaks and more constant low flows. Lower peaks mean less energy is available to rework the channel and flood plain. The channel banks and flood plain do not erode as much and sediment remains stored in the banks. More constant low flows mean vegetation can grow more easily (see vegetation encroachment section above), further reinforcing the existing bank line and perhaps storing even more sediment.

On the MRG, storage of sediment behind dams in both the main stem and tributaries, less watershed erosion due to land use changes, and bank and bed stabilization have so reduced the sediment supply such that, even with lower peaks, the sediment transport capacity is greater than the sediment supply for most of the MRG. Conditions in which the sediment transport capacity is greater than the sediment supply lead to river bed degradation or channel incision, as previously described. As the channel incises and narrows, the active channel planform moves from a wide braided channel with extensive mobile bars to a narrow single channel with few mobile bars. The wetted channel at higher flows changes from being wide and shallow with significant topographic and hydraulic variations, to narrow and deep with limited space for topography and hydraulic variations. These changes contribute to increased channel uniformity locally, and also on a reach basis as the irregularities of the natural channel become more and more alike. The general end result is a channel with more uniform slope and width, high steep banks, lower suspended sediment load, and coarser bed material.

Conditions in which the sediment transport capacity is less than the sediment supply lead to channel aggradation, as previously described. Since the majority of the MRG has lateral constraints, as the channel aggrades, the space between the constraints becomes elevated. This in turn raises the bed elevation of the main channel, creating greater opportunities for flooding and diminishing the topographical elevation variations between the main channel and the flood plain. Vegetation growth, as described in the section on vegetation encroachment, is encouraged by the smaller in-channel forces created by lower peak flows, and the greater connectivity between the main channel and the flood plain. Bars often attach to the bank as the channels fill in, decreasing bar mobility. Under these conditions, the active channel planform moves towards a narrow active channel with a more consistent width and limited sediment mobility.

Figure 8 illustrates one aspect of channel uniformity, the variability of the channel width within a reach. The maximum, 75th percentile, median, 25th percentile, and minimum reach average widths are shown. The narrowing of gap between these is an indication that widths are becoming increasingly uniform.

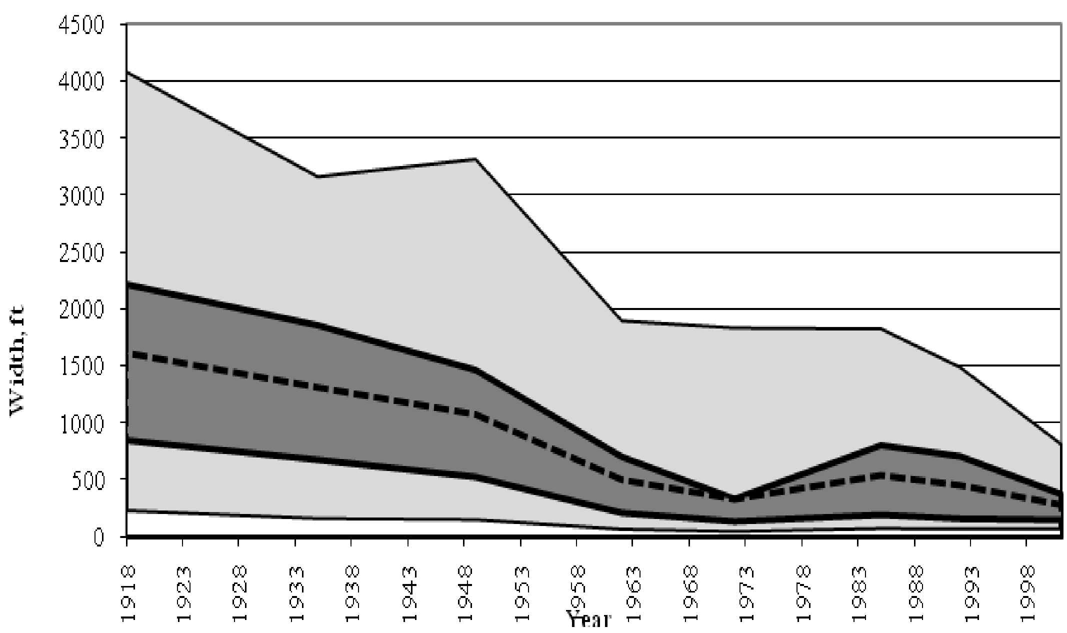


Figure 8. Average channel width over time between San Acacia to San Marcial

SUMMARY

The MRG is a complicated system and there are a variety of drivers and controls that feed into the actual changes seen on the system. The fact that many of these changes, both natural and anthropogenic, occurred contemporaneously on the Middle Rio Grande greatly complicates the task of interpreting the changes and basing predictions on them. Also confounding interpretation is that the changes can set up feedback loops that reinforce effects until a geomorphic threshold is reached, tipping the system into a different set of processes and effects. Rigorous data collection over multiple years and analyses and numerical modeling results can help separate the influences of these drivers and controls for better prediction of future channel responses to changes in the drivers. The relationship between sediment transport capacity and supply is key to anticipating future changes in observed trends and the direction of possible river responses. This relationship helps bridge the gap between observed trends of channel and flood plain adjustments and also the prediction of future trends by helping to identify commonalities on the way the MRG responds to drivers and controls.

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