ONE-DIMENSIONAL MODELING OF THE MIDDLE RIO GRANDE RIVER

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Abstract

A one-dimensional, mobile bed sediment routing model was utilized to obtain the future equilibrium slope of the Middle Rio Grande from Cochiti Dam downstream approximately 190 miles to Elephant Butte Reservoir. This information will be used by water managers to evaluate long term maintenance methods for the Middle Rio Grande. Modeling results are separated into 8 reaches for the purposes of this study.

Water year 1975 is representative of the gage records for the Middle Rio Grande for the post-1973 (Cochiti Dam) hydrology and this water year was repeated for numerical stability. Model geometry data is comprised of 234 cross sections, based on 105 representative sections and 129 interpolated cross sections incorporated to improve model numerical stability. The 78 available bed material grain size distributions were spatially applied to 78 of the 105 representative cross sections. Parker's transport equation coupled with Engelund-Hansen (Parker-EH) with a reference shear stress of 0.02 and a hiding factor of 0.2 was found to show the best fit to the sediment discharge Bureau of Reclamation Automated Modified Einstein Procedure (Holmquist-Johnson et al. 2009) data. Fine material was included in this modeling effort, as fine materials in large part dictate the properties in the downstream portion of the Middle Rio Grande, particularly those areas influenced by Elephant Butte Reservoir. The downstream boundary condition for the model was a fixed water surface elevation, representing the average pool elevation in 2008 of Elephant Butte Reservoir. Previous Reclamation studies (Bauer et al. 2006, Holmquist-Johnson 2004, Huang et al. 2005) identified 20 tributaries that have historically supplied significant flow to the Middle Rio Grande, where 19 of these also contribute significant sediment.

The one-dimensional model converged on a stable solution after a simulation period of approximately sixty years. In general, the model results show minimal change in bed elevation for the Middle Rio Grande from Cochiti Dam downstream to about Arroyo de las Cañas (reaches 1-5). The Middle Rio Grande from Arroyo de las Cañas downstream to about River Mile 78 is depositional (reaches 6,7), and from River Mile 78 downstream to Elephant Butte Reservoir (reach 8), the results show some degradation in upstream areas which gets deposited downstream.

Sesitivity analysis was performed for the following parameters: the treatment of the diversion dams, the downstream boundary condition, and the sediment loads supplied by the tributaries. The first sensitivity removed the bed control created at diversion dams. The second sensitivity analysis assumed a full reservoir pool elevation at Elephant Butte. The third sensitivity analysis used the estimated tributary loads from RTI (1994), where the total annual sediment load value is 1.5 times greater than the annual sediment load as estimated by Reclamation (Bauer et al. 2006, Holmquist-Johnson 2004, Huang et al. 2005).

The three reaches upstream of the Rio Puerco confluence (reaches 1, 2, and 3) are in a state of relative equilibrium, as indicated by the relatively low slope change and depositional volumes. Sensitivity analysis showed that the results of the upstream three reaches are insensitive to tributary sediment inputs, model downstream boundary condition, and the erosional and depositional limits at the diversion dams. Reach 4 encompasses significant geologic and geomorphic transitions – as well as a channel spanning hydraulic structure – which makes reach 4 a transitional reach, separating the upstream 3 reaches from the downstream four reaches. Reach 4 is insensitive to downstream boundary conditions and erosional and depositional limits at the diversion dams, but is highly sensitive to the tributary sediment inputs, particularly the Rio Puerco which constitutes the upstream extent of the reach. Reaches 4- 7 have high

sediment load delivered to them, leading them to be zones of deposition. The results of reaches 5, 6, 7, and 8 are sensitive to tributary sediment inputs and downstream boundary condition (i.e., reservoir pool elevation). Reach 8 – the longest and most downstream reach – is highly sensitive to the downstream boundary condition and may benefit in future analysis from being split into two sub-reaches for geomorphic characterization.

INTRODUCTION

The Middle Rio Grande valley between Cochiti Dam and Elephant Butte Reservoir is located in New Mexico and is represented by the blue line in the figure to the right. The Middle Rio Grande has been defined for river management purposes into 8 reaches. The reach numbering scheme and descriptions are provided in Table 1.

This area is a vital component to the economic vitality of the local region and provides a valuable ecological function. Various river management, engineering, and operational schemes have been applied since European settlement and continue currently to meet ever changing water resource management goals. These schemes include water resource development for irrigation and drainage, flood and sediment control, channelization, surface water delivery, and river restoration and rehabilitation. Numerous federal, state, local, tribal, and private entities all have responsibilities and interests for water resource management objectives in the valley.

Table 1 Reach definitions for the Middle Rio Grande

Reach	Description	Approx Length (mi)
1	Cochiti Dam to Angostura Dam	22.7
2	Angostura Dam to Isleta Dam	41.0
3	Isleta Dam to Rio Puerco	43.8
4	Rio Puerco to San Acacia Dam	9.9
5	San Acacia Dam to Arroyo de las Cañas	19.2
6	Arroyo de las Cañas to San Antonio Bridge	6.8
7	San Antonio Bridge to River Mile 78	13.3
8	River Mile 78 to River Mile 45.5	36.1

Extensive river channelization and sediment and flood control occurred at a large scale between the 1950's through the 1970's. Activities specific to the river channel in this period included various river training works involving many miles of steel jetties, cleared floodways, pilot channels, and a low flow conveyance channel. These activities occurred before the advent of federal laws intended to preserve and protect environmental resources (i.e. National Environmental Policy (1969), Clean Water (1972), and Endangered Species (1973) Acts).

In the decades following this period, channel maintenance involved clearing vegetation and debris for a defined active channel width (to maintain a nominal capacity) and maintaining its established channelization alignment. Maintenance practices changed in the mid 1980's and the late 1990's to focus on specific locations where river migration threatened nearby infrastructure, contrasting the fixed alignment methodology of the previous decade. In aggrading reaches, pilot channel maintenance continued to promote effective water delivery.

In the late 1990's, an immense environmental awareness took effect precipitated by the addition of the Rio Grande silvery minnow (*Hybognathus amarus*) in 1994 and the south western willow flycatcher (*Empidonaxt traili extimus*) in 1995 to the federal endangered species list. Reclamation reevaluated its river maintenance practices to more effectively address habitat needs to benefit endangered and threatened species. Maintenance planning strategies began looking at holistic, process-based, reach-wide approaches that incorporate habitat protection and enhancement.

River management strategies being considered for future implementation for the 21st century on the Middle Rio Grande fall into six basic strategies. These strategies are promoting elevation stability, alignment stability, maintaining channel capacity, increasing available area to the river, rehabilitation of the channel and floodplain, and managing sediment supply to reaches. To identify reaches with the highest potential to incorporate these strategies a one-dimensional (1D) sediment model was completed. Although constraints (infrastructure, politics, statutory requirements, etc.) limit the likelihood of a no action type alternative from being implemented, a no action alternative identified as "no maintenance future" (NMF) is a good basis for comparison for the six strategies listed above. This report will focus on the 1D model in which the channel adjustments are made in the vertical (NMF-V) direction with no change in width or channel alignment. Modeling of the six strategies listed above will not be discussed due to report page limit constraints.

SRH-1D MODELING

SRH-1D (Huang et al. 2007) is a one-dimensional, mobile bed sediment routing model that was employed to obtain a likely future equilibrium slope of the Middle Rio Grande (Varyu 2010). The model allows for vertical bed change but assumes that the channel width and length remain unchanged. Model input includes incoming upstream hydrograph, geometry, bed material, sediment load, a downstream boundary condition, and tributary contributions.

The water year 1975 was input as a repeating hydrograph because it is representative of the gage records for the Middle Rio Grande. This is based on assessing cumulative water volume and peak discharges for the following USGS gage records: San Felipe (08319000), Albuquerque (08330000), San Acacia (08354900 & 08354800), and San Marcial (08358300 & 08358400). Using a year-long hydrograph provides flow variability (unlike using a single representative discharge), and repeating that single year hydrograph increases the likelihood of numerical convergence.

The 234 cross sections making up the geometry data are based on 105 representative sections and 129 interpolated cross sections incorporated to increase numerical stability. Average cross section spacing, including interpolated cross sections, is about 4,450 feet. The 105 representative cross sections were developed from 2002 photogrammetric cross sections which were adjusted in terms of channel width based on digitized width from 2006 aerial photographs and adjusted in terms of elevation based on a 2007 longitudinal profile.

The 78 available bed material grain size distributions were applied to 78 of the 105 representative cross sections, and the grain size distributions for the rest of the representative and interpolated cross sections were populated by an interpolation scheme within SRH-1D.

The Parker transport equation coupled with Engelund-Hansen transport equation (Parker-EH) with a reference shear stress of 0.02 and a hiding factor of 0.2 was found to show the best fit to the sediment discharge Bureau of Reclamation Automated Modified Einstein Procedure (BORAMEP) data. The Parker

equation is a bedload equation and was developed for gravel bed streams. Engelund-Hansen is a bed material load equation and was developed for sand. This coupled equation allows for a consistent transport relationship to be used continuously across the entire solution domain from Cochiti Dam to Elephant Butte Reservoir, where the bed material changes from gravel to sand. The program selects which equation to use based on a combination of grain size and applied shear stress.

Fine material (< 0.0625mm) was included in this modeling effort, as fine materials in large part dictate the properties in the downstream portion of the Middle Rio Grande, particularly those areas influenced by Elephant Butte Reservoir. Vermeyen (1995) performed a series of tests on samples taken from Elephant Butte Reservoir, and the erosion and depositional properties were derived from the results of this report. These fine sediment parameters were applied to reaches 6, 7, and 8 from Arroyo de las Cañas to Elephant Butte Reservoir, and the upstream parameters were set such that there was no deposition of fine sediment (fine material transported as washload) as this is what has been observed in the field.

The downstream boundary condition for the model was a fixed water surface elevation, representing the pool elevation of Elephant Butte Reservoir. Although this elevation is bound to vary in time, the number of possible sequences involving wet and dry years (and associated water surface elevations) for the next sixty years represents a number of simulations which is outside of the scope of this study. It was decided to use the average water surface elevation from 2008 (representing the conditions at the time of this analysis) and assume that this represents the water surface elevation for the entire simulation period.

There are a large number of tributary rivers and arroyos along the Middle Rio Grande. Previous Reclamation studies (Bauer et al. 2006, Holmquist-Johnson 2004, Huang et al. 2005) identified 20 tributaries which have historically supplied significant flow to the Middle Rio Grande. Of these 20 tributaries, 19 also contribute significant sediment, with only the North AMAFCA Floodway not contributing sediment, as a sediment exclusion feature on this tributary limits sediment flow from entering the Rio Grande. No tributary inputs in reaches 7 and 8 are incorporated in this modeling. Five of the 20 tributaries have flow gages on them, and the remaining tributaries are ungaged. Flow for the ungaged basins was based on drainage area. The washload from the drainage area was estimated using the Modified Universal Soil Loss Equation (MUSLE) and the bed material load was estimated by developing a sediment rating curve based on tributary cross section measurements and bed material samples (Bauer et al. 2006, Holmquist-Johnson 2004, Huang et al. 2005). These initial estimates were then adjusted as part of the calibration effort of the previous studies. Part of the calibration included creating a hydrograph ranging from 3 days to 8 days in length to represent the yearly flow volumes and sediment load for each ungaged tributary. In addition, estimated diversions at Angostura and Isleta were made in the model to reflect the reduction of in-channel flows due to irrigation practices in the Rio Grande Valley.

RESULTS

The SRH-1D model converged in a simulation period of approximately sixty years. Two parameters were used to determine model convergence: volume of material deposited in a reach, and reach averaged slope. For both parameters, the values at the end of a simulation year (i) were compared to the values at the end of the previous simulation year (i-1) to determine when the change between year ends is minimized. Figure 1 shows the convergence plot for slope by reach.

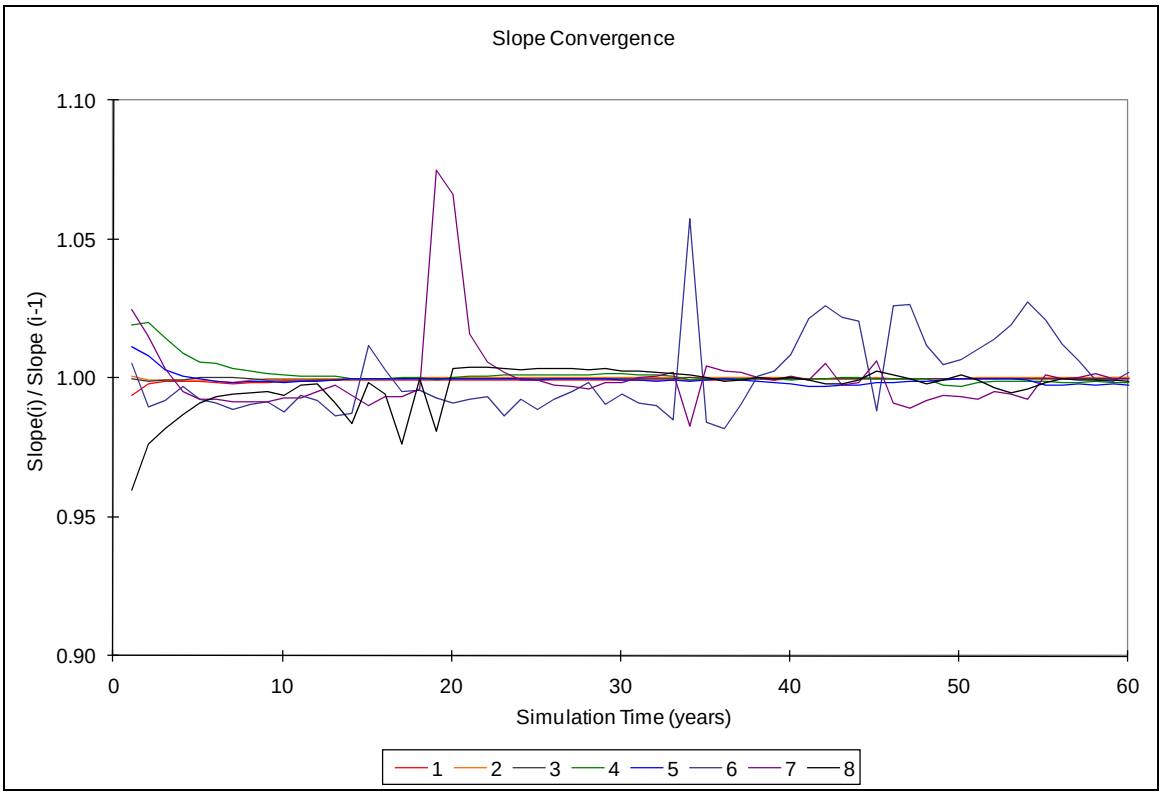

Figure 1 Convergence plot for reach slope.

In general, the model results show minimal change in bed elevation for the Middle Rio Grande from Cochiti Dam down to about Arroyo de las Cañas (reaches 1,2,3,4, and 5). The Middle Rio Grande from about Arroyo de las Cañas downstream to about River Mile 78 is depositional (reaches 6 and 7), and from River Mile 78 downstream to Elephant Butte Reservoir (reach 8), the results show some degradation upstream (near River Mile 78) and deposition downstream (near the reservoir). The reach averaged slopes and depositional volumes from the converged SRH-1D sixty-year simulation are presented in Table 1.

Table 1 Reach averaged slope and depositinoal volumes resulting from the SRH-1D model.

Reach	Slope (ft/ft)	Depositional Volume (tons/year/mile)
1	0.00118	1,414
2	0.00088	-409
3	0.00077	-1,404
4	0.00076	2,768
5	0.00078	3,973
6	0.00084	48,001
7	0.00071	19,970
8	0.00051	-2,270

Reach 8 has historically been aggradational and requires maintenance to keep a surface-water connection to the reservoir. The lowering pool elevation at Elephant Butte over the last decade and a half has caused the river to temporarily steepen in an attempt to keep up with this base level lowering. The steeper river sets up conditions where degradation occurs as the river has too much transport capacity and erodes the

bed. Since the eroded material is not entirely transported downstream instantaneously, river managers need to periodically redevelop a surface water connection from the river to the reservoir which gets blocked by the eroded material being stored in the channel. The proper interpretation of the model results for the reach for Reach 8 is that the reach does want to have a flatter slope and that continual variation in the base level (reservoir pool elevation) leads to continual river response.

Select Sensitivity Analysis

Sensitivity analysis was performed for the following parameters: the treatment of the diversion dams, the downstream boundary condition, and the sediment loads supplied by the tributaries. A sensitivity analysis for flow resistance was not done in this modeling effort as the roughness values for sediment continuity for the Middle Rio Grande have already been calibrated to an acceptable degree in previous Reclamation sediment modeling (Bauer et al. 2006, Holmquist-Johnson 2004, Huang et al. 2005).

Detailed geometry near the diversions was not included because the modeling effort was not focused on the diversion dams specifically and increasing the number of cross section would increase the computational time. Including the property of dams to limit vertical bed change was incorporated in the 1D model in another way. SRH-1D allows limits on the amount of erosion or deposition at any number of specific cross-sections. Because the cross sections near the diversion dams (Angostura, Isleta, and San Acacia) represent a length of river on the order of almost a mile (average cross section spacing is 4,450 feet), it was unreasonable to fix the elevation of the cross section (allow no erosion or deposition). In reality, the dams do limit the amount of deposition and/or erosion that can occur locally. Since the focus of the modeling was not on the diversion dams themselves, an alternate method of treatment was assumed and a sensitivity analysis on this treatment was made. The final model results reflect the cross sections nearest the dam being limited in terms of erosion to the base of the dams and limited in terms of deposition to the crest of the dams. A sensitivity analysis on this limitation was made by running a ‘free’ simulation where there was no limitation to the vertical adjustment for the cross sections near the diversion dams.

The second sensitivity analysis considers the effect of the downstream boundary condition; namely the assumed fixed elevation of Elephant Butte Reservoir. This sensitivity analysis assumes a full pool elevation of the reservoir. The elevation of the top of the storage pool of Elephant Butte Reservoir was set as the downstream boundary condition, as opposed to the assumed average water surface elevation for Elephant Butte Reservoir in 2008 for the ‘final’ boundary condition.

The third sensitivity analysis regards the incoming sediment load from the tributaries. As stated above, the tributary inputs were taken from previous Reclamation studies (Bauer et al. 2006, Holmquist-Johnson 2004, Huang et al. 2005). In addition, a 1994 study by Resource Technology, Inc. (RTI 1994), prepared for the United States Army Corps of Engineers, estimated different incoming sediment loads for the tributaries of the Middle Rio Grande. For the 19 tributaries contributing significant sediment to the Middle Rio Grande, the total annual sediment load based on the RTI value is 1.50 times greater than the annual sediment load as estimated by Reclamation.

Table 2 provides a summary of the three sensitivity analyses run, compared to the final results, which use the Reclamation sediment input volumes, assume a 2008 average Elephant Butte water surface elevation as the downstream boundary condition, and limited vertical adjustments occurring at the cross sections which represent the Angostura, Isleta, and San Acacia diversion dams. The RTI simulation refers to using the RTI sediment input values for the tributaries. RTI did not complete a sediment routing model to the knowledge of authors.

Table 2 Summary of sensitivity runs performed and the color code for Figure 2 - Figure 4.

Simulation ID	Diversion Dam Treatment	EB Elevation	Tributary Sediment Estimate	Color Code
Final	Limited Vertical Change	2008	Reclamation	Black
Free	***Unlimited Vertical Change***	2008	Reclamation	Red
Full Pool	Limited Vertical Change	***Full Pool***	Reclamation	Orange
RTI	Limited Vertical Change	2008	***RTI***	Green

Figure 2 presents the slopes resulting from the four simulations outlined in Table 2, along with the baseline (input geometry) slope for the sake of comparison. Figure 3 presents the average depositional volume for the entire Middle Rio Grande, and Figure 4 presents the same average depositional volume broken down by reach. Erosion is represented as a negative depositional volume.

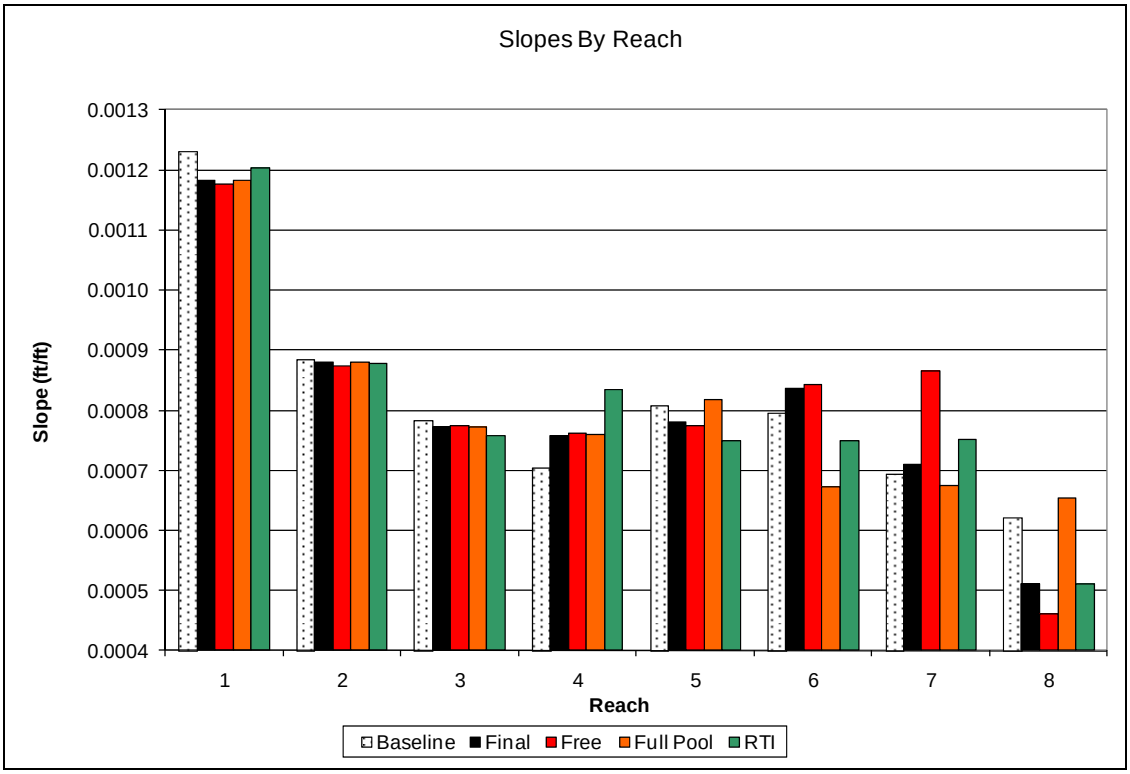

Figure 2 Reach averaged slopes from the three SRH-1D simulations, compared to baseline slopes.

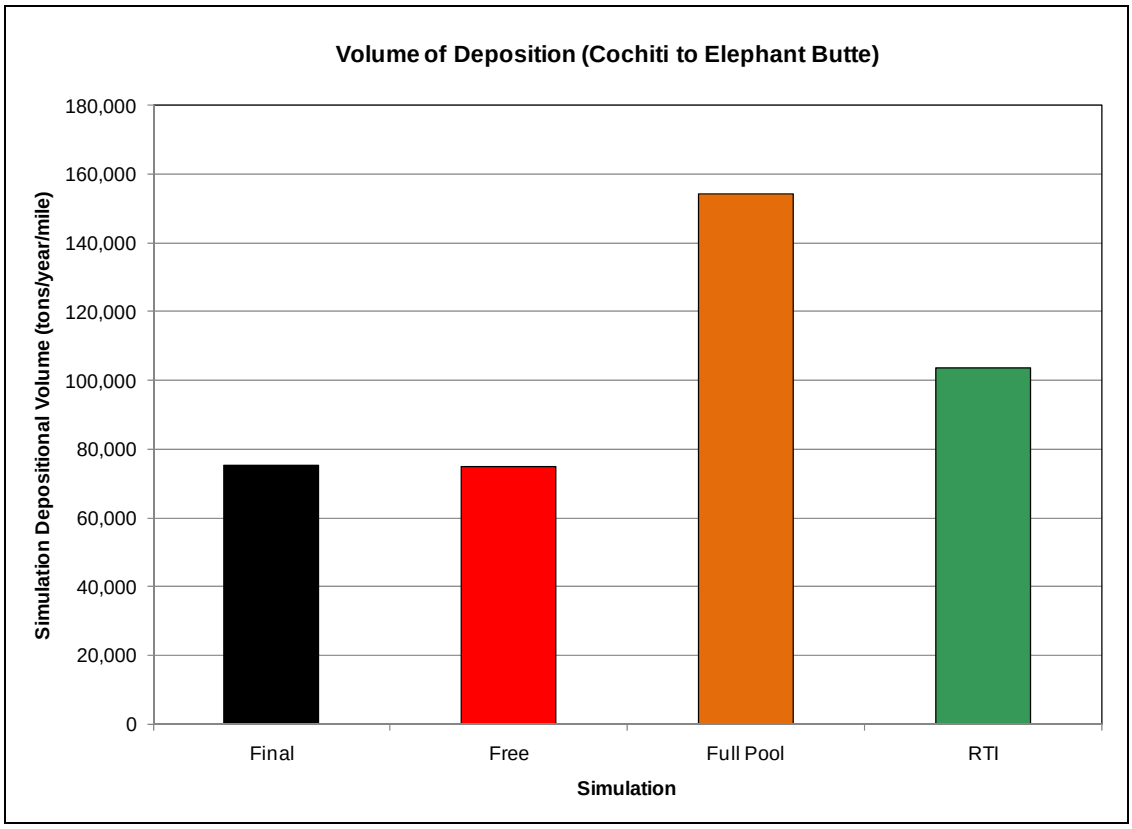

Figure 3 Length-averaged deposition volumes from the four SRH-1D simulations .

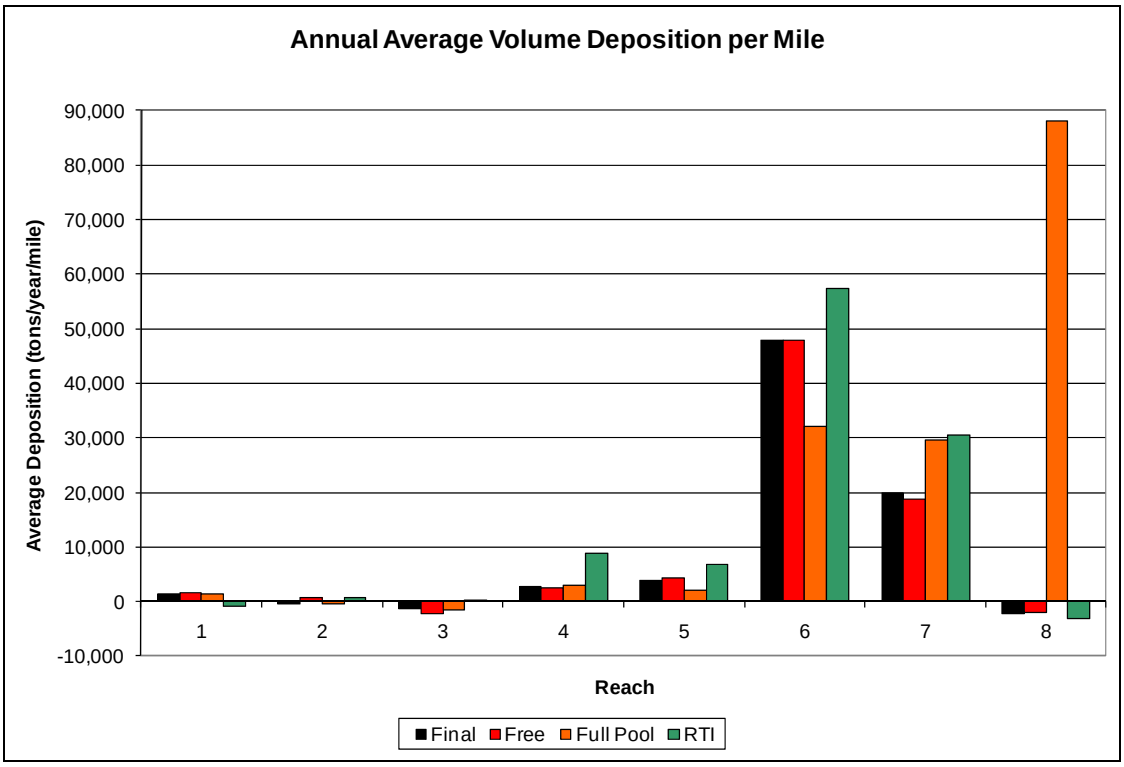

Figure 4 Reach averaged depositional volumes from the four SRH-1D simulations.

The free simulation relative to the final simulation did not produce significant differences overall or by reach, but there were some local differences. These sub-reach differences mostly had to do with where sediment was being eroded or deposited within a reach, and the 'final' simulation was decided upon over the 'free' simulation mostly due to the changes in bed elevation and the locations of those changes.

The full pool simulation shows no change (both in terms of resulting slope and in terms of depositional volume) upstream of San Acacia Diversion Dam (reaches 1, 2 , 3 and 4) relative to the final simulation. The most significant changes relative to the final simulation downstream of San Acacia Diversion Dam occur in reaches 6 and 8. The full pool simulation shows how sensitive the lower reaches are to the elevation in Elephant Butte Reservoir. A varying downstream boundary condition – as occurs in reality – would complicate the results and limit the likelihood of the simulations reaching any sort of equilibrium condition. The resulting deposition which occurs during a full pool condition at Elephant Butte Reservoir leads to the management practice of excavating a temporary channel to create a surface connection between the river and the reservoir after the pool recedes to a lower elevation. The full pool simulation is a unique sensitivity analysis and the following discussion will exclude this simulation. The results of the sensitivity analyses (excluding the full pool simulation) generally showed little difference in terms of trends or directions, mostly a change in the magnitude of those changes.

The amount of deposition for the entire model domain is about 1.4 times greater in the RTI simulation relative to the final simulation, whereas the tributary loads were 1.5 times greater. This discrepancy is due to the fact that a lot of the increased sediment loads in the RTI simulation increased the amount of fines entering the system, a lot of which wash downstream and exit the model domain. Although there is some disagreement between the sensitivity simulations as to whether Reaches 1, 2, and 3 will be erosional or depositional (Figure 4), the magnitudes are so small that there really is little difference between the results for these reaches. Reaches 4 through 8 show the same erosional or depositional trends (again, excluding the full pool simulation), with the difference between the simulation results lying in the magnitude of the deposition.

DISCUSSION

This modeling effort identifies which reaches are the furthest away from an equilibrium condition. The magnitude of the slope change and the magnitude of the depositional volumes rank the reaches in the following manner, based on the final simulation:

- Slope change (in order of magnitude): 8,4,6,1,5,7,2,3
- Deposition volume (in order of magnitude): 6,7,5,4,8,1,3,2

Reaches 4 and 6 appear in the top four of both rankings, while reaches 2 and 3 appear as the last two reaches in each ranking. Reaches 1, 5, 7, and 8 appear in the top four of one list but the bottom four of the other list, depending on the reach.

There is quite a bit of erosion in the upper portion of Reach 8 and deposition downstream, accounting for the large change in slope while maintaining a small change in net depositional volume. The results for reach 8 are highly dependent on the downstream boundary condition, as shown by the full pool simulation. The model results for all simulations do not lead to a single consistent slope for Reach 8, but typically show that Reach 8 could potentially be described by two characteristic slopes; one upstream of the San Marcial Railroad Bridge and another downstream. A linear regression slope for all of Reach 8 is misrepresentative.

Reaches 1, 2, and 3 show some potential room for further slope reduction through minor changes in net volume, regardless of the simulation. It is noteworthy that reaches 1, 2, and 3 are the longest reaches excluding Reach 8 (which has been shown to be highly dependent on the elevation of Elephant Butte Reservoir). However, the correlation between reach length and low slope change and small depositional volume for reaches 1-3 is due to the location of the long reaches. The upstream reaches are the longest (after Reach 8) and these reaches have already gone through a majority of the channel response to the construction of Cochiti Dam via channel incision and narrowing. These reaches have nearly reached a state of dynamic equilibrium and do not have much further adjustments to make. These three upstream reaches are also more similar to each other than they are to any of the downstream reaches.

The Middle Rio Grande downstream of the Rio Puerco and Rio Salado confluences (reaches 4-8) are geologically and geomorphically different than the Middle Rio Grande upstream of the areas near the Rio Puerco/Rio Salado. There exists a break in geologic basins somewhere near the Rio Puerco, Rio Salado, or San Acacia Diversion Dam (Bartolino et al. 2002). Geomorphically, the Rio Puerco contributes the most overall sediment (of all defined tributaries) to the Middle Rio Grande, and has recently been identified as a likely cause of the local convexity on the Rio Grande, supplanting the theory that the Socorro magma body has caused the uplift (Finnegan et al. 2009). The Rio Salado (middle of reach 4) is also a significant contributor of sediment, with substantial portions of that load being sand and fine gravel material. In addition, the San Acacia Diversion Dam (located at the upstream end of reach 5) is a channel-spanning hydraulic structure which until the mid 1980's diverted water from the Rio Grande to the Low Flow Conveyance Channel (which currently acts as a passive drain for the valley downstream of the dam) as well as diverting flow to the Socorro Main Canal. All of these influences act to separate the upstream three reaches of the Middle Rio Grande from the lower reaches of the Middle Rio Grande, with Reach 4 encompassing a lot of the transition in terms of geology, geomorphology, and hydraulic structures. Therefore it is not surprising to see such a different pattern of slope change and net deposition for the downstream reaches relative to the upstream reaches.

Note that the high deposition for the RTI simulation coincides with the RTI sediment load for the Rio Puerco being twice that of the Reclamation sediment load. Reaches 5, 6, and 7 are sensitive to tributary sediment load inputs and the downstream boundary conditions (elevation of the reservoir).

CONCLUSIONS

The SRH-1D modeling of the Middle Rio Grande yields the following general conclusions about the eight reaches:

- The three reaches upstream of the Rio Puerco (reaches 1, 2, and 3) are in a state or relative equilibrium, as indicated by the relatively low slope change and depositional volumes;
- Sensitivity analysis shows that the results of the upstream three reaches are insensitive to tributary sediment inputs, model downstream boundary condition, and the erosional and depositional limits at the diversion dams;
- Reach 4 encompasses significant geologic and geomorphic transitions – as well as a hydraulic structure – which makes reach 4 a transitional reach, separating the upstream 3 reaches from the downstream four reaches;
- Reach 4 is insensitive to downstream boundary conditions and erosional and depositional limits at the diversion dams, but is highly sensitive to the tributary sediment inputs, particularly the Rio Puerco which constitutes the upstream extent of the reach;
- Reaches 4, 5, 6, and 7 are reaches which have a high sediment load delivered to them which leads them to be zones of deposition.
- The results of reaches 5, 6, 7, and 8 are sensitive to tributary sediment inputs and downstream boundary condition (reservoir elevation);
- Reach 8 – the longest and most downstream reach – is highly sensitive to the downstream boundary condition and may benefit from being split into two sub-reaches for geomorphic characterization when further analysis is conducted.
- The design life of a strategy implementation in Reach 8 will be greatly reduced due to the likely fluctuation of water surface elevation in Elephant Butte Reservoir.

Currently, Reclamation is undertaking a comprehensive review of maintenance needs and strategies for the 21st century. The sediment continuity modeling for the various strategies and conditions presented herein is one of many tools Reclamation is utilizing for the evaluation of long term best management practices associated with water resources management involving river maintenance. Contemporary strategies are considering concepts that involve channel sustainability in terms of its functions for sediment and water continuity, ecosystem needs, and external inputs involving channel maintenance. Primary focuses are on protecting riverside infrastructure and resources, being ecosystem compatible, and continuing to promote effective water delivery between the upper and lower Rio Grande basins. In its evaluation, Reclamation is considering strategies and maintenance practices that promote elevation stability, alignment stability, maintaining channel capacity, increasing available area to the river, rehabilitation of the channel and floodplain, and managing sediment supply to reaches.

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