Channel Morphology Prediction with and without Temporary Channel Upstream of the Elephant Butte Reservoir

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ABSTRACT

A two-dimensional mobile-bed numerical model, SRH-2D v3, is used to evaluate a 10-year channel morphology of an 18-mile river reach upstream of the Elephant Butte Reservoir on the Rio Grande. Two scenarios are considered. One assumes that no temporary channel was excavated following the lowering of the reservoir pool; another assumes that a temporary channel was excavated instantly before the modeling period begins. The model simulation is carried out using the actual flow hydrograph from October, 2000 to June, 2010. The study aims to (a) determine the most likely channel morphology in 2010 had the temporary channel not been excavated and (b) help understand the impact of the temporary channel on the river morphology within the study reach. It is found that (a) no competent channel, similar to the excavated temporary channel, would form, had the temporary channel not been excavated; (b) the new predicted channel morphology is mostly in the form of a multi-channel type in 2010; and (c) the study points to the need for continued maintenance of the temporary channel at selected locations.

INTRODUCTION

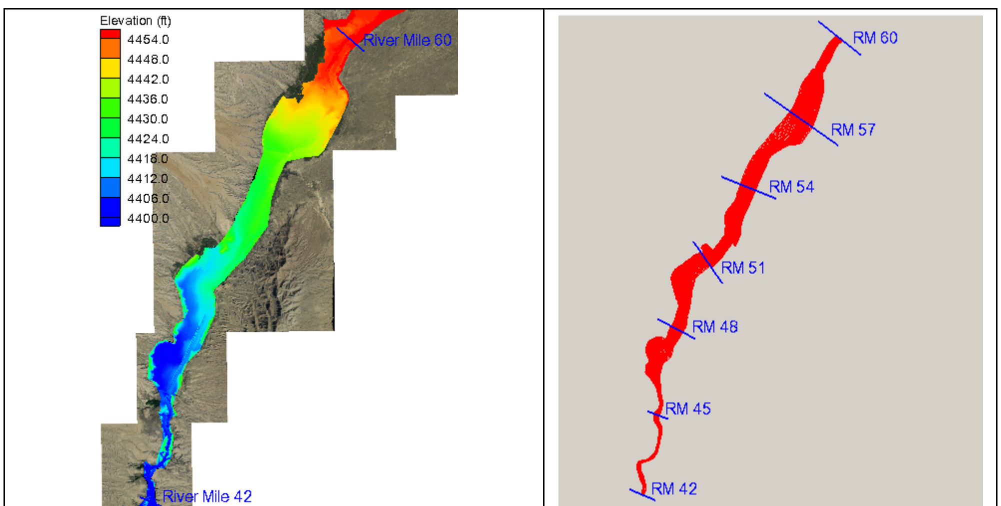
The drought in the 1990s resulted in a decrease of the Elephant Butte Reservoir pool elevation and inundation area. The exposed delta deposits disconnected the Rio Grande and the Reservoir and led to high water losses. As a result, the water delivery was negatively impacted according to the New Mexico's Rio Grande Compact. In response, a temporary channel, abbreviated as Temp Channel, was constructed since 2000. The Temp Channel was also maintained through the delta area of the Elephant Butte Reservoir. After the Temp Channel construction, degradation has been observed in the Rio Grande upstream of Elephant Butte Reservoir. The degradation has propagated upstream and in recent years reached the area of the Bosque del Apache National Wildlife Refuge (approximately RM 84). The base level lowering due to the pool elevation drop of the Elephant Butte Reservoir, coupled with relatively high flows in 2005 and 2008, was considered to be the leading causes of the degradation. It is unclear, however, whether the excavation of the Temp Channel contributed to the initiation of the degradation.

The Bureau of Reclamation, Albuquerque Area Office (AAO), is interested in quantifying the impact of the Temp Channel on upstream channel degradation. A bigger picture question is what would occur if no Temp Channel had been excavated. Such knowledge may be obtained using numerical analyses. In this study, SRH-2D v.3 is used to predict the channel morphology with and without the Temp Channel in order to gain knowledge about the impact of the Temp Channel. The study reach, upstream of the Elephant Butte Reservoir, is from RM 42 to 60. The objectives of the SRH-2D v.3 sediment transport modeling study are to determine the most likely channel location through which low flows will be routed in 2010, had the Temp Channel not been excavated, and help understand the impact of the Temp Channel on the river morphology within the study reach.

SURVEY DATA AND MODELING PARAMETERS

The present simulation starts from the river morphology before the excavation of the temporary channel and also before the reservoir pool lowering. The initial topography/bathymetry before 2000 is needed. A comprehensive survey of the Elephant Butte Reservoir, covering the present study area, was carried out in 1999 by Collins and Ferrari (2000). A topographic data set was constructed using a combination of the USGS quadrangle data and the underwater measured bathymetry. This 1999 data set is used as the initial bed condition for the modeling and the bed elevation contour is shown in shown in Figure 1a.

A 2D analysis begins by defining a solution domain and then generating a mesh that covers the domain. In this study, the solution domain selected covers the river reach upstream of the Elephant Butte Reservoir where a temporary channel has been excavated since 2000. The modeling solution domain ranges from RM 42, near the beginning of the Narrows, to RM 60, the old Low Flow Conveyance Channel (LFCC) temporary outfall (see Figure 1b). A mesh is generated using the Surface Water Modeling System software (SMS). The mesh consists of mixed quadrilaterals and triangles, with a total of 14,628 mesh cells (Figure 1b.).



(a) 1999 Bed Elevation Contour (b) Solution Domain

Figure 1. The bed elevation and solution domain/mesh (RM 42 to 60)

The upstream boundary at RM 60 is closer to the USGS gage #8358300 at San Marcial than other gages such as at San Acacia. According to a comparative study of the annual flow data between San Acacia and San Marcial by Huang (2011), variation between the two gages is relatively small. Therefore, the hydrological data at San Marcial gage is used. The daily flow discharge was downloaded from the automated USGS database for the period of January 1, 2000 to July 31, 2010 (Figure 2). This is used as the upstream flow condition. The total sediment load at the upstream boundary adopts the rating curve developed by Collins (2006), but modified using the field data collected by Tetra Tech (2008). The total load rating curve is expressed as:

$$Q_s = 0.0582 Q^{1.5075} \qquad (1)$$

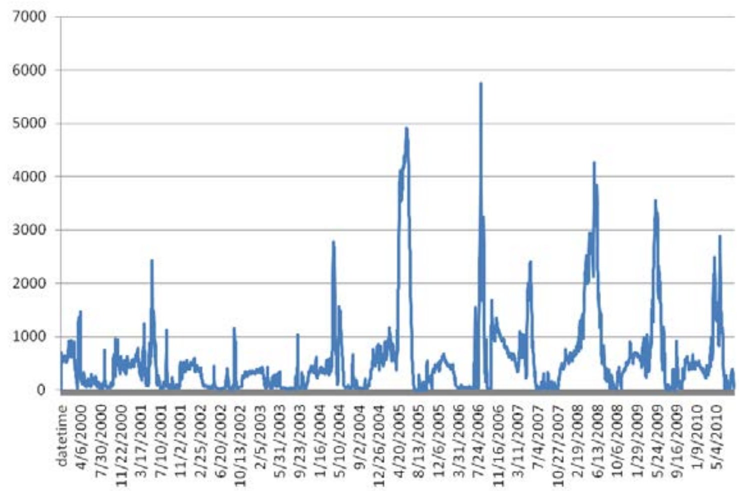


Figure 2. Daily discharge at the San Marcial gage from January 2000 to July 2010

Flow roughness may be calibrated using the measured water surface elevation data. Such a calibration has been done for the study reach using 1D models with a wide range of flow discharges (e.g., BOR 2002; Collins 2006). Most of the previous studies resulted in a value of 0.017 for the main channel. The same value was also used in our previous SRH-2D modeling for the reach from RM 79 to 84 (Lai, 2009). Therefore, the Manning's coefficient of 0.017, uniformly distributed in the entire solution domain, is used in the present study.

Representation of bed materials is needed, particularly in areas of degradation. A drill-hole study was carried out by Hilldale (2001) for the study reach during Jul 23 to 30 and Aug 31-Sep 4, 2001, with 20-ft deep drilling holes. Additional drilling holes were dug on Jan 17, 2003, covering EB-26 (slightly upstream of RM 59) to 2.7 miles downstream of EB-26. The study found that alternating layers of fine sand and silt-clay exist for most sites. On average, the bed may be described as consisting of two layers: the top sandy layer and the bottom silt-clay layer. The top layer is about six feet with dominant sands, while the bottom layer is about ten feet with about 80% silt-clay content.

In this study, the bed materials are represented with two bed layers using the survey data. The top layer has a thickness of six feet with the bed gradation listed in Table 1. The bottom layer has a thickness of ten feet with a silt-clay content of 80%. Surface bed materials were surveyed by Bauer (2006) between June 15 and June 20, 2006, and again between July 17 and 19, 2006. The median sediment diameter (d50), excluding the scattered gravel bars, is 0.27 mm for the study area. Since the variation of the sediment gradation is relatively small, a uniform gradation is used by averaging the gradations surveyed. The survey data were mostly concentrated in the sand bars which generally lack the presence of silt-clay. The area was subject to reservoir deposition before 1999. Therefore, silt-clay content should be added to the above gradation data. Based on our field trip on July 26-27, 2010, it was estimated that about 5-15% of silt-clay cohesive materials were present and should be added. A modified bed sediment gradation is used (Table 1) that added 10% silt-clay.

Table 1. Bed gradation of the top bed layer

Cohesive content	d(mm)	Up to 0.625	.125	.25	.5	1	2
10%	% pass by weight	10.0	13.5	33.3	98.5	99.6	100

OTHER MODEL PARAMETERS

The flow analysis capability of SRH-2D v2 is well documented by Lai (2008; 2010). The sediment module, SRH-2D v3, is less documented as it still an in-house development model, and a few references include Greimann et al. (2008), Lai and Greimann (2008; 2010), and Lai et al. (2011). A detailed description of the sediment analysis theory and methodology may be obtained from these references, as well as the work of Lai (2011). They are not repeated. Only the cohesive sediment modeling is presented next.

The transport equation for the cohesive sediment is as follows:

$$\frac{\partial hC}{\partial t}+\frac{\partial UhC}{\partial x}+\frac{\partial VhC}{\partial y}=v_e p-v_d C \tag{2}$$

where v_e and v_d are the rate of erosion and deposition, respectively, and p is the percentage of the cohesive sediments on the bed. The following erosion rate (v_e in mm/s) was used for the cohesive sediment based on the previously available measured data (Vermeyen, 1995):

$$v_e=0 \qquad \text{if} \qquad \tau\le\tau_{es} \tag{3a}$$

$$v_e=S_s\left(\frac{\tau-\tau_{es}}{\tau_{em}-\tau_{es}}\right) \qquad \text{if} \qquad \tau_{es}<\tau\le\tau_{em} \tag{3b}$$

$$v_e=S_s+S_m\left(\frac{\tau-\tau_{em}}{\tau_{em}}\right) \qquad \text{if} \qquad \tau>\tau_{em} \tag{3c}$$

with $\tau_{es}=0.125\, lb/ft^2$, $\tau_{em}=2.84\, lb/ft^2$, $S_s=0.25\, lb/hr\cdot ft^2$, and $S_m=1.07\, lb/hr\cdot ft^2$. In the above, τ_{es} and τ_{em} are the critical shear stress for surface and mass erosion, respectively; and S_s and S_m are the erosion slope for surface and mass erosion, respectively. The deposition rate is based on the fall velocity of the cohesive sediment, and the following rate (v_d in mm/s) was used:

$$v_d=(1-\frac{\tau}{\tau_{ref}})\omega \qquad \text{if} \qquad \tau\le\tau_{df} \tag{4a}$$

$$v_d=(1-\frac{\tau}{\tau_{dp}})\omega(1-\frac{C_{eq}}{C}) \qquad \text{if} \qquad \tau_{df}<\tau<\tau_{dp}\ and\ C>C_{eq} \tag{4b}$$

$$v_d = 0 \qquad \text{if} \qquad \tau \geq \tau_{dp} \;\; or \;\; C \leq C_{eq} \tag{4c}$$

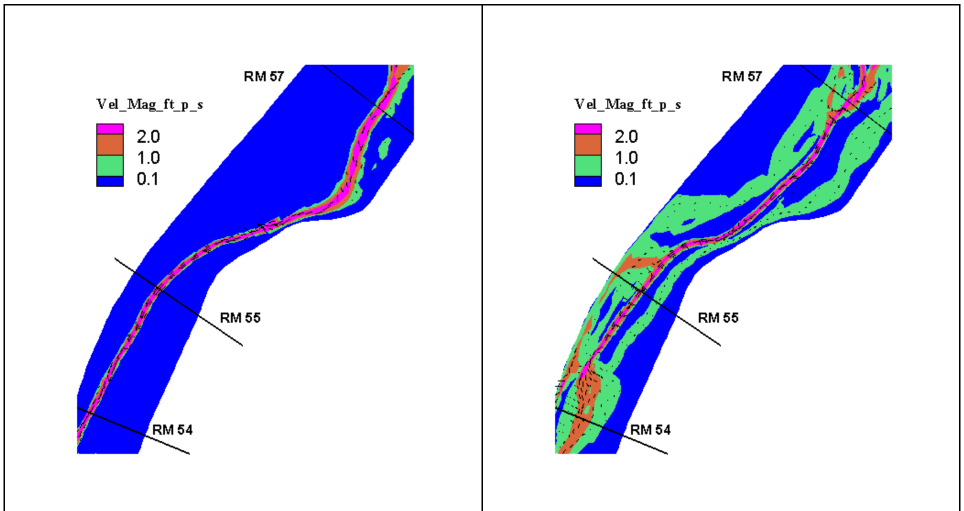
with $\tau_{df} = 0.005 \, lb/ft^2$, $\tau_{dp} = 0.021 \, lb/ft^2$, $C_{eq} = 3.0 \, g/l$, $\tau_{ref} = \dfrac{\tau_{df}\tau_{dp}}{\chi\tau_{df} + (1-\chi)\tau_{dp}}$ and $\chi = 1 - \dfrac{C_{eq}}{C}$. In the above, τ_{df} and τ_{dp} are the critical shear stress for full and partial deposition, respectively; C_{eq} is the equilibrium suspended sediment concentration. The erodibility data of the cohesive sediment used in the above were based on the measured data of Vermeyen (1995) for the consolidated sediment in the reach from San Marcial to Elephant Butte.

RESULTS AND DISCUSSION

Two modeling scenarios are considered in this study: the “With-TC” scenario in which the temporary channel is excavated in the study reach and the “No-TC” scenario in which no temporary channel is assumed. The No-TC scenario is based on the reservoir survey data in 1999 before the reservoir lowering and the temporary channel project. This scenario predicts how the channel would evolve “naturally” if no temporary channel was dug. The With-TC scenario is to represent the “existing condition”. However, the model deviates from the actual existing condition. Firstly, the temporary channel was excavated in stages from 2000 through 2005. The actual excavation process was not well documented enough for the present numerical model to replicate. In this study, the “temporary channel” is created instantly, not in stages. Secondly, other small projects might have been carried out since 2000 within the study reach, e.g., berm repairs (BOR, 2002). These works on the river changed the topographic features of the reach, but they are not incorporated in the numerical model. As such, the With-TC scenario should not be viewed as the actual existing condition model. Despite the above assumptions, the With-TC scenario is useful as it provides a comparison with the No-TC scenario. The difference between with- and without- the Temp Channel scenarios sheds light on the channel morphology and the impact of the Temp Channel. A detailed presentation of all model results can be found in Lai (2011). Only major findings are discussed.

The model results show that the temporary channel, and subsequent maintenance, achieved its primary purpose of maintaining a single channel to keep the river and the reservoir connected. The temporary channel prevented the large evaporative loss of water due to much reduced water surface area, which would have occurred if flows had spread out over the floodplain. It helps to maintain the water delivery.

According to the No-TC model results, it is concluded that no competent channel would form had the Temp Channel not been excavated. Actually, a multi-channel form with two to three channels is predicted at many locations in 2010. For example, Figure 3 shows the predicted channel forms from RM 57 to 54 about 10 years later. Without the Temp Channel, the developed channels are wider in width and shallower in depth in comparison to the excavated temporary channel. At some locations, e.g., RM 57-to-54 and RM 51-to-48, a dominant channel may still develop, although it is within a multi-channel system. Secondary channels have flowing water only with higher flows. At other locations, e.g., between RM 48 and RM 46, flows are widespread and no discernable channels are formed at all. More evaporative loss is expected with such a multi-channel system. The formation of multiple channels is typical of the delta dynamics and was reported for the Elephant Butte Reservoir (BOR 2002, p.1).

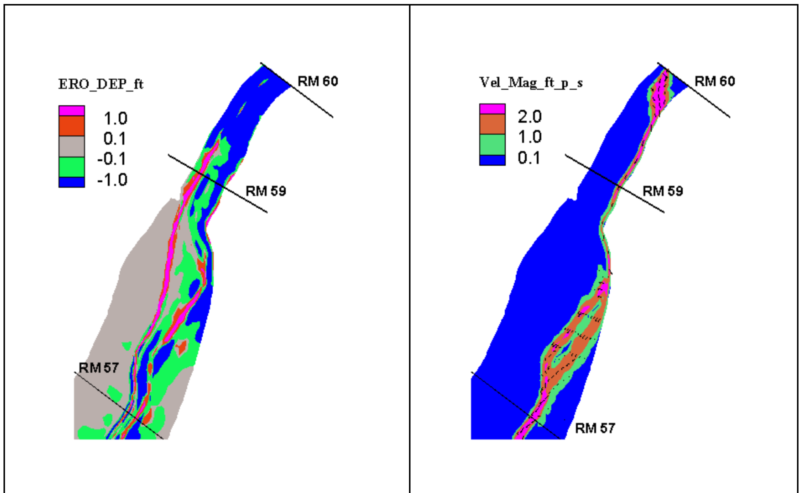


(a) With-TC Scenario (b) No-TC Scenario

Figure 3. Predicted channel form (velocity is shown) in early 2010

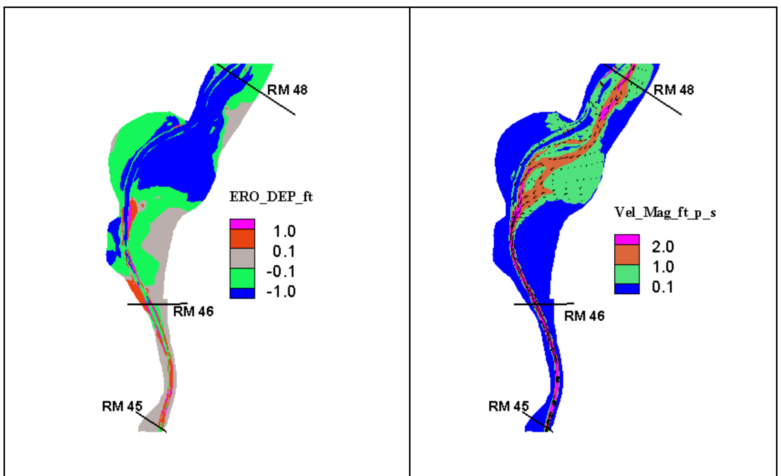
Based on the With-TC scenario, two river locations are identified that require continued monitoring and maintenance due to high risk of aggradation. Maintenance will continue to be required, even with the excavation of the temporary channel. One reach is from RM 60 to 59 (see Figure 4) where channel avulsion may occur as large aggradation is predicted. Despite high level of uncertainty of the prediction, the prediction is corroborated with field evidence. For example, it was reported that “the channel was originally constructed as designed, but persistent sediment accumulation within the channel became a maintenance problem,” during excavation of the 2000 temporary channel (AAO 2007). Also, the temporary channel berm was breached in May 2001 and the bank had to be “reinforced” and the channel had to be “modified”. The excavation and the continued maintenance of the temporary channel is the key that prevented avulsion from occurring and allowed a single stable channel to be maintained.

Another problem reach is between RM 50 and RM 47 where large aggradation is predicted (Figure 5). The aggradation leads to two phenomena: (a) a potential to develop a multi-channel system such as the one predicted at RM 48; and (b) a potential avulsion to the west upstream of RM 47. The model results are also partly corroborated with the field evidence. The channel in this reach did experience large aggradation in 2009, which led to the flow shifting to the west where it was still present during our July 2010 field trip.



(a) Net Eroded Depth (b) Velocity Pattern

Figure 4. Predicted results near the upstream end

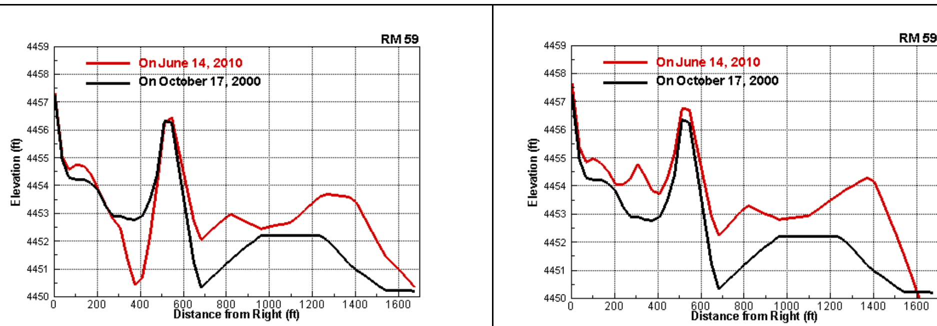


(a) Net Eroded Depth (b) Velocity Pattern

Figure 5. Predicted results between RM 48 to 45

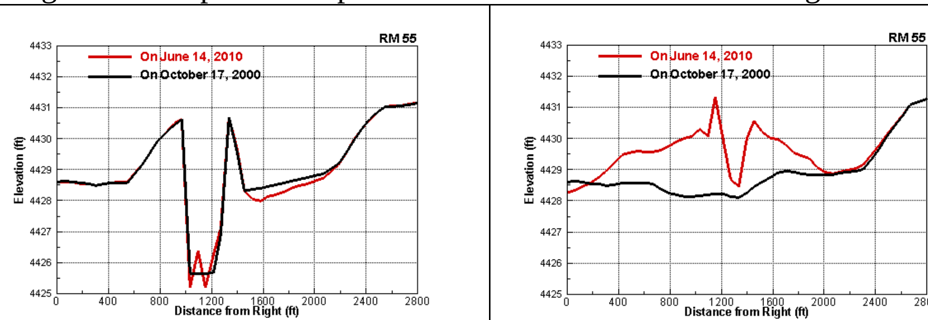
The model results for the rest of the temporary channel, RM 55 to RM 50 and RM 46 to RM 42 (in the Narrows), show that they are relatively stable without significant degradation or aggradation. Maintenance needs in these areas are less likely.

Selected comparisons of the channel cross sections for the With-TC and No-TC scenarios are shown in Figure 6 through Figure 9.



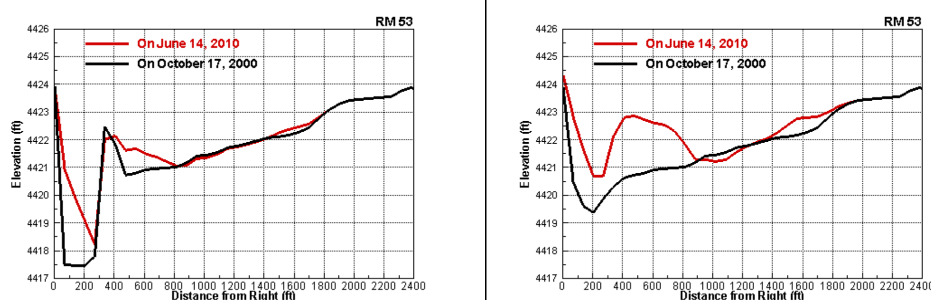
(a) With-TC (b) No-TC

Figure 6. Comparison of predicted channel cross section change at RM 59



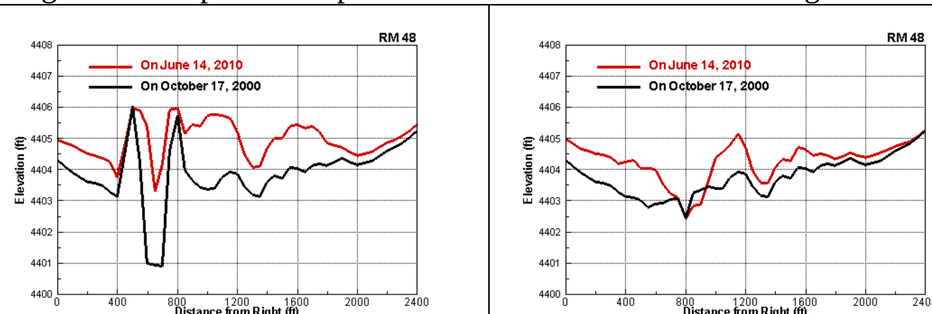
(a) With-TC (b) No-TC

Figure 7. Comparison of predicted channel cross section change at RM 55



(a) With-TC (b) No-TC

Figure 8. Comparison of predicted channel cross section change at RM 53



(a) With-TC (b) No-TC

Figure 9. Comparison of predicted channel cross section change at RM 48

CONCLUSIONS

A two-dimensional mobile-bed numerical model, SRH-2D v3, is used to conduct a 10-year 18-mile geomorphic and sediment transport study for the reach upstream of the Elephant Butte Reservoir on the Rio Grande. Modeling study with SRH-2D v3 has the following major conclusions:

- No competent channel similar to the excavated temporary channel would form, had the temporary channel not been excavated.
- The new predicted channel morphology is mostly in the form of a multi-channel type at the end of 2009.
- The study points to the need for continued maintenance of the temporary channel at selected locations.

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