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Applying numerical sediment transport models to examine river restoration sustainablilty at the Rio Grande Nature Center, New Mexico

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APPLYING NUMERICAL SEDIMENT TRANSPORT MODELS TO EXAMINE RIVER RESTORATION SUSTAINABILITY AT THE RIO GRANDE NATURE CENTER, NEW MEXICO

BY

KYLE SHOUR

B.S. CIVIL ENGINEERING, MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY, 2009

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science

Civil Engineering

The University of New Mexico
Albuquerque, New Mexico

August, 2011

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APPLYING NUMERICAL SEDIMENT TRANSPORT MODELS TO EXAMINE RIVER RESTORATION SUSTAINABILITY AT THE RIO GRANDE NATURE CENTER, NEW MEXICO

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ABSTRACT

Much of the Middle Rio Grande has severely degraded since 1930 when flood control institution began (Scurlock 1998). Since that time, additional anthropogenic stressors have continued to cause the river to incise and narrow and have harmed the ecological health of the system. As a result, many different entities have developed restoration projects along the Middle Rio Grande. These projects are often localized, small scale features that promote native vegetation establishment and improve habitat for endangered species without removing flood protection measures.

One such feature is the Rio Grande Nature Center (RGNC) Habitat Restoration project. The project consists of removing non-native plants and constructing an ephemeral, high-flow, side channel connected to the Rio Grande in Albuquerque, New Mexico. The channel provides habitat for the Rio Grande Silvery Minnow and helps connect the river to its floodplain, promoting establishment of native vegetation.

Since its completion in February 2008, the RGNC side channel has provided improved conditions for native vegetation and silvery minnow but has undergone significant aggradation. This deposition brings into question the sustainability of this project. One- and two-dimensional numerical models are developed to model the RGNC channel, determine project life-cycle, examine modeling approaces, and alternative designs.

One-dimensional modeling efforts were determined to be insufficient for capturing the sediment transport measured in the RGNC channel. Two-dimensional modeling results proved to be sufficient, indicating that this level of modeling can be applied as a useful design tool. Two-dimensional modeling suggests a project life of up to 50 years with the channel reaching a dynamic equilibrium after 15 to 20 years. Though the channel should last for 50 years, the duration and magnitudes of flows will likely be reduced. Alternative designs were modeled. These models suggest that embayments (described herein) are an effective, sustainable feature in high-flow, side channel restoration projects. However, the alternative designs suggest that the use of adverse slopes at the upstream of side channel restoration designs will contribute to a reduced project life.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION AND BACKGROUND

1.1 Importance of Research

The U.S. Environmental Protection Agency (EPA) has listed more than 71,000 bodies of water as impaired (EPA 2011). Of these bodies of water, approximately 4,000 of them are listed as high priority. The EPA considers a stream impaired if it requires "additional work beyond existing controls to achieve or maintain water quality standards" (EPA 1993). Pollutants can be physical (sediment, temperature, etc.), biological (pathogens), or chemical (organic chemicals, pH, heavy metals, etc.).

Pollutants, or stressors, have always acted on healthy, naturally functioning ecosystems. For example, Poff *et al.* (1997) examine disturbances resulting from a natural flow regime and discuss the role stressors play in creating a healthy riverine ecosystem. However, humans have applied stressors to rivers at a rate that caused rapid changes in river systems. These changes can be applied directly within the river floodplain or be the indirect result of watershed alterations (Allan *et al.* 1997). Rapid changes can yield a wide range of results, including incision (Vincent *et al.* 2009), flooding (Pinter *et al.* 2006), habitat loss or alteration (Groffman *et al.* 2003, Shafroth *et al.* 2002), bank erosion (Renwick and Rakovan 2010), or undesired bank stabilization (Pollen-Bankhead *et al.* 2009). To remove or mitigate these deteriorated conditions, engineers and scientists have instituted many river restoration projects.

1.2 Definitions

The term restoration is ambiguous. River "restoration" projects can be categorized many different ways. One way is to define three treatment levels (USDA 2007): restoration, rehabilitation, and reclamation (**Figure 1-1**). Restoration involves returning a river to some pre-disturbed state. Rehabilitation, a more common practice, entails recovering some degree of ecological function to a fluvial or riparian system. Finally, reclamation involves altering a system to provide structure or function that did not exist in the previous system. Despite further classification of the term river "restoration," it remains clear that each term—restoration, rehabilitation, and reclamation—still bears a certain amount of ambiguity. For instance, to what pre-disturbed state is a river being restored—10 years, 100 years, 1000 years ago? For the purposes of this paper, the terms restoration and rehabilitation will be used interchangeably to mean recovering of some degree of ecological function.

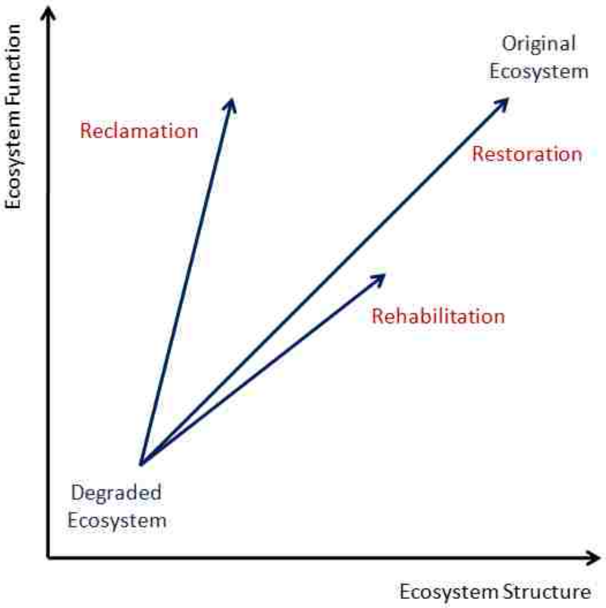


Figure 1-1: Restoration, Rehabilitation, and Reclamation (Modified from Bradshaw 1996)

Another way river restoration projects can be classified is based upon the size of the area affected and whether the actions taken are structural or non-structural. For the majority of rehabilitation projects, stream function, over structure, should guide design decisions to ensure project sustainability (Van der Velde *et al.* 2006). Though there is a time and place for structural improvement, the physical changes must be geared towards providing characteristics that support desired ecological functions. Naiman *et al.* (1999) reports that the physical environment impacts the ecological communities; in turn, the ecological communities impact the physical structure. Incorporating this feedback cycle will encourage project sustainability.

Projects can range from legislative policy changes over the whole watershed to reduce pollutant run-off to small scale channel alterations to provide river structure conducive to habitat for a desired species. This paper examines a small-scale rehabilitation project where structural changes are instituted to improve ecosystem health.

As with any other type of project, engineers ought to consider the sustainability of their design. The EPA (2010) defines sustainability as “polices and strategies that meet society’s present needs without compromising the ability of future generations to meet their own needs.” Similarly, the American Society of Civil Engineers (ASCE 2010) states that “sustainable development is the challenge of meeting human needs for natural resources…while conserving and protecting environmental quality and the natural resource base essential for future development.” Therefore, sustainable river restoration might be generally defined as design and management practices that improve ecologic function and meet the river needs of today without jeopardizing the river function and needs of the future.

Creating a sustainable design requires extensive knowledge of the forces that created a degraded system. Making changes to the physical structure of the river without a sound fluvial geomorphological and ecological analysis may be unsustainable simply because the river cannot support the alterations. Projects fail because designers assume that they have created a channel that appears more natural but have neglected the processes that have driven the channel into disequilibrium (Simon *et al.* 2007). Similarly, designing to provide an ecological function that has never existed in a system is likely to yield poor results.

1.3 Sediment Transport in Restoration

Sediment transport has a major impact on both the ecological function and physical structure of streams. Natural, alluvial systems erode, transport, and deposit sediment almost constantly. Many stressors affect sediment transport rates, driving the system to or from equilibrium. A river responds to changes in flow and slope by adjusting sediment transport, causing erosion or deposition. For this reason, designers should account for sediment transport to have a better understanding of why the degraded system exists as it does, to what state the system will evolve if left unchanged, and how the system will respond to the desired restoration work. Though transport of sediment is complex and the exact river response is impossible to know, sediment transport analyses can help ensure project sustainability.

Sediment transport impacts instream and floodplain habitat structure (Schwendel *et al.* 2010) and, therefore, ecological health of the riverine ecosystem. The sediment transport capabilities of a stream dictate what size material composes the bed and banks, which can dictate habitat quality. For instance, fish such as the Rio Grande Silvery Minnow prefer sandy riverbed habitat. Other fish species require coarser riverbeds to thrive and would be decremented by sandy channels.

Sediment transport estimation methods are derived from three-dimensional continuity, energy, and momentum equations. Depending upon the level of analysis, different simplifications are made. In essence, if the driving forces (depth, velocity, viscosity, buoyancy, and turbulence) acting on a particle outweigh the resisting forces (friction and weight) then the particle moves. Sediment transport exists as washload, suspended load, and bedload. Washload consists of light-weight particles, typically silts and clays, that have no interaction with river bed and typically come from the watershed. Washload has little impact on rehabilitation design. However, washload has a great impact on turbidity and could, therefore, impact instream habitat quality for some organisms (Diehl and Wolfe 2010). Suspended load is derived from the riverbed but moves great distances without interacting with the riverbed. Bedload is also derived from the bed but has frequent interaction with the bed. The relative composition of each component within a river varies from system to system.

Many sediment transport equations exist. Designers must have a complete understanding of the applicability and limitations of each equation. Lane (1955) presented the most simple sediment transport relationship (**Equation 1-1**). He stated that the product of the flowrate (Q) and energy grade line slope (S) is proportional to the product of sediment transport rate (Q_S) and particle size (D_{50}).

$$Q \cdot S \propto Q_S \cdot D_{50}$$

Equation 1-1

Empirical sediment transport capacity equations also exist. These equations were derived from flume experiments and measured field data. Knighton (1998) subdivides these equations into three categories: excess shear stress, excess discharge per unit width, and excess stream power. It should be noted that these equations do not calculate actual sediment transport. Instead, they calculate theoretical transport capacity. These equations produce a wide range of results given the same inputs (**Table 1-1**).

Formula	Sediment Load (lb/sec*ft)
Schoklitsch	0.086
Duboys	0.891
Meyer-Peter-Muller	0.054
Laursen	5.442
Yang's Sand	0.343
Tofalleti	3.039
Ackers-White (D50 Option)	0.576
Ackers-White (D35 Option)	0.704
Einstein Bed-Load	0.140
Colby Formula (Graph)	0.718

Table 1-1: Sediment Transport Capacity Variability within a Single Reach (Modified from Mays 2005)

Capacity equations are, perhaps, best used for rough estimating or determining reach trends and should be selected and applied with consideration for the limitations of each equation. If the transport capacity is larger than the measured sediment transport, the reach is supply limited. Conversely, if the transport capacity is approximately equal to the measured sediment transport, the reach is capacity limited. Armored streams are typically supply limited, while sand bed streams are often capacity limited. Furthermore, a stream that shows an increase in capacity without an increase in supply or bed material size will degrade. Likewise, a stream experiencing a decrease in capacity without a decrease in supply or particle size will aggrade.

The most accurate and complex sediment transport calculations use the Navier-Stokes equations (**Equation 1-2**). This set of physical, three-dimensional, partial differential equations is applicable for incompressible, unsteady, and turbulent flow with a constant viscosity. However, these equations do not have a general solution and must be solved for discrete temporal and spatial intervals. Simplifications are often made to the equations to reduce calculation effort. Common simplifying assumptions include steady flow, incompressible fluid, or a negligible velocity component in one or two directions. Variations on this set of equations are used in several modeling packages and will be discussed in more detail below.

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial P}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial (P+\rho g z)}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

Equation 1-2

In the Navier-Stokes equation, ρ is fluid density; t is time; u is velocity in the x-direction; v is velocity in the y-direction; w is velocity in the z-direction; P is pressure; and μ the dynamic viscosity of the fluid. Of these variables pressure and velocity are dependent. In essence, the equation is a three-dimensional version of Newton's Second Law of Motion—force equals the product of mass and acceleration—or the conservation of momentum. The components on the left side of the equation represent inertial forces, and the components on the right side of the equation represent the sum of external forces.

1.4 Sediment Transport Modeling in Restoration

Sediment transport models range from conceptual to three-dimensional, numerical models. Each design or analysis will require different levels of modeling depending upon physical limitations and cost constraints (Stone *et al*. 2007). These models allow designers to determine bed structure, sediment gradations, and planform alterations. Knowing bed structure and sediment gradations allow engineers to better determine habitat quality. Knowing how the forces in a river system impact planform allows engineers to protect infrastructure within the floodplain.

Additionally, sediment transport models can aid in creating a sediment budget. A sediment budget considers the sediment input into a reach, the erosion and deposition within a reach, and the sediment output from a reach. If sediment inputs equal sediment outputs, there will be no deposition or erosion and, therefore, equilibrium. Restoration projects should incorporate a sediment budget if they are to be sustainable.

Conceptual models require the least computational effort but possess the highest degree of uncertainty. These models may take the form of theories, regression equations, or empirical sediment transport capacity equations. As with any other empirical relationship or regression equations, sediment transport conceptual models are created within a certain context. Engineers should only apply models when the characteristics of their site fit the model limitations. Common gravel-bed sediment transport models include Parker (1978, 1979) and Miller (2005). Bank migration conceptual models include Ikeda *et al*. (1981), Parker *et al*. (1982), Johannesson and Parker (1989), Lancaster and Bras (2002), and Darby and Delbon (2002). Hydrology and ecology are also important to river restoration. Vannote *et al*. (1980), Junk *et al*. (1989), and Poff *et* *al*. (1997) have published well-established hydrologic and ecological conceptual models. Conceptual models are best used early in the design process as a rough estimate or later in the design process as verification.

One-dimensional numerical models require a little more computational effort than conceptual models but can provide increased certainty, especially in situations where particle movement in the longitudinal direction dominates, which is often true. This includes understanding general transport trends in long reaches, narrow channels, and shallow channels (Stone *et al*. 2007).

Two-dimensional, numerical models occupy the next level of sediment transport modeling. Two-dimensional models are perhaps most useful for shorter, more turbulent reaches (compared to the long reaches modeled by 1D software) or where lateral migration is of importance. Chen *et al*. (2007) used a two-dimensional model, CCHE2D, to model hydraulics and sediment transport in the Rio Grande between Alameda Boulevard and Paseo del Norte Boulevard in Albuquerque, New Mexico. They found CCHE2D to be more robust in predicting overbank flows and were able to provide higher precision results for sediment transport when compared with the widely used one-dimensional model, HEC-RAS.

Finally, three-dimensional, numerical models can produce the most accurate results but require the most intensive computations. Where one- and two-dimensional models are typically derived from simplifications of the Navier-Stokes equation (**Equation 1-2**), three-dimensional programs apply the full equation (Stone *et al*. 2007). These models are best applied to areas of exceptional local scour or over highly turbulent reaches of meandering channels (Stone *et al*. 2007). The complex nature of this kind of software is outside the scope of this thesis.

Engineers have applied numerical models to rehabilitation projects for some time. This includes solving sedimentation issues (Duan and Schwar 2003; Dargahi 2008), overcoming incision (Christensen *et al*. 2003), studying the effectiveness of paired deflectors at producing conditions conducive to aquatic habitat diversity (Carre *et al*. 2006), placing of islands in rivers (Bhowmik 2001), examining the impact of gravel augmentation over decadal timescales (Singer and Dunne 2006), and determining the impact of floodplain landscape improvements (Asselman and van Wijngaarden 2002). In only a portion of these studies did researchers use the numerical model as a design tool. Furthermore, there is little to no literature applying numerical models to ephemeral, side channels in semi-arid regions and only a few papers exist that compare the effectiveness of different levels of modeling (one-dimension versus two-dimension, etc.) in river restoration practices (*e.g.* Dargahi 2008; Lim and Cheok 2009)—none of which are applied to ephemeral, side channel projects.

1.5 Rio Grande Nature Center Rehabilitation Background

The Rio Grande Nature Center (RGNC) is located along the Rio Grande near Candelaria Road and Rio Grande Boulevard (**Figure 1-2**). In 2003, the US Army Corps of Engineers (USACE) submitted a proposal to perform 150,000 dollars of rehabilitation work in the RGNC (USACE 2006). The proposal was accepted later that year. USACE sought Middle Rio Grande Endangered Species Collaborative Program funding to improve habitat for the Rio Grande Silvery Minnow (RGSM) and the Willow Flycatcher. Engineers proposed reconnecting a historic, drainage channel and removing approximately 6 hectares (15 acres) of non-native vegetation. The channel would be ephemeral and provide sandy, low velocity, low depth spawning areas for the RGSM, satisfying the Biological Opinion released by the US Fish and Wildlife Service (USFWS 2003). Removing vegetation and reconnecting the floodplain to the main channel could also satisfy the 2003 Biological Opinion and provide improved conditions for native willow and cottonwood growth. Reconnection is vital for maintaining groundwater depths conducive to native vegetation growth because the river is incised an average of approximately 1.2 meters (4 feet) below the banks in the project reach (Massong *et al*. 2006). In addition, the proposed design would reduce fire potential and provide recreational opportunity for state park patrons.

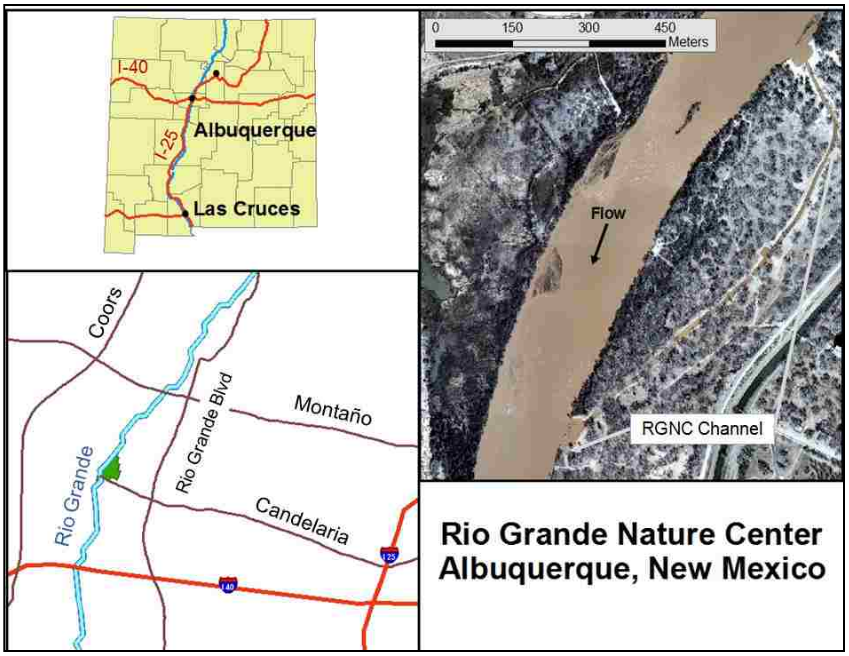


Figure 1-2: RGNC Vicinity Map

Final design (**Figure 1-3**) included excavation at both upstream and downstream ends of the remnant channel. Four embayments were included in the design. Large embayments were placed at the inlet and outlet with two smaller embayments constructed adjacent to the channel. The embayments would provide excellent RGSM habitat and would be designed to reduce the risk of minnow stranding (*i.e.* being caught in a quickly drying channel without escape). The total channel length was set just over 1000 meters (3300 feet). The first 174 meters (570 feet) of channel was sloped uphill, allowing only high flows through the channel. Engineers gave the channel a trapezoidal geometry with an average 6.1 meter (20 foot) base width and side slopes ranging from 1:3 to 1:30. The USACE planned for monitoring of RGSM, vegetation, groundwater, and sediment accumulation. 2006 design reports recognized the need for sediment removal to sustain channel function. Engineers used a design flow of 88.9 cms (3140 cfs). This flow would be sustained for a minimum 21 days. The channel inlet invert was set 0.3 meters (1 foot) below the Rio Grande water surface elevation corresponding to that modeled at 88.9 cms (3140 cfs) using HEC-RAS. The inlet invert was set at 1514.69 meters (4969.40 feet). USACE determined that there would be no adverse hydraulic effects and that annual net depletions would be 7400 cubic meters (6 acre-feet).

Many similar restoration projects have been instituted along the Middle Rio Grande such as the Revitalization at Route 66 (USACE 2008), the Albuquerque Overbank Project (MRGBI 2009), Isleta Reach Riverine Restoration Project (SWCA 2008), and the Rio Grande Habitat Restoration Project, Los Lunas, New Mexico (USACE 2002). For this reason, it is important for engineers to improve their understanding of these projects and the role sediment transport plays by developing and applying of numerical, sediment transport models.

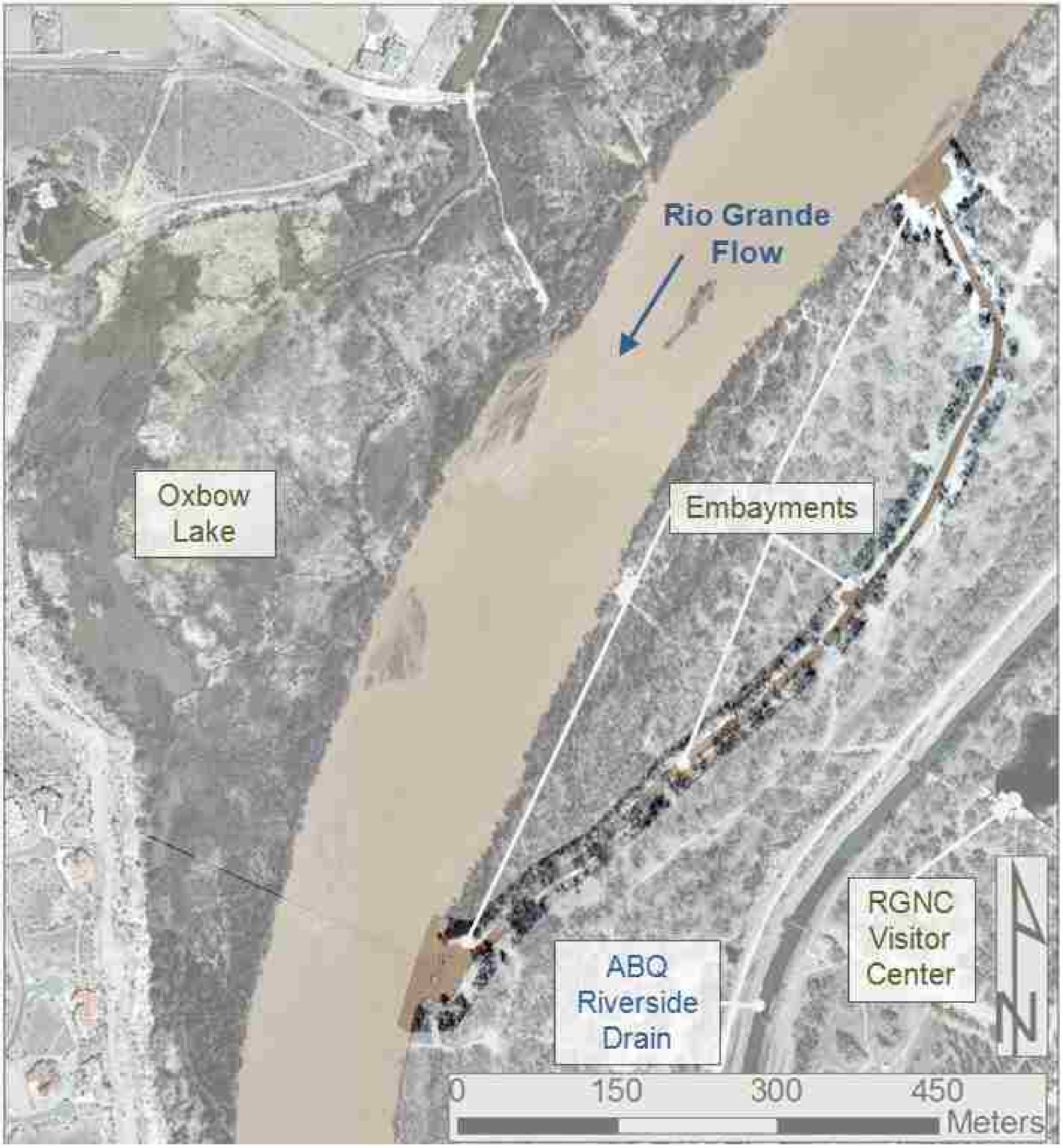


Figure 1-3: Aerial View of RGNC (2008 Bernalillo County Orthophotography)

2 DATA PROCESSING

2.1 Data Acquisition

Before the project site can be numerically modeled, an accurate terrain model must be constructed (Nicholas and Walling 1998). Three terrain data sources have been acquired, adjusted, and combined to create a terrain model of the study area. Data processing and application followed the method defined in **Figure 2-1**.

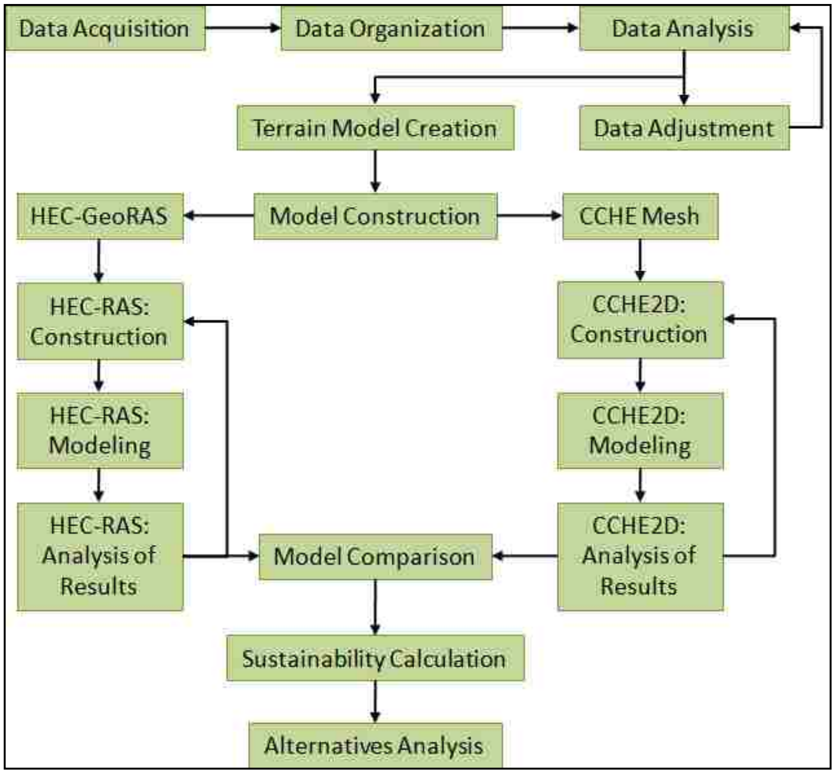


Figure 2-1: Data Processing and Application Methods

The majority of the ground surface data came from Isaacson (2009). Isaacson created a triangulated irregular network (TIN)—a digital surface model—of the Middle Rio Grande floodplain in Albuquerque, New Mexico using techniques from Merwade *et al*. (2008). The TIN was created with US Bureau of Reclamation Rio Grande cross-sections and 2006 Bernalillo County LiDAR (light detection and ranging) scans. Jed

Frechette of the University of New Mexico (UNM) LiDAR Lab supplied scans of the RGNC channel from February 2008 and March 2009 (**Figure 2-2**). These scans have a high resolution (15 cm by 15 cm) and record the channel's topography before it received any flow and after one year of flow, respectively. However, they do not span the entire length of the RGNC channel. To complete the terrain model upstream and downstream of the LiDAR scans, USACE of engineer designs were applied (**Figure 2-3**).

The USACE has a gage in the RGNC channel (**Figure 2-4**); the USGS has maintained the gage and developed a rating curve for the channel during water year 2009 (**Figure 2-5**). The rating curve data were supplied by the USACE; the trend line has been added as part of this thesis' research. The data appears to contain one outlier. No explanation can be provided for why this point is so far from the expected trend.

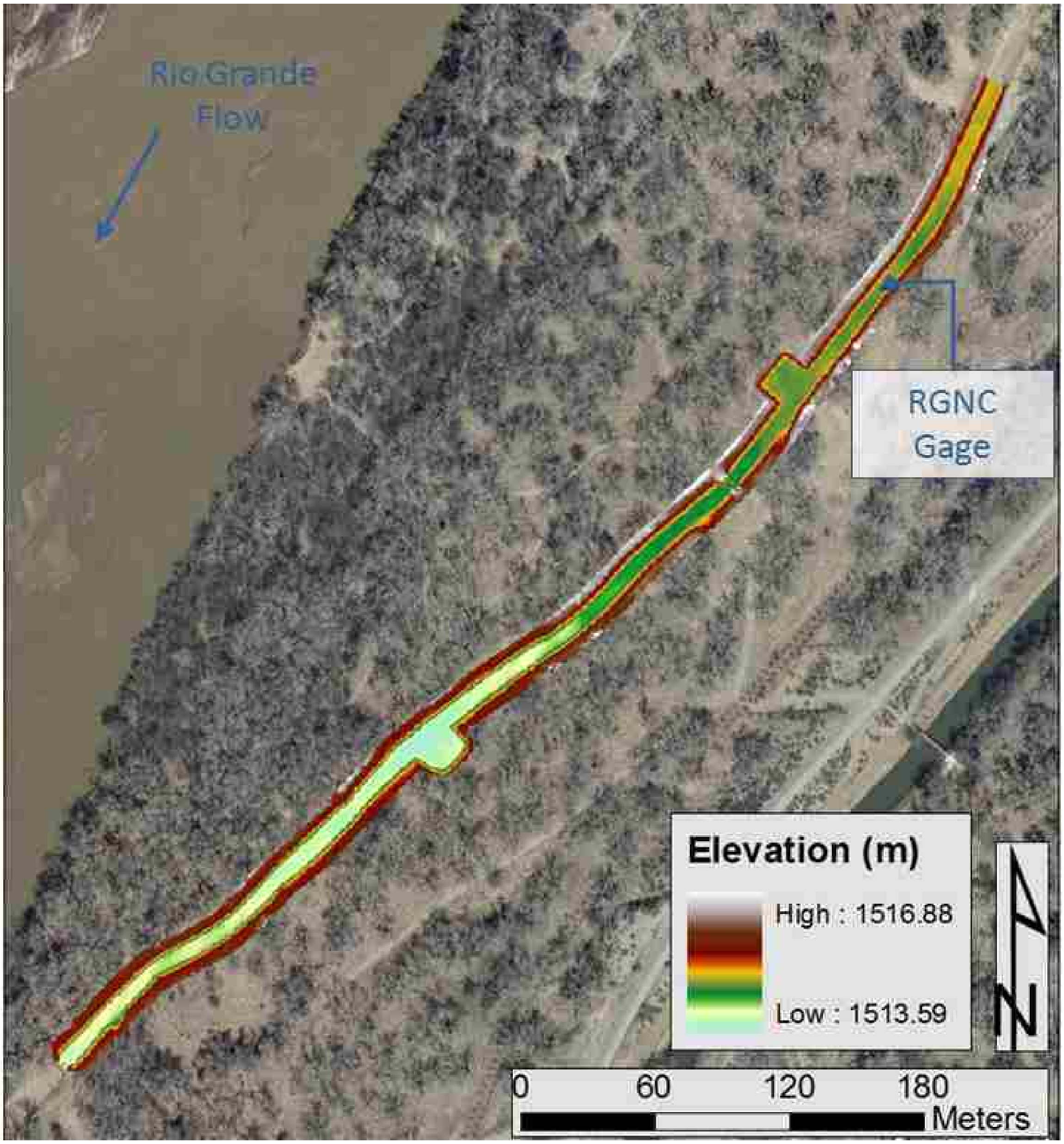
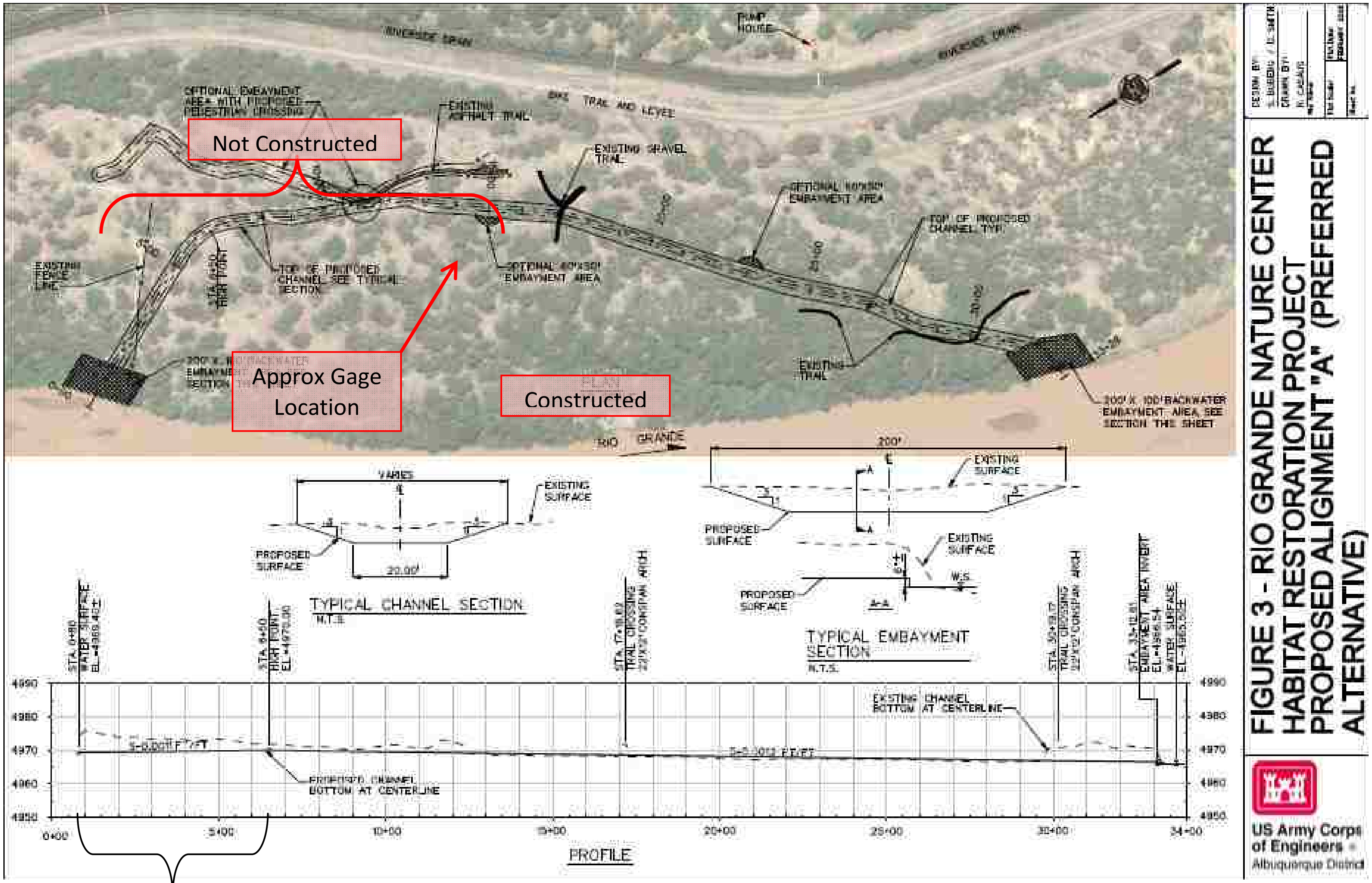


Figure 2-2: 2008 RGNC Channel LiDAR



Adverse Slope

Figure 2-3: USACE RGNC Channel Design (from USACE 2006)

Figure 2-4: USACE RGNC Channel Gage

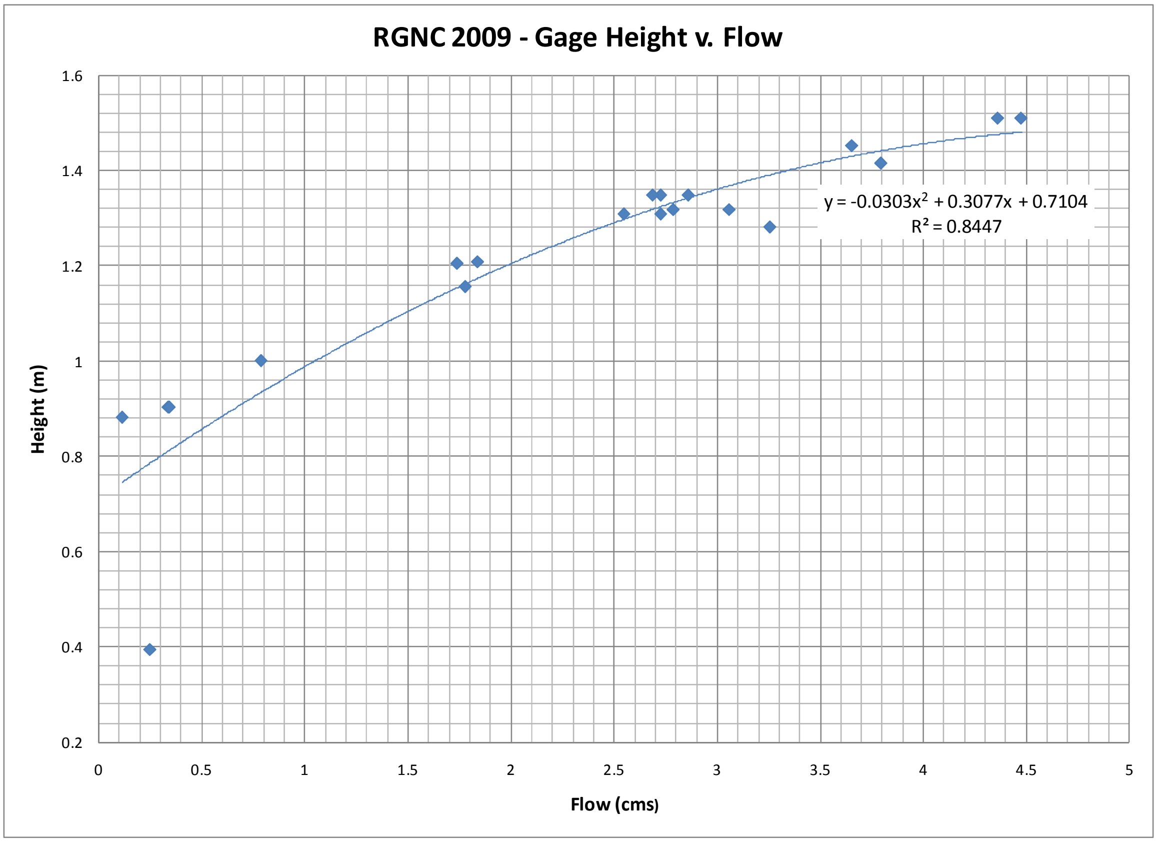


Figure 2-5: RGNC Channel Gage Rating Curve

2.2 Site Condition and Data Analysis

Based on LiDAR scans, the RGNC channel has aggraded significantly and non-uniformly since construction (**Figure 2-6**). Because elevation data have not been collected for the entire channel, exact values of bed elevation change for full length of the channel cannot be known.

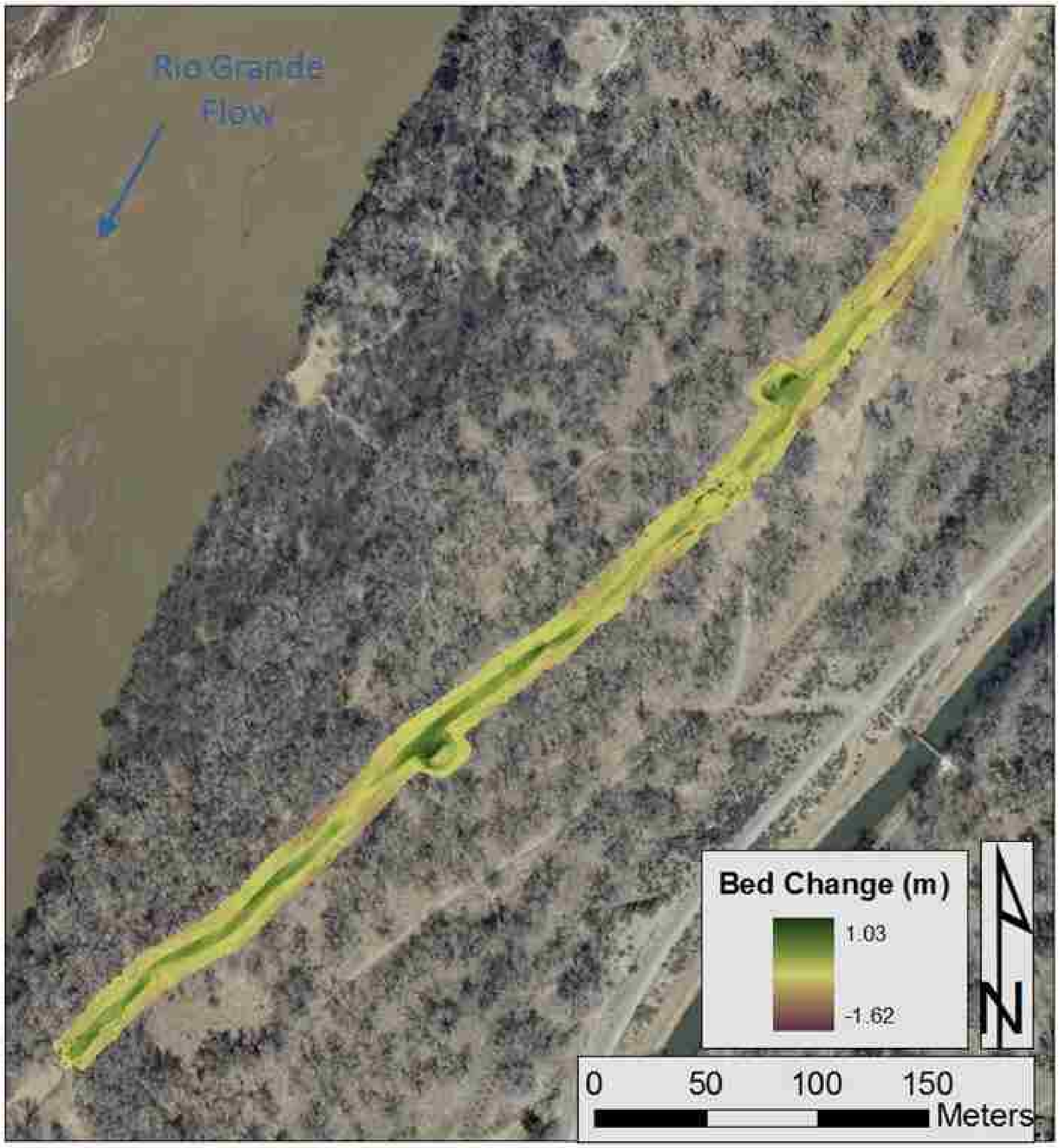


Figure 2-6: RGNC Channel Elevation Change from 2008 to 2009

The following seven observations have been made using the USACE gage and photographs. These changes are the result of spring 2010 flows. Generally, the channel appears to have aggraded, and native plants seem to be better established. **Figure 2-7** details locations of each observation.

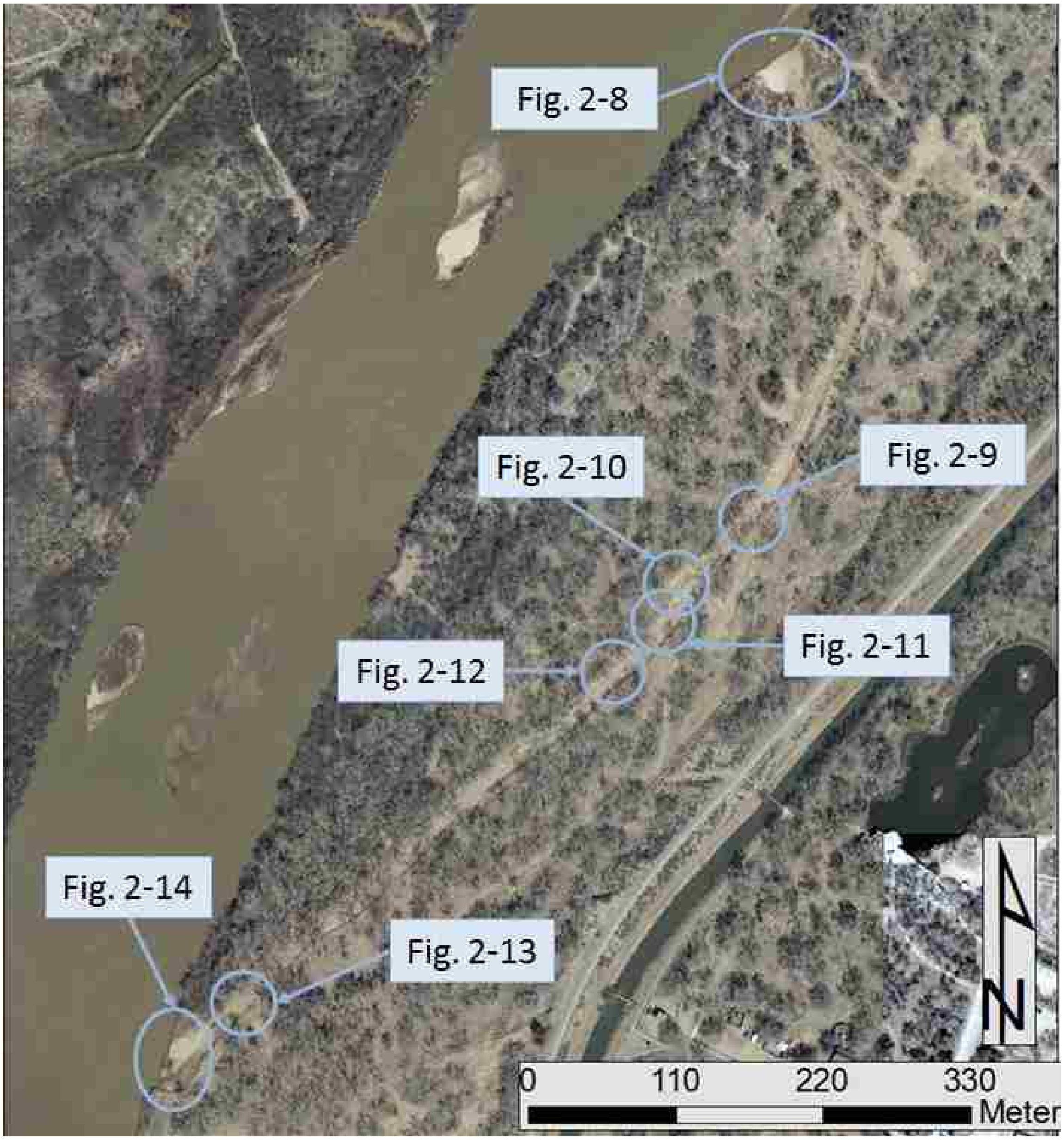


Figure 2-7: RGNC Channel Observation Location Map

1. The RGNC channel inlet shows signs of deposition and native vegetation establishment. However, since the Rio Grande flow varies between pictures, quantification of deposition is difficult. Finally, note the thalweg—the lowest point in the channel bed—has narrowed, migrating slightly towards the left bank (**Figure 2-8**).

Figure 2-8: Inlet 02/2010 (left) & 11/2010 (right)

2. The channel has aggraded by approximately 0.10 meters (0.33 feet) at the USACE gage (**Figure 2-9**).

Figure 2-9: USACE Gage 02/2010 (left) & 11/2010 (right)

3. Though both embayments have experienced significant deposition since construction, they did not visibly aggrade during 2010 flows (**Figure 2-10**).

Figure 2-10: North Embayment 02/2010 (left) & 11/2010 (right)

4. New bed and bank deposits are visible upstream of the north culvert (**Figure 2-11**).

Figure 2-11: Channel Looking Upstream from the North Culvert Bridge 02/2010 (left) & 11/2010 (right)

5. New bank deposits downstream of the north culvert could be the result of the left culvert barrel blockage and an early stage of two-stage channel development (**Figure 2-12**).

Figure 2-12: Channel Looking Downstream from the North Culvert Bridge 02/2010 (left) & 11/2010 (right)

6. Long-term south culvert blockage exhibits a potential lack of maintenance and causes scour at the culvert outlet (**Figure 2-13**).

Figure 2-13: South Culvert Blockage Increased from 02/2010 (left) to 11/2010 (right)

7. The channel outlet also exhibits significant native vegetation establishment (**Figure 2-14**).

Figure 2-14: Outlet Vegetation Establishment from 02/2010 (left) to 11/2010 (right)

2.3 Data Adjustment

All data were projected into a Universal Transverse Mercator (UTM) Zone 13 North coordinate system. No data source required horizontal transformation. However, vertical discrepancies existed between Isaacson's (2009) TIN and the 2008 and 2009 LiDAR scans. Isaacson's terrain data were assumed to be correct because the LiDAR was not tied into any vertical control when they were taken. First, 2008 and 2009 LiDAR scans were vertically adjusted to match one another. This was done by measuring elevation differences between hard points (*e.g.* top of concrete wing walls at each culvert) on the digital elevation model (DEM). Then each LiDAR DEM was adjusted to match the top of banks of the remnant channel in Isaacson's TIN. Review of USACE documents suggests that the nature center channel would be excavated to match elevations of the historic drainage channel with no additional earth work in the historic channel. However, examination of the channel profile suggested otherwise (**Figure 2-15**).

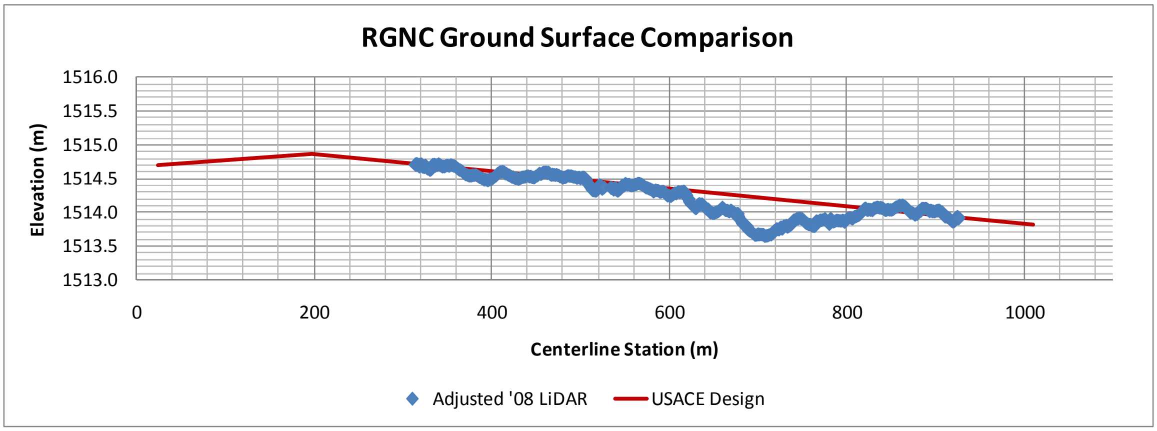


Figure 2-15: Designed and Actual RGNC Channel Centerline Profile

To determine how the historic channel compared to the LiDAR data, a portion of Isaacson's TIN, having the same extents as the LiDAR scans, was converted to a raster. This allowed for easy quantitative comparison with ArcMap's Raster Calculator. The LiDAR DEM showed greater depths along the length of the remnant channel (**Figure 2-16**) than the TIN. At this point, the LiDAR depths were accepted as correct since they had the most recent timestamp (Merwade 2008). The Raster Calculator was used to subtract Isaacson's TIN from each LiDAR scan. In this difference raster, positive values represented areas where the LiDAR was above the TIN (**Figure 2-17**). Positive values existed predominantly along channel banks. Because the banks had not undergone significant change, bank elevations were used to adjust the LiDAR data. Therefore, negative values were removed from the difference raster with a conditional statement (**Figure 2-18**). The average positive value was determined by examining raster properties. Each LiDAR scan was adjusted vertically by this average value using Raster Calculator. After this adjustment the data was vertically aligned.

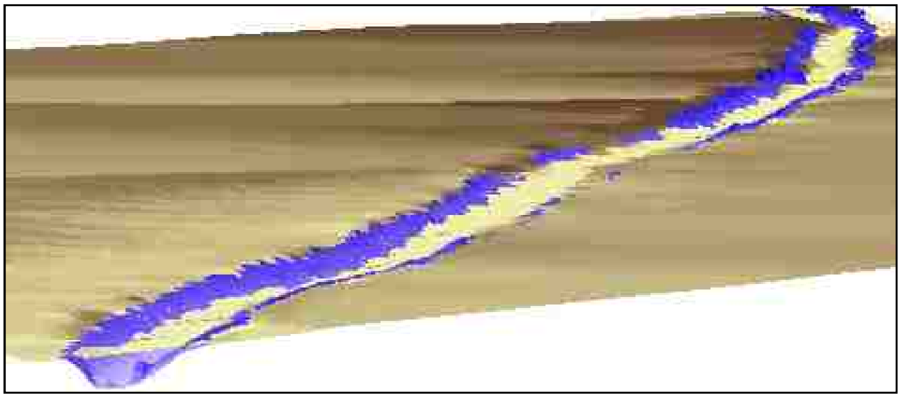


Figure 2-16: 2008 LiDAR Data (Blue) against Isaacson's (2009) TIN (Brown)

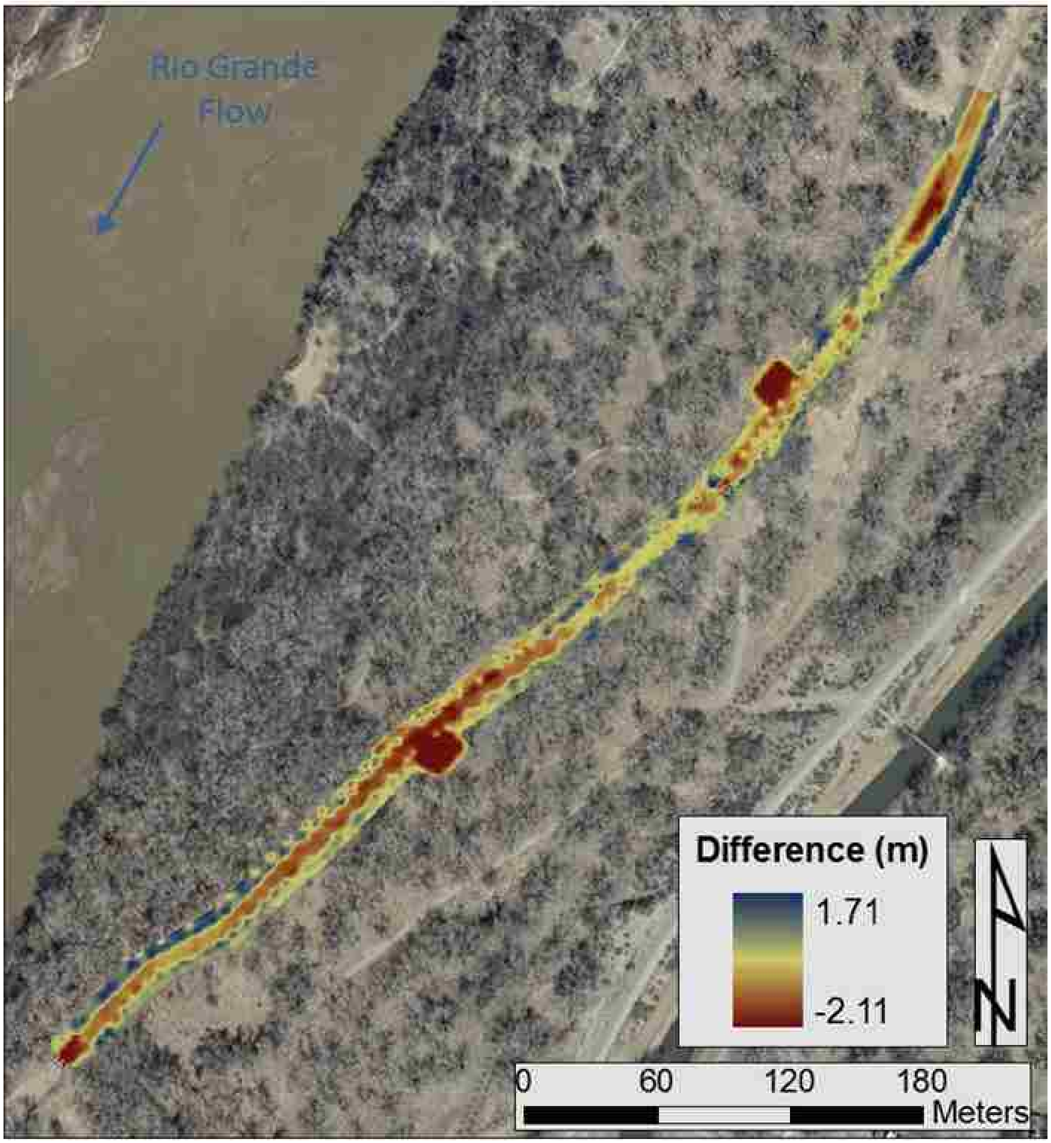


Figure 2-17: Difference Raster – Historical Channel Minus 2008 LiDAR

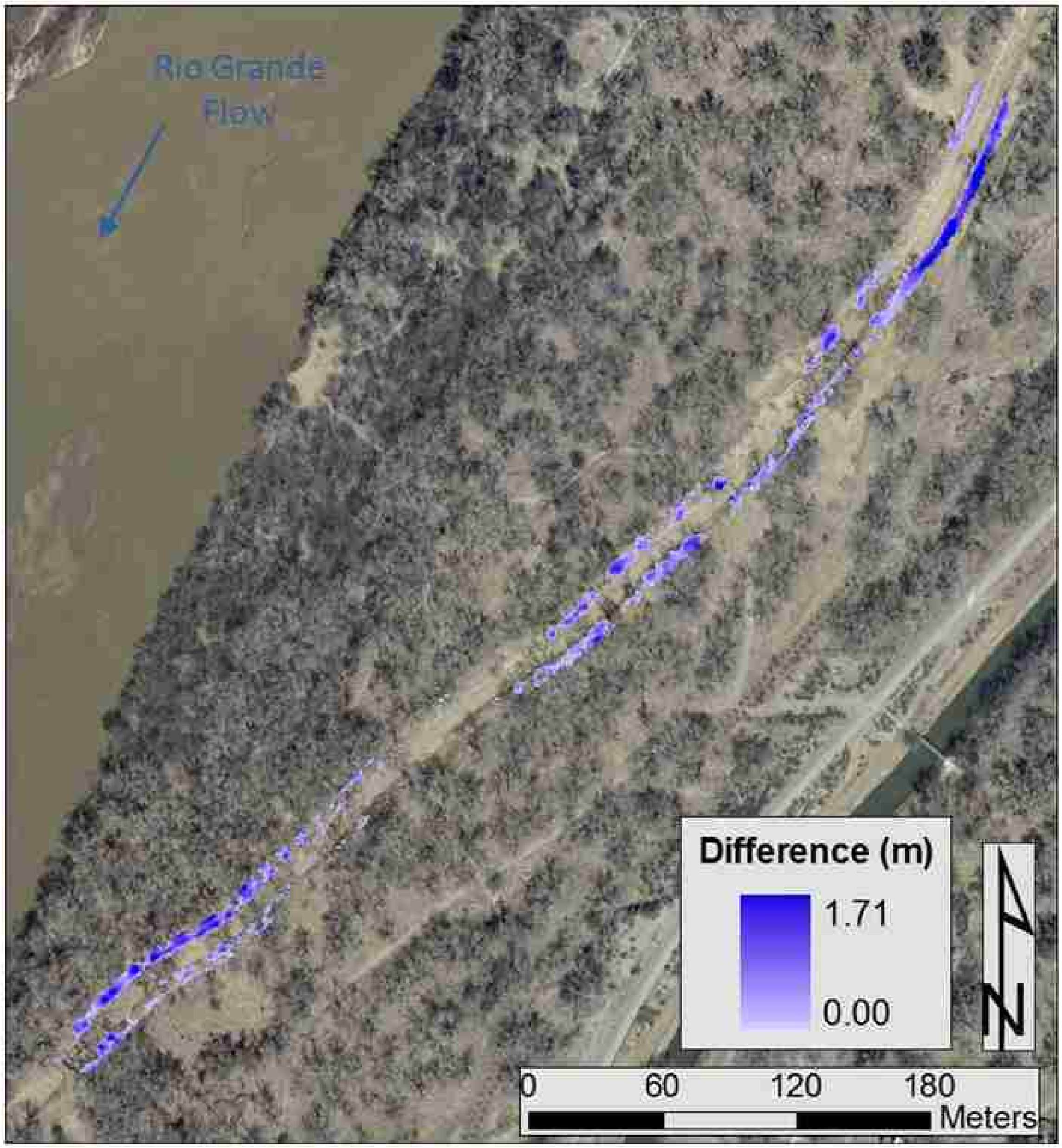


Figure 2-18: Difference Raster with Negative Values Removed

2.4 Terrain Model Development

All the data were first converted to points; the points were merged and, finally, converted into a single TIN. The LiDAR scans were first converted to TINs then to points, resulting in fewer points than just converting a raster to points. Therefore, the terrain model file size decreased. However, with fewer points the accuracy of the data could have been compromised. To ensure that it was not compromised, the points were converted back into a raster—an analysis raster. The analysis raster was subtracted from the original LiDAR scan (**Figure 2-19**). At first look, the subtraction raster has a wide range of values and seems inaccurate. However, examination of the raster statistics (**Table 2-1**) reveals that the method is sound. The portion of Isaacson's (2009) TIN coinciding with the modeled area was converted directly to points. Finally, points were created using USACE designs. These points required no manipulation.

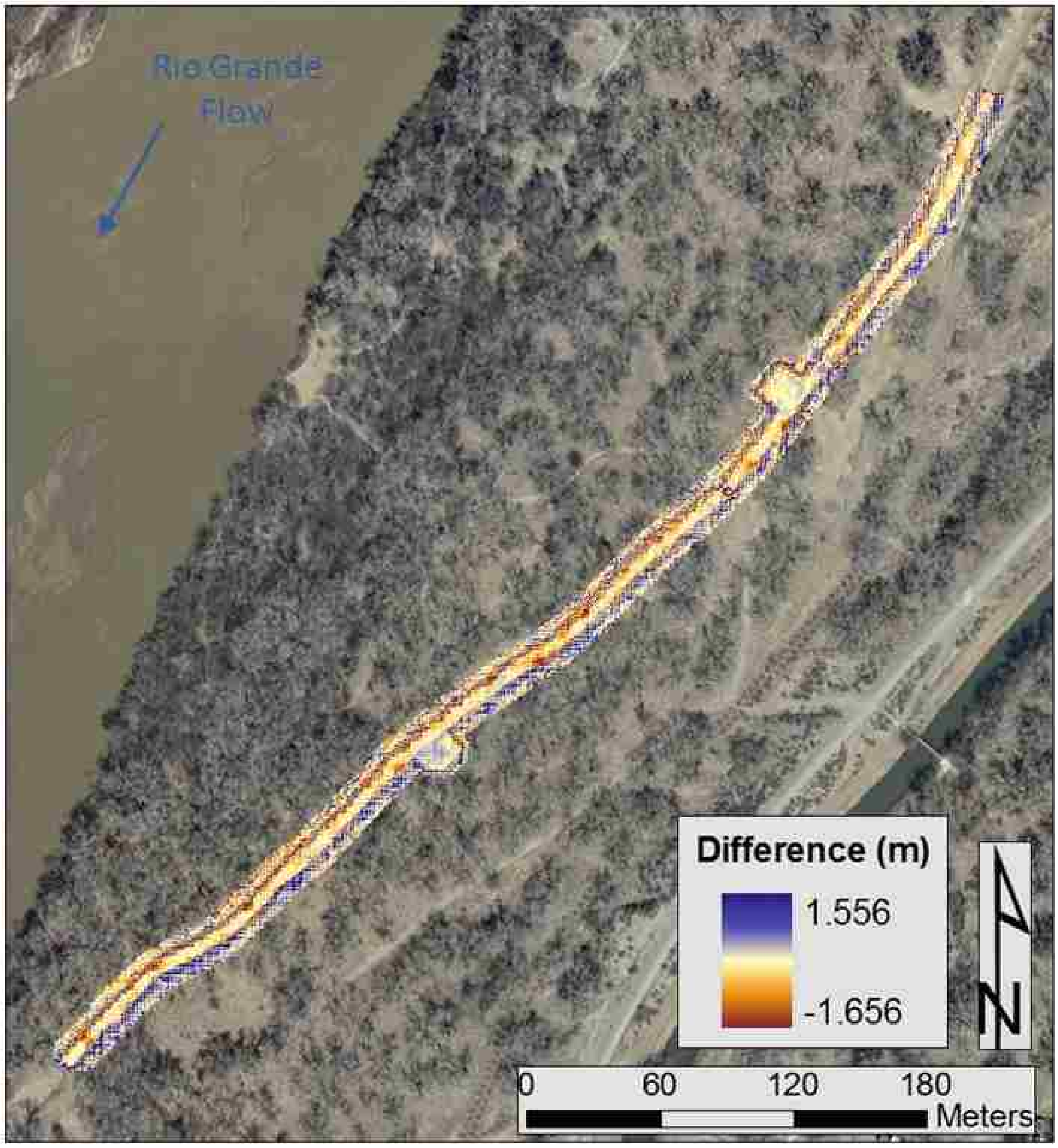


Figure 2-19: Analysis Raster Used to Examine Terrain Conversion Techniques

Mean Diff. (m)	Standard Deviation (m)
-0.01	0.15

Table 2-1: Analysis Raster Statistics

Once all terrain data existed as points, X, Y, and Z coordinates were added to each point using ArcGIS. First, attribute fields for X, Y, and Z coordinates were added.

ArcMap's field calculator was utilized to calculate X and Y coordinates. Z data was calculated using the SurfaceSpot_3d tool in ArcMap's 3D Analyst except for points created using USACE design documents. For USACE design points, elevations were manually calculated and entered in a GIS editing session.

The points from all terrain data sources were merged, and a TIN was created. The TIN was created to visualize the terrain model. The TIN revealed inaccuracies at locations in both the up and downstream ends of the RGNC channel where terrain points were created using USACE design documents (**Figure 2-20**). Inaccuracies occurred where there were too few points to interpolate the terrain correctly. The high-point-density floodplain was interpolated to the toe of bank points instead of top of bank points because of the low-point-density in the channel. TINs cannot be directly edited like other features (*e.g.* a polygon) in ArcGIS. Therefore, inaccuracies in the TIN were corrected by adding points to the RGNC channel. These points were added to the TIN, finalizing the terrain model (**Figures 2-21 and 2-22**).

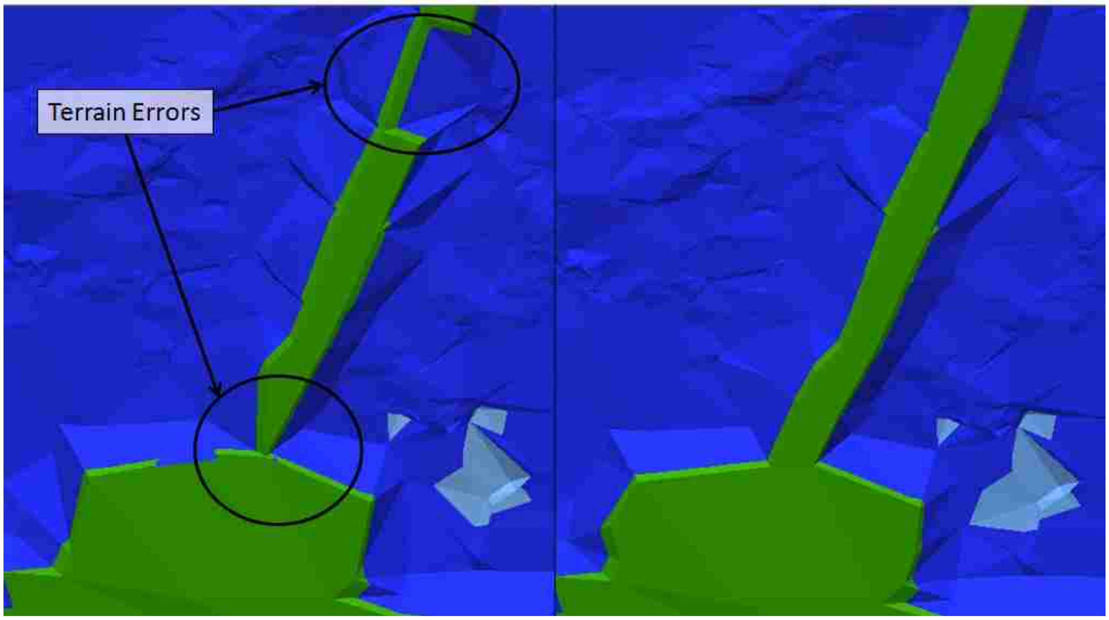


Figure 2-20: TIN Inaccuracies and Improvements

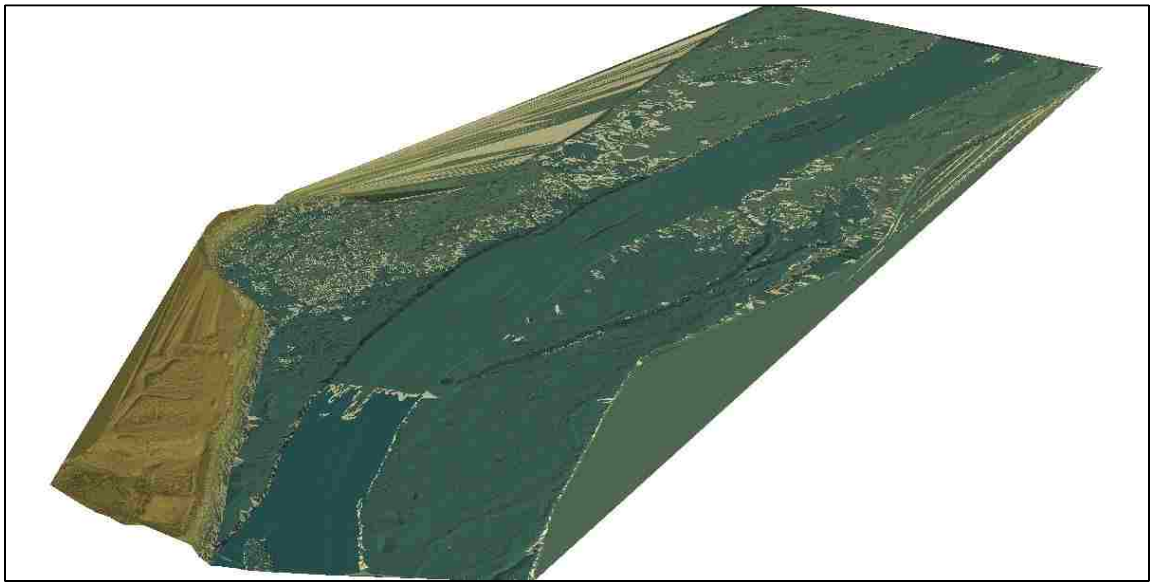


Figure 2-21: TIN of Final Terrain Model

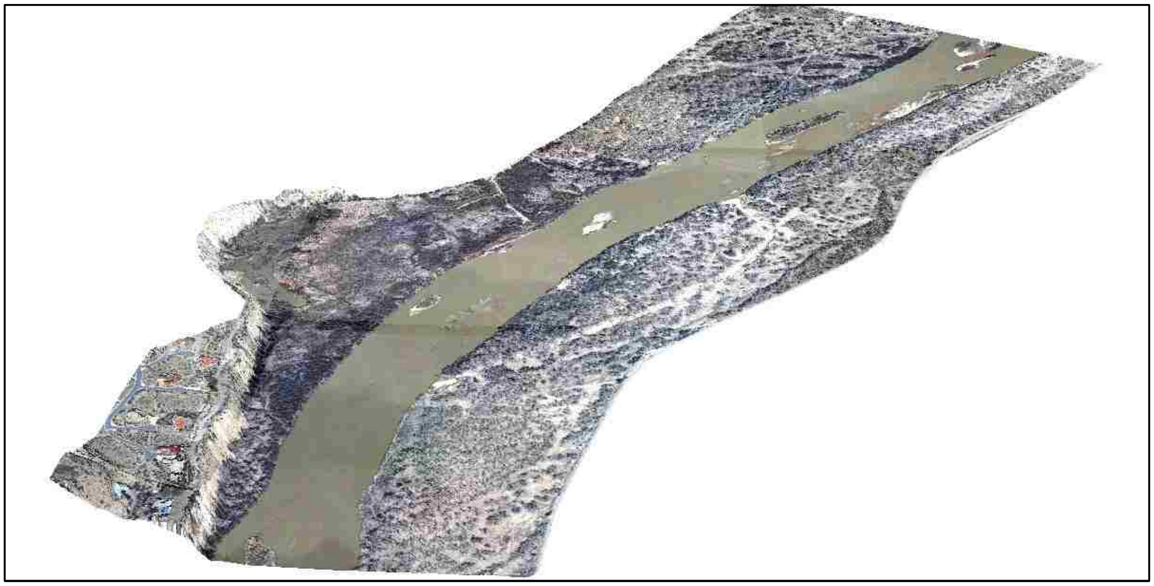


Figure 2-22: TIN of Final Terrain Model with 2010 Bernalillo County Orthophotography Draping

3 ONE-DIMENSIONAL NUMERICAL MODELING

3.1 Description of Selected Software

The USACE's Hydraulic Engineering Center (HEC) has published a software package for creating one-dimensional numerical models—the River Analysis System (RAS) or HEC-RAS. The Hydraulic Engineering Center created HEC-GeoRAS to aid modelers in pre- and post-processing of HEC-RAS data.

HEC-GeoRAS exists as a toolset in ArcGIS that allows GIS users to create HEC-RAS terrain data, called geometry, from either a raster or a TIN (USACE 2009). Modelers can digitize cross-sections wherever there are features of interest that need to be captured. Once features are digitized, GeoRAS computes all the necessary information (*e.g.* bank and river stations, downstream reach lengths, etc.), saving modelers time by removing once tedious tasks. GeoRAS then converts all the GIS data into a format usable in HEC-RAS and exports it. After HEC-RAS modeling is complete, HEC-GeoRAS can be applied to convert HEC-RAS results to a format that GIS can read. From these re-formatted results, GIS can be applied to produce quality figures and aid in analysis of model results.

HEC-RAS is a one-dimensional, depth-averaged numerical model with the capability of simulating both hydrodynamics and sediment transport (USACE 2010). HEC-RAS reduces terrain models to cross-sectional data. Cross-sectional data is divided into rivers and sub-divided into reaches; rivers and reaches are connected by nodes called junctions. HEC-RAS interpolates modeled values linearly between cross-sections. Although outside the scope of this paper, the program can also be applied to model both steady and unsteady flows as well as perform water quality simulations.

3.2 HEC-GeoRAS Work

HEC-GeoRAS was used to create two HEC-RAS models. Each model had different strengths and weaknesses; these pros and cons will be discussed in the following section. The first model included only one river, having one reach (**Figure 3-1**). Cross-sections extended from the left levee to the right levee throughout the entire reach. The RGNC channel was modeled with the same cross-sections as the Rio Grande. Cross-section spacing was approximately 50 meters up and downstream of the RGNC. Within the RGNC, cross-section spacing was approximately 25 meters.

Figure 3-1: Plan View of First HEC-RAS Model Geometry

The second model was divided into four rivers—each river having only one reach (**Figure 3-2**). The four rivers were the RGNC channel, the Rio Grande upstream of the RGNC, parallel to the RGNC, and downstream of the RGNC. For HEC-RAS to correctly apply the junctions between the Rio Grande and the RGNC channel, each channel leaving or entering the junction must be digitized as a separate river in HEC-GeoRAS. Therefore, the Rio Grande was divided into three rivers each having one reach instead of one river with three reaches. Similarly to the first model, cross-sections were separated by 50 meters along the Rio Grande and 25 meters along the RGNC channel. Because of the way the model was structured, cross-sections do not extend from left to right levee.

Figure 3-2: Plan View of Second HEC-RAS Model Geometry

3.3 HEC-RAS Work

The first model was easy to run because flow in the RGNC channel was automatically calculated by HEC-RAS. Not having to estimate flow diversions at junctions simplified hydraulic calibration slightly. However, the model had a few shortcomings that made it inaccurate for sediment transport applications. These downfalls were inherent, preventing it from accurately modeling this kind of site. HEC-RAS calculates average values for the cross-section (water surface elevation, sediment deposition, etc.) and applies those values to the entire cross-section. This meant that the Rio Grande and the RGNC channel deposition were calculated to be the same. This is not the case. The ability to determine separate hydraulic and sediment transport values in a side channel would have been useful.

In the second model, HEC-RAS required flow diversion at each node to be input manually. To determine diversion flowrate into the RGNC channel, USACE rating curve data were used (**Figure 2-5**). The USACE rating curves come from the gage located near the mid-point of the RGNC channel. However, since the RGNC channel was modeled as a separate river, hydraulic and sediment transport parameters would be calculated separately. This would allow for greater accuracy and an improved ability to analyze results.

Model calibration was divided into two parts: the Rio Grande sections of the model and the RGNC channel. This method was more manageable because of availability of measured data. No measured data were available along the reach of the Rio Grande being modeled, so the model was matched to Isaacson's (2009) model. Her model was calibrated to USGS gage data. Hydraulics in the RGNC channel were calibrated against the USACE gage. Steady state hydraulic calibration resulted in the selection of 0.021 for a Manning's n-value for both the Rio Grande and the RGNC channel.

Sediment transport calibration of the Rio Grande portion of the model was carried out by matching suspended sediment values measured at the USGS gage at Albuquerque (08330000) to those modeled in a cross-section most similar to the cross-section containing the USGS gage. Cross-section similarity was based on hydraulic depth and friction slope. Assuming the Rio Grande is a wide channel, hydraulic depth is an acceptable approximation for depth. Similarly, depth is an acceptable approximation for hydraulic radius in wide channels. Therefore, hydraulic depth and radius are approximately equal in wide channels. Hydraulic radius, and therefore hydraulic depth, and slope are the parameters that drive bed shear stress which heavily influences sediment transport.

Using the hydraulically similar cross-section, sediment calibration was performed. The Toffaleti equation (Toffaleti 1968) was determined to best represent sediment transport in the Rio Grande. This is applicable because the equation was developed from stream data and is used to calculate total sediment load—suspended load plus bed load. The Toffaleti equation was developed for large sand-bed (0.062-16 mm) rivers like the Rio Grande (Mays 2005).

Difficulties arose when sediment transport calibration was attempted in the RGNC channel. Sedimentation calibration was attempted using Spring, 2008 flow data from the USGS and measured deposition resulting from 2008 (**Figure 2-6**). The Laursen (Copeland) equation (Copeland and Thomas 1989) seemed best suited for the RGNC channel. It was developed from flume data and can be applied to sediments with specific gravity of 2.65 in shallow rivers with fine sand and coarse silt. The Laursen (Copeland) equation was developed with sediment ranging from 0.01 mm to 4.08 mm, this range captures over 99 percent of the sediment in the RGNC channel.

Though, the Laursen equation yielded the best results. It was not significantly better than any other acceptable transport capacity equation. On average, the model under-predicted deposition by approximately an order of magnitude across the entire nature center channel. Many changes have been made to the model, including altering grain-size distribution in the channel bed and in the upstream suspended sediment load, increasing the upstream suspended sediment load, varying channel Manning's N-values, changing bed slopes to reflect proposed conditions and no-adverse-slope conditions, varying computational interval, simulation times and magnitudes, and increasing downstream friction slopes. Initially, these alterations were made within a reasonable range. However, after this produced little change, parameters were varied outside a legitimate range. In simulating extreme circumstances, the modeler was hoping to learn about model limitations and capabilities. However, though all of these alterations have had some impact, HEC-RAS modeled deposition is still approximately an order of magnitude below observed deposition.

Further examination of sediment model results reveals that shear stresses are also approximately one order of magnitude low. Since HEC-RAS calculates shear stress in both the hydraulics and sediment transport modules, hydraulics results for the RGNC channel were examined. Curiously, the hydraulics model results seem to independently predict reasonable values (**Figure 3-3**).

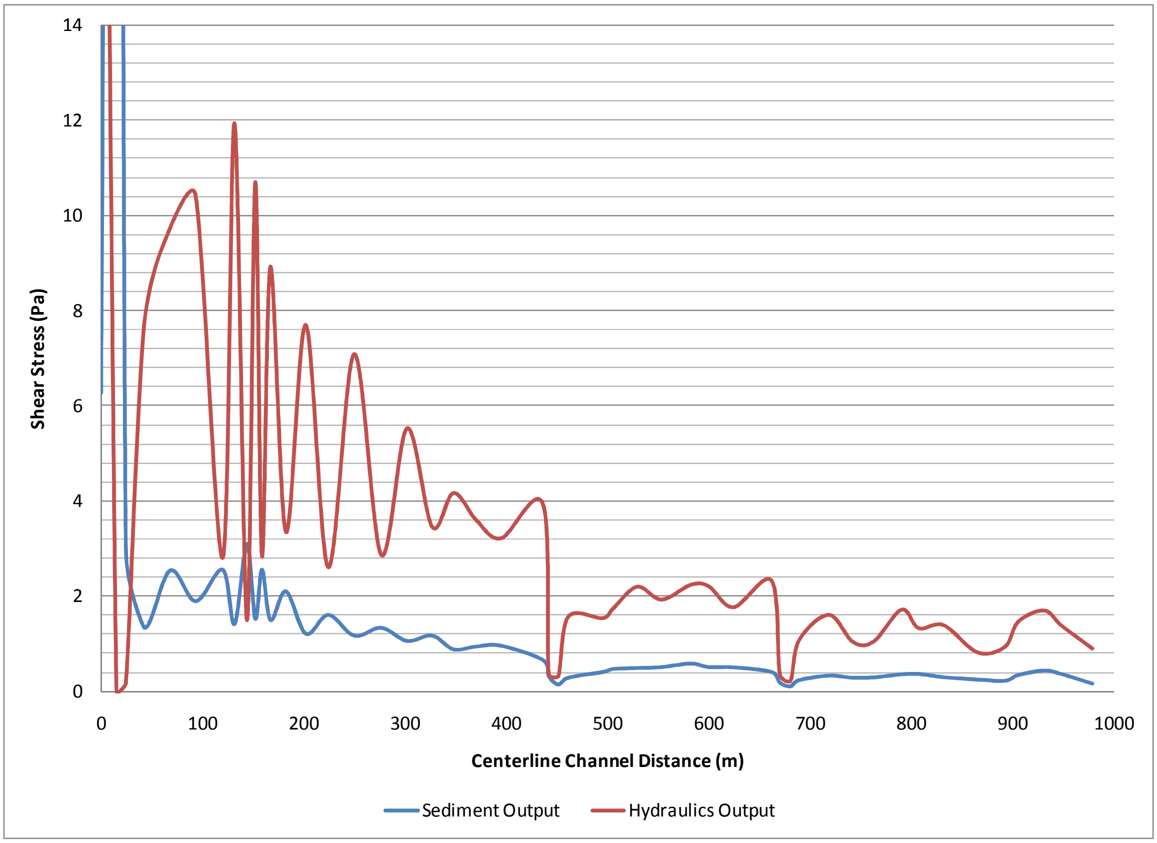


Figure 3-3: Longitudinal Distributions of Shear Stresses

Interestingly, both the hydraulic and sediment transport modules of HEC-RAS predict large values of shear near the upstream of the RGNC channel. HEC-RAS does not permit information about upstream water surface elevation to be input in a quasi-steady state flow profile (required for sediment transport), resulting in an under-prediction of depth at the channel inlet for this case. As a result of these low depths, HEC-RAS "chokes" the flow transitioning from the inlet to the channel, causing increased depth and, therefore, increased shear stress.

The cross-section spacing in the RGNC portion of the model was decreased to approximately 0.5 m by interpolating existing cross-sections. By increasing cross-section resolution, the modeler hoped to remove modeling errors. If the results improved or, at least seemed more numerically meaningful, the previous results could have been the consequence of a lack of convergence in the model. The same general problems occurred with results appearing to be slightly less sporadic along the channel. HEC-RAS still over-predicted deposition and shear stress in the upstream of the channel and under-predicted them over the majority of the length (**Figure 3-4**). However, these shear stresses seem more physically meaningful.

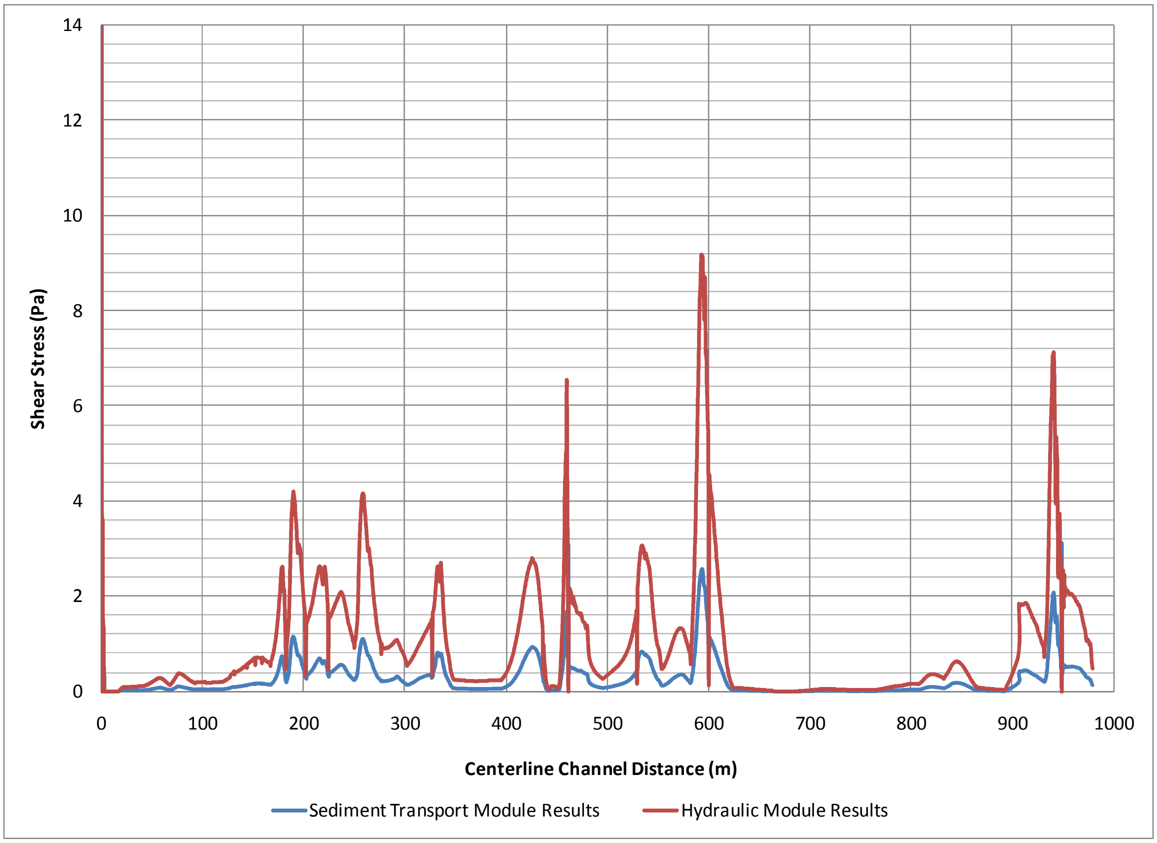


Figure 3-4: Longitudinal Distribution of Shear Stress (Refined Geometry)

Examining **Figure 3-4** in the context of **Figure 3-5**—the longitudinal water surface elevation profile for the RGNC channel—helps make sense of the shear stress variations. Areas of low or zero shear stress correlate to areas with a zero friction slope. Additionally, **Figure 3-5** reveals that depth and, therefore, the hydraulic radius are highly variable along the channel. This will cause the shear stress to vary similarly.

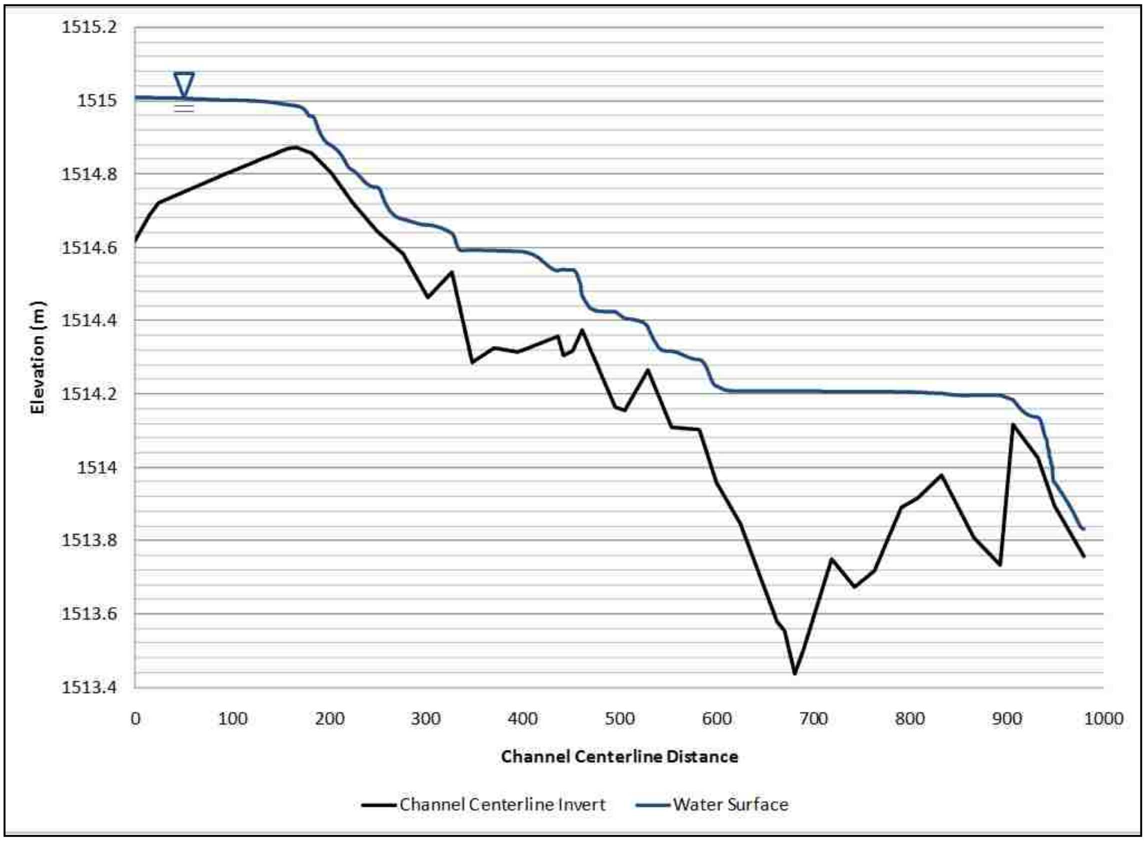


Figure 3-5: Longitudinal Water Surface Profile

Shear stress issues have not been resolved. The HEC-RAS model remains only partially calibrated. Without knowing how to resolve the discrepancy between the hydraulics and sediment transport modules in HEC-RAS, the author concludes that HEC-RAS is not sufficient for modeling sediment transport in ephemeral side channels. Other one-dimensional models exist; however, due to time constraints these programs have not been examined for this application.

4 TWO-DIMENSIONAL NUMERICAL MODELING

4.1 Description of Selected Software

The programs CCHE Mesh 3.0 and CCHE2D 3.26 have been selected for this research. Both programs are free and developed by the National Center for Computational Hydrodynamics and Engineering (NCCHE). CCHE Mesh is a GUI program used to develop a structured finite difference method (FDM) mesh for use in CCHE2D (Zhang and Jia 2009). CCHE2D is capable of modeling two-dimensional hydraulics and sediment transport for both steady and unsteady open channel flows (Zhang 2006). The program is depth integrated, solving for parameters in the longitudinal and transverse directions. The program is also capable of modeling water quality parameters; however, that is outside the scope of this report and will not be analyzed.

4.2 CCHE Mesh Construction

Mesh development begins by importing topographic data. CCHE Mesh can import cross sectional data, scattered points (non-structured points with X, Y, and Z data), and digital elevation models (DEMs). Next, the area to be modeled is defined by drawing polygons called blocks. Zhang and Jia (2009) provide rules for block creation. For example, each side of a block can connect to only one other side of a block and adjacent sides must be identical. However, each block can have a unique grid size. If multiple blocks are defined, adjacent blocks must be connected. CCHE Mesh connects blocks automatically when corresponding vertices of adjacent blocks are overlapping; once a segment of a block is connected it will turn from pink to cyan. Next, the mesh is generated. Each mesh is divided into I-lines and J-lines representing longitudinal and transverse flow direction, respectively. Algebraic meshes should be created first by defining the number of I-lines and J-lines. The algebraic mesh can then be used to generate a numerical mesh. Zhang and Jia (2009) recommend using a RL (Ryskin and Leal 1983) Orthogonal Mesh with smoothness controls for "natural rivers with irregular boundaries," saying that it is "very reliable and robust to generate quality meshes." The numerical mesh can be evaluated and refined using smoothness controls. Additionally, editing tools can be applied to make local improvements. Finally, elevations should be applied to the mesh from the topographic data, typically by random interpolation.

Four meshes, each with a different resolution, have been created (**Figure 4-1**), following recommendations by Hardy *et al*. (1999). Hardy *et al*. (1999) show that grid element size can have a large impact on hydraulic model results and, therefore, recommend selection of at least three grid sizes for modeling. This allows modelers to test for mesh convergence. Each mesh contains only one block. The average element size for each mesh was selected based upon the bottom width of the nature center channel. This practice follows that suggested by Nicholas and Walling (1998) who recommend a grid size to feature length ratio of 0.5 to 0.1 for numerical hydrodynamic models. The feature length of interest in this study is the bed of the RGNC channel. The average bottom width of the channel is 6.1 meters (20 feet). Therefore, the following square grid sizes have been chosen: 3.0 m (0.5 of length scale), 2.0 m, 1.0 m, and 0.5 m (approximately 0.1 of length scale). Once these meshes were created, the terrain model was imported to CCHE Mesh and random interpolation was performed.

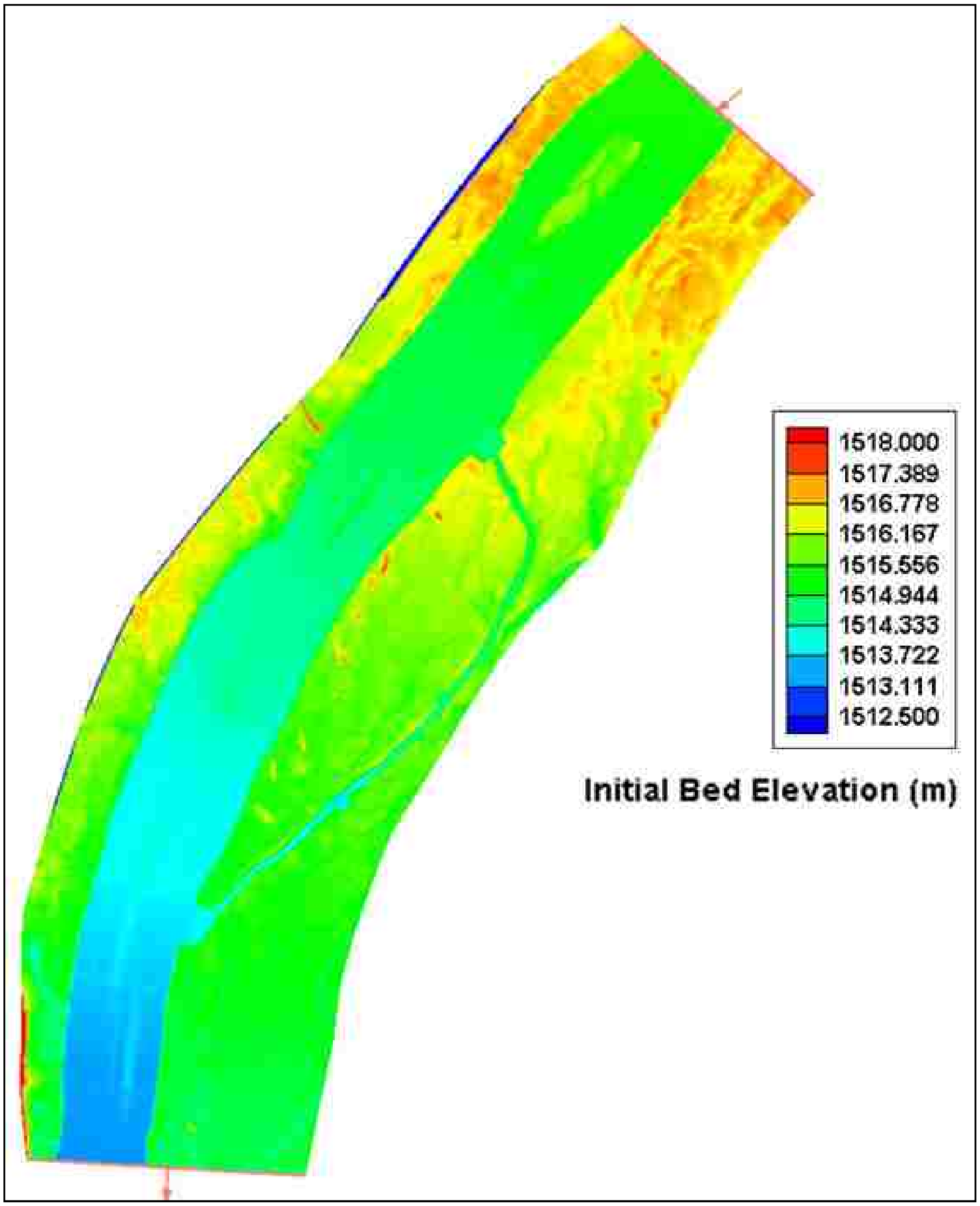


Figure 4-1: Initial Area Modeled with CCHE2D

Because of problems running the higher resolution grids with the initial CCHE2D meshes, an additional three meshes, containing only the RGNC channel, were created (**Figure 4-2**). Specific CCHE2D problems will be discussed in the following section. The feature length of interest remains the bottom width of the RGNC channel. The three RGNC-only grids had the resolution of 2.0 m, 1.0 m, and 0.5 m.

Figure 4-2: Final Area Modeled with CCHE2D

4.3 CCHE2D Modeling

Beginning with the initially modeled area, steady state calibration was performed using three flow rates: 48.14 cms (1700 cfs), 88.72 cms (3133 cfs), and 127.43 (4500 cfs). These correspond to the flow rate at which the RGNC channel barely flows, the average flow over the time in 2008 that the RGNC channel received flow, and one of the highest flows that was seen during spring of 2008, respectively. Similarly to the HEC-RAS modeling, hydraulics and sediment transport were calibrated in two parts: the Rio Grande main channel and the RGNC channel. Additionally, calibration benchmarks were the same as those used during HEC-RAS modeling. Hydraulics in the Rio Grande were matched to Isaacson's (2009) HEC-RAS model of the Rio Grande through Albuquerque. Sediment transport in the Rio Grande was calibrated using suspended sediment data from the USGS Rio Grande at Albuquerque, NM gage (08330000).

Initial modeling revealed that the highest resolution mesh (0.5 m) could not run because of a lack of virtual memory. The 1.0 m mesh could run, but required several days to perform steady state calibrations. The 2.0 and 3.0 m meshes could be modeled in a reasonable amount of time. A qualitative examination of the hydraulic results showed that 3.0 m mesh insufficiently modeled the RGNC channel; the 2.0 m mesh results were slightly better but still seemed inadequate. Hydraulic results in the Rio Grande appeared sufficient for all mesh resolutions. Calibration of the Rio Grande resulted in the Manning's n-value being set at 0.02. Sediment transport was best modeled as total load (bed load plus suspended load) with the Wu *et al*. (2000) formula.

Since the initial model could not perform sufficiently, a second model was created. The second model represented a smaller area but had higher resolution. The boundary conditions for this model would come from the initial model. Hydraulics were calibrated against the USACE gage in the channel. Hydraulic calibration was steady state and performed at 0.35 cms (12.36 cfs), 1.59 cms (56.15 cfs), and 4.08 cms (144.08 cfs). Hydraulic calibration resulted in an n-value of 0.02 being selected for the RGNC channel. Simulations revealed mesh 1 (2.0 x 2.0 m) to be insufficient. However, mesh 2 (1.0 x 1.0 m) was sufficient, and mesh 3 (0.5 x 0.5 m) showed convergence. Therefore, mesh 2 was used for further simulations.

Sediment transport was calibrated against known bed elevation changes occurring during spring 2008 flows. Sediment transport simulations were performed using steady and unsteady flow. The steady flow rate of 1.59 cms (56.15 cfs) represented the average for the 2008 spring runoff. The unsteady flow was taken from spring 2008 daily average flows (**Figure 4-3**) recorded by the USGS gage Rio Grande at Albuquerque, NM gage (08330000).

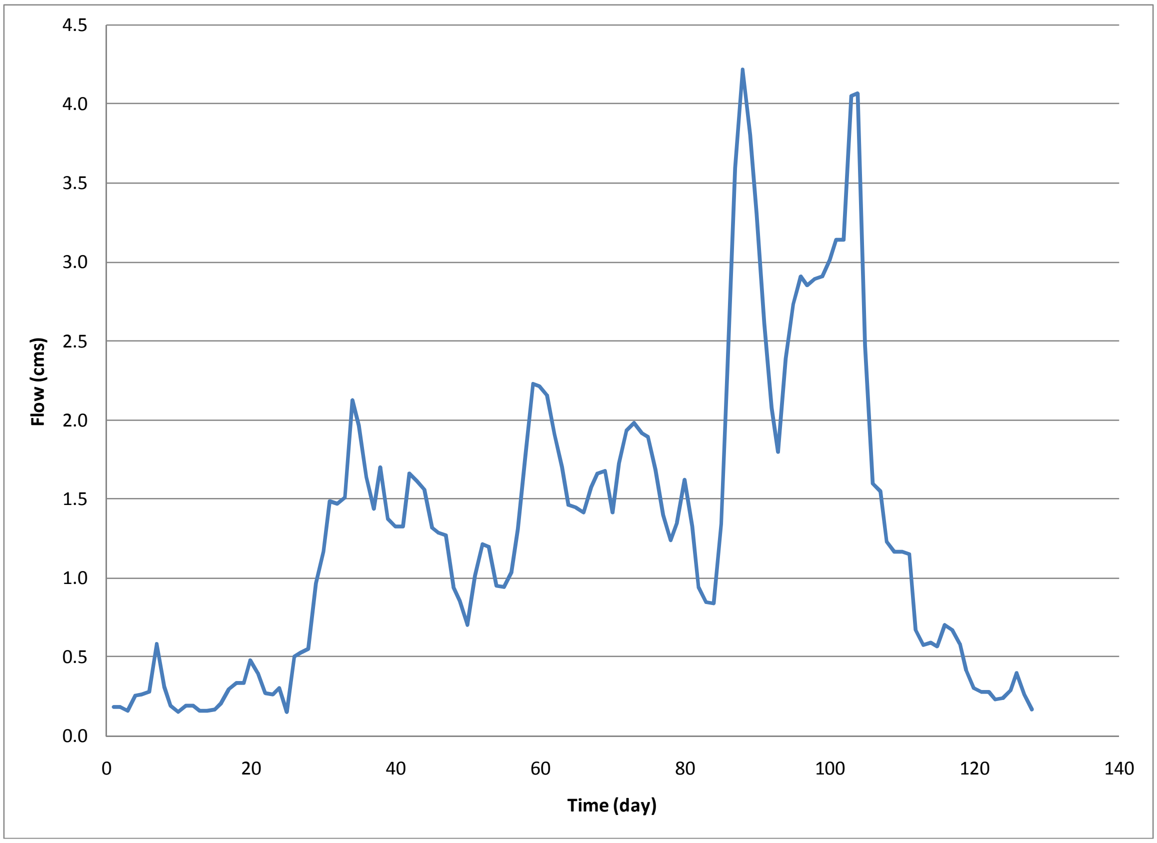


Figure 4-3: RGNC Channel Hydrograph from Spring 2008

CCHE2D has several sediment transport formula options. The model splits the empirical sediment transport formulas into three categories, or schemes, total load as bed load, total load as suspended load, and total load as bed load plus suspended load (Wu 2001). Total load as suspended load and total load as bed load each have several equations for modeling; however, the model did not produce accurate results with either of these schemes. Therefore, the total load as bed load plus suspended load scheme with the Wu *et al*. (2000) formula was used for all simulations. This formula was developed with a wide range of data sets collected in natural rivers and flumes.

A sensitivity analysis was performed with several variables within reasonable ranges. These variables included inlet suspended load concentration (**Table 4-1**), inlet suspended load gradation (**Table 4-2**), channel bed gradation (**Table 4-3**), turbulence model (**Table 4-4**), bend accounting (**Table 4-5**), and flow regime (**Table 4-6**). In the tables below, positive values indicate that the model over-predicts observed bed change. Of these parameters, the turbulence model and bend accounting had the greatest impact on bed change. Changes in the bed gradation and inlet suspended sediment concentration produced variations in average bed change of only approximately 2 mm. While varying the inlet suspended sediment gradation yielded a difference of 6 to 7 mm in bed change.

Boundary Condition	Sus Sed Conc (kg/m^3)	Average Difference (m)	Std. Dev. (m)
Measured Low	0.070	0.0243	0.2366
Low	0.096	0.0219	0.2214
Measured	0.110	0.0547	0.2538
Moderate	0.145	0.0216	0.2324
High	0.193	0.0353	0.2474

Table 4-1: Impacts of Inlet Suspended Sediment Concentration on Bed Elevation Change

Table 4-1 indicates that lower suspended sediment concentrations would likely produce the best results. This seems reasonable since the first CCHE2D model showed low suspended sediment concentration entering the RGNC channel from the Rio Grande.

Boundary Condition	Average Difference (m)	Difference Grad. (m)
Low	0.0390	0.0079
Low-High	0.0311	
High	0.0420	-0.0060
High-Low	0.0480	

Table 4-2: Impacts of Inlet Suspended Sediment Gradation on Bed Elevation Change

The low and high suspended concentrations are the same as described in Table 4-1. The low-high and high-low indicate that the low boundary condition concentration was paired with the high boundary condition gradation and vice versa. Suspended sediment grain-size distributions were taken from the results of the first CCHE2D model. **Table 4-2** shows that altering the gradations of the suspended sediment at the upstream boundary yields a 6 to 8 mm difference in average deposition. Altering the concentration only results in a 3 mm difference in deposition; altering both the suspended sediment gradation and concentration at the upstream boundary results in a 9 to 17 mm change in deposition.

Bed Gradation	Average Difference (m)
Fine	0.0392
Average	0.0401
Coarse	0.042

Table 4-3: Impacts of Channel Bed Gradation on Bed Elevation Change

Average bed gradations were calculated using measured values at the Rio Grande at Albuquerque USGS gage (08330000). The fine and coarse gradations represent the lower and upper 95% confidence interval of the USGS data, respectively. **Table 4-3** shows only a 3 mm change in average sedimentation from a fine bed grain-size distribution and a coarse grain-size distribution. Channel bed gradation appears to have a minimal impact on sedimentation.

Turbulence Model	Average Difference (m)
Parabolic Eddy Viscosity	0.0219
Mixing Length Method	0.0390
K-E Method	0.0425

Table 4-4: Impacts of Turbulence Model on Bed Elevation Change

Altering the turbulence calculation method has a significant impact (**Table 4-4**). The maximum possible change is about 21 mm.

Bends Accounted For?	Average Difference (m)
No	0.0243
Yes	-0.1163

Table 4-5: Impacts of Bend Accounting on Bed Elevation Change

Table 4-5 indicates that accounting for bends in the model significantly impacts modeled deposition values—approximately 13 cm of variation. CCHE2D user's manuals provided little discussion on how bends are accounted for. Therefore, it is difficult to discuss why this parameter so greatly impacts model results.

Flow Regime	Average Difference (m)
Steady	0.0219
Unsteady	-0.2730

Table 4-6: Impacts of Flow Regime on Bed Elevation Change

Table 4-6 shows flow regime greatly impacts modeled sedimentation values. However, due to the significantly increased simulation times, unsteady flows were not used to calibrate the model. The calibration of unsteady flow is outside the scope of this paper and will not be discussed.

Given the uncertain nature of sediment transport estimation, it should be noted that a change of millimeters and even centimeters in this context is not meaningful. For the most meaningful results each parameter has been optimized, resulting in a noticeable cumulative impact. The best overall result was achieved using the total load scheme with the Wu *et al*. (2000) formula, the low suspended sediment concentration, a fine suspended sediment gradation, a coarse bed gradation, the parabolic eddy viscosity model, and no bend accounting. This combination of parameters over-predicted deposition by an average of 2 cm with a standard deviation of 22 cm. Surprisingly, when the same combination of variables was modeled except with a fine bed load, the model over-predicted bed change by 3 cm with a standard deviation of 28 cm. The relatively low average and high standard deviation may suggest that the model accurately predicts general trends but with low precision.

Modeled data were plotted against observed data (**Figure 4-4**). The graph confirms that the model generally over-predicts measured data because the data are biased above the one-to-one line. A linear regression revealed an R^2-value of 0.27; this is typical for sediment transport modeling. Middlekoop and Van der Perk (1998) presented R^2-values between 0.10 and 0.64 when modeling overbank deposition. Root mean square error (RMSE) was calculated to be 0.30 meters. This seems reasonable considering Ferguson (2001) modeled long profile deposition with several techniques with RMSE ranging from 0.39 to 0.72 meters with an average of 0.48 meters.

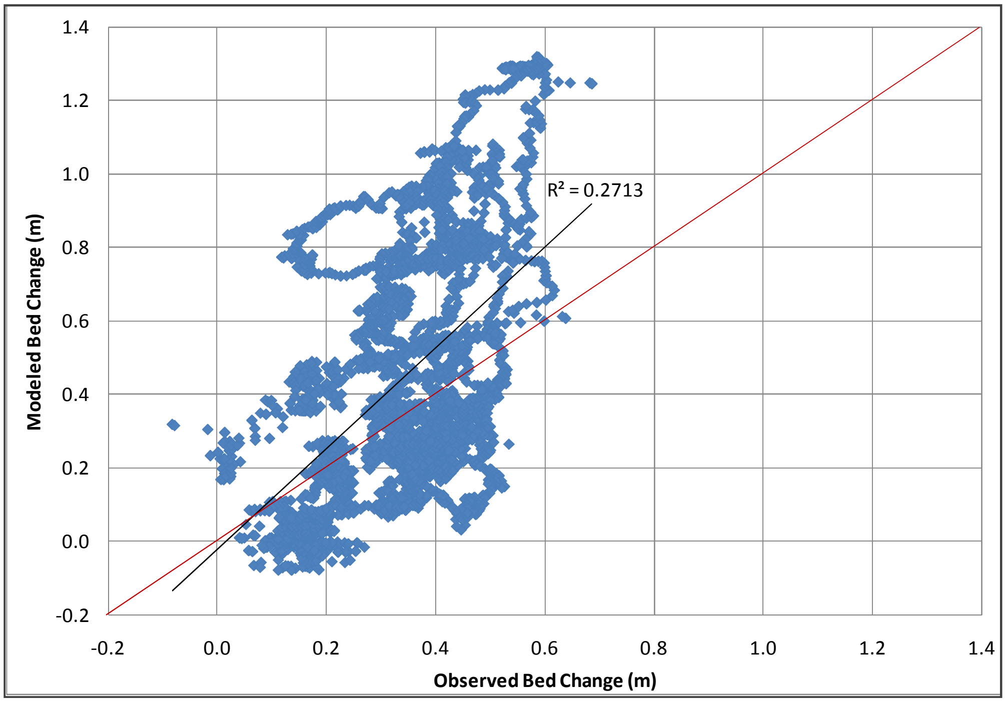


Figure 4-4: Comparison of Modeled Results and Observed Data

5 MODEL APPLICATION

5.1 Sustainability Analysis

The calibrated CCHE2D model was applied to estimate long-term sedimentation. To begin, average spring runoff parameters were determined. Daily mean flow values from the USGS gage Rio Grande at Albuquerque (08330000) were analyzed from 1976 to 2010 (post-Cochiti Dam completion to present). Generally, average spring runoff was defined as March through July. Occasionally, flows in February and August were included. Extrapolation of USGS gage data revealed that the RGNC channel begins flowing at approximately 46.7 cms (1650 cfs). Therefore, for each spring runoff period, the number of days that the flow exceeded 46.7 cms was determined. Additionally, the average flow rate for these days was calculated. An average spring runoff flow rate and duration were calculated by averaging values from each spring runoff period.

On average, the Rio Grande at Albuquerque exceeded 46.7 cms for 70 days during spring runoff periods with an average flow rate of 81.0 cms (2859 cfs). This corresponds to a flow of 1.2 cms (44.1 cfs) in the RGNC channel. Hydraulic and sediment transport simulations were performed on the first CCHE2D model to determine boundary on the second CCHE2D model.

Long-term sediment transport simulations were performed to simulate 50 years from construction in 5 year increments to examine long-term bed elevation change (**Figure 5-1**). In a modeling report written to the USACE, Mussetter Engineering (MEI) states that the desired project life for restoration projects on the Middle Rio Grande was 50 years (MEI 2008).

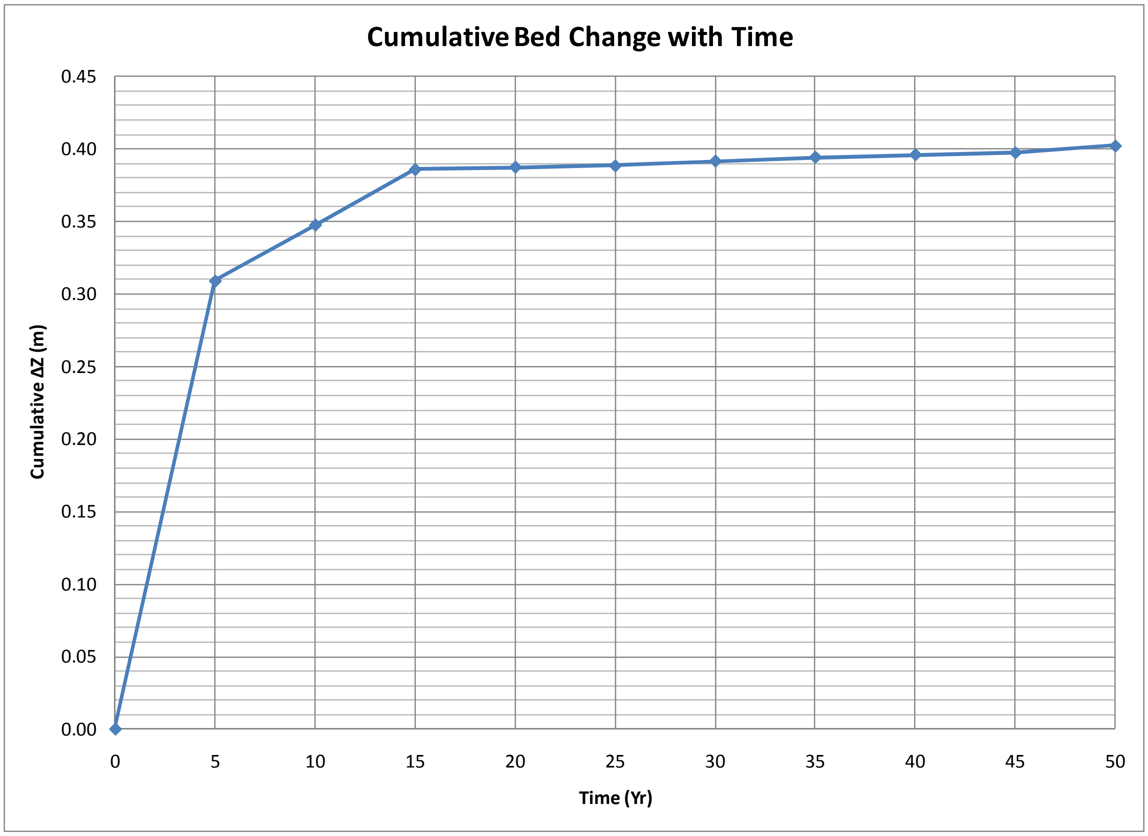


Figure 5-1: Long-term RGNC Channel Bed Elevation Change

Figure 5-1 reveals a general trend of aggradation at a decreasing rate. The high rate of bed change in the first five years is the result of the dips in channel profile being filled (**Figure 2-14**). The rate of deposition in the RGNC channel slows between 5 and 15 years and again between 15 and 35 years before slowing a last time at 35 years.

A more careful examination of the results reveals other important trends. CCHE2D predicts deposition in the inlet on the order of 0.6 meters after 10 years and 1 meter after 30 years (**Figure 5-2**). There is no measured data at the inlet but this seems logical since the inlet was designed to be a low-velocity embayment to be used by the RGSM. The model does predict a thalweg formation; **Figure 2-7** shows a thalweg. The thalweg does not appear reasonable. This is likely a limitation of the boundary condition at the inlet that does not account for hydraulics in the Rio Grande. Inlet bed elevation changes play a critical role in the sustainability of the project. If the inlet fills, flow diversion will be significantly reduced or even eliminated. Thus the channel would not function as intended—flowing for a minimum of 21 days during an average spring hydrograph (USACE 2006).

It should be noted that CCHE2D will tend to over-predict deposition in the inlet for two reasons. First, an average steady flow is used in simulations. Realistically, the channel will see higher flows that will remove some deposited sediment. Second, as the inlet aggrades, the flow rate diverted into the channel will decrease with time while modeled diversions are constant. This will impact sediment transport throughout the RGNC channel.

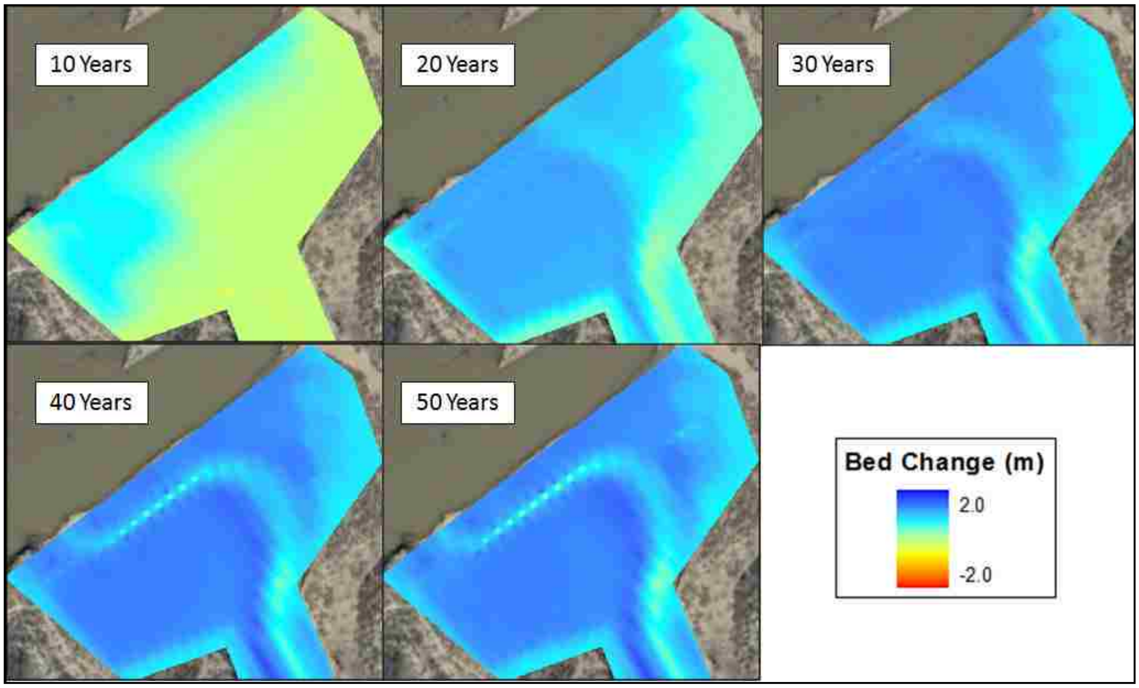


Figure 5-2: Cumulative Inlet Embayment Bed Elevation Change

The next feature worth examining in greater detail is the bend occurring roughly 170 meters (560 feet) from the inlet. This bend is the only major bend in the channel and contains the high point in the channel. In the first 10 years, this high point is eroded

(**Figure 5-3**). For the next 40 years, a cut bar and point bank form as the right bank approaching the bend and the left bank in the bend apex erode and the right bank and part of the original channel bed aggrade. This trend is not surprising; after only a few years the left bank in the bend has begun to erode (**Figure 5-4**).

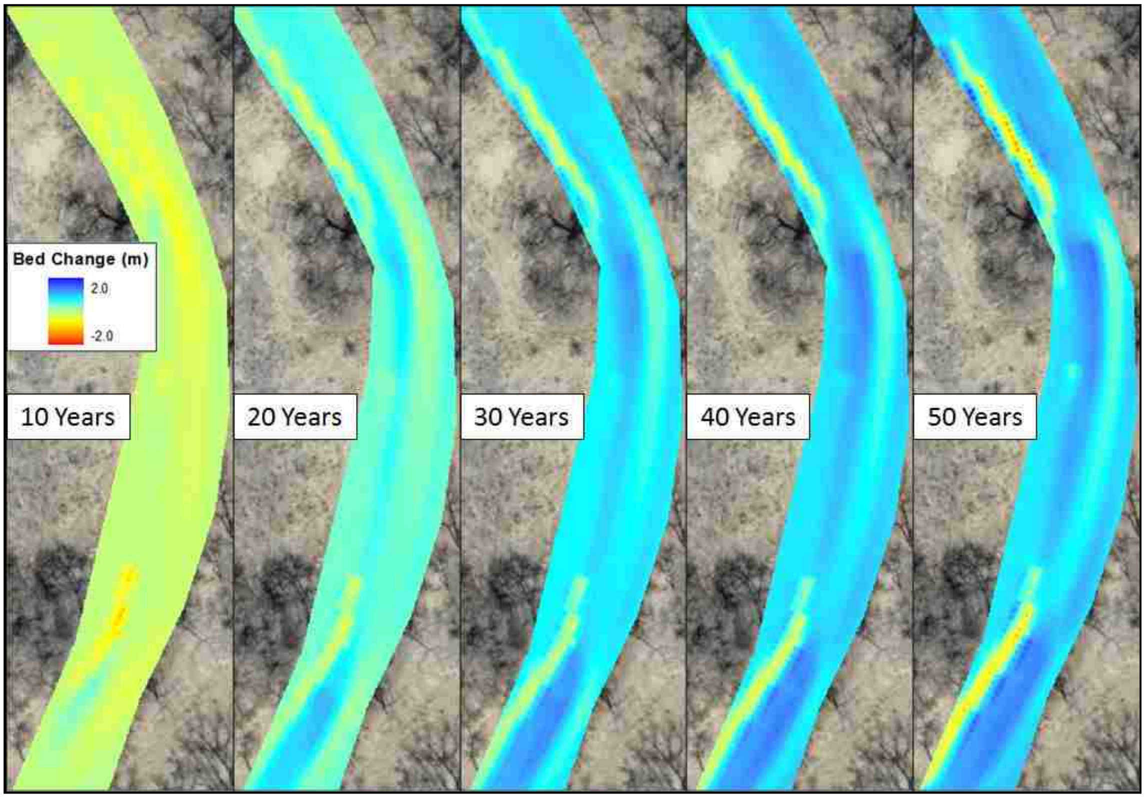


Figure 5-3: Cumulative Bend Bed Elevation Change

Figure 5-4: Bank Erosion along the Major Bend (02/2010)

Though many backwater features have been constructed in Rio Grande rehabilitation projects, the embayments designed in the RGNC channel are fairly unique since they were placed parallel to the flow and at the same elevation as the adjacent channel bed, leaving them vulnerable to sedimentation. These features functioned extremely well. **Figure 5-5** shows the majority of the embayment deposition occurring in the first 10 years. This deposition forms a bar across the embayment; this approximates the sedimentation that has occurred well (**Figure 2-6**). It should be noted that after 50 years of simulations CCHE2D still predicts that the embayments will receive water, allowing them to function as RGSM spawning areas.

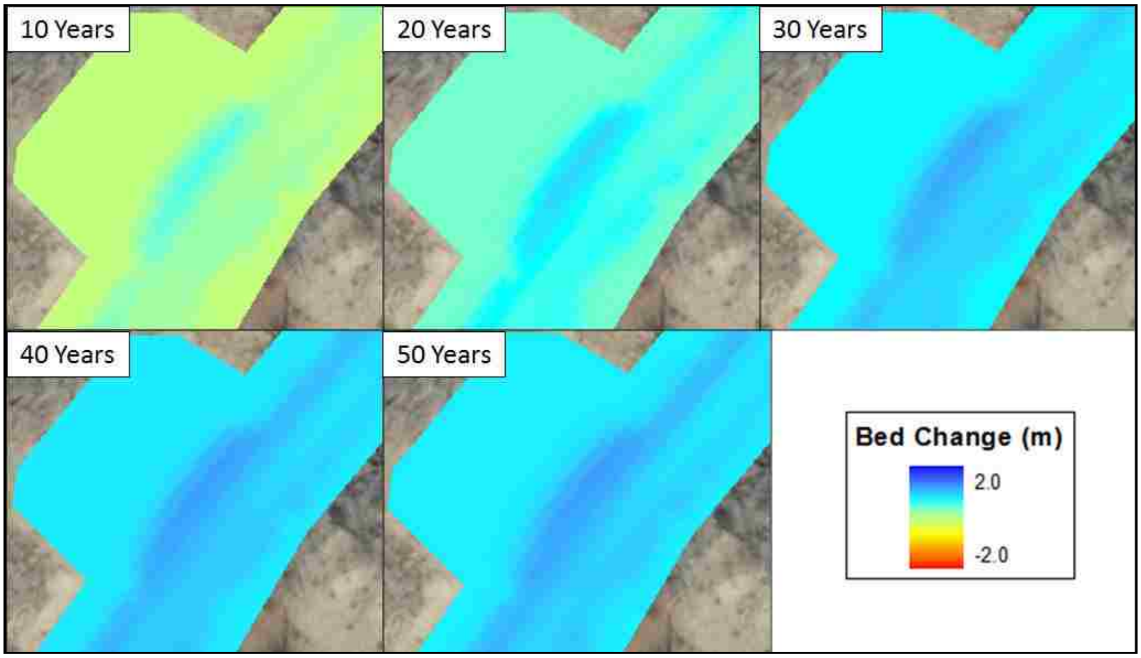


Figure 5-5: Cumulative Upstream Embayment Bed Elevation Change

Interestingly, the long-term modeling suggested that the channel would move to a braided, two-stage channel (**Figure 5-6**). It is difficult to comment on the likelihood of this result. Jayakaran and Ward (2008) observed a two-stage channel forming when modeling agricultural channels with CCHE2D. There is some evidence that channel is moving towards a two-stage morphology (**Figure 2-11**). Should this braided system develop, velocities in the deeper parts of the channel would be slightly over the 0.61 meters per second (2 fps) recommended by the US Fish and Wildlife Service (USFWS 2003). Braided channel velocities would reach about 0.7 meters per second (2.3 fps) above the thalweg. Velocities elsewhere would be sufficiently low.

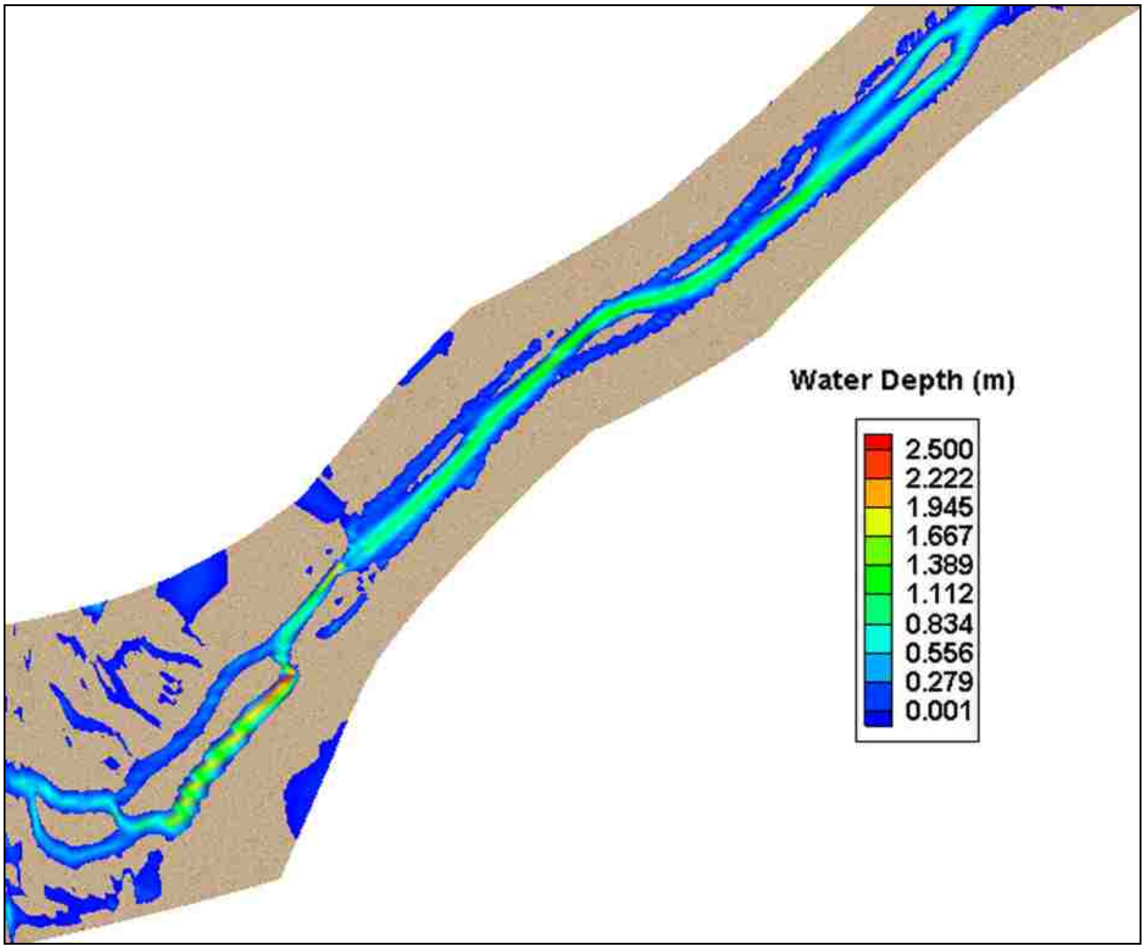


Figure 5-6: Braids Formed in the Downstream of Channel at 50 Years

5.2 Alternate Terrains

Long-term simulations were performed on two alternative meshes: a design mesh and a no-adverse slope mesh. The design mesh was created because the channel was not constructed as designed (**Figure 5-7**). The no-adverse slope mesh was created to examine the impacts of the adverse slope designed into the upstream end of the channel (**Figure 5-7**). Simulation procedures, parameters, and initial conditions followed that used in the previous mesh that models the channel as constructed. Steady flow and sediment transport simulations were performed using the same average flow and annual spring runoff duration described above in five year increments for a total of 50 years.

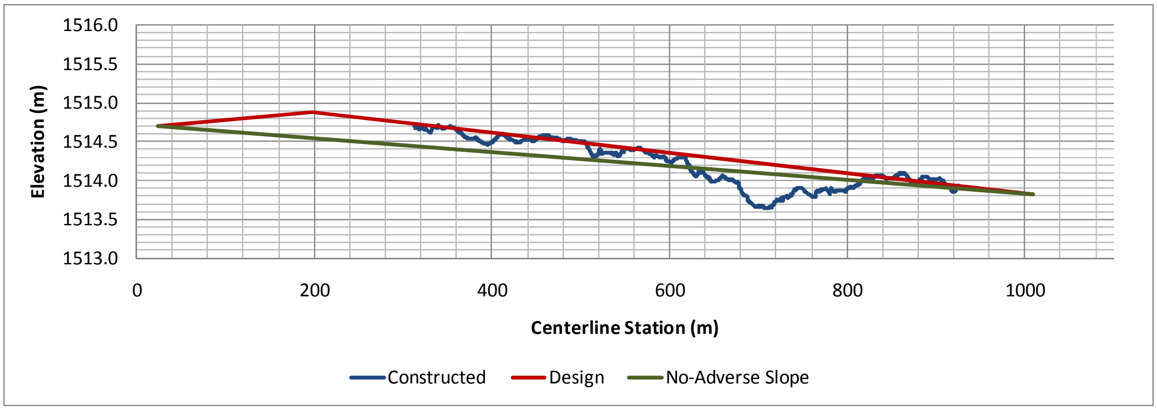


Figure 5-7: Longitudinal Profiles of Modeled CCHE2D Meshes

Analysis of long-term bed elevation change in both profiles followed nearly the same trend as constructed condition model (**Figure 5-8**). The majority of the bed change occurs in the first 20 years before the channel reaches a dynamic equilibrium. The constructed condition model aggrades significantly more than the two alternative designs in the first 20 years; this is the result of all the "dips" (**Figure 5-7**) in the channel profile filling. The cause of the sudden increase in deposition in final 10 years of the designed condition model is difficult to know. However, it appears as though a sediment plug has been created and is moving through the system (**Figure 5-9**). Comparison of the final channel profile reveals that the no-adverse slope model estimates the least aggradation while the constructed condition model predicts the most (**Figure 5-10**). In neither the designed nor the constructed condition model is a distinct high point recognizable. This confirms that it will ultimately be eroded as **Figure 5-3** illustrates. Interestingly, the design and constructed condition models predict significantly higher final bed elevations downstream of the north culvert (at 523 m). This could imply that high point has eroded and deposited downstream of the north culvert. This might have instigated the braided channel form and the possible sediment plug formation in the constructed condition model.

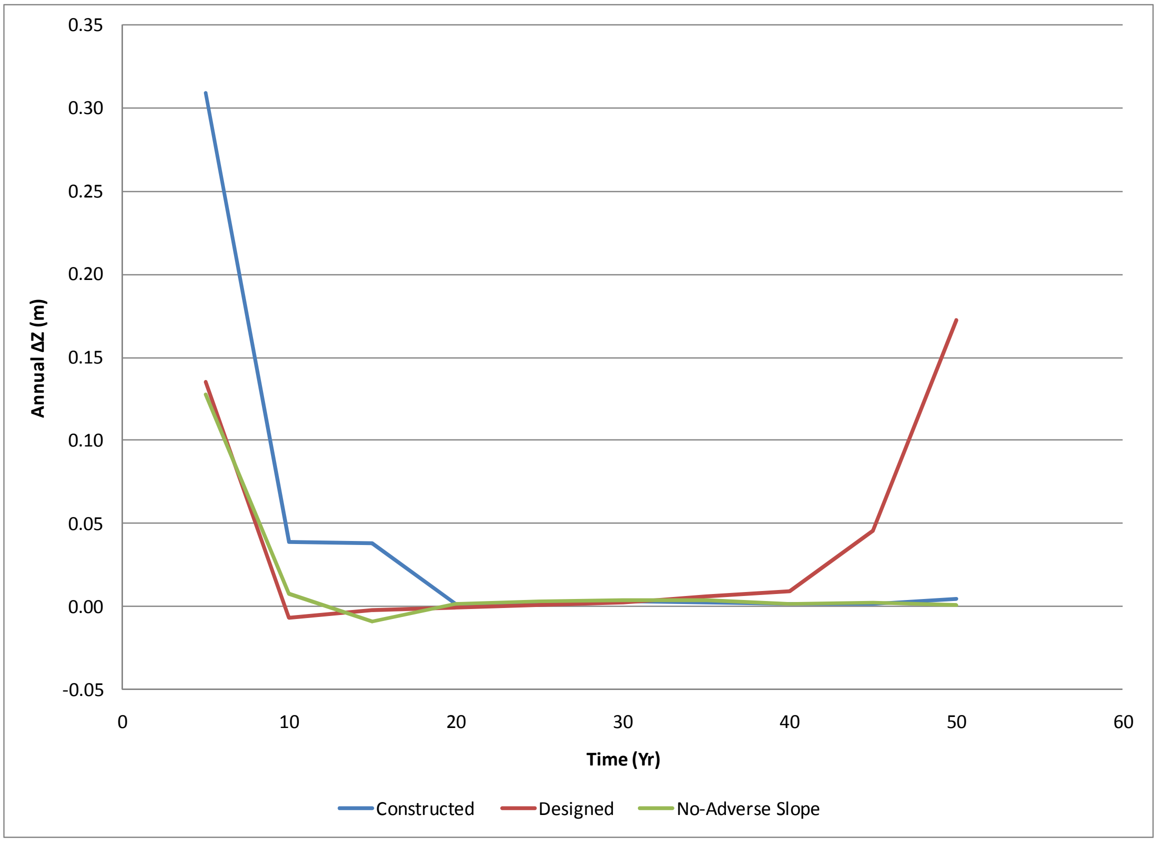


Figure 5-8: Average Quinquennial Bed Elevation Change

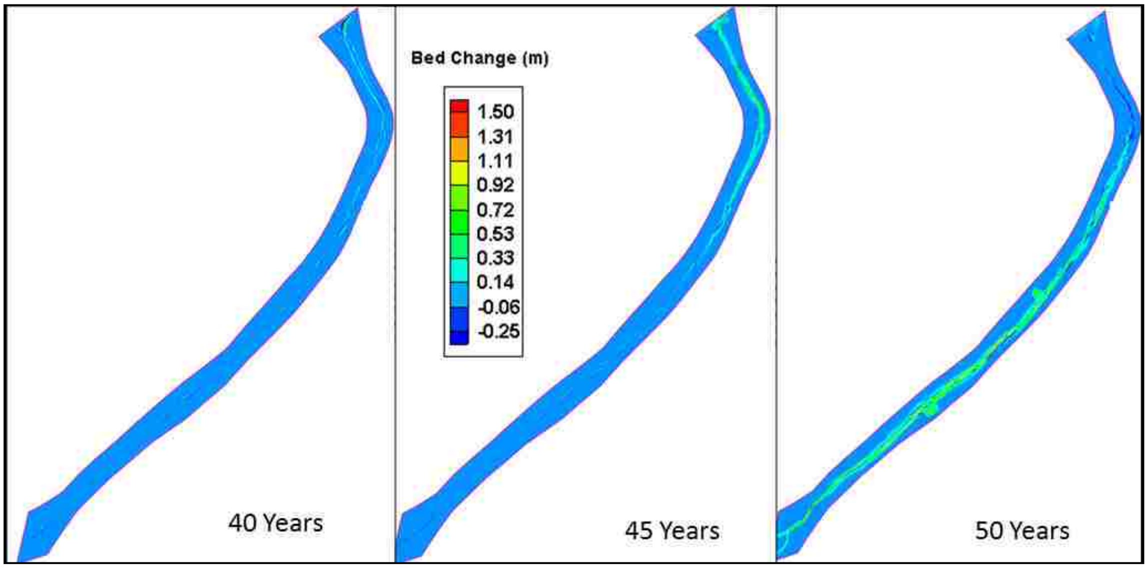


Figure 5-9: Possible Sediment Plug Moving through the Channel at 40 to 50 Years

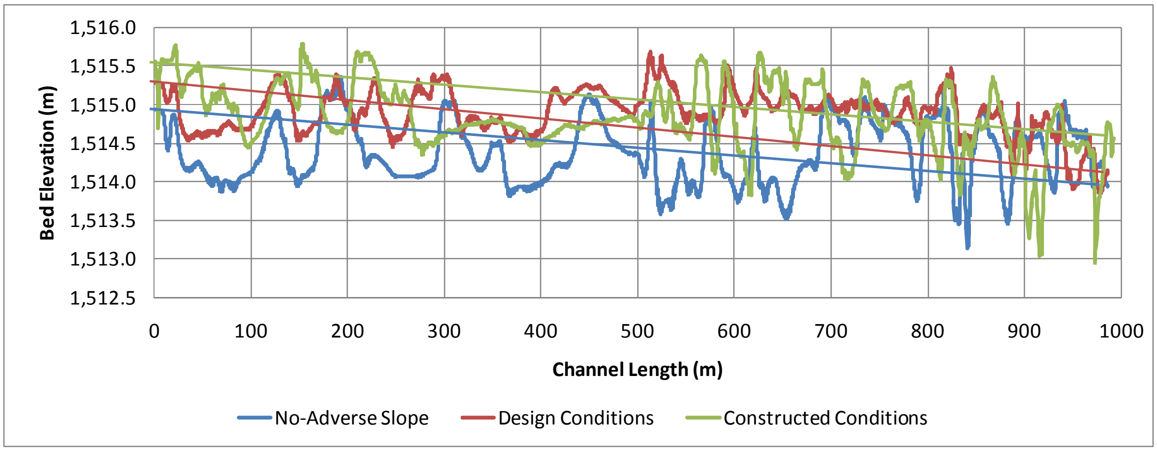


Figure 5-10: Channel Longitudinal Profiles at 50 years

Alternative models were examined in the same three locations as the constructed condition model: the inlet embayment, the major bend, and the north embayment. Generally, the inlet shows the same depositional and thalweg formation trends in the design condition (**Figure 5-11**) and the no-adverse slope model (**Figure 5-12**) as in the constructed condition model (**Figure 5-2**). Both alternatives predict some erosion in the first 10 years. The no-adverse slope condition predicts higher erosion likely due to higher slopes causing higher bed shear stress; therefore, this alternative will have the greatest sediment transport capacity. Overall, the no-adverse alternative models less inlet sedimentation, verifying observations made above. The design condition shows a reduction in bed elevation from 40 to 50 years. Again, the cause of this change is difficult to know, but it does verify previous observations (**Figures 5-8 and 5-9**).

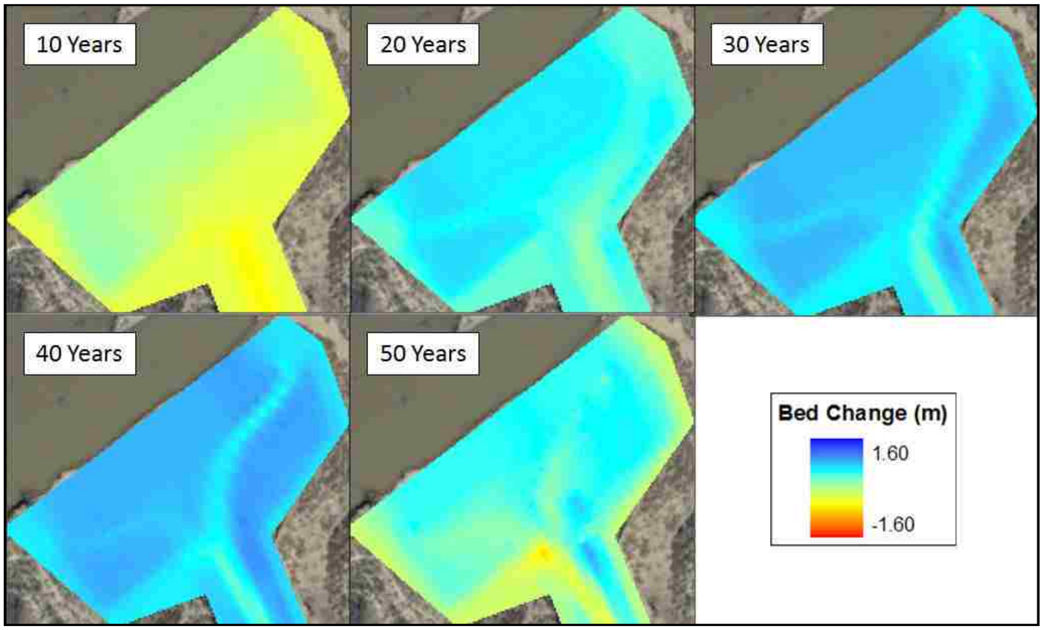


Figure 5-11: Design Condition Cumulative Inlet Embayment Bed Elevation Change

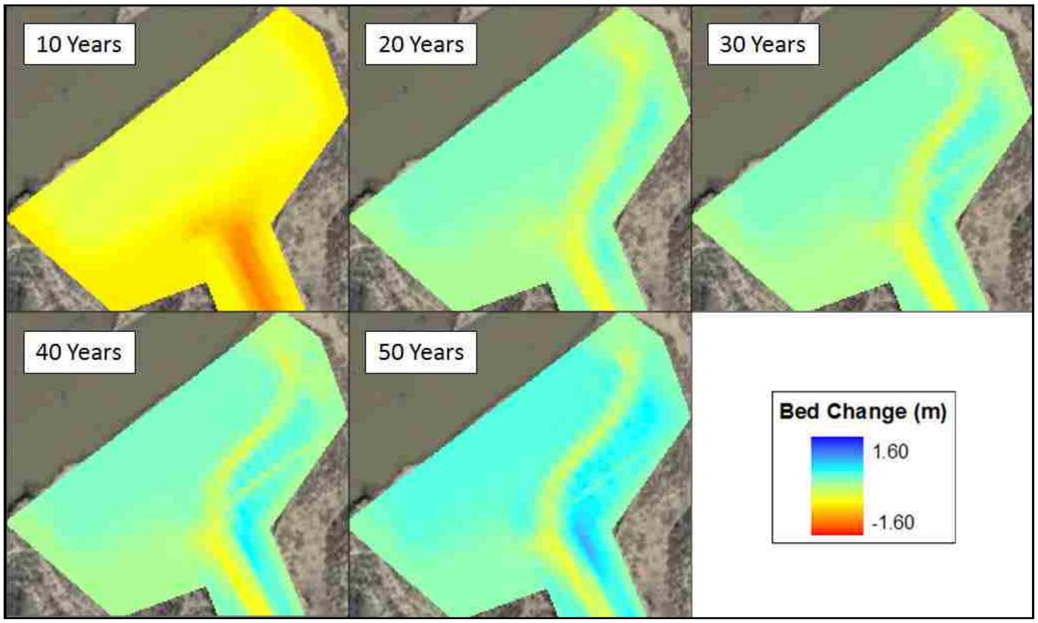


Figure 5-12: No-Adverse Slope Cumulative Inlet Embayment Bed Elevation Change

Examination of the bend in the alternative models (**Figures 5-13 and 5-14**) reveals some, but not all, the same patterns observed in the constructed condition model (**Figure 5-3**). The alternative models seem to show the development of a two-stage channel in the bend. Like the constructed condition, the models predict an initial high rate of erosion as a two-stage channel forms. However, there is no evidence of bank erosion in the alternative models. Bed aggradation does occur in both alternative conditions with sediment being deposited within and out of the low stage channel.

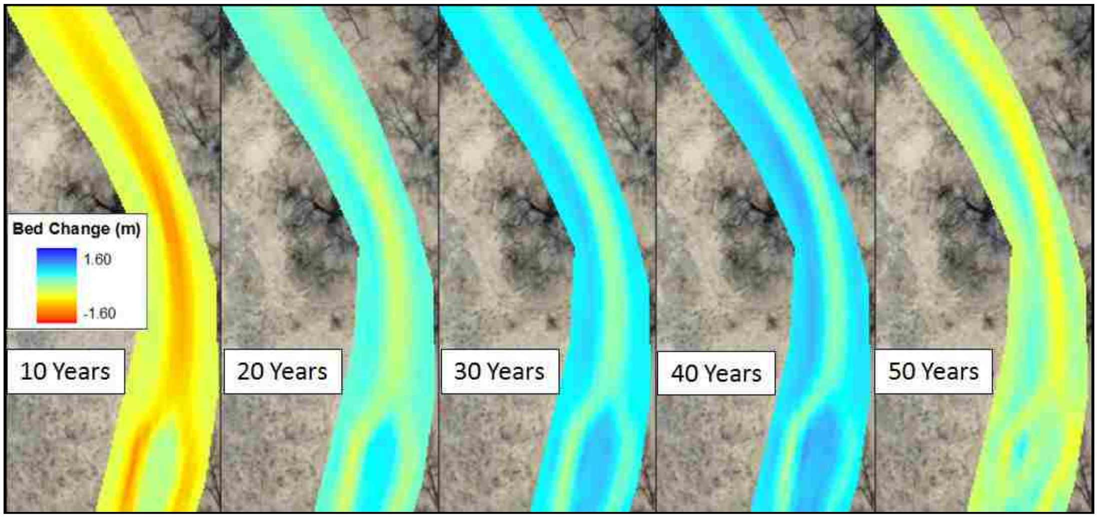


Figure 5-13: Design Condition Cumulative Bend Bed Elevation Change

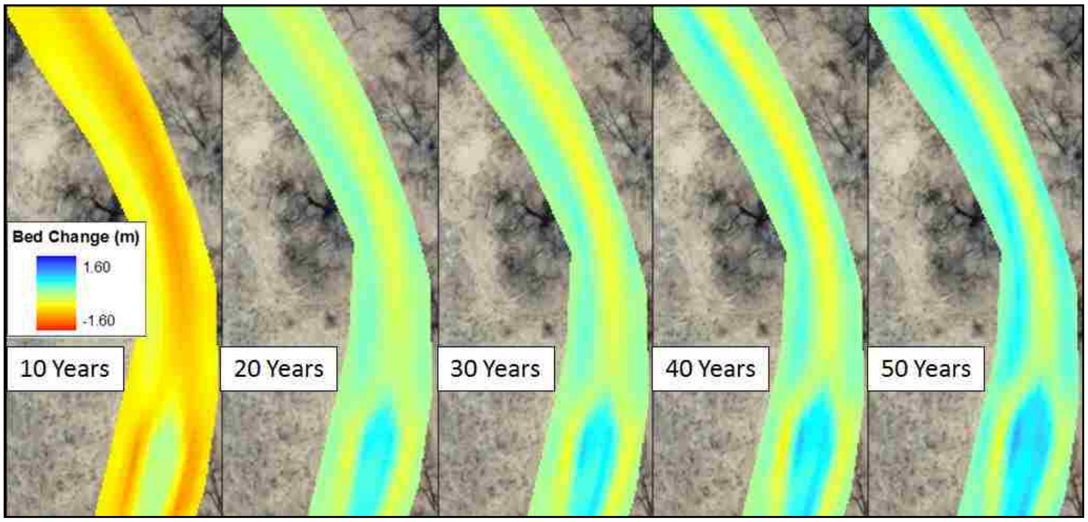


Figure 5-14: No-Adverse Slope Condition Cumulative Bend Bed Elevation Change

Both alternative condition models predict a similar result in the north embayment as the constructed condition model (**Figures 5-15 and 5-16**). However, the bar that forms along the embayment opening is less pronounced in the alternatives models. The sediment deposition occurs outside the embayment, causing the flow to be diverted and the bank opposite the embayment to erode. Examination of the initial terrain for the all conditions indicates one difference. The embayment is slightly lower than the channel in the constructed condition and at the same elevation as the channel in the alternative condition. It seems reasonable that this elevation drop into the embayment causes sediment to be deposited further into the embayment and prevents bank erosion opposite the embayment.

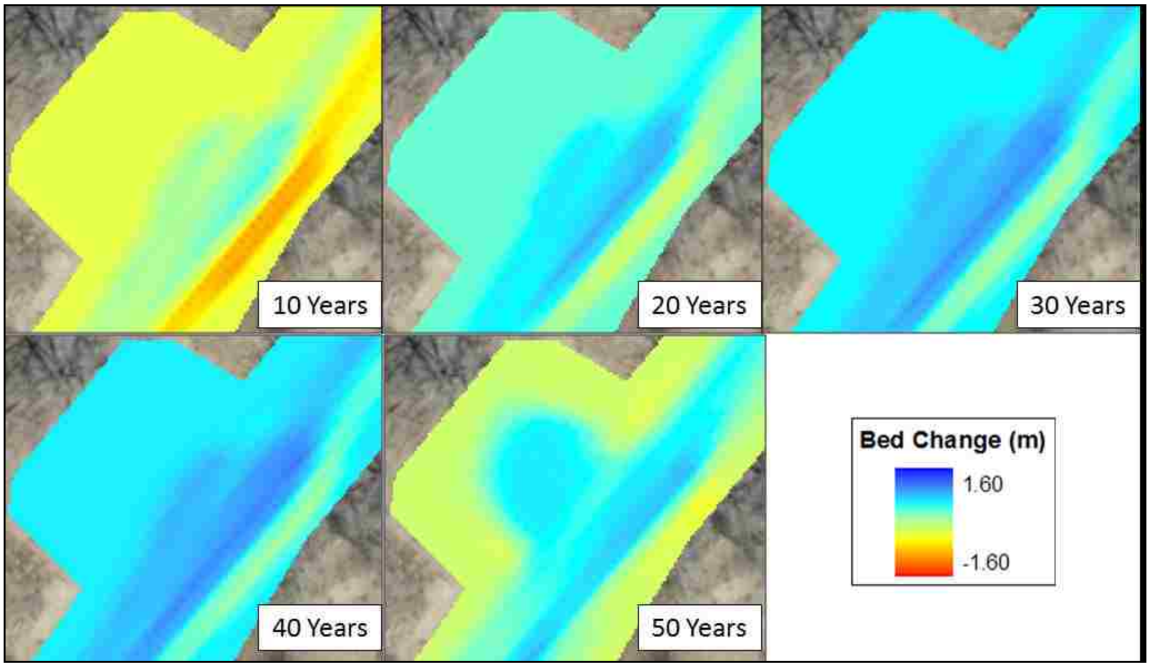


Figure 5-15: Design Condition Cumulative Upstream Embayment Bed Elevation Change

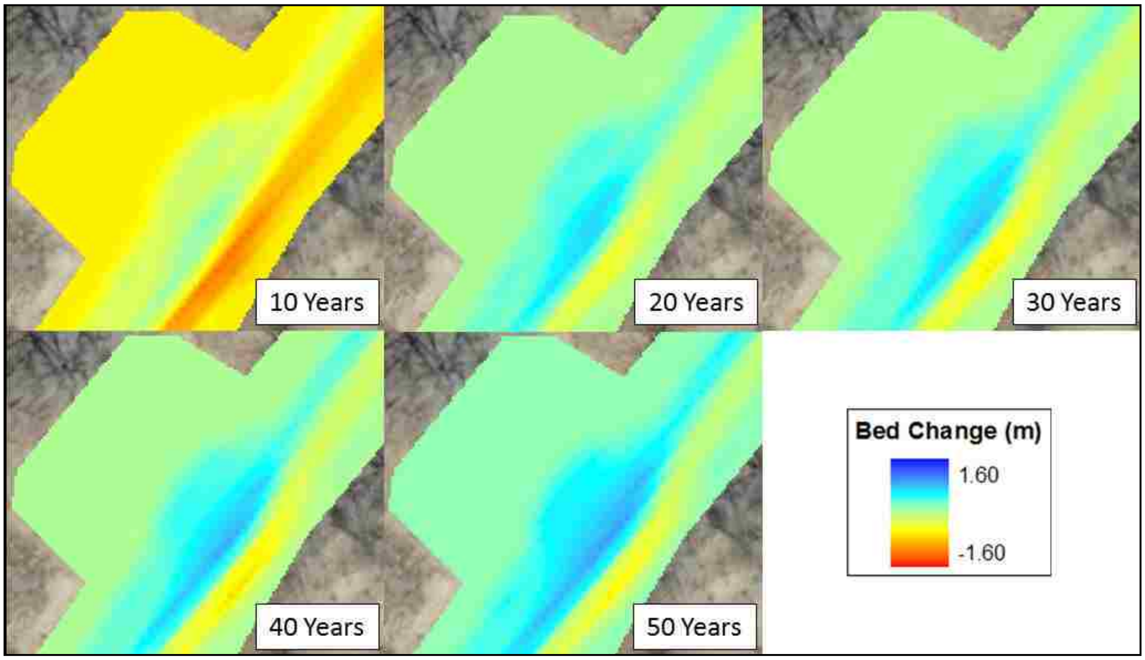


Figure 5-16: No-Adverse Slope Cumulative Upstream Embayment Bed Elevation Change

5.3 Model Limitations

This model was constructed without the impact of vegetation in mind. The inclusion of vegetation to the RGNC channel modeling would add significant complexity beyond the scope of this thesis. Vegetation would increase roughness; this would, in turn, change the hydraulic function which would impact the sediment transport in the system. Plants would encourage sediment to be removed from suspension, accelerating aggradation of the channel. Roots would provide stability, preventing erosion. Though the channel would lose its ability to function as a silvery minnow spawning area, it would continue to function by providing floodplain connectivity and promoting establishment of native plants.

As mentioned in the previous sections of this document, modeling was performed with a steady flow regime. Sediment transport calibration revealed this method to produce acceptable results, while reducing simulation time over using a more complex, unsteady flow regime. The steady flow parameters will tend to over-predict sedimentation because they do not capture the higher RGNC flows. These higher flows will erode some of the sediment that has deposited during lower flows. Calibrating the model with unsteady flows could produce a more accurate model.

Some modeling inaccuracies arise because the model used for analysis herein did not include the main channel of the Rio Grande. Though the diversion rate into the RGNC channel was estimated with measured data, this diversion rate is expected to change for two reasons. First, the RGNC channel bed will aggrade, decreasing the diversion rate. Second, the Rio Grande bed will be subject to many alterations. The Rio Grande will tend to degrade by roughly 0.02 m (0.06 ft) during an average year (MEI 2008), decreasing the diversion rate into the RGNC channel. The method for inputting boundary conditions does not allow upstream water surface elevation to be entered, preventing the model from accounting for these bed changes. Developing a model that included the Rio Grande main channel may overcome this problem, but it would also add uncertainty.

A three-dimensional model would likely yield more accurate results around bends, embayments, and culverts where velocity vectors in the vertical direction were more significant. The extent of these gains in accuracy is difficult to know with certainty without performing the modeling work. Further measured terrain data would prove beneficial in determining the gains of a three-dimensional model as well. However, this author predicts that the overall benefit of the added dimension would not outweigh the costs of the additional computational effort.

6 DISCUSSION

6.1 Future Work

Additional surveys and measured sediment transport data improve model calibration and increase model confidence. It is important for many of these high-flow restoration features to be monitored well into the future. Both physical structure and ecological health should be monitored. This will improve future modeling and design efforts, allowing for more sustainable and healthily functioning channels. Often, monitoring and design practices in the southwest lag behind other regions of the country. When these practices are implemented, they frequently match those used elsewhere with little change for the climate and geology. However, the semi-arid southwest poses a unique set of challenges. For example, many systems outside the southwest are perennial channels; whereas, many of the restoration projects in the southwest are ephemeral. Additionally, the sand-bed rivers of the southwest can vary rapidly in comparison to their gravel, silt, or clay counterparts. Performing monitoring within the southwest will provide valuable insight that might not be realized by only looking elsewhere.

The alternatives examined within this report primarily considered change in longitudinal river profile. Considering changes in cross-section, vegetation, river bed form, will allow engineers to design restoration features with a greater level of confidence. All these variables can and should be considered in future research. As computational power increases and costs decrease, performing three-dimensional modeling of similar projects and comparing the results to one and two-dimensional models, would prove constructive. Engineers should know about the cost to benefit of all the tools that are available.

6.2 Conclusions

Several elevation data sources were acquired that defined the terrain surrounding the RGNC. These sources included Isaacson's (2009) TIN, LiDAR scans from the UNM LiDAR lab, and USACE design documents. The LiDAR scans were adjusted, and data from the design documents were digitized using ArcGIS. Elevation data was compiled into a final terrain model (**Figures 2-20 and 2-21**). Additional information was acquired (*e.g*. photographs, RGNC gage, etc.). Analysis of the data showed that the RGNC channel was aggrading and that native vegetation had been established. This analysis prompted a one and two-dimensional modeling of the channel to determine project life expectancy and improve restoration design techniques for high-flow, side channel projects.

HEC-GeoRAS was applied to create one-dimensional, HEC-RAS models of the RGNC. Initially, the HEC-RAS model included the main channel of the Rio Grande. This model could easily predict flow diversions into the RGNC channel, but could not accurately model sediment transport in the RGNC channel. A second HEC-RAS model that consisted of only the RGNC channel was constructed. Hydraulics were calibrated in this model, but the model could not reasonably predict sediment transport. The model would over predict sedimentation near the channel inlet by approximately an order of magnitude while under-predicting bed changes by nearly an order of magnitude along the remaining length of the channel. Closer examination revealed that HEC-RAS was under-predicting shear stress by approximately an order of magnitude in the sediment transport module, while calculating reasonable shear stress values in the hydraulics module. This discrepancy was an inherent mistake within HEC-RAS and likely impacted the ability of HEC-RAS to model such a project.

A two-dimensional model was developed using CCHE2D. Two models were created. The first consisted of the Rio Grande main channel and the RGNC channel, and the second included only the RGNC channel. The first model was calibrated for hydraulics and sediment transport in the Rio Grande, but could not accurately model hydraulics and sediment transport in the RGNC channel because mesh resolution was too low. The second model used the first model's results as boundary and initial condition. Flow calibration, sediment transport calibration, and a sediment transport sensitivity analysis were successfully performed on the second model.

The calibrated model was used to perform long-term sedimentation simulations on the constructed (existing) condition, design condition, and no-adverse slope terrains. Long-term model results will likely tend to over-predict sedimentation under all conditions primarily because of the steady flow regime used for simulation. All terrains show a general aggradation pattern. The constructed condition model indicates that the channel will reach a dynamic equilibrium after 10 to 20 years and should continue functioning for 50 years. However, the duration that the channel functions as a spawning area for the RGSM may decrease in the future due to inlet deposition. Though the channels RGSM habitat function may be reduced, it would not fill completely and still provide improved floodplain connectivity and aid in native plant establishment.

Analysis of results from all the terrain alternatives indicates that embayments like those designed into the RGNC channel are effective, sustainable features in high-flow restoration projects. Modeling and site observations show that a stable bar forms along the entrance of the embayment that allows water into the embayment area. Modeled results suggest that constructing the entrance of the embayment slightly lower than the adjacent channel is favorable. This practice prevents deposition from occurring in the channel, protecting the opposite river bank from erosion.

The adverse slope at the upstream end of the channel is a unique feature that was designed to prevent lower flows from passing through the channel. The no-adverse slope terrain was developed to analyze the impact of this design. The adverse slope resulted in increased sedimentation at the inlet and generally higher bed elevation along the entire channel length. The increased sedimentation at the inlet is the result of lower bed slopes causing lower shear stress and sediment transport capacities. The increased deposition along the channel is the result of the sediment being eroded from the channel high point and deposited downstream. This increased sedimentation reduces the capacity of the channel, and, therefore, its ability to function as RGSM by decreasing flow rates and durations.

Alternative terrains representing idealized design conditions were developed. Many modeled results between the alternative terrains and the constructed condition terrain were similar, despite the fact that alternative terrains were slightly less-than-realistic. This indicates that CCHE2D can be utilized as a valuable design tool. Furthermore, the results of this research suggest that two-dimensional modeling produces much better results for high-flow, side channel restoration projects when compared to one-dimensional modeling. Engineers will have little data with which to calibrate models applied as design tools. Therefore, it is important to collect data at restoration sites and learn from previous designs where modeling was applied.

This thesis examines the RGNC rehabilitation project at a detailed level. The nature center channel does not act alone; it is connected to the Rio Grande. The Rio Grande is a dynamic system containing many similar restoration projects. Examination of the Middle Rio Grande through Albuquerque reveals a river that is degrading as a result of Cochiti Dam removing upstream sediment loads. Engineers and scientists have instituted several small-scale rehabilitation projects throughout Albuquerque to provide habitat for endangered species and reconnect the river to its floodplain. In doing so, river managers hope to promote a floodplain the functions with greater ecological health. As more of these small-scale projects are instituted this goal might be attainable. However, all these projects depend on the stability of the Rio Grande. If the river continues to degrade, these projects will not function or function at a reduced capacity. Minimizing the degradation of the Rio Grande through Albuquerque, whether through grade control or improved sediment release practices at Cochiti or other means, will increase the sustainability and success of restoration projects.

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