RIO GRANDE AND COCHITI RESERVOIR SEDIMENTATION ISSUES: ARE THERE SUSTAINABLE SOLUTIONS?

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Abstract: The Pueblo de Cochiti (Pueblo), in cooperation with the U.S. Army Corps of Engineers, Albuquerque District (USACE-SPA), conducted a program of studies, known as the Cochiti Baseline Study, to define existing and historical environmental conditions of the Cochiti Dam and Lake located on tribal lands of the Pueblo de Cochiti, New Mexico. These included numerical sediment transport modeling of the Rio Grande upstream and downstream of Cochiti Dam completed by WEST Consultants. The purpose of this study was to better understand the impacts of reservoir sedimentation on the sediment processes in the study reach over time, to provide a tool to better manage the project within the Tribe's resource objectives and to help evaluate potential sedimentation effects on Tribal resources that could result from possible future changes in dam operations.

Cochiti Dam, closed in 1973, was constructed primarily for flood control and sediment retention. The dam traps sediment, reducing the suspended sediment loads downstream between 87% and 98%, and has created a lacustrine delta in the reservoir headwaters. The reach below Cochiti Dam responded to dam closure in typical ways including: thalweg degradation, bed armoring, and channel narrowing. The study reach is a highly complex system from a sediment transport perspective due to the two primary sediment inflows: the Rio Grande contributing primarily coarse-grained, non-cohesive sediment to Cochiti Lake, and the Rio Chama contributing primarily fine-grained, cohesive sediment.

This study applied the mobile-bed module of the USACE Hydrologic Engineering Center's River Analysis System (HEC-RAS) software to model sediment erosion, entrainment, transport, and deposition processes of cohesive and non-cohesive sediments. Cohesive sediment erosion/deposition parameters were estimated based on measured responses of samples collected in the lacustrine deposits in Cochiti Lake. Sample responses were measured using the Engineering Research Development Center's SEDflume mobile laboratory (erosion rates) and the Particle Imaging Camera System (PICS) developed by Smith and Friedrichs (settling properties). The numerical model utilized a volumetric limiter on the continuity routing for sediment deposition in the reservoir. Working with HEC and USACE-SPA, WEST developed a well-calibrated HEC-RAS model considering the system's complex cohesive aggregation processes. This base conditions model replicated the deltaic profile evolution spatially and temporally. The calibrated model was robust to wide ranges of sediment input parameters. Finally, this calibrated model was used to predict prototype response to a limited range of

representative theoretical future reservoir operation scenarios and to qualitatively assess long-term reservoir sustainability associated with these scenarios.

This effort determined that, while sediment could be redistributed higher in the reservoir and upstream canyon using increased pool elevations, operational constraints imposed by the dam infrastructure (e.g., minimum pool elevation) will make it difficult to pass significant sediment downstream with drawdown scenarios. The model predicted virtually no change in the downstream virtual river reach in response to the reservoir scenario modeling. These models are being used to help assess sustainability in a responsible and proactive manner. The models support the evaluation of a wider range of future operation scenarios by the Pueblo and USACE-SPA, within a virtual environment, thereby avoiding harmful effects to the actual environment, and permitting evaluation of (fully-reversible) impacts from alternative mitigation strategies.

INTRODUCTION

The Pueblo de Cochiti (Pueblo), in cooperation with the U.S. Army Corps of Engineers, Albuquerque District (USACE-SPA), conducted the Cochiti Baseline Assessment, a series of studies to define the existing and historical environmental conditions of the area surrounding Cochiti Dam and Lake on and near the Pueblo de Cochiti Reservation, New Mexico. The purposes of these studies were two-fold: first, to define existing conditions of the system, and second, to investigate and characterize impacts that have occurred to resources on Pueblo de Cochiti lands from operation and maintenance of Cochiti Dam and Lake. This information is being used to evaluate the potential effects on Tribal resources resulting from possible future changes in operations at Cochiti Dam and Lake. One of the studies within the Cochiti Baseline Assessment was a sediment modeling study of the Rio Grande upstream and downstream of the dam and reservoir, which is documented in this paper. Cochiti Dam, which began operation in 1973, was constructed primarily for flood control and sediment retention; many secondary uses exist for this reservoir as well, such as recreation.

Worldwide, the rate at which reservoir storage volume was added outpaced population growth from 1950 through about 1980. The rate of dam construction began to decrease in the 1980s, as it has continued to do to this day (Annandale, 2013). Even with increasingly efficient use of water resources, for an increasing world population to continue to beneficially utilize a much slower-growing amount of storage, the need to sustainably manage reservoir storage is paramount. The impact of reservoir sedimentation further complicates this need, as do the uncertainties imposed by climate change.

Morris and Fan (1998) summarized reservoir sustainability into three key parameters: water quantity, quality, and diversity. Sustainable use maintains all three of these parameters at a level equal to or higher than current conditions (or historic conditions, considering the system in question). All three of these issues have been impacted in the Rio Grande due to the closure of Cochiti Dam. As Morris and Fan (1998) point out,

> *Reservoirs also require unique natural components (dam sites having appropriate topography, hydrology, geology) and engineered components (dam, delivery canals, etc.). Replacement of the engineered components has no purpose if the storage volume is lost to sediment accumulation… A number of factors indicate that reservoirs should be*

> *considered as irreplaceable resources, no less important than [groundwater] aquifers, and should be designed and operated in accordance with the objective of sustained long-term utilization.*

These principles can readily be applied to the case study of Cochiti Dam. Drought and water scarcity issues of the western United States are often highlighted in popular media (*e.g.*, Bryan, 2014). Population growth, increasing dependence on irrigated agriculture, climate variability, and others factors threaten water quantity, in this region and worldwide (Morris and Fan, 1998). Dam closure already impacted water quality in the Rio Grande and impacted critical habitat of some endangered species with less turbid, cooler water being released from the reservoir. Changes in bed substrate particle size distribution and channel geometries downstream of the dam have also impacted aquatic and riparian habitat (USACE, 2007). Finally, the dam impacted both ecological and cultural diversity (Sallenave et al., 2010). Therefore, stakeholders must reach a consensus on future sustainable use of this reservoir. This definition may not be a fixed target, but a moving one. For example, if a continued future drought were to threaten downstream water supplies, would the impacted stakeholders possibly repurpose Cochiti Reservoir for water supply use? Annandale (2013) points out that prudent water resource planning should consider the ways that climate change might affect water supply reliability and sustainability. While water supply was not an objective in the design and construction of Cochiti Dam, its primary flood control purpose shares the requirement of excess water storage capacity with that of water supply projects. How might the sediment that depletes this available storage capacity be more effectively managed to preserve or prolong the useful benefits of the project while lessening impacts to the surrounding environment? Questions like these lie at the heart of reservoir sustainability, and the problems facing each new generation for sustainable water resources can only be solved through continuing study and communication of issues that arise.

Due to these concepts of sustainable use and oftentimes conflicting definitions of sustainability for different stakeholders, governmental agencies and other private entities have studied sedimentation problems along the Rio Grande for several decades. Several of these studies proposed projects to reduce bed aggradation while maintaining water quality, quantity, and diversity for downstream use. Channel modifications, levees, and dams were constructed to reduce flooding in Albuquerque and other areas, control sediment concentrations in the river, and increase sediment transport capacity.

Cochiti Dam reduces peak flows in the Rio Grande River below the dam to less than 10,000 cfs compared to common peak flows greater than 10,000 at the Otowi gage (the nearest gage upstream of the dam) and some flows in excess of 20,000 cfs throughout the period of record. The dam reduces the suspended sediment loading in the flows downstream of the dam between 87% and 98% (USACE, 2007; Novak, 2006). MEI (2002) estimated that Cochiti Dam traps approximately 1,100 acre-feet of sediment annually, releasing clear water with very low sediment concentrations, subjecting the downstream reach of the Rio Grande to highly erodible flows. As a result, there has been significant thalweg degradation downstream of the dam as well as some slight channel narrowing. The median bed sediment sizes have increased from an average of 0.1 mm in 1962 to an average of 24 mm in 1998 (Novak, 2006), armoring the bed downstream of the dam. Dam effects diminish downstream because of tributary sediment delivery and in-channel sources of sediment.

The purpose of this study for the Pueblo was to analyze present and historic geomorphic processes of Cochiti Lake and the Rio Grande River in the reservoir influence area with emphasis on landforms, erosion, sediment transport, and deposition. This study analyzed historical and new landscape-scale topographic, geomorphic, and sediment data, and developed two sediment transport models. Modeling objectives included:

- Identify past and current geologic and geomorphic conditions of the Rio Grande River channel and floodplain in the Cochiti Lake influence area;
- Assess sediment erosion, transport, deposition, and routing into, through, and downstream of Cochiti Lake; and
- Evaluate the influence on sediment mobilization, transport, and deposition for select reservoir operations scenarios to better understand prototype behavior.

The sediment transport models provided to the Pueblo and USACE-SPA were a tool for assessing long-term reservoir sustainability, especially in the event that alternative dam operations are proposed. This study explicitly considered water quantity impacts of reservoir storage losses to reservoir sedimentation. The models assessed changes in location and magnitude of erosion and deposition upstream and downstream of the dam. The models also support future ecological and human health risk assessments (water quality), and diversity analyses. This paper will focus on reservoir sustainability considerations in light of water quantity issues.

A model was developed for each of the two study areas: from below the Otowi gage to Cochiti Dam, and from below Cochiti Dam to Angostura Diversion Dam (located just upstream of the confluence of the Jemez River with the Rio Grande). WEST analyzed topographic, geomorphic, and sediment data, built the sediment transport models, and ran the models for the various proposed operational scenarios.

STUDY SITE

The Rio Grande River drains approximately 11,695 square miles above Cochiti Dam including portions of northern New Mexico and southern Colorado. The Rio Grande River enters the Cochiti Reservoir just downstream of White Rock Canyon, which has a slope of 10 ft/mile. Cochiti Dam is the upper limit of the “Middle Rio Grande Valley.” This reach of the Rio Grande stretches from Cochiti Dam to the Elephant Butte Reservoir approximately 190 miles downstream. In the portion of the study reach below Cochiti Dam, the Rio Grande has cut an alluvial valley in the semiarid desert 100 to 300 feet deep and 1 and 3 miles wide. The elevation of the study reach drops from approximately 5,480 feet (NGVD 1929) at the thalweg of the Rio Grande near Otowi Bridge to approximately 5,100 feet (NGVD 1929) near the crest of the Angostura Diversion Dam, approximately 20 miles downstream of Cochiti Dam.

Important tributaries that feed the Rio Grande near the study reach include (from upstream to downstream) the Rio Chama, Santa Cruz River, and Santa Fe River above Cochiti Dam; and the Galisteo Creek and Jemez River below Cochiti Dam. Several smaller streams also feed the Rio Grande within the study reach. Although the water supply from these tributaries do not typically deliver most of the total volume of water transported in the study reach, these tributaries can provide major sources of water and sediment during certain hydrologic conditions.

GEOMORPHIC ASSESSMENT OF THE STUDY REACH

Two primary factors affect the geomorphology and sediment conditions of the upper study reach (i.e., above Cochiti Dam): the geologic control of White Rock Canyon and the water level in Cochiti Lake. Horizontal restrictions imposed by the canyon limit the Rio Grande planform in this reach. It cannot migrate laterally more than a few hundred feet at any location (i.e., approximately 2-3 times the typical top width of the river flow). The meander paths are constantly shifting and adjusting locally in the lateral direction (i.e., bend growth or bend decay) and longitudinally (i.e., down-valley migration) in response to hydrologic and sediment loading, but the general river path is confined to a meander band defined by the canyon walls.

The upstream sediment loads contain substantial fine materials. The main stem of the Rio Grande usually delivers mostly coarse-grained sediment (i.e., >62.5 μm), while the Rio Chama load can be dominated by fine-grained sediment (i.e., ≤62.5 μm). The load diversity generates alluvial "stratigraphy," alternating "layers" of coarse and fine sediment deposited along the banks of the Rio Grande and in the reservoir delta depending on the primary sediment source during the event represented. The material along the river subsequently erodes through bank failure and mass wasting processes delivering highly graded (poorly sorted) non-cohesive suspended sediment and bedload including fine sands to boulders.

The geomorphology and planform of the study reach shift to a much more depositional system above Cochiti Dam, immediately below the confluence of the Frijoles Canyon Creek and the Rio Grande River, because of the effects of the reservoir backwater. In 1992, the thalweg elevation near Frijoles Canyon Creek was 5,359.8 feet NGVD29. During the period from 1975-1996, the reservoir exceeded 5,350 feet NGVD29 several times (primarily between 1985 and 1988). Therefore, backwater frequently affects the area downstream of Frijoles Canyon and influences the geomorphic transition in this reach. This backwater effect created a significant headwater delta in the reservoir (see Figure 1).

Many studies and reports have characterized the geomorphology of the Middle Rio Grande downstream of Cochiti Dam and upstream of Angostura Diversion Dam (Novak, 2006; Sixta, 2004; Porter and Massong, 2004; MEI, 2002; Richard, 2001; Leon, 1998). These reports generally identify two primary geomorphic changes occurring in this reach as a response to the closure of Cochiti Dam: (1) streambed degradation throughout this reach and the bed armoring; and (2) a change in planform of the river from a braided, flat-bottom river in the early 1900's to a single-thread, meandering, deeper river. Additionally, most of these reports conclude that this reach is approaching a state of dynamic equilibrium. The rate of vertical (i.e., bed elevation) or horizontal (i.e., lateral migration, stream narrowing, and avulsion) change has reduced significantly since the period immediately following dam closure and are not expected to increase significantly in the near future. Anthropomorphic modifications have also reduced the rate of vertical and lateral erosion. The channel has been armored to mitigate stream bed degradation, and 115,000 Kellner jetty jacks were installed in the overbanks of the Middle Rio Grande between 1954 and 1962 (Grassel, 2002) to address lateral migration.

NUMERICAL SEDIMENT TRANSPORT MODELING

Calibrated fixed-bed hydraulic models built in HEC-RAS were used to develop HEC-RAS sediment transport models (USACE, 2011). Fixed-bed hydraulic model development followed standard procedures including: spatially georeferenced cross sections derived from digital elevation data, downstream reach lengths, bank stations, Manning's roughness coefficients, and ineffective flow areas. Each of these items was determined with the requisite engineering judgment and standard of practice. While the development of an accurate fixed-bed hydraulic model is an essential pre-requisite developing a mobile-bed sediment transport model (HEC, 1993; Thomas and Chang, 2008), this paper will focus on sediment transport modeling, methods and results.

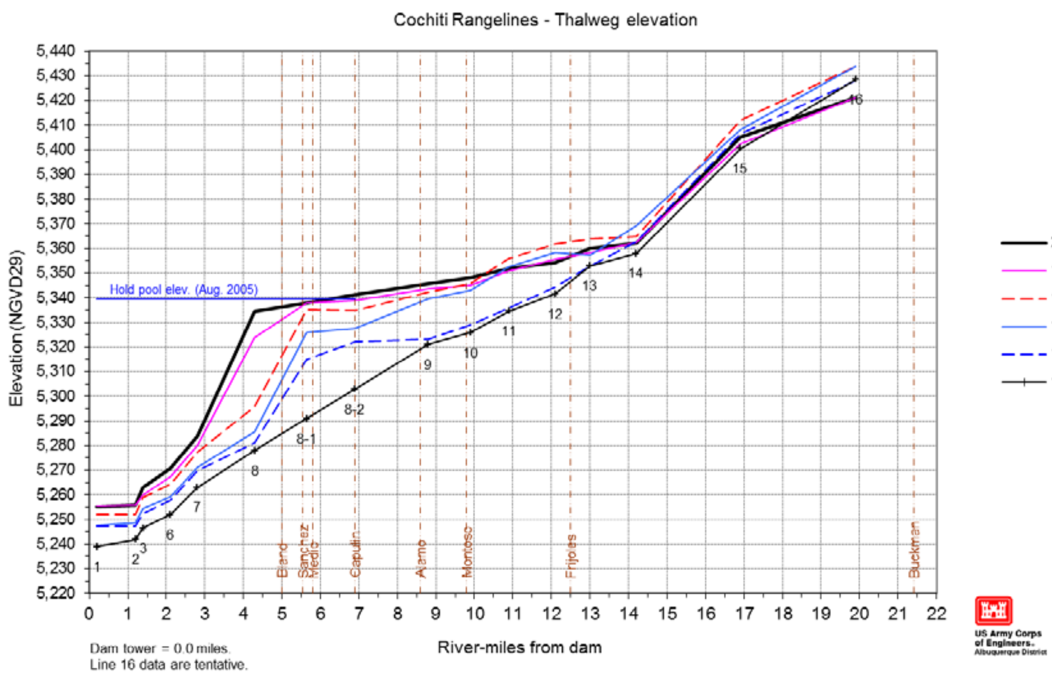

Figure 1. Growth of Cochiti Reservoir headwater delta based on Range Line surveys provided by USACE-SPA for survey years 1976, 1981, 1986, 1991, 1998, and 2005.

The base condition sediment transport models required input data (e.g., inflowing sediment loads, bed sediment gradations, suspended sediment gradations, and cohesive sediment parameters); calibration and verification. The different hydraulic and sediment conditions of the study reach upstream and downstream of Cochiti Dam, and the limitations of the quasi-unsteady hydrodynamic model in HEC-RAS when this study was conducted, the two reaches were modeled and discussed separately.

The base condition sediment transport models upstream and downstream of the dam included hydrology from shortly after dam closure in 1975 to present. The average bed elevation, (ABE) for each cross section at the end of each calibration period was compared to the average bed elevation of the measured cross section at the end of the same calibration period. Adjustments were made to the base conditions model such that the computed ABEs would reasonably approximate the measured ones. Upstream of the dam, these adjustments included primarily changes to calibrated gradations and volumes of inflowing sediment load. Downstream of the dam, these adjustments included primarily changes to calibrated bed sediment gradations. Once the base conditions models were calibrated and verified, they were executed to predict future conditions for operational evaluation scenarios, as described in the next section.

The sediment transport module in HEC-RAS (USACE, 2011; Gibson et al., 2006) is a one-dimensional, movable boundary, open channel flow model designed to simulate stream bed profile changes over fairly long time periods. One dimensional sediment modeling can be very effective in reservoir scenarios, but there are some limitations inherent to the 1D framework. For example, it cannot simulate meander development or compute a lateral distribution of sediment load across a cross section. Finally, sediment transport results are strongly dependent on which transport function is selected and whether it was developed for the range of hydraulic conditions and sediment grain sizes representative of the study reach. It is paramount that an experienced modeler assesses the model results in light of these limitations.

Sediment Transport Model Upstream of Cochiti Dam: The quasi-unsteady flow model used for sediment transport in HEC-RAS 4.1 (the version available at the time of this study) approximates a hydrograph with a series of steady flows. Mean daily flow at the Otowi USGS Gage (USGS Gage ID 08313000) and mean daily water surface elevation at Cochiti Dam were provided by the USACE-SPA for the calibration period from 1975-2009 for the model upstream of Cochiti Dam. A maximum computational time step of one half of an hour was used for the computations. The hydrology used in the model consisted of a condensed record of mean daily flow values for the Rio Grande River at Otowi Bridge for flows greater than 1,000 cfs.

The Rio Grande River is the major sediment source, delivering most of the inflowing sediment to the study reach upstream of Cochiti Dam. Sediment loads from tributaries upstream of Cochiti Dam and downstream of the Otowi Gage are minor. The upstream load (inflowing sediment load and gradation from the Rio Grande) was developed from a combination bedload from the Española Sediment Transport Study (MEI, 2009) and the suspended sediment load data collected by the USGS. The D50 was approximately 0.07 millimeters indicating that inflowing load included both coarse-grained, non-cohesive sediment and fine-grained, cohesive sediment.

Sediment loads from tributaries upstream of Cochiti Dam were estimated based on the report completed by Resources Technology, Inc. (1994) for the USACE-SPA. This report developed regression equations for sediment loading based on drainage area. An additional correction based on a later study (Tetra Tech, 2005) was also applied to this methodology.

WEST used several bed sediment gradations collected by the USGS at gages in the study reach, including the Rio Grande at Otowi Bridge and the Rio Grande near White Rock, to define model bed gradations. The D50 of these samples were generally between 0.5 and 1.0 millimeter. Also, the USACE Engineering Research and Development Center (ERDC) collected core samples in the reservoir for this study. The D50 were all in the fine-grained, cohesive soils range (i.e., particle diameters less than 62.5 micrometers). ERDC also performed SEDFLUME analyses to parameterize the shear threshold, erosion rate, mass wasting threshold, and mass wasting rate for the Krone (1962) and Parthenaides (1962) algorithms used for cohesive sediment deposition and erosion, respectively, in HEC-RAS. The τ_c of these samples varied from 0.79 Pa ($1.65x10^{-2}$ lb/ft^2) to 0.12 Pa ($2.51x10^{-3}$ lb/ft^2) and the erodibilities from $5.88x10^{-2}$ kg/m^2/sec (43.4 lb/ft^2/hr) to $3.78x10^{-3}$ kg/m^2/sec (2.8 lb/ft^2/hr), generally increasing with depth, but also influenced by the stratigraphy, alternating fine and coarse lenses from localized events in the main source tributaries.

A sediment transport function was selected based on a comparison of hydraulic and sediment parameters in the study reach with the range of data used to develop the transport functions. Copeland's (1989) modification of Laursen's (1958) relationship was used for this reach due to the significant contribution of fine sediments to the inflowing load. The model also limited sediment velocity to the water velocity to compute fine sediment deposition based on realistic residence times, which the Exner equation underpredicts without physical limiters.

WEST calibrated the model to twenty-three years (1975-1998) of bed change. After completing the calibration, a verification run was performed from 1998 to 2005 to demonstrate that the selected algorithms and parameters were robust. The results of the final verification run after model calibration are included in Figure 2. Additionally, the model replicated downstream bed fining (approaching the dam) (Figure 3). Corresponding sensitivity analyses were performed on this data to determine the sensitivity of the results to the variation in modeling parameters including sediment transport function, Manning's roughness, cohesive parameters, and others.

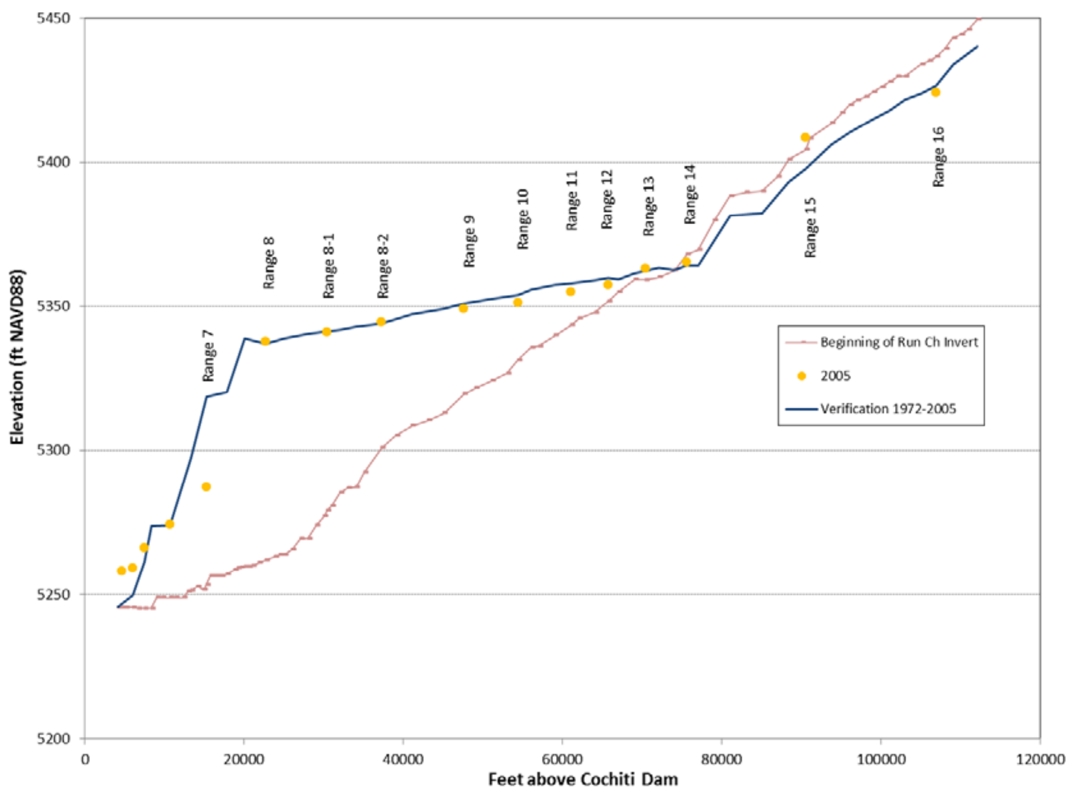

Figure 2. Bed profile results from the calibrated HEC-RAS model for the verification period (1975 – 2005) compared to measured data (points) in 2005.

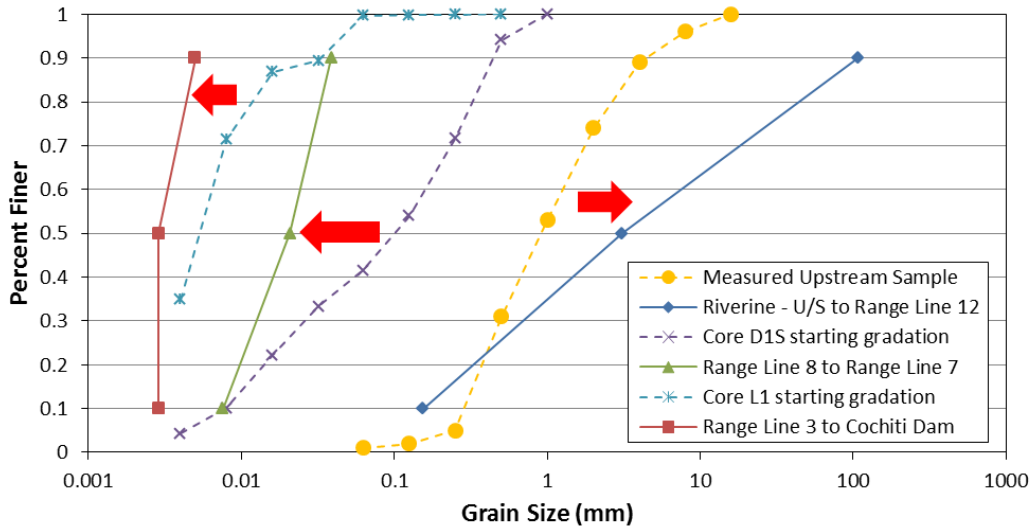

Figure 3. Reach-averaged bed gradation results from the calibrated HEC-RAS model for the verification period (1975-2005) shown in solid lines compared to the initial conditions data used in the sediment transport model shown in dashed lines; arrows indicate the direction of coarsening or fining of the bed.

Sediment Transport Model Downstream of Cochiti Dam: Mean daily flow at the USGS Gage below Cochiti Dam (USGS Gage ID 08317400) and a normal depth downstream boundary condition at Angostura Diversion Dam were used for the calibration and verification period from 1975-2009 for the model downstream of Cochiti Dam. A maximum time step of 0.5 hours was used as the computational time step with a condensed record of mean daily flow values for the Rio Grande River below Cochiti Dam for flows greater than 1,000 cfs.

Unlike the study reach above Cochiti Dam, the Rio Grande does not supply a significant source of sediment to the study reach below Cochiti Dam due to the trapping efficiency of the dam itself. Therefore, the primary sediment sources to the reach downstream of the dam are the local tributaries: Peralta Canyon, Borrego Canyon, Galisteo Creek, Arroyo de la Vega de los Tanos, Arroyo Tonque, and others. Sediment loads from tributaries downstream of Cochiti Dam were estimated based on the report completed by Resources Technology, Inc. (1994) for the USACE-SPA. This report developed regression equations for sediment loading based on drainage area. An additional correction based on a later study (Tetra Tech, 2005) was also applied to this methodology. Gradations for the tributary inflowing sediment loads were derived from sampling routines and estimates from these two studies.

Bed gradations downstream of Cochiti Dam were based on samples collected by the USGS at gaging stations in the study reach, including Rio Grande below Cochiti Dam and the Rio Grande at San Felipe. The D50 of these samples before dam closure were between 0.5 and 1.0 millimeter. Time series sampling at these locations showed bed coarsening over time, increasing the D50 at these locations by more than an order of magnitude. The final calibrated HEC-RAS sediment transport model reflected this bed coarsening over time.

A sediment transport function was selected based on a comparison of hydraulic and sediment parameters in the study reach with the range of data used to develop the individual sediment transport functions available in HEC-RAS. Yang's equation (1973, 1984) was used for this reach due to the inclusion of both sands and gravels in the transported sediment load.

The model was run for a period of twenty-three years (1975-1998) as a calibration period. After completing the calibration, a verification run was performed from 1998 to 2009 to verify the modeling output, and results matched closely with observed values. Sensitivity analyses were performed for this model as well.

OPERATIONAL EVALUATION SCENARIO MODELING

This study also evaluated the influence of reservoir operation scenarios on sediment mobilization, transport, and deposition to evaluate scenarios outside of normal operations, providing a tool to assess conceptual alternate dam operations. The models can assess the relative location and magnitude of erosion and deposition upstream and downstream of the dam for operational alternatives evaluation, and support future ecological and human health risk assessments. It should be noted that this study only developed modeling tools for future operational alternative evaluations; no approved operational alternatives were developed herein.

USACE-SPA and WEST engineers computed reservoir boundary conditions (elevations and outflows) to model the three possible operational evaluation scenarios in the HEC-RAS quasi-unsteady flow model. These three operational alternatives were then implemented in the numerical sediment transport models, beginning with the final conditions of the calibrated base conditions model and run into the run into the future for 50 additional years.

Under current operations, the only permanent storage in Cochiti Reservoir is the 1,200-acre surface area pool that is used for recreation. During non-flood flows, the lake must be kept at a constant elevation to maintain this surface area requirement. There is no sediment management strategy based on the congressional authorization of this dam (USACE, 1996).

The first scenario increased reservoir elevations, raising the operational elevation approximately 50 feet (5,340 to 5,390 feet NGVD29). This scenario stored water for other possible uses (e.g., water supply for irrigation, additional recreational uses, etc.) recruiting sediment deposition further upstream in the reservoir headwater.

The second scenario drew the reservoir pool down for extended periods to erode the large headwater reservoir delta. The alternative was constrained by a minimum drawdown elevation of 5,322 feet NGVD29 to avoid unfavorable conditions at the reservoir outlet intake. However, the model was "stressed" to the operational constraints, dropping the reservoir level to 5,323 feet NGVD29 for the whole drawdown to evaluate the maximum possible response to this operational technique.

The third scenario lowered the reservoir seasonally (in the winter) to 5,323 feet NGVD29, then refilled the reservoir to the current operating elevation of 5,340 feet NGVD29 in the summer. The model drew down the reservoir gradually at the end of the Middle Rio Grande Valley irrigation season, to an elevation of 5,323 feet NGVD29, and the reservoir level stayed at this lowered pool for one month. The reservoir was then refilled in the spring back to an elevation of

5,340 feet NGVD29. This operation was designed to flush sediment from the reservoir and maximize the benefit of bypassing inflowing sediment load through the reservoir, while maintaining the standard pool for summer recreation. The cycle was repeated annually for the entire 50-year simulation period.

Results of the three scenarios compared to continuing normal operations in the reservoir for 50 years into the figure are included in Figure 4. The model did not compute significant sediment transported through the reservoir because of the physical characteristics of the reservoir itself and infrastructure limitations prohibiting further drawdown at this time. It did, however, indicate significant influence on the upstream deposition distribution was possible.

DISCUSSION

This paper attempts to answer questions regarding reservoir sustainability in terms of water storage capacity. In terms of usable reservoir life, defined by Morris and Fan (1998) as "*the period during which the reservoir may be operated for either its original or a modified purpose,*" Cochiti Dam appears to be able to meet its originally intended purpose and a broad range of modified purposes for at least the next 50 years despite reservoir sedimentation.

The design philosophy when Cochiti Dam was conceived was based on an implied consideration of reservoir storage as an exhaustible resource. Annandale (2013) presents a convincing argument for the consideration of reservoir storage as a potentially sustainable resource. Because of the economics of dam construction, most prime sites for reservoir storage creation have largely been exhausted, with only less desirable and more-costly locations remaining. Thus, adding more reservoir capacity becomes more costly, and the need to preserve existing storage becomes more important in the hierarchy of approaches. Couple this with the uncertainties of watershed sedimentation from climate change, and the capacity issue becomes more complex. Understanding the sedimentation behavior of the project becomes an important planning and management tool in this respect.

The final calibrated sediment transport models also provide tools for the Pueblo and the USACE-SPA to further assess water quality and diversity issues in the study reach towards holistic reservoir sustainability analyses. Unsteady sediment transport in HEC-RAS 5.0, released after this work was complete, simplified the process of defining future operational alternatives for reservoir sediment management (Gibson and Boyd, 2014, Shelley et al., 2015), which will make additional alternative evaluation easier.

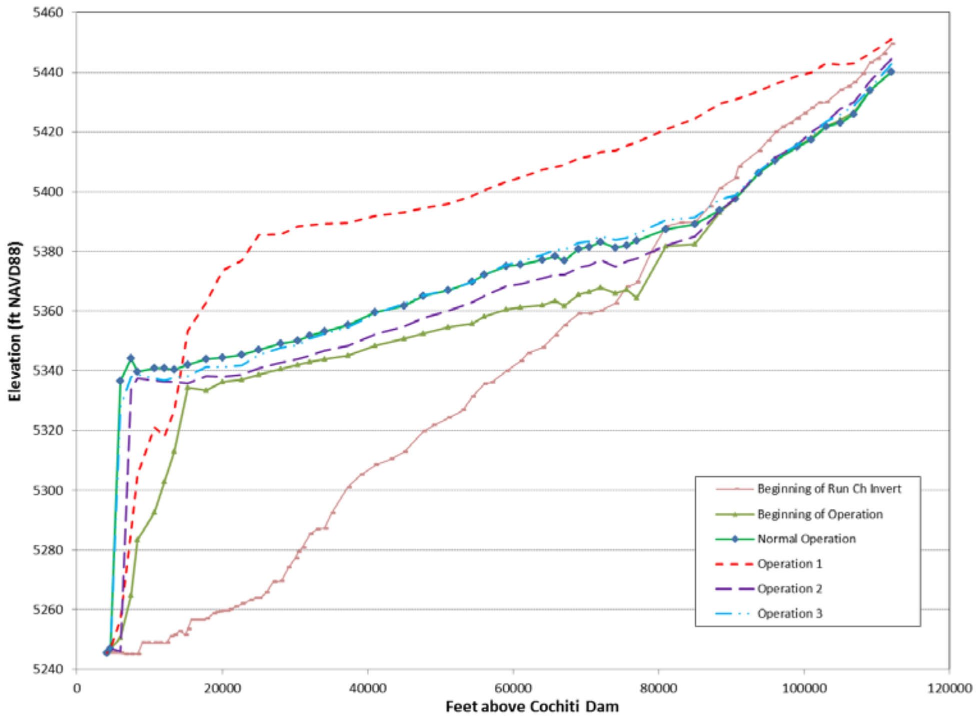

Figure 4. Bed profile results from various operational evaluation scenario HEC-RAS sediment transport models for the 50 year simulation window (2010-2059).

Limitations of this study include density current effects that probably affect Cochiti Reservoir (i.e. a "muddy lake effect" appears in range line profile plots) and remobilization of compacted alternating "layers" of cohesive and non-cohesive sediments in a lacustrine headwater delta, which will be explicitly modeled with future versions of HEC-RAS. The implications of climate change, and the associated response of watershed soils and vegetation, were also excluded from the current study, but are planned for future studies. As our knowledge improves regarding changes that might affect sediment supply to reservoirs, the ability to model and test reservoir responses will become more important. Sustainable solutions to reservoir sedimentation issues require a strong toolbox of continuously updating knowledge and information. In the case of Cochiti Reservoir, as in many other reservoirs, we must tackle the problem one step at a time.

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