RECLAMATION

Managing Water in the West

Geomorphic Assessment of the Rio Grande Upstream of Elephant Butte Reservoir

U.S. Department of the Interior
Bureau of Reclamation
Albuquerque Area Office
Albuquerque, New Mexico

April 2013

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Geomorphic Assessment of the Rio Grande Upstream of Elephant Butte Reservoir

prepared by

Technical Services Division
River Analysis Group

Nathan Holste, M.S., P.E.
Hydraulic Engineer

Cover Photograph: Elephant Butte Reservoir Delta, looking downstream from near RM 39
(photo taken April 23, 2013)

U.S. Department of the Interior
Bureau of Reclamation
Albuquerque Area Office
Albuquerque, New Mexico

April 2013

Table of Contents

Page

Executive Summary **1**
Geomorphology and Channel Adjustment Concepts and Analyses **4**
Sediment Balance 8
Drivers 10
Flow Magnitude, Frequency, and Duration 11
Sediment Supply 12
Controls 14
Channel and Floodplain 14
Base Level 15
Reservoir Analysis 16
Slope Analysis 19
Bed Elevation Analysis 23
Summary of Channel Conditions and Dynamics 27
Geomorphic Effects of Channel Maintenance **27**
Initial Channel Construction 28
Groundwater Analysis 29
Recurring Channel Maintenance 32
Conclusions **38**
Acknowledgements **40**
References **41**
Appendix A: Thalweg Profiles **44**
Appendix B: River Miles and Rangelines Location Map **49**

List of Figures

Figure 1. Short-term cross-sectional changes at SO-1550. 6
Figure 2. Short-term cross-sectional changes at SO-1566. 7
Figure 3. Conceptual diagram of upstream headcutting caused by base level lowering 8
Figure 4. Sediment transport capacity and supply curves (after Julien, 1998). 9
Figure 5. Lane's Balance (after E.W. Lane, from W. Borland) from *Demonstration Erosion Control Design Manual* (Watson et al., 1999) with adaptations. 10
Figure 6. Annual valley flow volume at San Marcial (1895–2012) 12
Figure 7. Cumulative suspended sediment versus discharge of the Rio Grande Floodway at San Marcial 13
Figure 8. Bed material size over time at different locations upstream of Elephant Butte Reservoir pool (modified from Owen, 2012) 15
Figure 9. Elephant Butte Reservoir pool elevation time series (1915–2012) (modified from Owen, 2012) 17
Figure 10. Elephant Butte Reservoir longitudinal profiles and pool elevations (modified from Ferrari, 2008) 18
Figure 11. Typical reservoir delta sediment deposition profile (modified from Strand and Pemberton, 1982) 19
Figure 12. Thalweg profile from Highway 380 Bridge to the Narrows 20
Figure 13. Changes to Rio Grande lower subreach channel slope and Elephant Butte reservoir pool elevation over time (1999–2012) 21
Figure 14. Changes to Rio Grande channel slope over time (1999–2012) 21
Figure 15. Elevation changes of the USGS San Marcial gauge and Elephant Butte Reservoir pool over time (modified from Makar 2013, pers. comm.) 24
Figure 16. Change in thalweg and reservoir pool elevation over time (after Owen, 2012) 25
Figure 17. Change in thalweg elevation from 2004 to 2009 (from Owen, 2012). 26
Figure 18. River thalweg elevation, groundwater elevation, and river discharge over time near BDANWR south boundary 31
Figure 19. River thalweg elevation, groundwater elevation, and river discharge over time near San Marcial 31
Figure 20. River thalweg elevation, groundwater elevation, and river discharge over time near RM 63 32
Figure 21. Partial Temporary Channel thalweg profiles over time during recurring channel maintenance 33
Figure 22. Distance-weighted average thalweg elevation over time for the Temporary Channel between EB-28 and EB-50 during recurring channel maintenance 34
Figure 23. EB-32.7 cross section plots (looking downstream) during recurring channel maintenance (near thalweg profile station 194,900) 35

Figure 24. EB-37.5 cross section plots (looking downstream) during recurring channel maintenance (near thalweg profile station 210,200) 35
Figure 25. EB-43 cross section plots (looking downstream) during recurring channel maintenance (near thalweg profile station 230,600) 36
Figure 26. Naturally formed reservoir delta channel and flowpaths downstream of the Narrows:..... 37

List of Tables

Table 1. Average daily suspended sediment concentration of the Rio Grande Floodway at San Marcial 13
Table 2. Main Causes of Streambed Elevation Change (adapted from Knighton, 1998) 16
Table 3. Detailed explanation of Rio Grande slope changes (see Figure 13 and Figure 14)..... 22
Table 4. Total channel length for the Rio Grande between RM 58 and RM 47 (2002 River Miles)..... 29

Executive Summary

The Rio Grande has episodically become disconnected from the Elephant Butte Reservoir pool after periods of drastic reservoir recession, most recently from 1998 to 2004. Relatively high sediment loads coupled with low water discharge and a flat valley slope caused the river channel to lose form within the reservoir delta. Water and sediment could not be effectively delivered to the reservoir pool due to the lack of an established channel, which led to high evapotranspiration water loss within the delta area. Therefore, a channel was constructed between 2000 and 2004 to maintain a connection from the river to the reservoir pool. Maintenance of this channel has been required every year since initial construction because of the prevailing aggradational trend that results in loss of channel capacity and breaches of the spoil berms. A thorough assessment was performed to examine potential effects from initial channel construction and recurring maintenance activities. Channel conditions and dynamics were assessed within a geomorphic framework that considers the primary physical processes that govern alluvial river morphology. A reach length of 60 miles was evaluated from Elephant Butte Dam to the Highway 380 Bridge, with emphasis on the subreaches closest to the reservoir pool.

This reach of the Rio Grande, upstream of Elephant Butte Reservoir, is highly dynamic and behaves with a great deal of complexity. The geomorphic drivers of water discharge and sediment load, coupled with the primary control of downstream base level (reservoir pool) elevation, have varied significantly from the early 1900's to the present. After a period of initial reservoir filling that followed dam construction in 1915, the reservoir water surface has fluctuated over a vertical range of 150 feet (a shift in the horizontal water surface of around 32 river miles) corresponding to climatic wet and dry periods. Given that the Rio Grande's water and sediment inputs are varying while the downstream control is changing, it is clear that a complex series of responses should be expected. The river's planform, cross-sectional shape, slope, bed elevation, and other morphological characteristics are continuously changing in response to alterations in water discharge, sediment load, base level, and anthropogenic actions.

The relationship between upstream geomorphic drivers and the downstream control often results in a sediment imbalance upstream of the reservoir pool. An imbalance between sediment supply and sediment transport capacity is the prevailing condition within this reach of the Rio Grande, which causes frequent channel adjustments over space and time. Analysis demonstrates that the slope and bed elevation of the Rio Grande through this reach respond to a rising or falling reservoir pool. For example, a 100 foot decrease in reservoir pool elevation between November 1998 and September 2004 resulted in a wave of up to 12 feet of degradation (riverbed lowering) that migrated several miles upstream. Additionally, a 60 foot increase in pool elevation from September 2004 to February 2009 induced a wave of up to 10 feet of aggradation (riverbed rise) that also migrated upstream. Locations near the reservoir pool tend to adjust quickly, while channel response further upstream occurs later in time and at a lesser rate. Upstream water and sediment discharge may amplify or dampen effects from the downstream reservoir. Time-series bed elevation data at the San Marcial gauge about 5 miles upstream of the full reservoir pool show two periods of historical degradation, both following a similar decline in reservoir elevation: 1949–1972 and 2005–2011. The 1949–1972 degradation rate was only about one half to one third that of the recent rate, mostly due to the substantially higher sediment load during 1949–1972.

Although periods of degradation have been initiated when a high flow event occurs while the reservoir pool is low, aggradation is the most dominant characteristic of this reach over time. The riverbed elevation at San Marcial has increased by a cumulative total of about 18 feet since 1915, while areas further downstream near the historic average pool location (the Narrows) have aggraded 40–50 feet. In addition to the aggradational trend, historic reservoir longitudinal profiles show the development of grade breaks (knickpoints) corresponding to specific pool water surface locations. These knickpoints affect channel response when areas formerly inundated by the reservoir pool become the river thalweg as the reservoir recedes. A knickpoint is evident in the 1999 thalweg profile near River Mile (RM) 56, which was just downstream of the pool location during the previous 15 years. When the reservoir pool dropped below this knickpoint, the local slope became three times steeper than the river slope upstream of RM 56.

The previous discussion of geomorphic concepts that determine the Rio Grande's morphology upstream of Elephant Butte Reservoir provides necessary context for river maintenance actions within this reach. Adaptive management is likely the most appropriate strategy, given that the design life of any maintenance approach will be greatly reduced because of fluctuations in the upstream drivers (water and sediment discharge) and downstream control (reservoir pool elevation) (Reclamation, 2012). The Temporary Channel has been adaptively maintained in response to river channel adjustments to the drivers and control. Anthropogenic Temporary Channel actions and effects can be divided into two distinct periods: initial channel construction (2000–2004) and recurring channel maintenance (2005–2012).

Initial channel construction restored the Rio Grande's connection to the receding reservoir pool by excavating a flowpath about 3 feet deep through the delta. Sinuosity was incorporated into the design so that the channel length was within 1% of the 1972 length. A close examination of the 1999, 2002, and 2004 thalweg profiles reveals that it is probable that initial excavation was responsible for a slope increase of about 8–12% within the upper reservoir delta (from about RM 58 to RM 46). The riverbed elevation upstream of the Temporary Channel was very stable during initial construction (2000–2004), although the preexisting knickpoint near RM 56 moved about three miles upstream between 1999 and 2004. Significant degradation took place during the 2005 spring runoff for several miles upstream of the Temporary Channel as the headcut migration was accelerated. This degradation occurred during a high magnitude, long duration spring runoff event combined with a sediment plug that blocked sediment supply upstream of San Marcial, which was subsequent to a rapidly and substantially lowered reservoir pool. Historical data and an understanding of fundamental geomorphic concepts show the relative effect of the Temporary Channel, compared to other reach processes, on upstream riverbed elevation. Levish (2012) concludes that Temporary Channel construction may have initiated and temporarily increased the rate of channel lowering, but this elevation change would have eventually occurred in response to the lower reservoir pool elevation.

Riverbed adjustment, such as the 2005 degradation, is an important environmental concern because of the potential to affect aquatic and riparian habitat and species. One specific consideration is the impact on vegetation and the relationship between groundwater elevation and riverbed elevation. Groundwater elevation is complex, highly variable, and appears to be primarily a function of river discharge (or river water surface elevation) and nearby groundwater controls (i.e., LFCC and ponded areas). River thalweg elevation trends over time and space can influence, but may not directly correspond to, trends in groundwater elevation.

Recurring channel maintenance differs from initial construction because there was an existing river channel being adaptively maintained rather than a new channel that was excavated. The goal of recurring maintenance actions (2005–2012) was to maintain sufficient channel conveyance by removing accumulated sediment deposits and repairing spoil berms. During recurring maintenance, the average Temporary Channel thalweg elevation responded directly to the reservoir pool: aggradation occurred between 2004 and 2010 as the pool elevation increased and degradation occurred between 2010 and 2012 while the pool receded. The Temporary Channel planform did not change during recurring maintenance and cross section plots illustrate the variable depth and morphology that is typical of alluvial rivers. In a dynamic and complex system, geomorphic effects that may have been caused by maintenance actions are not discernable compared to the significant effects from the geomorphic drivers and the primary control of base level elevation.

Geomorphology and Channel Adjustment Concepts and Analyses

Geomorphology is the study of landforms and the processes which control them, while fluvial geomorphology is specific to landforms that are shaped by the action of flowing water. The fluvial system is formed by the interrelationship between several factors: climate and geology, independent basin controls (basin physiography, vegetation, soils, land use), independent channel controls (valley slope, stream discharge, sediment load input, bank material composition), and dependent channel and flow geometry parameters (channel slope, width, depth, roughness) (Knighton, 1998). Anthropogenic influences and controls are also extremely important and must be considered. The interaction between river channel boundaries and the flow of water and sediment essentially determines the channel morphology (Schumm, 1977; Leopold et al., 1964). Ultimately, channel form is not the product of a single formative discharge, but of a range of discharges and of the temporal sequence of flows (Wohl, 2007; Knighton, 1998).

Temporal and spatial scale

Knighton's (1998) discussion of geomorphic variables implies a consideration of multiple temporal and spatial scales. The complexity and dynamic nature of the river system make it important to define an appropriate timescale prior to beginning a geomorphic analysis. The timescale of interest changes the relationships between independent and dependent variables (cause and effect). Schumm (1977), Knighton (1998), and Watson et al. (2007) discuss several different timescale definitions and the implications when analyzing fluvial systems. Geologic time is typically measured in thousands or millions of years, while engineers usually consider a time scale between 10 and 100 years. For example, valley dimensions within geologic time are a function of paleoclimate and tectonic activity, yet an engineer may assume that valley characteristics are an independent constant that influences river behavior. Biologists are often concerned with a shorter time scale depending on the species of interest. Some species may be sensitive to fluctuations (anthropogenic or natural) on the order of one to three years or less, which may otherwise be insignificant within the context of a long-term trend. Data exists for many river system parameters on the Middle Rio Grande over the last 100 years, while some qualitative accounts date back 500 years. This historical information provides insight regarding the natural tendencies of the river and the system's response to changes in conditions over space and time.

Spatial scale should also be considered when conducting a geomorphic analysis. Channel adjustment at specific locations may or may not be indicative of a reach-wide trend. It is important and often difficult to distinguish local instability from system instability. A dynamically stable system will still exhibit local adjustments such as channel lengthening through bank erosion in growing meander bends that is offset by cutoffs at other bends. Local instability exists where there are adjustments at individual locations, while reach-averaged parameters such as hydraulic geometry and slope remain steady. Conversely, system instability propagates throughout a stream network as a result of water and sediment discontinuity, changes to downstream base level, and land use changes. System instability is visible through reach-wide aggradation, degradation, or planform metamorphosis. Most importantly in a dynamically changing system, short-term or local changes are not necessarily indicative of long-term or system-wide behavior (Watson et al., 2007).

Dynamic equilibrium and stability

A stable alluvial channel means that the cross-sectional form and longitudinal slope of a stream have adjusted to convey the available water and sediment discharges with no net change to hydraulic geometry or planform. Stability requires a consideration of time scale because temporary morphological adjustments to extreme events can still occur in a stable (graded) stream (Watson et al., 2007). A short-term adjustment will return to the average condition over time in a stable system. Conversely, a river that appears stable in the short term may actually be unstable and moving toward a new condition over the long term. Dynamic equilibrium is often a more appropriate descriptor than stable, because it accounts for the naturally frequent short-term changes within a river system. Schumm (1977) clarifies that a river in dynamic equilibrium is not static or fixed, but oscillates around an average condition. Dynamic equilibrium also requires a general balance between sediment transport capacity and supply. Sediment balance will be discussed in more detail later, and is necessary for dynamic equilibrium so that sediment transported into a reach is also transported out, without net aggradation or degradation (Watson et al., 2007).

A stable system contains negative feedback mechanisms that dampen external factors and allow moderate events to restore the graded condition (recovery time). An example of negative feedback is a well-connected floodplain that dissipates increasing energy during large overbanking flows. For an unstable system, positive feedback amplifies any displacement in the same direction, thereby resulting in a new position (Knighton, 1998). A channel avulsion that results in a new long-term river location is indicative of an unstable system.

Dynamic equilibrium implies that the recovery time is shorter than the return period for the extreme event (recurrence interval). Formative flows in a dynamically stable stream work to restore morphology to the graded condition after disturbance, rather than perpetuating the changes of the extreme event. Sufficient time and space are also required for the stream to make necessary adjustments. It should be noted that few natural rivers are truly stable due to changes in water discharge and sediment load, but the concept indicates stream evolution trends and how the river will adjust to intervention. Rivers in disequilibrium tend to be close to a geomorphic threshold in which the system is sensitive to destabilization and a minor change may result in a dramatic response (Watson et al., 2007). For example, a small amount of degradation in an incised channel may cause the riverbed to lower below the vegetative root mass, thereby crossing a geomorphic threshold and causing widespread bank collapse.

The system is dynamic

The Rio Grande, like all alluvial rivers, is dynamic and continuously changes planform, cross-sectional shape, slope, and other morphological characteristics in response to alterations in water discharge, sediment load, and boundary conditions (Watson et al., 2007). The fine sand bed material present in the Rio Grande upstream of Elephant Butte Reservoir makes the channel quite susceptible to change from perturbations (e.g., flow events, reservoir levels, anthropogenic actions). This concept is helpful to consider when analyzing bathymetric, topographic, and sediment data collected from the river. Data collection efforts are snapshots in time that represent river conditions at a specific moment. Data is often interpreted to represent periods of a year or longer, but the dataset may only be truly accurate for the day it was collected, depending on antecedent or subsequent flow events. Conclusions regarding riverine processes and trends should be made cautiously, and only after consideration of numerous datasets.

Figure 1 and Figure 2 show two cross sections that were each surveyed five months apart (July and December, 2009) with no spring runoff events between the survey dates. The cross sections are located within Bosque del Apache National Wildlife Refuge (BDANWR) about 36 miles downstream of the San Acacia Gauge and 12 miles upstream of the San Marcial Gauge. SO-1566 is about 1.7 river miles downstream of SO-1550. The maximum mean daily flow that occurred between the two surveys was approximately 900 cfs (894 cfs at San Acacia and 912 cfs at San Marcial). The corresponding maximum instantaneous flow was 2,280 cfs as measured at the San Marcial Floodway Gauge (#08358400). At SO-1550, the thalweg elevation increased by 1.9 feet between July and December. At SO-1566, the thalweg elevation decreased by 1.8 feet between July and December. The modeled 500 cfs water surface elevation and the calculated mean bed elevation were within 0.2 feet for the two survey dates at both cross sections. The cross section plots illustrate the dynamic nature of the Rio Grande and that the mean bed elevation often controls the water surface and channel capacity more than the thalweg elevation. Thalweg elevation changes of less than 2–3 feet should be examined within the context of mean bed elevation, nearby cross section data, and reach longitudinal profiles to determine if a true shift in bed elevation has occurred.

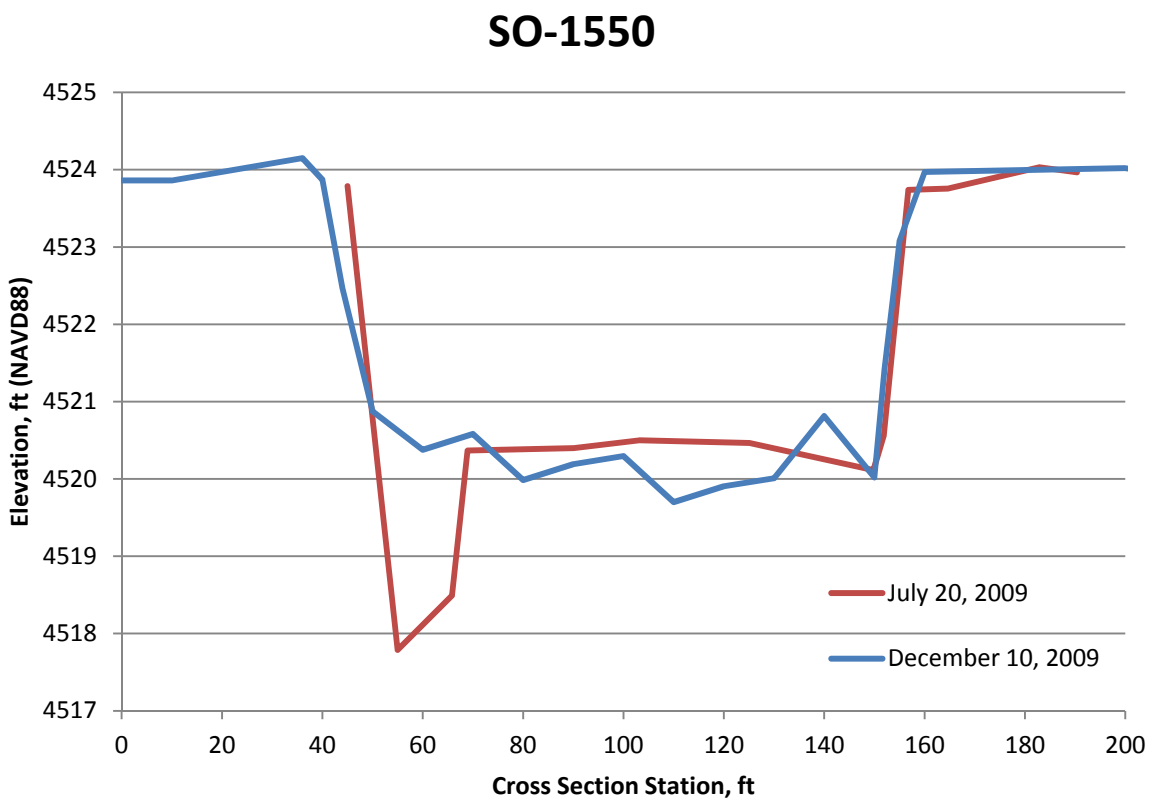


Figure 1. Short-term cross-sectional changes at SO-1550.

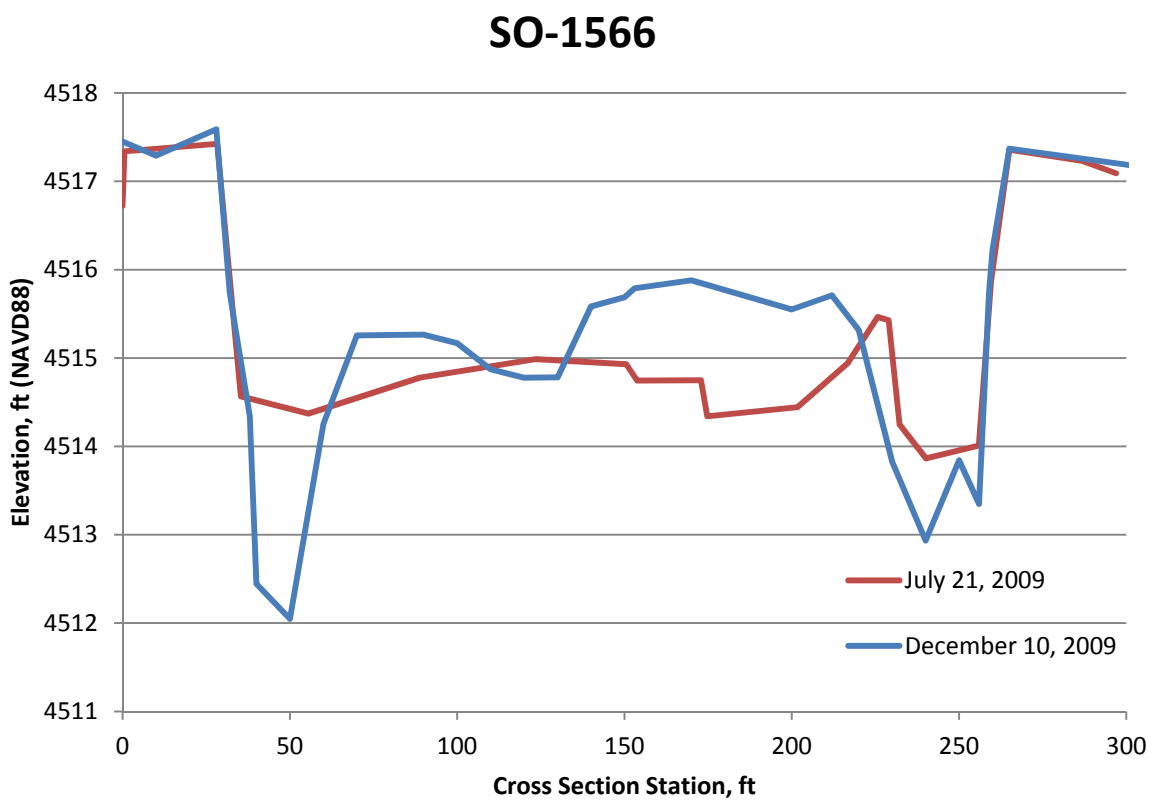


Figure 2. Short-term cross-sectional changes at SO-1566.

The system behaves with complexity

Schumm (1977) introduced the idea of complex geomorphic response, which is further discussed by Watson et al. (2007). The fluvial system responds through different processes at different locations and times to changes in hydrology, sediment, base level, or anthropogenic intervention. For example, base level lowering in a drainage basin can cause erosion and adjustment in the main channel near the mouth of the basin. The steepened slope may increase the sediment transport capacity beyond what is supplied from upstream, thereby resulting in headcutting that migrates upstream as the stream adjusts through degradation. Figure 3 illustrates this process of a lowered base level (reservoir level) resulting in a steeper slope and causing upstream riverbed degradation. A lowered main channel bed elevation is also a lowered base level for any tributaries, and a similar process is likely to occur throughout the upper reaches of the basin. As erosion progresses upstream, an increased sediment supply will be provided to the downstream main channel that has already adjusted to the lowered base level. However, the downstream reach is not yet adjusted to the increased sediment supply and a new phase of responses will begin. Aggradation may result from the reduced slope and increased sediment supply with multiple cycles of degradation/aggradation occurring over a period of time. The example shows a likely series of complex responses to a single perturbation (base level lowering) and also demonstrates the importance of temporal and spatial scale. Downstream reaches are closest to the reservoir and respond quickly to base level changes but more slowly to changes in upstream sediment supply. Upstream reaches are farthest from the reservoir and respond to base level changes at a later time. Given the complex responses to a single perturbation, it is evident that dynamic equilibrium is nearly impossible in a system with frequent variations to upstream and downstream conditions.

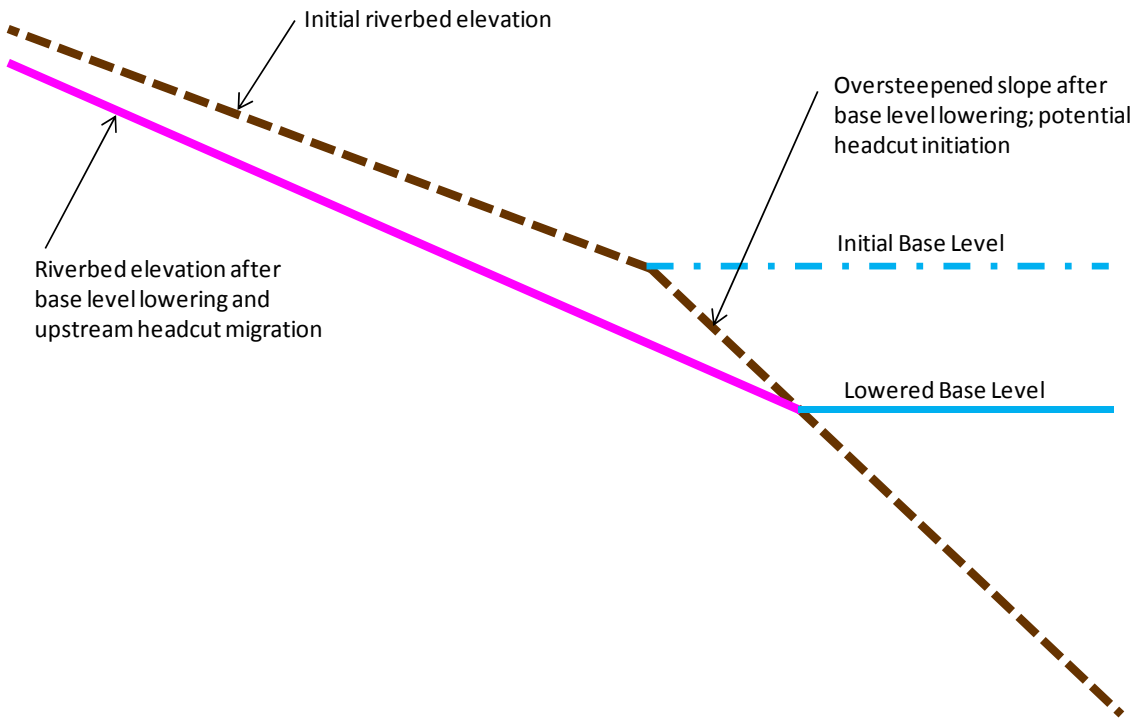


Figure 3. Conceptual diagram of upstream headcutting caused by base level lowering

Davis (1895) explains how the gradient of a stream is adjusted so that the capacity to do work (related to sediment transport capacity) is equal to the work that must be done (related to sediment supply). Both sediment transport capacity and supply will be discussed in the Sediment Balance section below. Davis's description of work is essentially the river's ability to effectively transport the available water and sediment. Water and sediment inputs fluctuate constantly, which drive frequent adjustments to the river's slope and cross-sectional form. The river morphology adjusts in an attempt to maintain dynamic equilibrium while balancing the capacity to do work with the work that must be done. Considering that the Rio Grande's water and sediment inputs are varying while other factors such as reservoir level are also changing, it is clear that a series of complex responses should be expected.

Sediment Balance

Sediment balance implies a relative equality between the material made available to a stream from a watershed (sediment supply) and the capacity of a stream to convey the available material (sediment transport capacity). Sediment supply to a river is primarily a function of water discharge and the quantity and characteristics of available sediment. Sediment transport capacity is determined by the channel morphology and its interaction with flowing water. A thorough understanding of the relationship between sediment supply and transport capacity is essential so that the causes of channel instability may be treated rather than the symptoms (Schumm et al., 1984). The fundamental cause of most channel and floodplain adjustments is an imbalance between sediment supply and transport capacity (Lane, 1955; Schumm, 1977; Biedenharn et al., 2008).

Figure 4 shows that the rate of sediment transport in a river, or section of river, is governed by a limited sediment supply (supply limited) or a limited transport capacity (capacity limited) (Julien, 1998). The relative magnitude of these two variables determines the response of the river. Where a river system has excess transport capacity, typical adjustments include channel incision, bank erosion, and potential planform change from a braided sand bed channel to a single thread, mildly sinuous channel with a coarser bed. Additionally, a reduction in sediment supply generally results in a narrower, deeper channel with a flatter local slope and increased sinuosity. Where a river has excess sediment supply and limited transport capacity, channel aggradation will occur. Aggradation usually causes a wider, shallower channel with a steeper slope, decreased sinuosity, and reduced flow capacity (Reclamation, 2012). Reduced flow capacity under aggrading conditions assumes that there is a net loss in cross-sectional area as riverbed rise exceeds channel widening, which is typically the case on the Rio Grande. A greater amount of channel adjustment is expected for a severe imbalance between sediment supply and transport capacity, while a balance between these two conditions indicates that a river is near dynamic equilibrium.

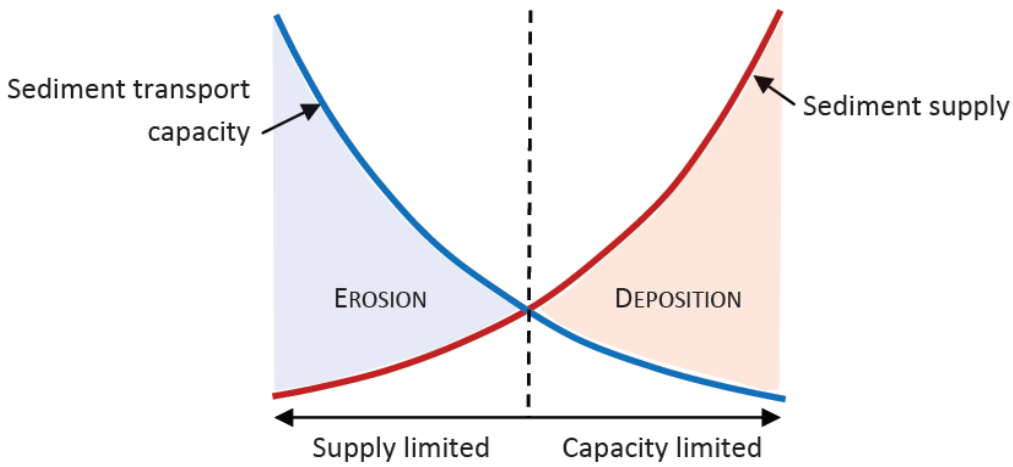


Figure 4. Sediment transport capacity and supply curves (after Julien, 1998).

Lane (1955) proposed a qualitative relationship for adjustment in alluvial streams as a function of sediment supply and transport capacity. This relationship, known as Lane's balance ($Q_s d_{50} \sim QS$), states that the river's sediment load (Q_s) and median sediment size (d_{50}) are proportional to the river's water discharge (Q) and slope (S). Figure 5 illustrates Lane's balance and how changes to any of the four driving parameters will tend to affect the others so that a balance is achieved. Assuming that each variable is dependent, the expected responses are also described below, where a plus (+) indicates an increase and a minus (–) indicates a decrease. Water discharge is actually independent of the other three variables and sediment load may or may not be independent depending on the temporal and spatial scale. Regardless of a variable's independence or dependence, the plus or minus sign shows the direction of change that would restore balance to the system.

Increased water discharge: $Q^{+} \sim Q_s^{+} d_{50}^{+} S^{-}$

Decreased water discharge: $Q^{-} \sim Q_s^{-} d_{50}^{-} S^{+}$

Increased sediment load: $Q_s^{+} \sim Q^{+} S^{+} d_{50}^{-}$

Decreased sediment load: $Q_s^{-} \sim Q^{-} S^{-} d_{50}^{+}$

Increased slope: $S^{+} \sim Q_s^{+} d_{50}^{+} Q^{-}$

Decreased slope: $S^{-} \sim Q_s^{-} d_{50}^{-} Q^{+}$

Increased sediment size: $d_{50}^{+} \sim Q^{+} S^{+} Q_s^{-}$

Decreased sediment size: $d_{50}^{-} \sim Q^{-} S^{-} Q_s^{+}$

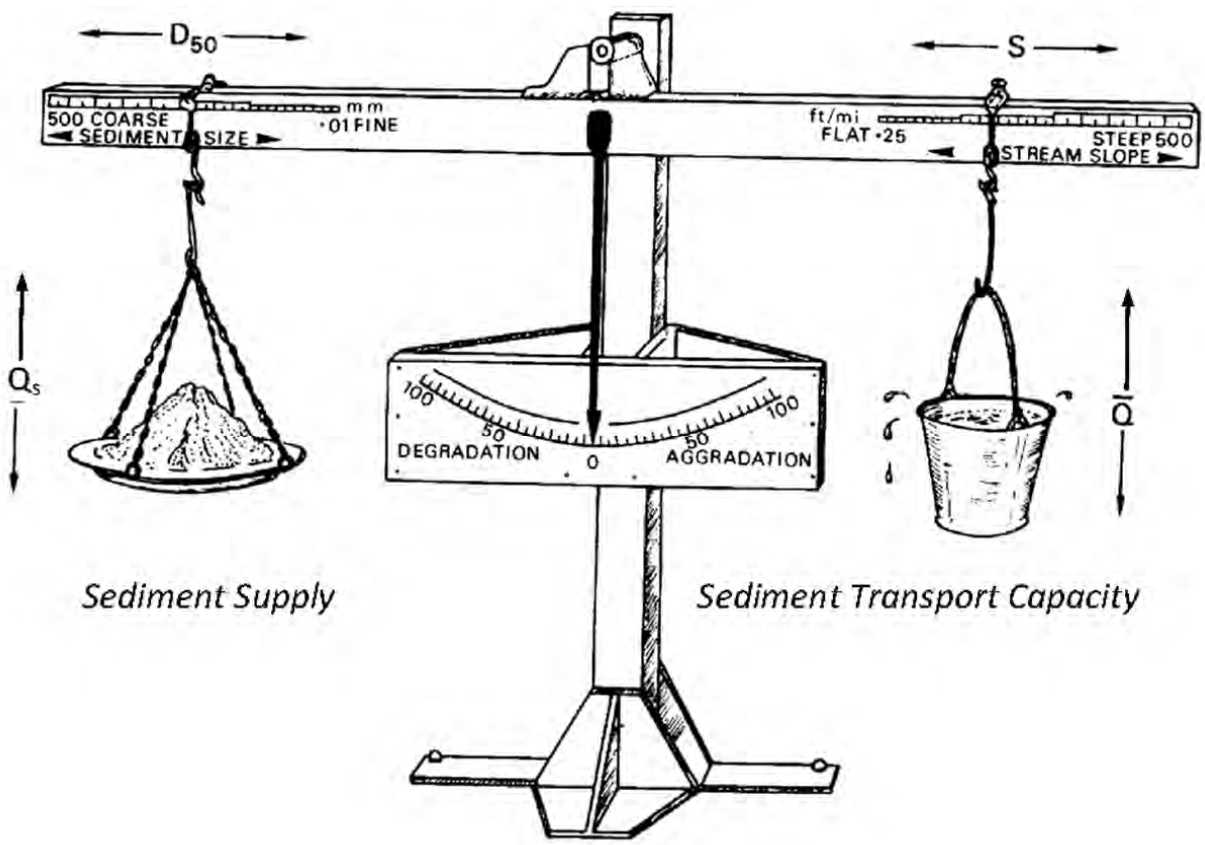


Figure 5. Lane's Balance (after E.W. Lane, from W. Borland) from *Demonstration Erosion Control Design Manual* (Watson et al., 1999) with adaptations.

Drivers

Sediment balance, or imbalance, is affected by two types of factors: drivers of channel adjustment and controls on channel adjustment (Makar and AuBuchon, 2012). During a period of years, decades, or centuries, the primary drivers that determine alluvial channel morphology are the flow regime and sediment load (Schumm, 1977; Watson et al., 2007).

Flow Magnitude, Frequency, and Duration

Water discharge determines the energy provided to the fluvial system over space and time. Flow magnitude and frequency are a measure of the size of specific flow events and how often a given flow event occurs. Duration is important because peak discharges may occur during prolonged snowmelt runoff events or short-lived monsoon events. Monsoon events supply a tremendous amount of sediment to the river system during arroyo flows, which can influence the channel morphology through the input of both cohesive and coarse material. The extended duration of spring runoff events allows for the downstream transport of a larger total volume of sediment and provides a greater opportunity for the flow to modify channel form. This sequencing, or relationship, between monsoon and spring runoff events contributes to the sediment balance complexity because much of the sediment is supplied to the river during monsoons and transported during spring runoff flows.

On the Middle Rio Grande, flood and sediment control dams have altered the recent hydrologic regime by reducing flood peaks. Natural climate cycles have also affected peak streamflow. During dry periods from 1943–1978 and 1996–present (data includes 2012, although current dry period may continue indefinitely) most of the recorded peak flows are substantially less than 5,000 cfs, and the annual flow volume is typically less than one million acre-feet. Wetter cycles from 1903–1942 and 1979–1995 resulted in peaks significantly greater than 5,000 cfs and annual flow volumes greater than one million acre-feet. The variable and irregular wet and dry periods are typical of southwestern rivers and continue to this day on the Middle Rio Grande.

Figure 6 illustrates the total annual valley flow volume, as calculated by combining values from the Rio Grande Floodway at San Marcial (USGS Gauge 08358500 and 08358400) and the Rio Grande Conveyance Channel at San Marcial (USGS Gauge 08358300). The two gauge locations are combined in order to maintain consistency across the period of record while accounting for operation of the Low Flow Conveyance Channel (LFCC) from 1952 to 1975 and 1983 to 1985. A graph of the annual peak flows would show similar trends, although the wet and dry periods are not as distinct. The annual flow volume incorporates both the magnitude and duration of flow events so it is a good indication of the energy provided to the river. Historically, most significant channel adjustments on the Middle Rio Grande have occurred during high magnitude, long duration runoff events. The river also adjusts to periods of low flows, but at a more gradual rate. The channel planform has narrowed and become more uniform as decreased peak flows result in the channel not being reworked to the degree it was historically. Increased duration of low flows from anthropogenic regulation can also aid encroachment of vegetation into the active channel, which narrows it and increases the geotechnical strength of channel banks (Makar and AuBuchon, 2012). It is evident that flows upstream of Elephant Butte are quite dynamic; the variability exists within wet/dry cycles and across the entire period of record.

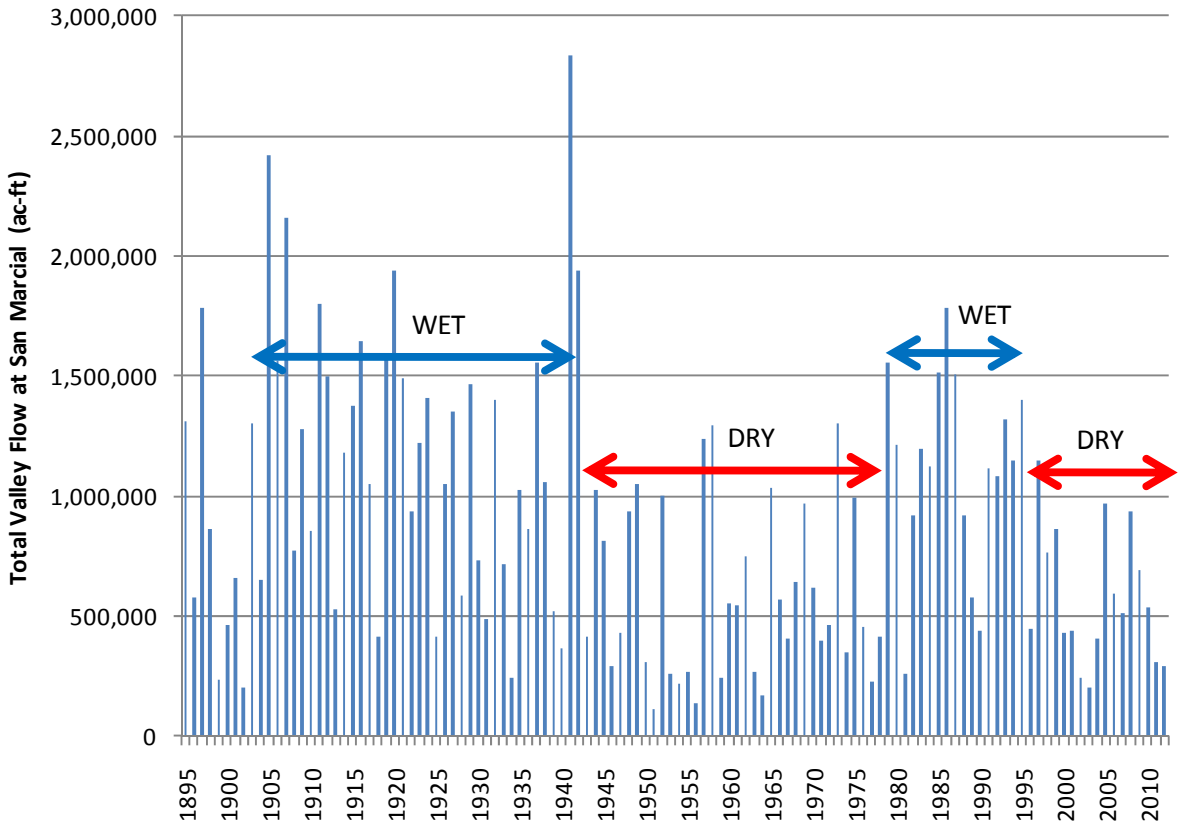


Figure 6. Annual valley flow volume at San Marcial (1895–2012)

Sediment Supply

Sediment supply is coupled with water discharge as the primary driver of channel morphology and is also half of the sediment balance equation. Sediment particles at a given stream cross section must have been eroded from within the watershed above the cross section and also transported by flow from the place of erosion to the cross section (Julien, 1998). The Rio Grande is a sediment-laden river with many sources contributing to the total load including upland erosion (overland flow), tributaries (arroyo flow), and bed/bank erosion (main channel flow). Sediment supply is difficult to quantify due to the highly spatially and temporally variable physical processes that are not easily measured. Julien (1998) has identified several variables that contribute to the character and quantity of sediment supply such as watershed topography, geology, the magnitude, intensity, and duration of rainfall and snowmelt, vegetation, grazing and land use, soil type, cohesion, surface erosion, bank cutting, and sediment supply from tributaries. Bed material from upstream river sections is also an important component of sediment supply and is related to several of the factors mentioned by Julien.

Land use practices and changes to upland vegetation have had a significant impact on sediment load. Vogt (2003) describes the most recent period of arroyo formation (1865–1915) in the southwest and the causative factors of climate, land use, and internal adjustments. Unusually large floods in the late 1800's were likely the primary driver, followed by livestock overgrazing and tributary incision. The Rio Puerco alone added nearly 400,000 acre-feet of sediment to the Rio Grande between 1885 and 1929 (Leopold et al., 1964). Sediment loads of the Middle Rio Grande may have been unusually high during the late 1800's through mid 1900's due to the wet climate, arroyo formation, and land use.

Sediment loads have been reduced on the Middle Rio Grande due to reduction of peak flows, deposition in reservoirs, and other sediment control measures (Makar and AuBuchon, 2012). Figure 7 is a double mass curve of cumulative suspended sediment load versus water discharge at San Marcial. It should be noted that suspended load is only a portion of the total load and does not include coarser particles that are transported near the bed. A steeper slope on the graph indicates that a greater volume of sediment is being carried for an equal discharge, as compared to a flatter slope that represents a smaller volume of suspended sediment for the same discharge. The figure shows a high concentration of sediment from 1955 to 1977, a slightly lower concentration from 1978 to 1982, and an even lower concentration from 1983 to 1992. Beginning in 1993, it appears that the concentration increased for a period through 2006, after which it decreased again between 2007 and 2011. Table 1 presents average suspended sediment concentration values for the discussed time periods.

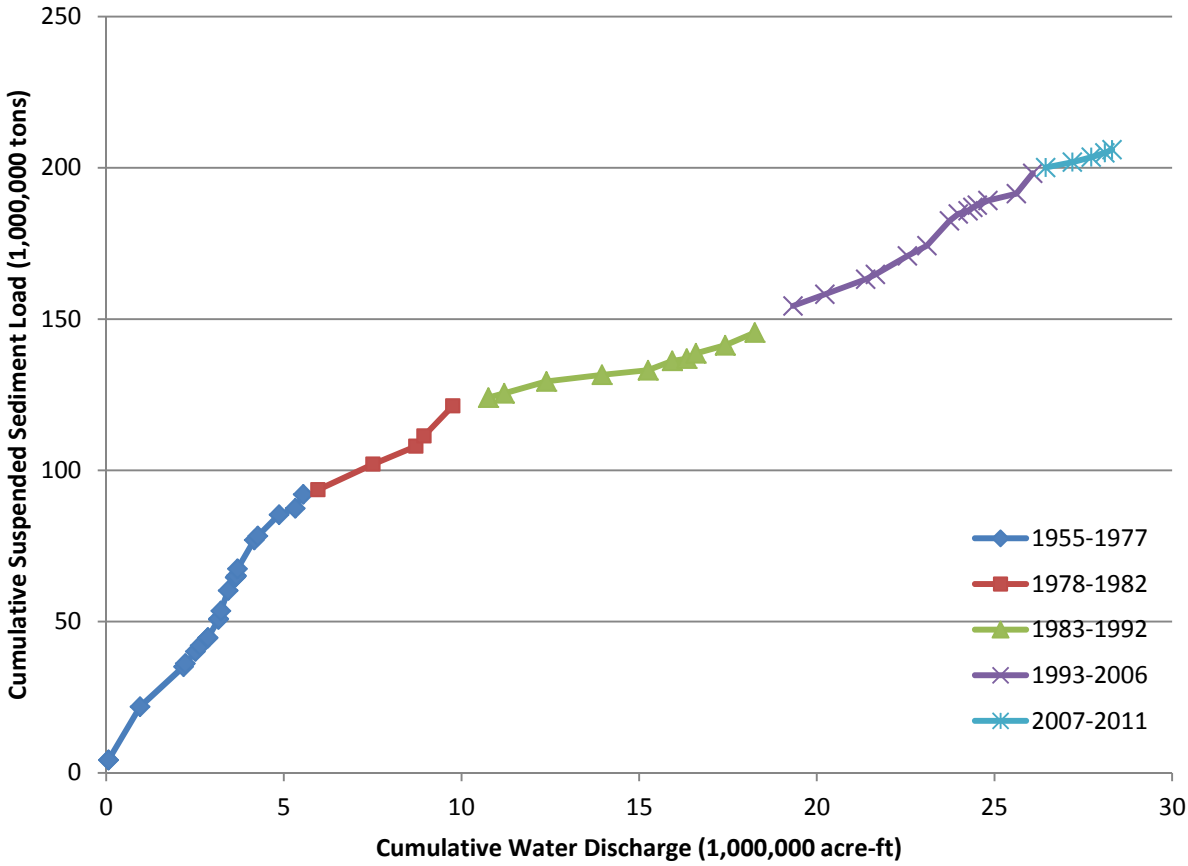


Figure 7. Cumulative suspended sediment versus discharge of the Rio Grande Floodway at San Marcial

Table 1. Average daily suspended sediment concentration of the Rio Grande Floodway at San Marcial

1957–1977	9,882 mg/L
1978–1982	6,989 mg/L
1983–1992	2,573 mg/L
1993–2006	3,989 mg/L
2007–2011	3,291 mg/L

Controls

Controls can be defined as factors that limit or influence the effect that drivers have on channel adjustment (Makar and AuBuchon, 2012). These factors are further characterized as channel and floodplain controls or base level control.

Channel and Floodplain

The channel boundary consists of the stream bed and stream banks; the material composition of these features significantly affects channel planform and cross-sectional geometry. Bed and banks that are erodible allow the river to freely shift position or pattern. The relative stability and roughness of the bed and banks often determines whether the channel will adjust laterally or vertically. When sediment transport capacity exceeds supply, a channel with an erodible bed and resistant banks will tend to incise. Over time, the bed material may coarsen and the incision may continue below the vegetative root mass, thus stabilizing the bed and destabilizing the banks. At this time, lateral erosion of the banks will occur as described in the Channel Evolution Model (Schumm et al, 1984; Watson et al., 2007). Coarser bed and bank material typically provide enhanced stability, but fine-grained cohesive sediments may also be relatively erosion resistant. The presence of clay layers has been well documented within the study area (Hilldale, 2001 and 2003; Bauer, 2004 and 2007). Cohesive silt and clay are usually most prominent on bars and floodplain surfaces, although there have been observations of clay spanning the entire riverbed. Existing clay layers may have been deposited long ago in former overbank or reservoir pool areas, but there is also a significant amount of cohesive material deposited annually by arroyo flows. Analysis has shown that the Rio Puerco and Rio Salado contribute the majority of tributary sediments supplied to the river downstream of Albuquerque. Most of this input load from the arroyos is cohesive, but there is some sand and gravel as well (Reclamation, 2012). The stability added to channel boundaries by cohesive sediment varies by location and depends on the thickness and if the deposits are intermittent or continuous.

Figure 8 shows the median bed material size over time at a number of locations upstream of the reservoir pool. It is clear that coarsening has occurred during the previous 40 years, a trend that is consistent with other reaches throughout the Middle Rio Grande (Makar and AuBuchon, 2012; Bauer, 2009). Grain size within this reach is classified as fine sand (0.125–0.25 mm) but may shift to medium sand (0.25–0.5 mm) if coarsening continues over the next several years. The increase in bed material size could have significant implications to sediment transport and the overall sediment load (Makar and AuBuchon, 2012). Lane’s balance indicates that a larger bed material size could lead to a reduction in sediment load because it would be more difficult to mobilize the coarser particles. Also, a slope increase would be required to transport the same amount of bed material with the same water discharge.

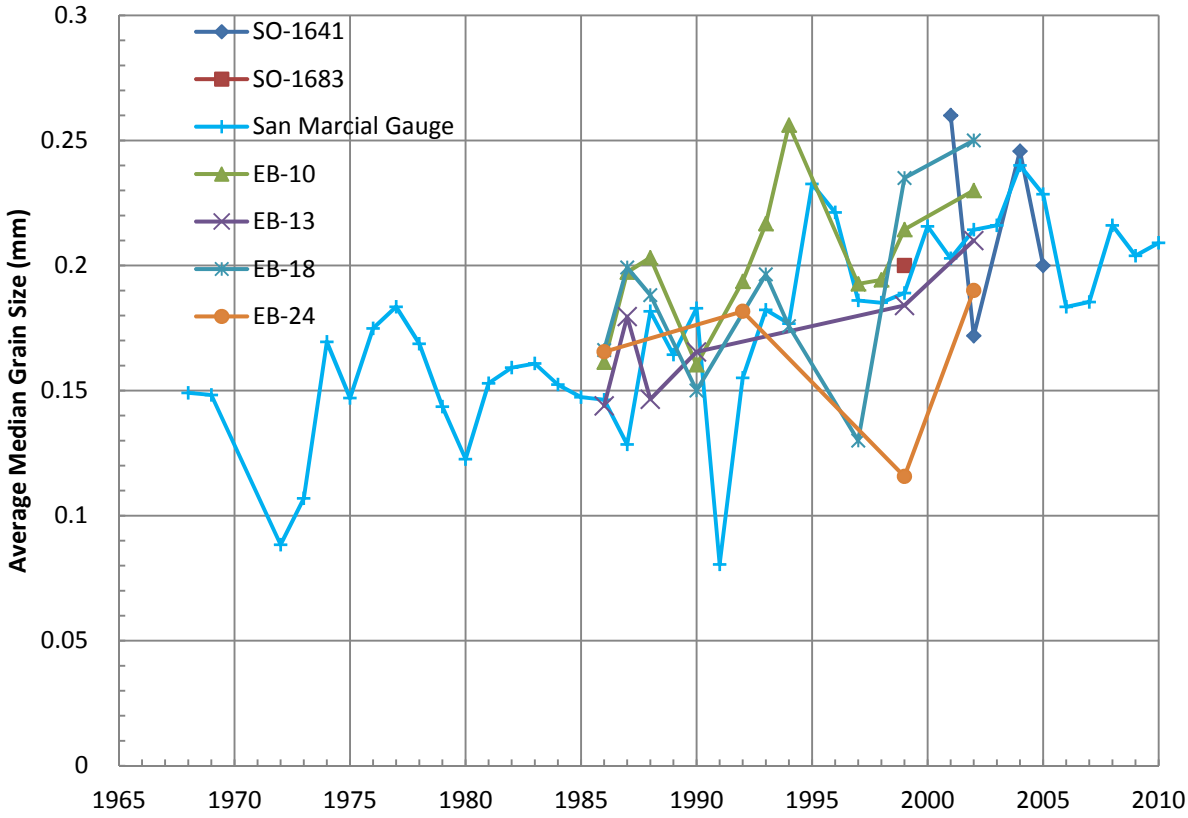


Figure 8. Bed material size over time at different locations upstream of Elephant Butte Reservoir pool (modified from Owen, 2012)

Floodplain characteristics also act as a control on channel adjustment. A well connected floodplain in which flows frequently go overbank provides a negative feedback mechanism that dissipates energy during large floods. A positive feedback loop occurs in channels with a disconnected floodplain as the energy is confined to the channel and increasing velocity and shear stress are amplified. Floodplain confinement is a control that limits the width of overbanking flow due to natural geologic outcrops or artificial levees. Lateral constraints confine sediment-carrying flood waters and may increase the depth of deposition because the available area is reduced. However, floodplain sediment deposition depends on a variety of factors such as the frequency, magnitude, and duration of overbanking events during a time period. Deposition across a river and floodplain cross section is not uniform, owing to the non-uniform vertical sediment concentration profile and local site conditions. Many cross sections within BDANWR or near San Marcial show a channel perched above the floodplain, and a floodplain perched above the valley. Overbanking flows within these areas are often separated from main channel flows, thereby reducing channel sediment transport capacity and contributing to sediment imbalance. A perched system is indicative of disequilibrium and increases the probability of channel avulsions or levee breaches. Lateral constraints may also limit the lateral migration or meandering of the river channel.

Base Level

Base level, the downstream limit of the stream network and origin of the thalweg profile, can greatly affect the stability of a fluvial system. The elevation of this downstream limit controls the longitudinal water surface profile for typical alluvial rivers. Changes in base level have the potential to initiate instability within the river system (Watson et al., 2007). Table 2 distinguishes

the primary causes of downstream progressing bed elevation change (water and sediment discharge) from that of an upstream progression (base level). The channel response to base level lowering, such as a drop in reservoir pool elevation, is often upstream-progressing degradation. Slope at the channel outlet (e.g., reservoir delta) is locally steepened thus increasing sediment transport capacity. If the increased capacity exceeds sediment supply, the abrupt break of slope (headcut or knickpoint) migrates upstream through the system. The peak rate of degradation usually occurs fairly quickly and then slows over time, while also declining at further distances upstream. Incision may trigger bank instability that generates lateral erosion and channel widening. Bank erosion provides additional sediment input to the stream and the system oscillates through a series of adjustments to the new base level until stability is restored. (Stability may never be restored if the base level continues to fluctuate and there is not a balance between sediment supply and transport capacity.) In the absence of a geologic control, the final gradient resembles the same form as the original slope, but at a lower bed elevation throughout the affected reach (Knighton, 1998; Watson et al., 2007).

Table 2. Main Causes of Streambed Elevation Change (adapted from Knighton, 1998)

Type of Bed Elevation Change	Upstream Driver: Cause of Downstream Progression	Downstream Control: Cause of Upstream Progression
Degradation	water discharge increase; sediment supply decrease	base-level fall
Aggradation	water discharge decrease; sediment supply increase	base-level rise

Conversely, a rise in base level reduces local transport capacity at the river/pool interface and initiates or increases deposition. Aggradational effects due to a rising base level do not have a tendency to continue as far upstream as headcut migration caused by reservoir lowering (Knighton, 1998; Leopold et al., 1964). This is likely the result of the concave shape of the longitudinal profile and the transition curve between the sloping river and flat reservoir pool. Lai and Capart (2008) conducted physical and numerical modeling to examine longitudinal delta profile evolutions over time for a constant base level and a steadily rising base level. For both cases, the greatest amount of aggradation occurred at the intersection of the pool water surface and the riverbed, while the rate of aggradation decreased further upstream. The rising base level models showed that the zone of greatest aggradation moved upstream in response to the advancing reservoir pool shoreline. At a constant location significantly upstream of the reservoir pool, there was more aggradation during the rising base level experiment than the steady base level experiment.

Reservoir Analysis

Construction of Elephant Butte Dam began in 1908 and was completed in 1916, with water storage operations beginning in 1915. The dam's spillway is an uncontrolled ogee crest weir structure and has a crest elevation of 4407 feet in the original project datum, which is 4452.5 feet in the NAVD88 datum (Ferrari, 2008). Figure 9 shows a time series plot of the annual minimum, average, and maximum pool water surface elevation. The water surface elevation of Elephant Butte Reservoir is related to the climatic wet and dry periods presented earlier in Figure 6. Operation of the LFCC also provided water salvage and increased delivery to the reservoir from about 1959 to 1975 (Reclamation, 1981). The reservoir filled fairly rapidly between 1915 and 1920, then declined slightly until large floods in 1941 and 1942 completely filled the reservoir. The average annual pool elevation dropped 114 feet between 1942 and 1951, while the minimum pool elevation dropped 132 feet. The reservoir pool stayed fairly low through the end of the dry

period in 1978 and then increased to full pool elevation in 1986 due to large flows in the early 1980's. The average annual pool elevation increased 101 feet between 1978 and 1986, while the minimum pool elevation increased by 113 feet. The reservoir was essentially full between 1985 and 1995, before declining slightly through 1998. Between 1998 and 2004, the average pool elevation dropped 90 feet and the minimum elevation declined by 98 feet. A moderate increase of 35–40 feet occurred between 2004 and 2009 prior to a similar decrease of 30–40 feet through 2012. The minimum 2012 elevation was only 3.2 feet higher than the minimum 2004 elevation (both in September).

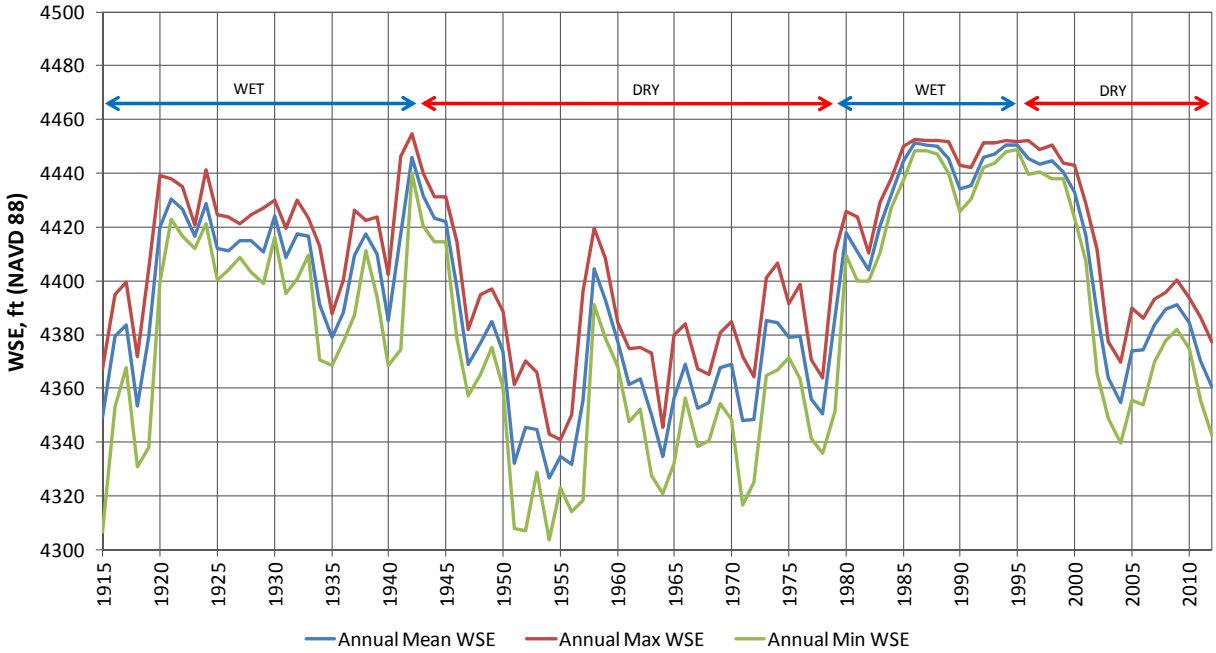


Figure 9. Elephant Butte Reservoir pool elevation time series (1915–2012) (modified from Owen, 2012)

It is instructive to consider the geographic locations of the reservoir pool shoreline that correspond to the varying elevations presented in the above figure. Figure 10 overlays six different pool elevations on longitudinal reservoir profiles from 1915, 1988, 1999, and 2007. Sonic depth sounding equipment was used to conduct the underwater portion of the surveys, which was combined with topographic data upstream of the reservoir pool. Upstream of about EB-23, the channel is perched in some areas, so the main channel thalweg may be higher than the reservoir profile that is shown in the figure. When the reservoir was full during the 1988 survey, the pool intersected the Rio Grande thalweg about 34 miles upstream of the dam (~RM 61) and the valley thalweg about 37 miles upstream of the dam. The average 1999 pool elevation reached about 30 miles upstream of the dam (~RM 57) and the average 2007 pool elevation was about 15 miles upstream of the dam (~RM 42). The reservoir was nearly full in February 1998 at a pool elevation of 4450 feet that matched the Rio Grande thalweg elevation at RM 59.4. Less than seven years later in September 2004, the reservoir had receded 24 miles to an elevation of 4340 feet at RM 35.3. (River Mile locations referenced in this report use the 2002 designations based on the channel centerline in 2002. River Mile delineations are not an exact measurement of channel distance and are adjusted approximately every ten years. RM 0.0 begins at Caballo Dam, with mile numbers increasing while moving upstream. 2012 RM locations are now available, and both 2002 and 2012 RM designations are presented along with Rangeline locations in Appendix B. Rangeline locations are fixed and carry the prefix SO- for Socorro and EB- for Elephant Butte. Also, Rangeline numbers increase while moving downstream.)

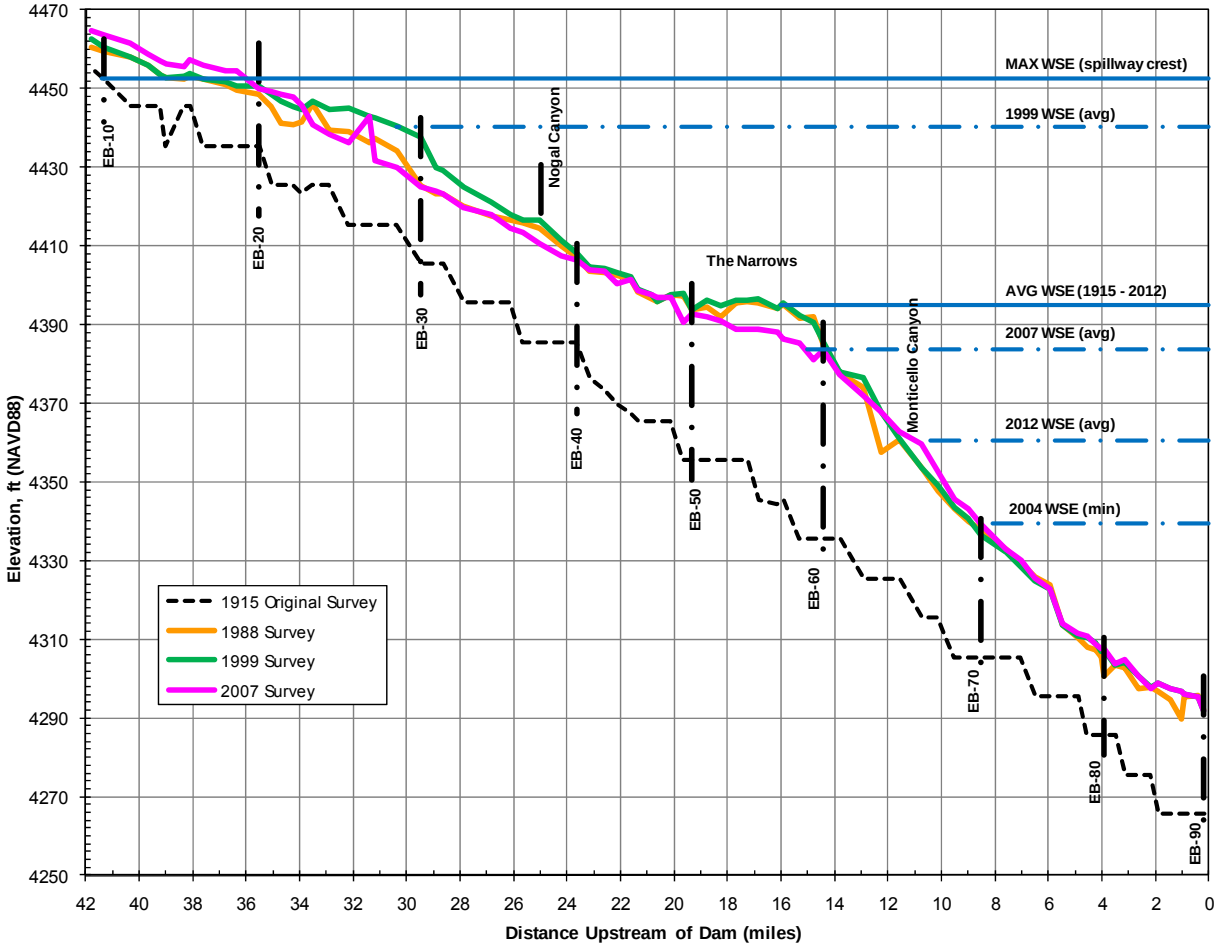


Figure 10. Elephant Butte Reservoir longitudinal profiles and pool elevations (modified from Ferrari, 2008)

The slope of the reservoir longitudinal profiles can also be analyzed within the context of the pool water surface elevations. It is evident that the original 1915 slope was fairly uniform from the dam upstream to EB-10. The more recent profiles show a break in slope (pivot point or knickpoint) at the Narrows where the greatest amount of historical aggradation has occurred. This is also the historical average pool elevation, corroborating the model results of Lai and Capart (2008). (Degradation at the Narrows and locations further upstream can be observed in the profiles between 1999 and 2007, corresponding to a decline in reservoir pool elevation.) Strand and Pemberton (1982) describe the development of a topset slope and foreset slope during the delta formation process as shown below in Figure 11. They found that, on average, the topset slope is half of the original channel slope and the foreset slope is 6.5 times steeper than the topset slope. The grade break between the two slopes is known as the pivot point, which becomes a knickpoint or headcut within the river channel after the pool water surface lowers. Strand and Pemberton suggest that if the reservoir water surface fluctuates often, the pivot point will be established at the mean operating level. Otherwise, the pivot point elevation will be at the top of the conservation pool if the reservoir is usually full. A pivot point does not develop when a reservoir is emptied every year.

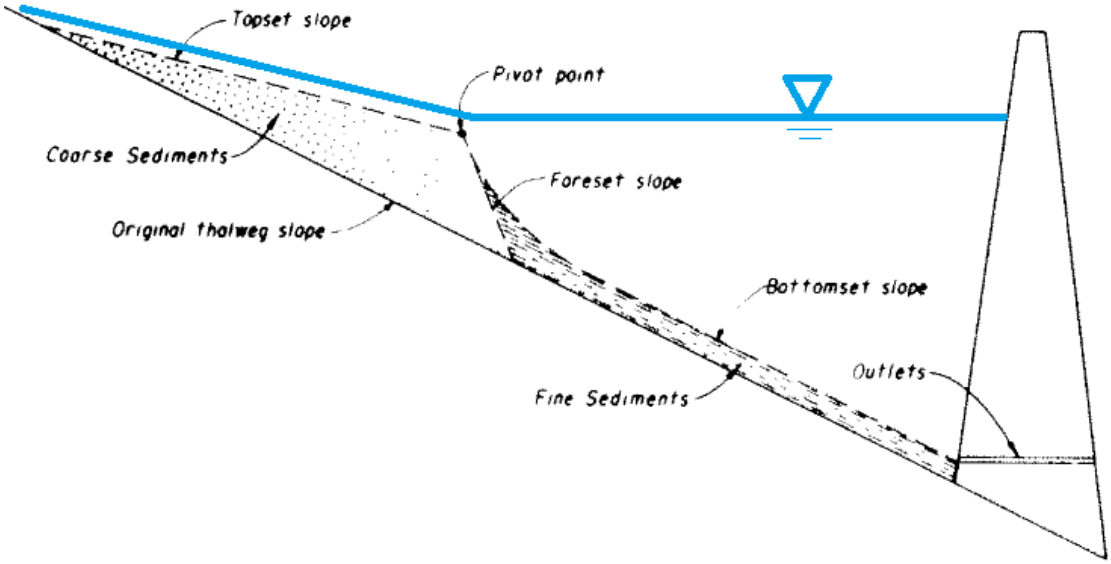


Figure 11. Typical reservoir delta sediment deposition profile (modified from Strand and Pemberton, 1982)

A closer examination of the 1999 longitudinal profile reveals a second pivot point at EB-30. The reservoir pool had been mostly full and operating at an elevation between 4450 feet and 4440 feet from 1985 to 1999 so the development of a pivot point (knickpoint) at an elevation of approximately 4438 feet is not surprising. The 1999 topset slope above EB-30 is about 70% of the 1915 bed slope, and the 1999 foreset slope is about 3 times steeper than the topset slope. As the reservoir pool continued to drop between 1999 and 2004, the previously submerged foreset slope was exposed and became the new river thalweg. This resulted in an oversteepened local slope between EB-30 and EB-33 and a relatively steep slope between EB-30 and EB-47 upstream of the Narrows.

Slope Analysis

River slope is one of the best indicators of the river's ability to do morphological work (Watson et al., 2007) and, as discussed earlier, slope directly affects the transport capacity and sediment balance of a river system. Fundamentally, sediment transport capacity is a function of the shape of the river cross section and the hydraulic properties of the flow (Julien, 1998). There are a multitude of transport capacity formulas in the literature, and they are primarily empirical. A vast majority of the formulas are strongly dependent on, and directly proportional to, hydraulic radius and slope. An increase or decrease in the river slope over time provides insight regarding the river's response to changes in upstream drivers (water and sediment discharge) and downstream control (base level). It should be noted that the thalweg, water surface, and energy slopes are not necessarily equal, but the thalweg slope provides a reasonable basis for calculating stream power (Watson et al., 2007). Figure 12 presents thalweg profiles of the Rio Grande from the Highway 380 Bridge to the Narrows between 1999 and 2012. (Larger profiles on 11x17 plots are provided in Appendix A, and bed elevation adjustments will be discussed further in the next section.) Changes in slope are a measure of the relative bed adjustment between the upper and lower sections of a reach; if all cross sections aggraded or degraded equally the slope would not change. A steeper slope that provides increased transport capacity would result from aggradation at the upper portion of a reach and/or degradation at the lower end. A flatter slope that provides reduced transport capacity could by created by degradation at the upstream section of a reach and/or aggradation downstream.

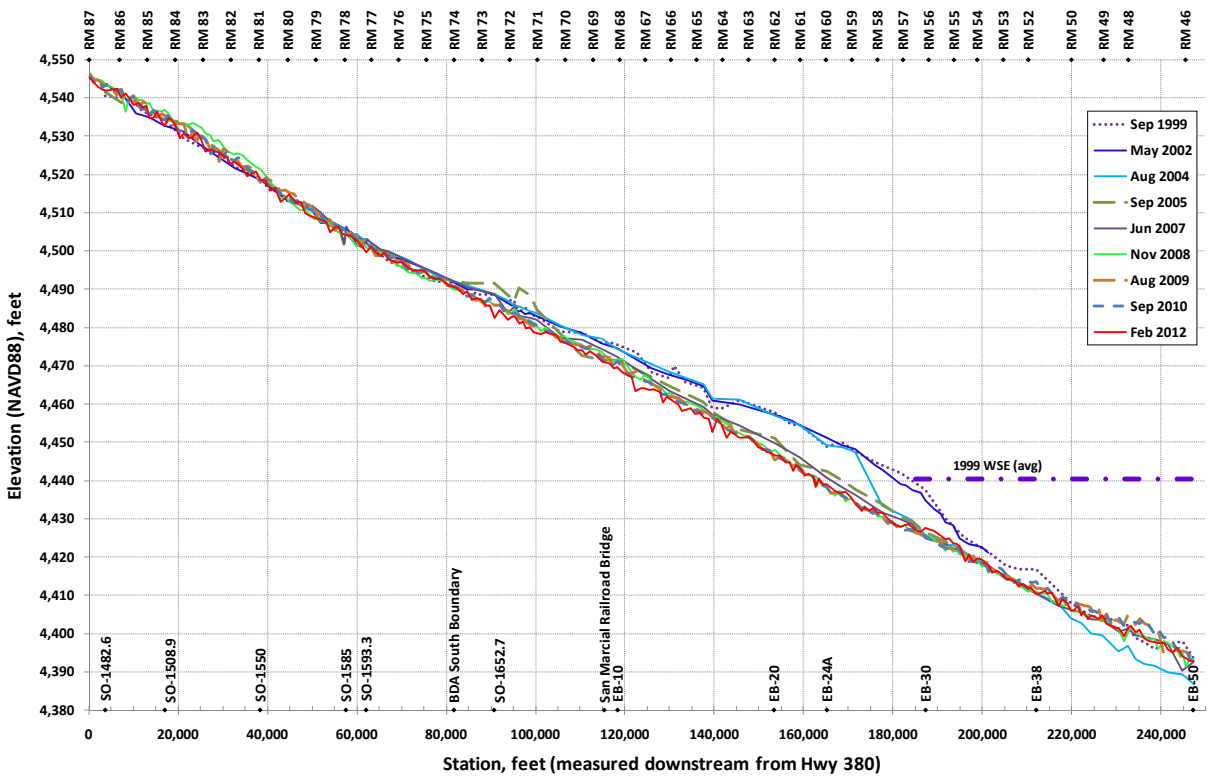


Figure 12. Thalweg profile from Highway 380 Bridge to the Narrows

Figure 13 and Figure 14 show the relationship between channel slope and reservoir pool elevation, and channel slope over time for different Rio Grande subreaches upstream of the reservoir pool, respectively. The upper subreach contains 8.87 miles, measured along the thalweg, from near RM 68 to near RM 60 (EB-10 to EB-24A) and the lower subreach contains 8.87 thalweg miles, from near RM 60 to near RM 52 (EB-24A to EB-38). Results for the entire 17.74-mile reach are also shown for comparison. Subreach and reach lengths, in addition to longitudinal profile stationing, were measured along the 2010 thalweg. The lower subreach was partially inundated by the reservoir pool in 1999 and includes the transition into the upper Temporary Channel work area that began in 2000. The lower subreach also includes the 1999 pivot point at EB-30 and is assumed to be the critical sediment transport capacity subreach in which capacity must exceed supply for a headcut to migrate upstream of RM 60. Downstream of the lower subreach, the section between EB-38 and EB-50 was not included because data was not always available, and it should also be noted that this area is flatter as the Rio Grande enters the Narrows. The graphics illustrate the highly variable slope over time as the river attempts to adjust to changes in downstream base level or upstream drivers. The lower subreach is particularly sensitive to the reservoir pool and the river slope trend closely follows the pool elevation. Although the response is not as dramatic, the overall reach slope adjustment is also in sequence with the reservoir pool elevation, steepening when the pool elevation drops and flattening when the pool elevation rises. For the upper subreach, the change in slope is out of phase with changes to the pool elevation. This indicates a delayed response in which the upper subreach adjusts to changes in the lower subreach. Table 3 provides a more detailed explanation of the specific slope changes for each period of time. Note that lines connecting discrete slope

values in the graphics illustrate trends over time (direction of slope change), and actual channel slope values are labeled on the reversed y-axes (steeper slopes are near bottom of graphs).

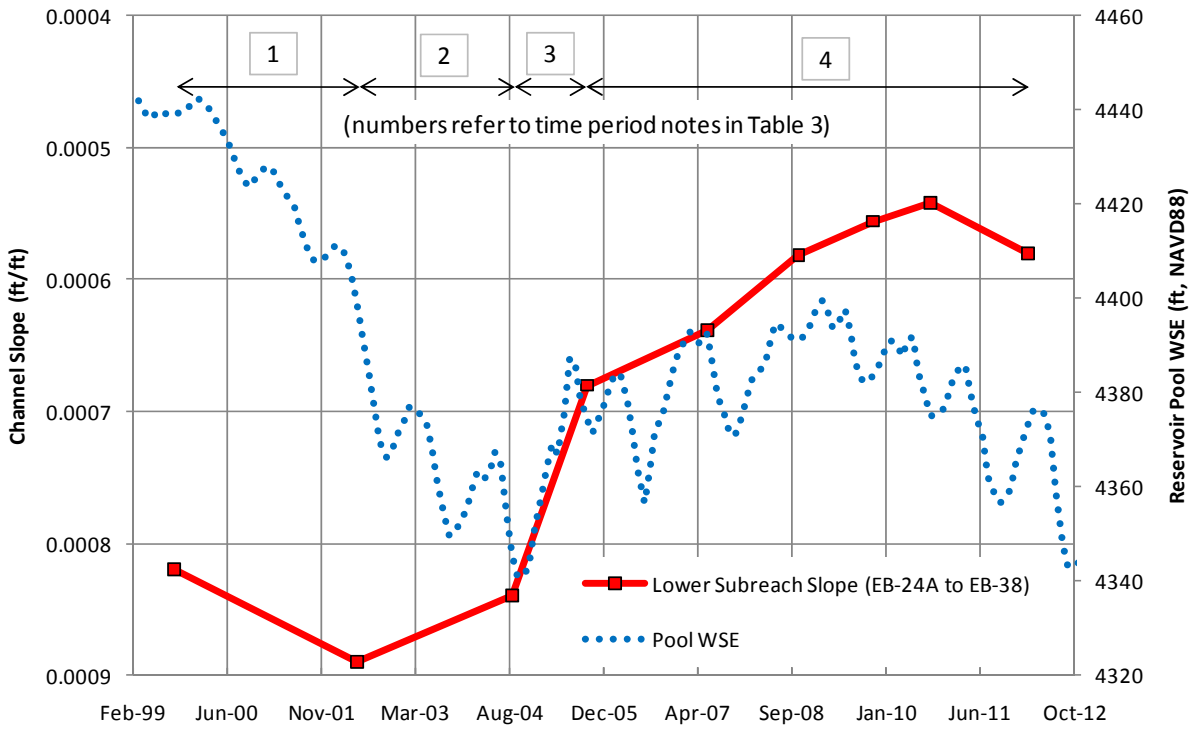


Figure 13. Changes to Rio Grande lower subreach channel slope and Elephant Butte reservoir pool elevation over time (1999–2012)

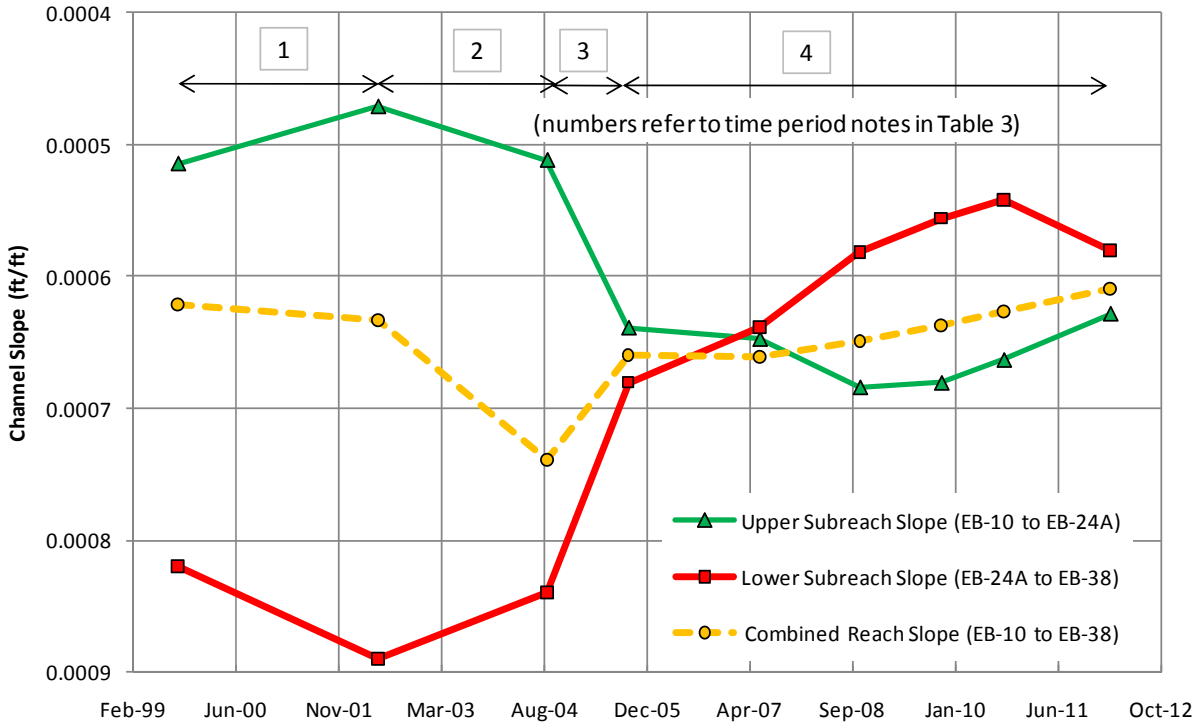


Figure 14. Changes to Rio Grande channel slope over time (1999–2012)

Table 3. Detailed explanation of Rio Grande slope changes (see Figure 13 and Figure 14)

Note	Time Period	Lower Subreach (8.9 mi) (EB-24A to EB-38)	Upper Subreach (8.9 mi) (EB-10 to EB-24A)	Combined Reach (17.7 mi) (EB-10 to EB-38)
1	Sep 1999 to May 2002	-Initially steep slope (S=0.00082) due to transition from topset to foreset (pivot point or knickpoint at EB-30). -Slope steepens (to S=0.00089) as pool elevation drops (slight aggradation upstream at RM 60, slight degradation downstream RM 54–58).	-Initially flat slope (S=0.00051) due to deposition upstream of full reservoir pool. -Slope flattens (to S=0.00047) due to slight aggradation downstream at RM 60 and slight degradation upstream at RM 68.	-Initially flat slope (S=0.00062) due to 2/3 of reach being just above reservoir pool (1/3 underwater) -Slope change almost negligible (slightly steeper to S=0.00063). Overall more areas of aggradation upstream and degradation downstream in response to falling reservoir pool.
2	May 2002 to Aug 2004	-Slope flattens as knickpoint moves about 2.8 miles upstream. -Severe degradation near upstream end of subreach, moderate degradation within downstream section of subreach.	-Slope steepens. Some areas of slight aggradation upstream (RM 65–67) with some degradation downstream near RM 60.	-Significant slope increase due to degradation and headcutting within lower section as reservoir continued to drop.
3	Aug 2004 to Sep 2005	-Slope flattens drastically as headcut moves upstream of this subreach. -Downstream portion of subreach stabilizes as reservoir begins to rise, severe degradation upstream.	-Slope steepens severely as headcut moves through this subreach. -Degradation throughout subreach, but disproportionate amount within lower area of subreach.	-Slope flattens as downstream section of reach is stable and large degradation occurs upstream.
4	Sep 2005 to Feb 2012	-Slope continuously flattens 2005–2010, then steepens 2010–2012. -Flatter slope from 2005–2008 primarily due to some degradation within upper half of subreach. -Flatter slope from 2008–2010 primarily due to some aggradation within lower half of subreach. -Steeper slope from 2010–2012 due to some aggradation within upper half of subreach and some degradation within lower half of subreach.	-Slope steepens slightly 2005–2008, then flattens 2008–2012. -Steeper slope 2005–2007 due to aggradation within upper half of subreach. Steeper slope 2007–2008 due to degradation within lower half of subreach. -Flatter slope from 2008–2012 generally due to some degradation within upper half of subreach and a stable lower half of subreach.	-Slope flattens continuously, generally due to some degradation within upper half of reach and some aggradation within lower areas of reach.

Using a constant reservoir water surface elevation at the average 2008 level, mobile bed modeling results predict that the stable slope between RM 78 and RM 46 is flatter than the existing slope. This means that a combination of aggradation in the lower portion of the modeled reach (~RM 62–46) and degradation in the upper portion of the modeled reach (~RM 62–78) is expected (Reclamation, 2012). Of course, these results are only appropriate for the representative hydrology, sediment, and base level conditions used in the modeling effort. As part of a sensitivity analysis, Reclamation (2012) also found that for some discharge scenarios this reach did not achieve equilibrium even after 120 years of simulation. The model results show that the Rio Grande upstream of Elephant Butte Reservoir is inherently unstable and terms such as equilibrium or stable slope do not apply for timescales less than about 100 years.

Bed Elevation Analysis

Aggradation or degradation within the river channel can change the flow capacity, floodplain connectivity, and potentially the groundwater elevation. If the channel banks aggrade or degrade by the same height as the riverbed, then the main channel flow capacity and floodplain connectivity will remain relatively unchanged. Figure 15 shows the average bed elevation at San Marcial compared to the water surface elevation of Elephant Butte Reservoir from 1895 to 2012. San Marcial is about 42 miles upstream of Elephant Butte Dam (see Figure 10), 31 miles upstream of the average 2012 pool elevation, and 5 miles upstream of the full pool elevation. The largest rates of aggradation (1920–1948 and 1978–1995) have occurred during periods of increasing or full reservoir pool elevations. Periods of riverbed degradation (1949–1972 and 2005–2011) correspond to low or decreasing reservoir pool elevations. The periods of degradation began during large spring runoff events of 1949 and 2005, both about 7–10 years after the reservoir pool started to lower. Bed elevation stabilized briefly from 1950 to 1956, before large flows in 1957 and 1958 initiated a more constant degradational trend through about 1972. A sediment plug formed during the 2005 spring runoff slightly upstream of San Marcial that blocked most of the upstream sediment supply. All three of the primary degradation causes (Table 2) were present during the 2005 spring runoff: water supply increase, sediment supply decrease, and a lowered base level. The 1949–1972 degradation rate was only about one half to one third that of the recent rate, most likely due to the substantially higher sediment load (Figure 7 and Table 1). Temporary degradation during 1937 (Happ, 1948), 1991, and 1995 was caused by avulsions or sediment plugs that reduced upstream sediment supply. Although degradation has occurred during the identified periods, the overall dominant historic trend is aggradational. The average riverbed elevation at San Marcial has increased by about 21 feet since 1895 and by about 18 feet since Elephant Butte water storage began in 1915.

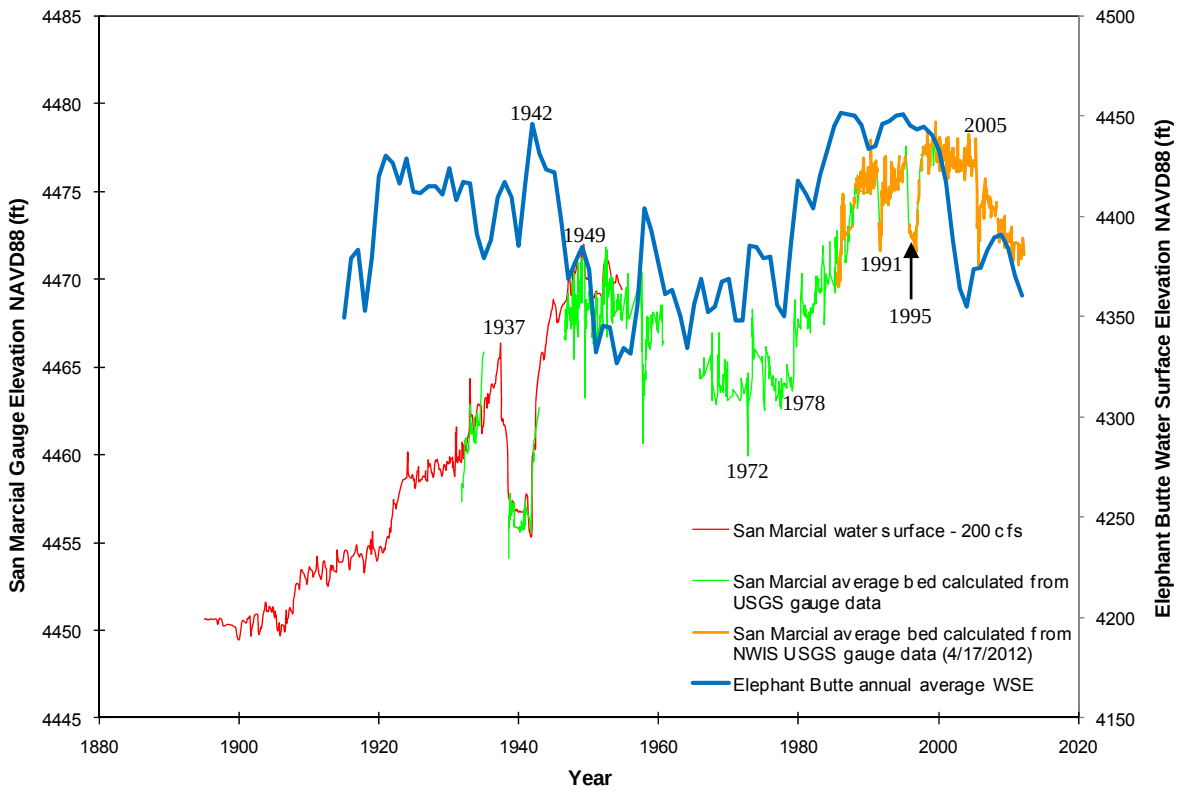


Figure 15. Elevation changes of the USGS San Marcial gauge and Elephant Butte Reservoir pool over time (modified from Makar 2013, pers. comm.)

The San Marcial bed elevation historical analysis can be expanded to include multiple locations between RM 78 (SO-1585) and RM 46 (EB-50). Figure 16 presents a time-series plot of selected rangeline thalweg elevations and shows the relationship to the reservoir pool. The orange lines (EB-29 to EB-50) are within the Temporary Channel, the green lines (SO-1701.3 to EB-24A) are just upstream of the full reservoir pool, and the purple lines (SO-1585 to SO-1652.7) are near the southern portion of BDANWR. It is clear that rangelines closer to the reservoir become increasingly sensitive to fluctuations in pool elevation and the effect is damped as the changes propogate upstream. The orange rangeline thalweg elevations degraded between 1999 and 2004 as the reservoir pool dropped, and aggraded or stabilized between 2004 and 2010 as the pool elevation increased. Elevations of the green rangelines were stable or slightly aggrading between 1999 and 2004 before degrading rapidly between 2004 and 2005 as the headcut moved upstream. Some degradation at these locations has continued from 2005 to 2012 as the river continues to adjust to the lowered reservoir pool. The purple lines have been relatively stable since 1990, and the 2005 sediment plug can be seen at SO-1665. After river connectivity was restored, sediment was eroded from the plug and deposited downstream as represented by the 2005–2007 aggradation at SO-1701.3. Attenuation of the upstream migrating headcut is depicted by degradation at SO-1665 from 2005 to 2007, and a minor or negligible amount of degradation at SO-1626 and SO-1585 from 2007 to 2008. The area between RM 78 and RM 74, represented by SO-1585 and SO-1626, has been the most stable section between Highway 380 and the reservoir pool.

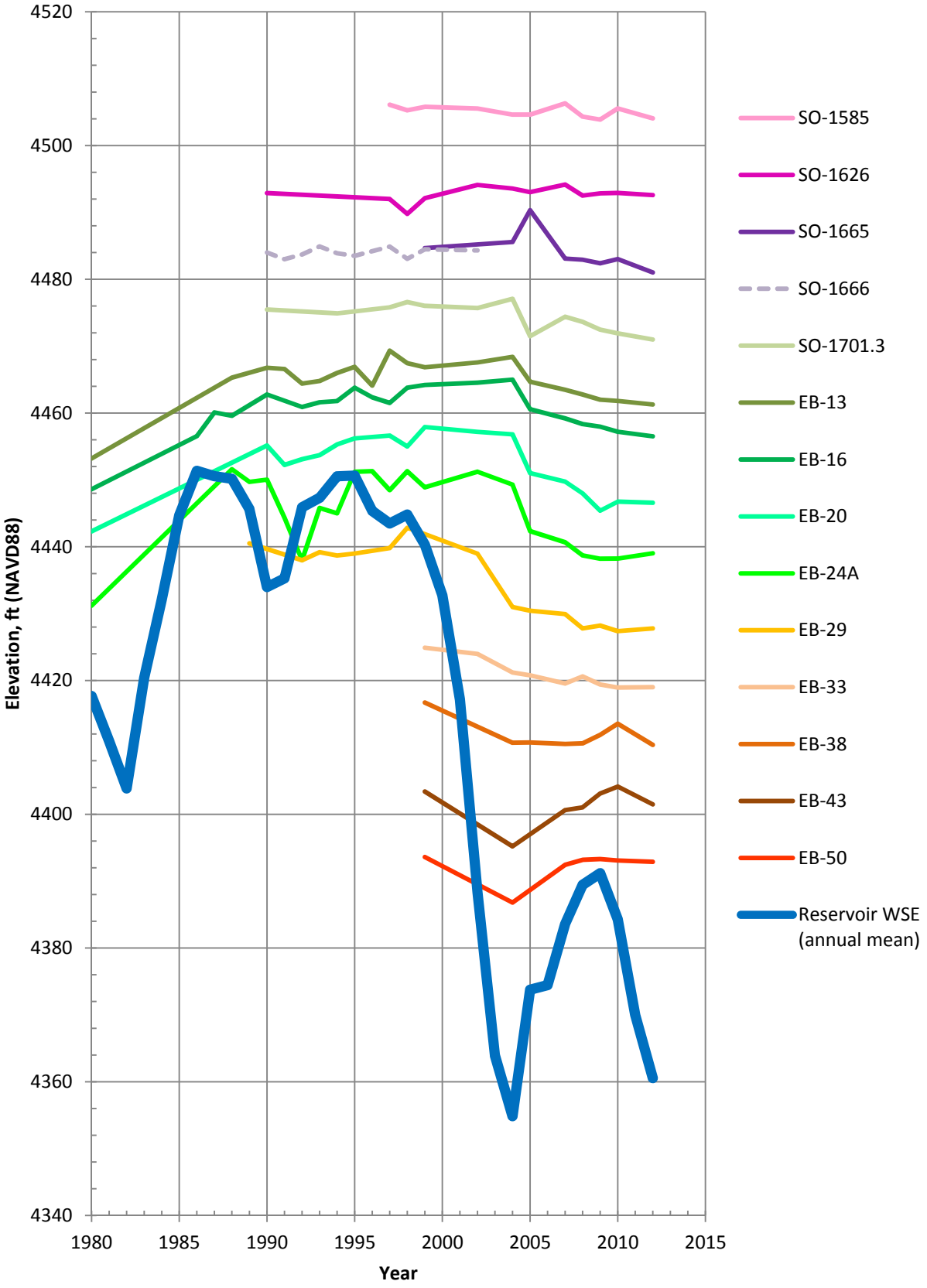


Figure 16. Change in thalweg and reservoir pool elevation over time (after Owen, 2012)

The response of riverbed elevation to reservoir pool elevation is best illustrated by rangeline EB-24A near RM 60. Thalweg elevation increased by 20 feet between 1980 and 1988 as the pool elevation increased by 32 feet during the same time period. Next, thalweg elevation decreased 12 feet between 1990 and 1992 before increasing 13 feet between 1992 and 1995. The reservoir pool elevation decreased 16 feet between 1988 and 1990 before increasing 17 feet between 1990 and 1994. The shape of changes to thalweg elevation mirrors the shape of changes to pool elevation with a lag time of about 1–2 years. After 1999, when the pool elevation is substantially downstream of EB-24A, an attenuated relationship exists with increased lag time and a damped response. Between 2002 and 2008, the thalweg elevation at EB-24A lowered by approximately the same amount as between 1990 and 1992 (~12 feet). However, the reservoir pool had lowered by about 90 feet between 1998 and 2004, compared to only 16 feet from 1988 to 1990.

Owen (2012) identified "waves" of degradation and aggradation that resulted from changes to reservoir level as seen in Figure 17. A degradation wave began at EB-30 (~RM 56) in 1999, and the headcut was most noticeable at EB-26 (~RM 59) in 2004. The rate of upstream headcut migration accelerated during the 2005 spring runoff while moving to near SO-1692 (~RM 69.4) by September 2005. Finally, the degradation wave propagated upstream to near the BDANWR south boundary (~SO-1641, ~RM 74) by 2008, where it tapered out in 2009. This degradation was in response to a pool elevation decrease of about 14 feet/year and a recession of about 3 miles/year from 1997 to 2004. A wave of aggradation resulted from an increase in base level (pool water surface) elevation of about 7 feet/year and a progression of 1.4 miles/year from 2004 to 2009. The induced aggradational wave began at the reservoir pool in 2004 (~EB-66, ~RM 37) and moved upstream to near EB-37.5 (~RM 52) by 2010. The graphic illustrates two separate degradation/aggradation waves during the same time period because the upstream portion of the degradation wave was a delayed response to the previously lowered reservoir level.

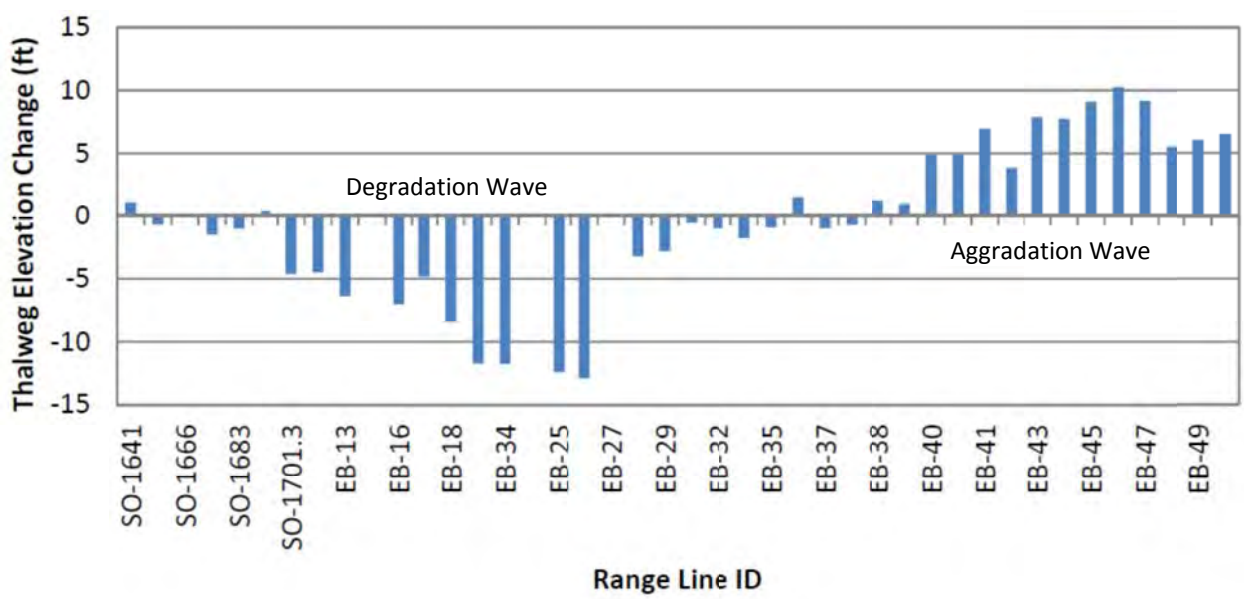


Figure 17. Change in thalweg elevation from 2004 to 2009 (from Owen, 2012)

Summary of Channel Conditions and Dynamics

The Rio Grande fluvial system upstream of Elephant Butte Reservoir is highly dynamic and behaves with a great deal of complexity. The primary drivers of water discharge (Figure 6) and sediment load (Figure 7), coupled with the primary control of base level elevation (Figure 9 and Figure 10), exhibit a large degree of variability. An imbalance between sediment supply and sediment transport capacity is the prevailing condition that necessitates continuous channel adjustments over space and time (Figure 4 and Figure 5). Typically, sediment supply exceeds sediment transport capacity due to high sediment loads and a relatively flat river slope upstream of the reservoir pool. This type of sediment imbalance causes deposition within the river channel. Occasionally, sediment transport capacity exceeds sediment supply due to a steeper slope from a lowered reservoir pool, a reduction in sediment load, or both. This form of sediment imbalance causes erosion of the river channel bed and banks. Sediment imbalance has occurred during periods with a relatively stable reservoir pool (i.e., 1905–1915, 1920–1932, 1985–1998), but is often exacerbated by frequent changes to water discharge, sediment load, and base level elevation.

Equilibrium or stability over a period of several years is not a reasonable outcome for this reach, owing to the variable nature of the drivers and controls. As the pool elevation of Elephant Butte Reservoir rises or falls, the slope of the Rio Grande is forced to respond (Figure 13). The river's response to fluctuations in base level and delta formation has controlled the channel elevation upstream of the reservoir (Figure 15 and Figure 16). The rate and magnitude of bed elevation changes is highly dependent on proximity to the reservoir pool and upstream water and sediment discharge (Levish, 2012). Channel bed adjustment is a function of sediment imbalance, which generally depends on the relative magnitude of upstream sediment supply and effects from the downstream reservoir (Park et al., 2012).

Significant aggradation is the most defining historical characteristic of the Rio Grande upstream of Elephant Butte Reservoir (Makar and AuBuchon, 2012). This aggradation is primarily caused by low valley and channel slopes combined with a relatively high sediment load (Levish, 2012). During wet periods with a full reservoir, the reach experiences high levels of aggradation. Aggradation appears to slow in upstream reaches as the reservoir pool elevation drops, and degradation is initiated when a high flow event occurs when the reservoir is low. Degradation is likely to continue for a period of time as the river adjusts to the initial reservoir recession, and the bed may eventually stabilize if the reservoir pool remains at a constant low elevation for several years. The dominant aggradational trend will resume when the reservoir begins to rise. Adaptive management is likely the most appropriate strategy for this reach, given that the design life of any maintenance approach will be greatly reduced due to fluctuations in the upstream water discharge and sediment load and the downstream base level control (reservoir pool elevation) (Reclamation, 2012).

Geomorphic Effects of Channel Maintenance

In 1998, the Rio Grande became disconnected from the reservoir pool as the water surface drastically receded. High evapotranspiration water loss within the delta negatively impacted New Mexico's Rio Grande Compact deliveries. A channel, termed the Temporary Channel as it will

be inundated by future increases in reservoir level, was constructed to maintain the connection from the river to the reservoir pool by providing effective transport of water and sediment. Construction began on the upper Temporary Channel reach (RM 57.8 to RM 51.2) in 2000 and continued through 2004. The middle reach (RM 51.2 to RM 40.7) was built between 2003 and 2004, while construction was initiated for the lower reach (RM 40.7 to the reservoir pool) in 2005. The channel was initially excavated at a depth of about 3 feet to follow the declining reservoir pool and subsequent adaptive maintenance activities have occurred every year to maintain the general form and function of the existing channel.

Effects of channel maintenance are best analyzed within a geomorphic framework that considers impacts from maintenance actions relative to the principles of sediment balance, upstream drivers, and downstream controls. Channel adjustment and geomorphic effects can be discussed in two phases: initial construction (2000–2004) and recurring maintenance (2005–2012).

Initial Channel Construction

It is difficult to separate the effects of initial channel construction from the rapid base level lowering since they occurred contemporaneously. The preceding discussion of fundamental geomorphic concepts, including historical and recent Middle Rio Grande data analysis, demonstrates the range of effects that result from changes to the drivers (water and sediment discharge) and controls (primarily reservoir pool elevation). Within the Temporary Channel area, the effect from construction activities was essentially the creation of a river channel through the reservoir delta. Prior to channel construction, water within the delta area was consumed by evapotranspiration, or flowed as shallow overland flow. After construction, the river channel conveyed the majority of water and sediment directly to the reservoir pool. The water table adjacent to the Temporary Channel may have been lowered by 1–3 feet during initial construction, although overbanking still occurred and other sources (such as springs and a naturally high water table) provided water to the riparian delta. For river sections upstream of the Temporary Channel, initial construction can be considered as a type of downstream boundary condition effect. Therefore, a comparison between the relative magnitude of channel excavation and reservoir pool lowering provides insight regarding the individual effects.

An important concern for the period of initial construction and base level lowering is the wave of degradation that propagated upstream. As discussed, there was a knickpoint (pivot point) in the channel thalweg profile present in 1999 near RM 56 before any channel excavation began. This headcut moved about 3 miles upstream between 1999 and 2004 and about 10 miles upstream during the 2005 snowmelt runoff. The average annual pool elevation lowered about 85 feet between 1999 and 2004, and this strong control on upstream channel elevation was described in the Base Level section. Temporary Channel excavation of about 3 feet, compared to the 85 feet of reservoir lowering, would have a negligible effect on the downstream base level elevation. Any degradation potentially caused by the Temporary Channel would more likely be the result of a locally increased slope that increased the sediment transport capacity, thus allowing a headcut to migrate upstream.

For a reach of the same length and slope as the lower subreach (EB-24A to EB-38) in 1999, mathematically lowering the downstream half of the subreach by 3 feet would increase the slope by 10%. This is in agreement with the actual change between 1999 and 2002 of an 8% increase. Between 2002 and 2004, the slope flattened by 6% for an overall increase of 2% from 1999 to

2004. It is reasonable to assume that the thalweg profile changes from RM 58 to RM 54 between 1999 and 2002 show the effect from the initial channel excavation. The 1999 and 2002 profiles converge at RM 54 and data is not available downstream of RM 54 for 2002. A comparison between 1999 and 2004 from RM 54 to RM 46 shows a slope increase of about 15%. It is reasonable to assume that some, but not all, of this 15% slope increase is the result of Temporary Channel construction. Therefore, it is probable that initial Temporary Channel construction was responsible for steepening the local slope (~RM 58 to RM 46) by about 8–12%.

Another possible effect of the Temporary Channel on slope is if the constructed channel alignment significantly shortened the channel length. Table 4 shows that all river adjustments (not just Temporary Channel construction) between 1972 and 2006 resulted in a channel shortening of about 550 feet, which would only steepen the slope by about 1%. This is relatively minor compared to the approximately 13,000 feet that the channel has shortened since 1918 due to a variety of factors (Levish, 2012). The cause of channel shortening between 1918 and 1935 is unknown; Reclamation's river maintenance activities did not start until the early 1950's. The 1918 channel centerline meanders across the entire valley between the mesas, while the 1935 alignment is fairly straight against the west mesa (RM 58 to RM 52) or east mesa (RM 50 to RM 47). One possible cause for this channel straightening is the large floods that occurred in the 1920's, such as the 47,000 cfs peak flow in 1929. Levish (2012) concludes that excavation of the Temporary Channel may have initiated and temporarily increased the rate of channel lowering, but ***this elevation change would have eventually occurred in response to the lower reservoir pool elevation***.

Table 4. Total channel length for the Rio Grande between RM 58 and RM 47 (2002 River Miles)

Year	Channel Length (ft)	Channel Length (mi)	Difference in Channel Length Compared to 2010 (ft)
1918	75,613	14.32	+13,400
1935	61,530	11.65	–683
1949	65,167	12.34	+2,955
1962	66,076	12.51	+3,863
1972	62,778	11.89	+565
2006	62,225	11.78	+12
2010	62,213	11.78	0

Groundwater Analysis

The effect of riverbed elevation adjustments on groundwater elevation is an important environmental concern along the Middle Rio Grande. Floodplain vegetation is dependent on the water table for a large portion of its water supply. An increase in groundwater elevation may saturate the soil root zone, while a decrease in groundwater elevation could result in drying of the soil root zone. Saturation or drying of the roots would significantly impact vegetation health throughout the floodplain, which would then impact any species relying on the vegetation for

habitat. Interactions between the river and groundwater can be analyzed to infer how changes to the channel bed would affect riparian vegetation and species.

Tetra Tech (2010) assessed the relationship between groundwater, surface water, and wetlands between RM 79 and RM 85 on the east side of the Rio Grande. Their discussion relies heavily on observation well data near Highway 380 coupled with river discharge hydrographs during the 2009 spring runoff. Groundwater modeling was also conducted for several inundation scenarios corresponding to varied river conditions and flow rates. Tetra Tech observed that groundwater levels respond directly to river stage elevation, which responds to riverbed elevation. Therefore, Tetra Tech concluded that changes in river morphology that cause changes in river stage lead to corresponding changes in groundwater elevation.

Data from other observation wells at different locations near the Rio Grande also demonstrate a relationship between river water surface elevation and groundwater level, but suggest that the interaction is more complex than suggested by Tetra Tech (2010). Figure 18, Figure 19, and Figure 20 show the river thalweg elevation compared to nearby groundwater elevation at locations near the BDANWR south boundary, near San Marcial, and south of Fort Craig, respectively. River discharge is also shown on the secondary axes for reference. Figure 18 includes a well about 30 feet east of the river (SBB-E01B) and a well about 250 feet east of the river (SBB-E02B); both wells are approximately 1,200 feet upstream of SO-1641. The river has been slightly degradational since 1999 and the thalweg has lowered about one foot since water table monitoring began in 2003. The groundwater elevation shows either no trend, or a slightly increasing elevation trend. Figure 19 includes a well about 200 feet west of the river (SMC-W08EX) and a well about 1200 feet west of the river (SMC-W04B); both wells are between SO-1701.3 and EB-10. SMC-W04B is also about 40 feet east of the LFCC. The river thalweg lowered about 5 feet between 2003 and 2011, while the water table lowered 0–1 feet during the same period. There is not much of a trend in the water table elevation compared to the trend in thalweg elevation. Figure 20 includes a well about 300 feet west of the river (SFC-W05B) and a well about 450 feet west of the river (SFC-W04A); both wells are between EB-18 and EB-20 and within 50 feet the LFCC. (SFC-W05B is to the east of the LFCC and SFC-W04A is to the west of the LFCC.) The river thalweg lowered about 9–10 feet between 2003 and 2011, while the water table trend remained constant. The groundwater elevation was about 3–4 feet below the river thalweg in 2003 and 5–6 feet above the river thalweg in 2011 as the riverbed was no longer perched above the LFCC. Also, there are other ponded areas of water to the west of the river and LFCC between RM 60 and RM 64 that indicate a very high water table in this area. Groundwater elevation for the west floodplain is essentially a gradient between the river water surface and the LFCC water surface. All three figures show a higher groundwater table near the river, particularly at San Marcial where the river is perched above the west floodplain and the LFCC. Groundwater data is limited or not available for locations near the river and south of San Marcial, where most of the degradation occurred during the monitoring period.

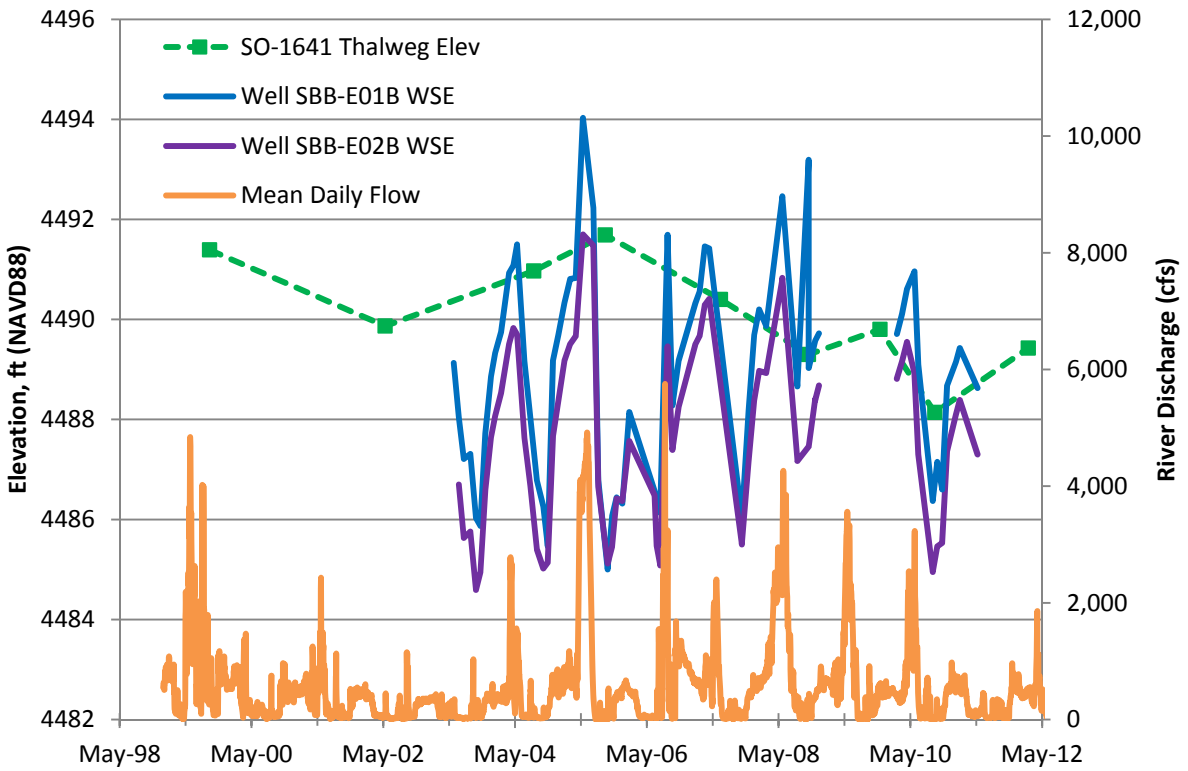


Figure 18. River thalweg elevation, groundwater elevation, and river discharge over time near BDANWR south boundary

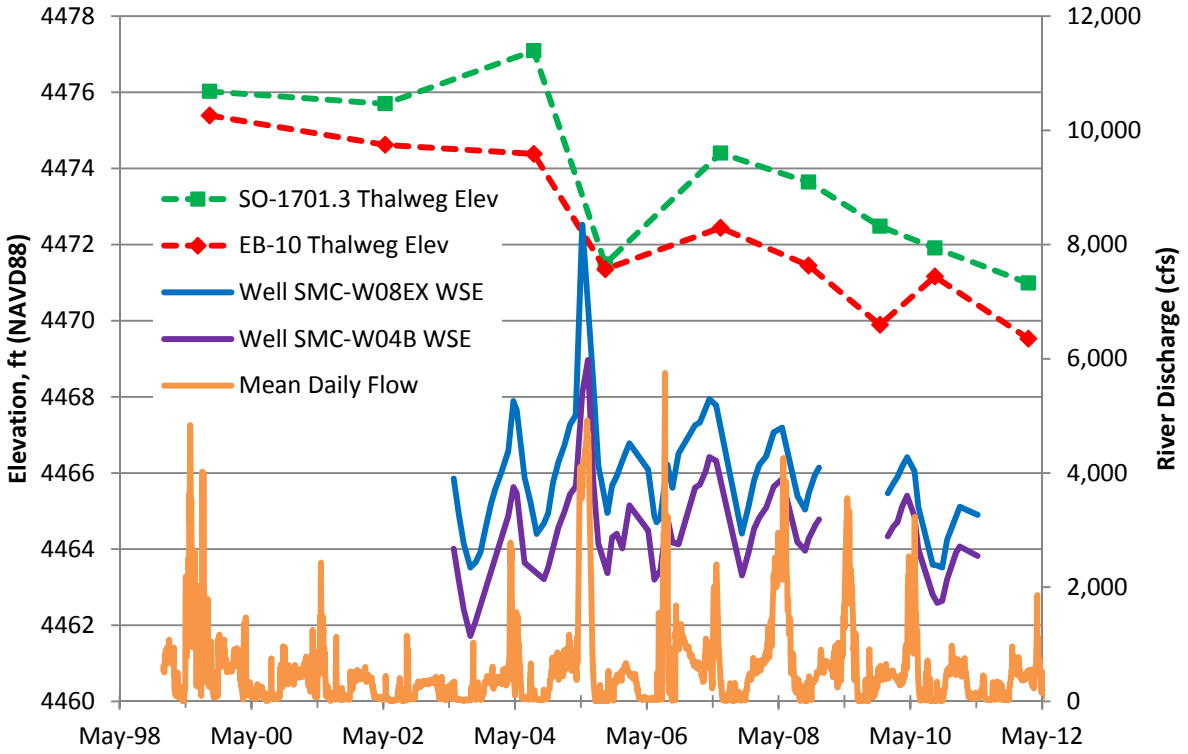


Figure 19. River thalweg elevation, groundwater elevation, and river discharge over time near San Marcial

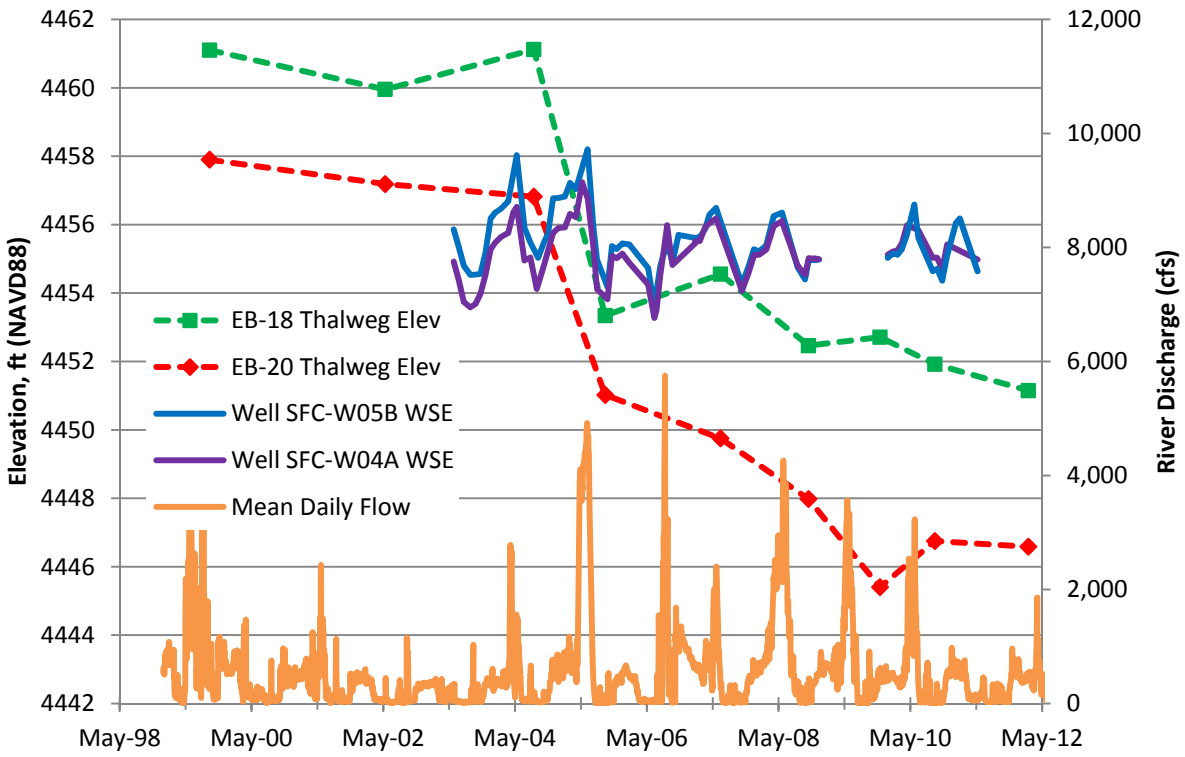


Figure 20. River thalweg elevation, groundwater elevation, and river discharge over time near RM 63

All three graphics show that the strongest correlation is between groundwater elevation and river discharge, not thalweg elevation. Peaks in groundwater elevation occur during spring runoff or other high flow events, and the highest groundwater peak in all three graphs is during the 2005 spring runoff, which was the largest flow event during the monitoring period. (The August 2006 monsoon had a higher peak flow, but a shorter duration, thus the smaller effect on groundwater.) Low groundwater elevations occur during periods of low river flow rates. Additional river water surface elevation, thalweg elevation, and mean bed elevation data would be needed to expand this analysis and draw more definitive conclusions. Specifically, river geometry and water surface data would need to be collected concurrently with groundwater data multiple times per year, especially during high flow events, to thoroughly examine the relationship. Collection of this amount of data is probably cost-prohibitive, but the currently available data demonstrates average trends and correlations over a period of several years. Groundwater elevation is complex, highly variable, and appears to be ***primarily a function of river discharge (or river water surface elevation) and nearby groundwater controls*** (i.e., LFCC and ponded areas). River thalweg elevation trends over time and space can influence, but may not directly correspond to, trends in groundwater elevation.

Recurring Channel Maintenance

Initial Temporary Channel construction was substantially finished by the end of 2004, so activities completed between 2005 and 2012 can be described as recurring channel maintenance. Recurring maintenance actions were primarily the removal of accumulated sediment to maintain channel capacity (bar lowering, pilot channel excavation through sediment plugs, etc.) and repair of spoil berms near the constructed channel banks. Specific maintenance activities varied slightly every year depending on channel conditions, but all maintenance essentially had those two

functions. Data collected from 2005 to 2012 illustrate the geomorphic effects of recurring channel maintenance during a period with the given changes to drivers and controls. Within the Temporary Channel project area, 2005 data is not available below Nogal Canyon (near EB-38) so cross section data from August/September 2004 was used to represent the "as-built" conditions after initial construction and prior to recurring maintenance.

Figure 21 shows thalweg profile snapshots in time during the period of recurring channel maintenance. The profiles begin at the upper end of the work area (EB-28) and continue to the start of the Narrows (EB-50); this includes the Upper Reach and half of the Middle Reach. Data was often not collected below EB-50 due to inundation from the reservoir pool. Aggradation has been the prevailing trend within the Temporary Channel during recurring channel maintenance, especially downstream of EB-38. The profiles also illustrate a significant degree of variability, even though it is likely that continuing maintenance minimized the amount of aggradation that would have occurred in some years. Figure 22 uses the same data from Figure 21 and calculates a distance-weighted, reach-averaged thalweg elevation for each year. This procedure reduces the multiple data points collected over approximately 12 river miles to a single representative thalweg elevation. Although spatial variability is no longer evident in the graphic, the dominant temporal trend of aggradation is more easily seen. The average thalweg elevation adjustment presented in Figure 22 strongly resembles the trend in reservoir pool elevation over the same time period (shown on secondary axis and previously discussed in Base Level section). Sediment was frequently removed in order to maintain channel capacity, yet the riverbed aggraded by a cumulative average of almost 3 feet from 2004 to 2010 before degrading about 0.5 feet from 2010 to 2012. Geomorphic effects from recurring channel maintenance are dominated by effects from the primary drivers (water and sediment discharge) and control (base level).

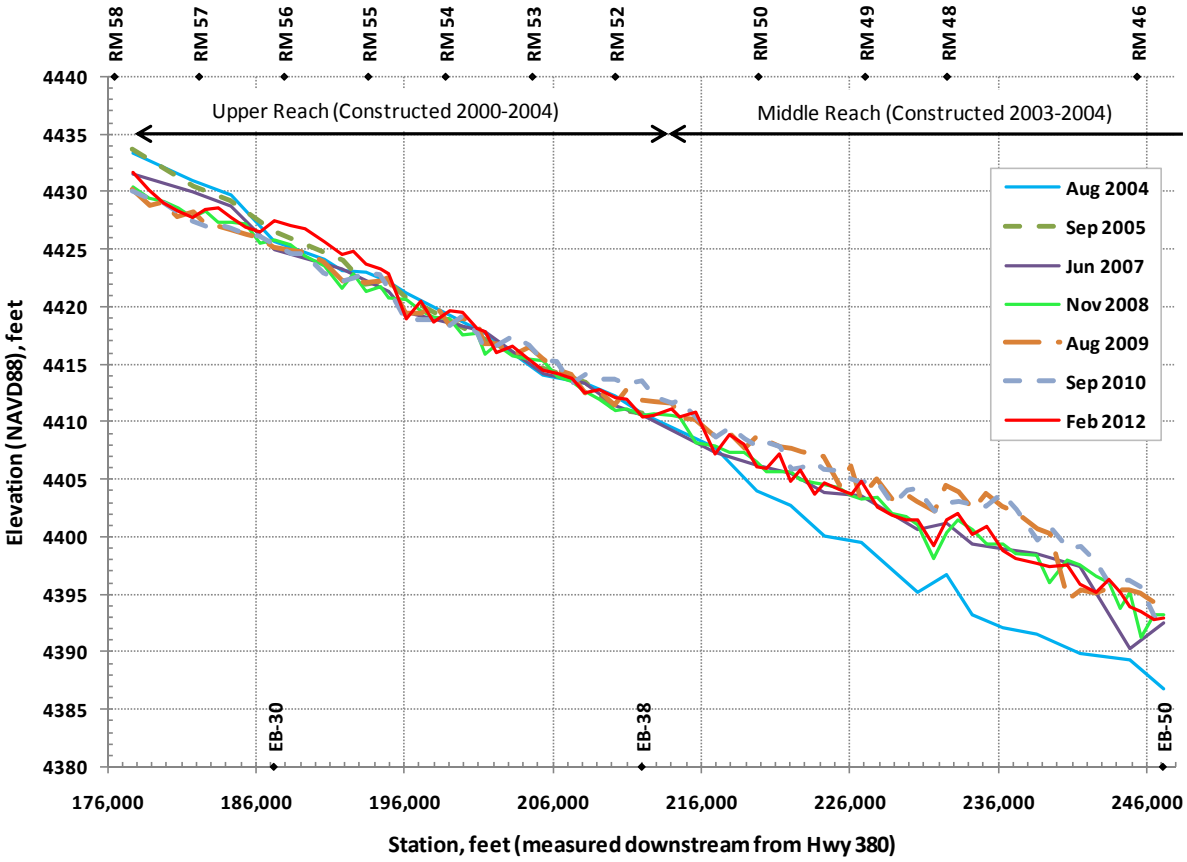


Figure 21. Partial Temporary Channel thalweg profiles over time during recurring channel maintenance

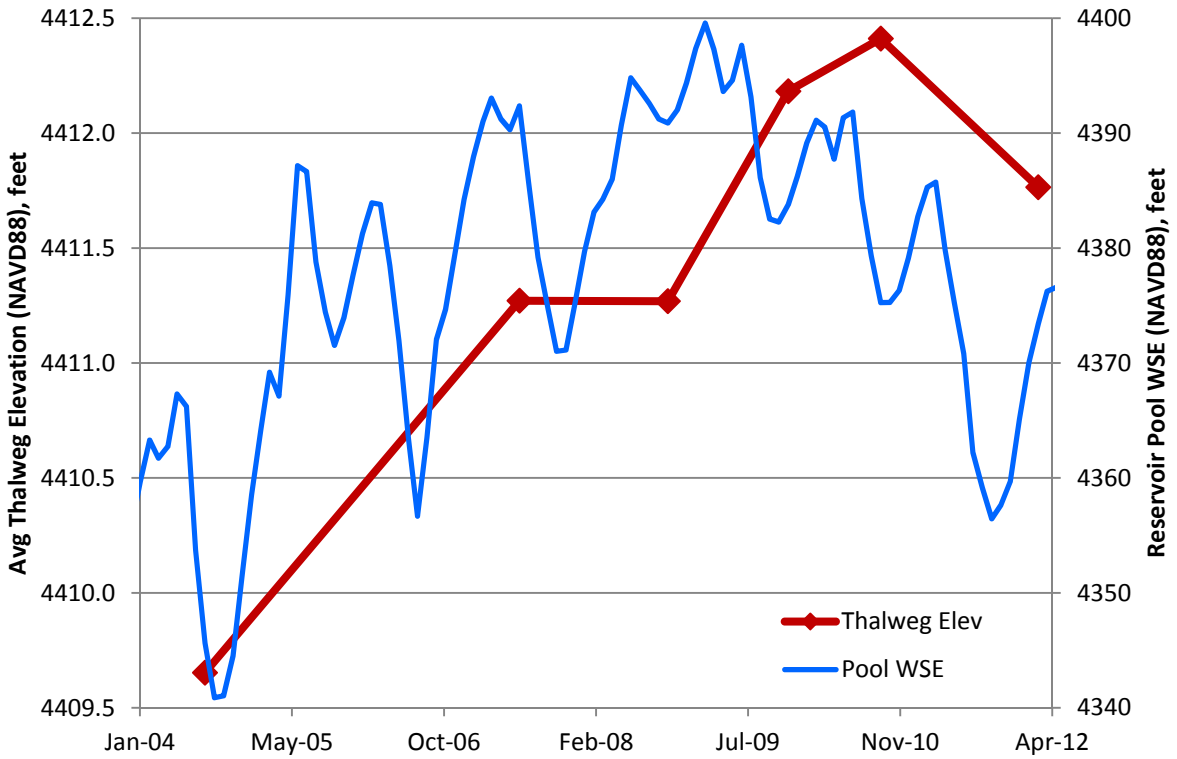


Figure 22. Distance-weighted average thalweg elevation over time for the Temporary Channel between EB-28 and EB-50 during recurring channel maintenance

Changes to channel planform and cross-sectional shape are also an important consideration when analyzing the geomorphic effects of recurring channel maintenance. Recurring maintenance actions either reconstruct or maintain the original channel, so there would not be any expected changes to channel planform. Table 4 and a review of aerial imagery confirm that there were not any significant alterations to channel planform or sinuosity between 2004 and 2012. Cross section plots complement thalweg profile analyses to present a more complete picture of the flow depth and velocity variability across the entire channel. Figure 23, Figure 24, and Figure 25 show three example cross sections within the Temporary Channel (EB-32.7, EB-37.5, and EB-43, respectively). The cross sections were selected at approximately 25%, 50%, and 75% of the total channel distance from EB-28 to EB-50. At EB-32.7 the lowest recorded thalweg elevation was 4420.74 feet in 2008 and the highest recorded thalweg elevation was 4422.93 feet in 2012 for a measured range of about 2.2 feet. During 2004 and 2005, the primary flow path was along the toe of the right (west) bank before an additional flow path developed near the channel center as seen in the 2007 cross section. Formation of a mid-channel bar from 2007 to 2012 caused aggradation near the channel center as dual flow paths developed along the toe of the left (east) and right banks. Other notable changes include the apparent lowering of the left berm crest by about 3 feet between 2009 and 2010 and the lowering of the right berm crest by about 4 feet between 2005 and 2007. These specific channel adjustments are limited to EB-32.7, but the trends of a relatively stable riverbed with yearly (or more frequent) variations in morphology would apply to other nearby locations.

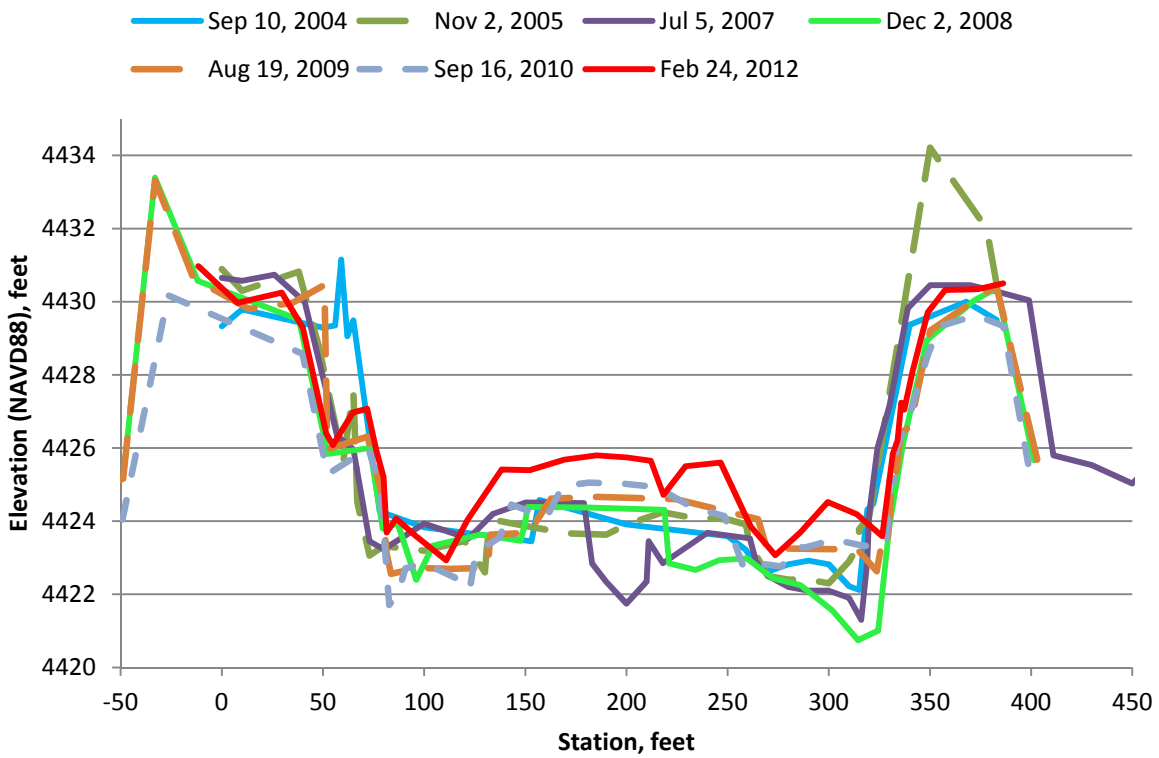


Figure 23. EB-32.7 cross section plots (looking downstream) during recurring channel maintenance (near thalweg profile station 194,900)

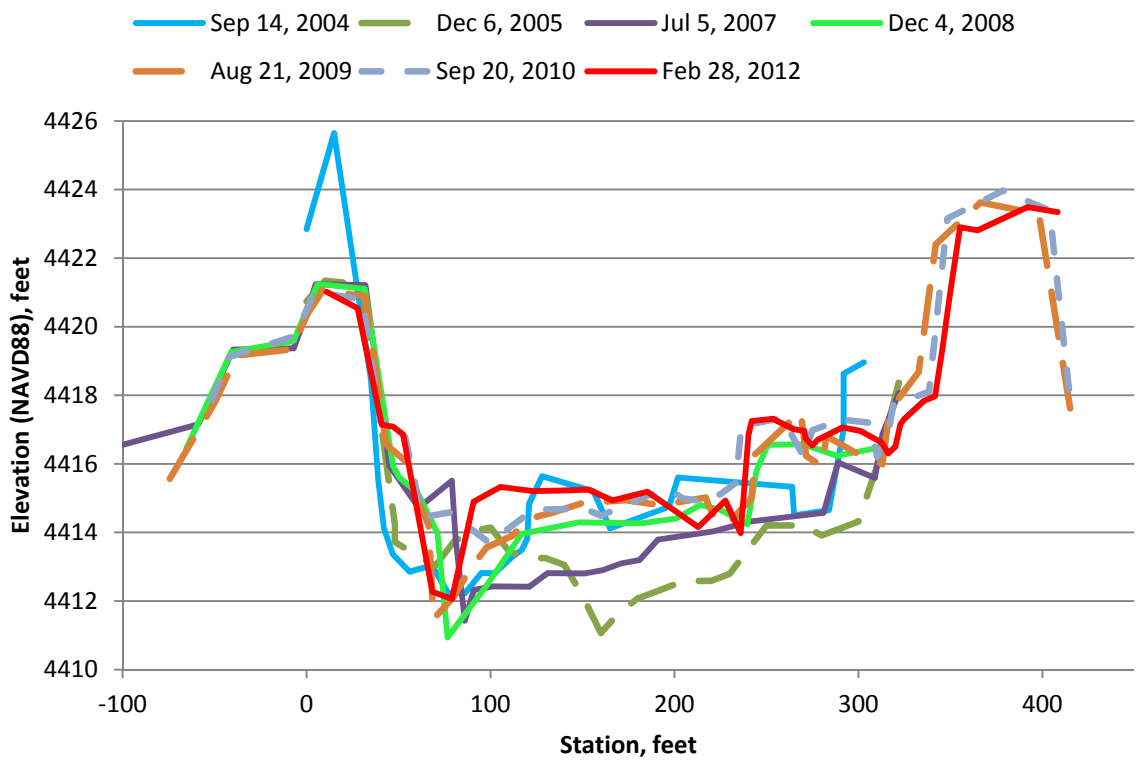


Figure 24. EB-37.5 cross section plots (looking downstream) during recurring channel maintenance (near thalweg profile station 210,200)

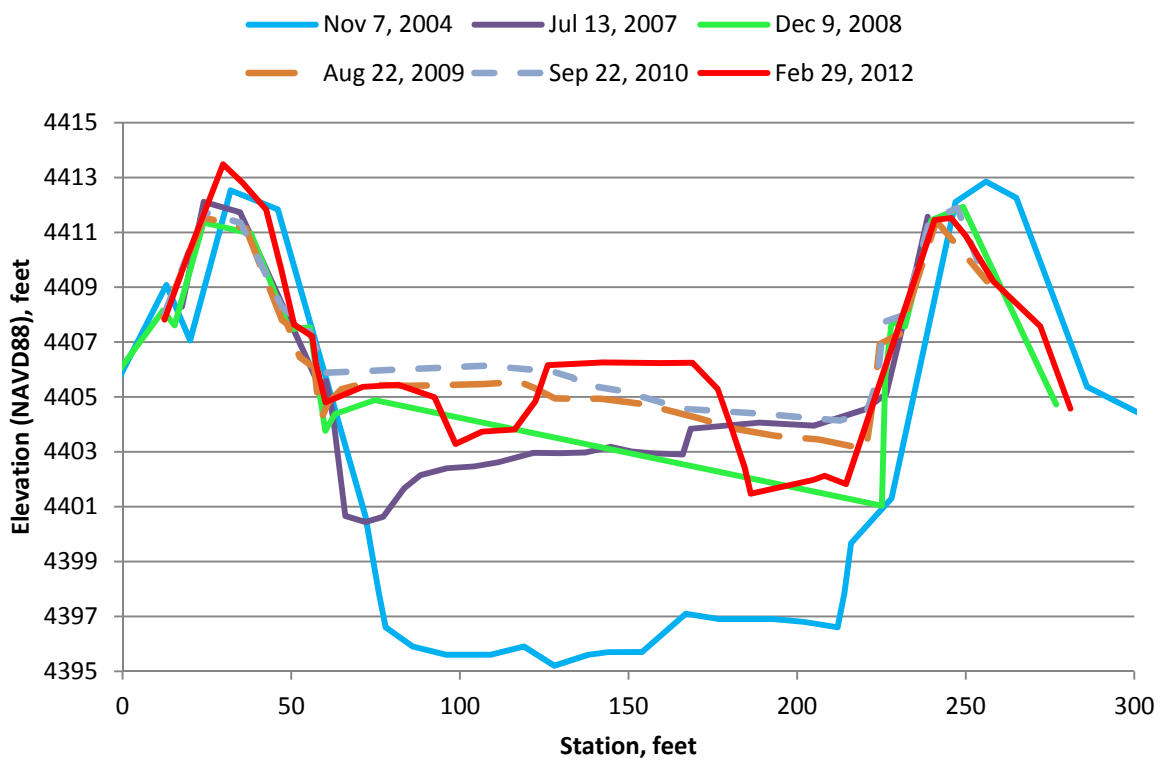


Figure 25. EB-43 cross section plots (looking downstream) during recurring channel maintenance (near thalweg profile station 230,600)

At EB-37.5 the lowest recorded thalweg elevation was 4410.94 feet in 2008 and the highest recorded thalweg elevation was 4413.69 feet in 2010 for a measured range of about 2.8 feet. EB-37.5 is near the apex of a bend, with the outside of the bend along the left bank (looking downstream). Therefore, the cross section plots show the expected shape of the deepest channel section near the toe of the outside bank. 2005 is the only year in which the thalweg is near the channel center rather than along the left bank. Most of the cross section adjustments occurred during the 2004–2007 time period, and the channel shape is relatively unchanged between 2007 and 2012. The specific channel adjustments are limited to EB-37.5 as discussed, but thalweg profiles and other cross section plots suggest that the channel morphology has been relatively stable at nearby locations.

At EB-43 the lowest recorded thalweg elevation was 4395.20 feet in 2004 and the highest recorded thalweg elevation was 4404.14 feet in 2010 for a measured range of about 8.9 feet. EB-43 is in the middle of a relatively straight channel section about 0.5 miles upstream of the Red Rock Staging Area. Significant aggradation occurred across the entire channel between 2004 and 2007, followed by a shift in thalweg location from near the left bank to near the right bank between 2007 and 2008. Both the thalweg and mean bed elevation continued to increase from 2007 to 2010 before decreasing between 2010 and 2012. 2012 is the first year in which two low flow paths exist due to the presence of a mid-channel bar. The aggradation seen at EB-43 and in the thalweg profiles between RM 46 and RM 50 (Figure 21) correspond to field observations of sediment plugs and multiple channel breaches within this area, which are indicative of a general loss of channel capacity despite the recurring maintenance activities.

Although data is limited below EB-50, field observations can be used to assess the general effects of channel maintenance. Within the Narrows (~EB-50 to EB-60; ~RM 46 to RM 41), flow is geologically confined by mesas on each side and maintenance needs have been minimal, such as removal of in-channel vegetation. A sediment plug formed just downstream of the Narrows near RM 41 in 2005 and was later removed. The valley width expands and meanders abruptly to the east between about RM 41 and RM 38, and some recurring work has been required in this area to maintain an effective connection with the reservoir pool. As the reservoir pool receded below RM 38, the effect of the longitudinal reservoir profile (Figure 10) could be examined. The slope is naturally steeper below the Narrows than above the Narrows (foreset and topset slopes, Figure 11), and this difference in slope should allow the river to form a competent channel downstream of about RM 38. Figure 26 illustrates that this concept was observed in the field during August 2012 near RM 37 and from the air in April 2013. The reservoir inundated the Narrows in 2009, and maintenance has never been performed downstream of about RM 38 or RM 39. A channel with defined banks became naturally established for a distance of more than one mile during April–September 2012 as the reservoir receded below RM 37. Additional distributary flowpaths have also formed through the reservoir delta. It is likely that sediment will deposit in the existing flowpaths once the reservoir stops receding, thus flattening the slope upstream of the reservoir pool and requiring maintenance.

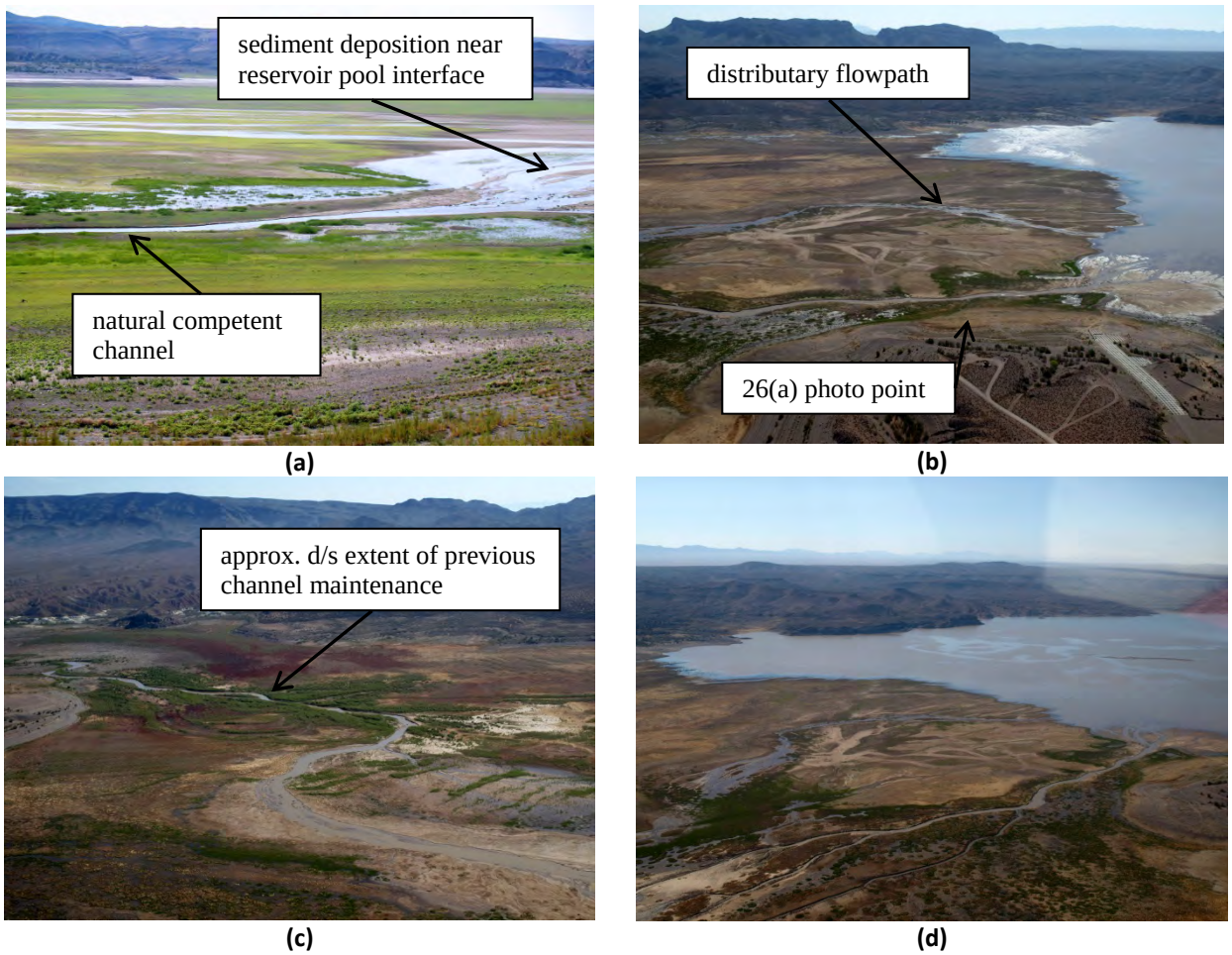


Figure 26. Naturally formed reservoir delta channel and flowpaths downstream of the Narrows: (a) on ground looking southeast near RM 37, August 2012 (b) oblique aerial looking southeast near RM 37.5, April 2013 (c) oblique aerial looking northeast near RM 37.5, April 2013 (d) oblique aerial looking southeast near RM 38, April 2013

In summary, analysis of data within the defined Temporary Channel work area verifies that the primary drivers (water and sediment discharge) and control (base level) dominate any effects from recurring channel maintenance. Also, potential effects from channel maintenance would be evident within the Temporary Channel prior to being observed in upstream reaches. The average thalweg elevation between EB-28 and EB-50 mirrors the temporal reservoir pool elevation trends (Figure 22). Aggradation occurred as the reservoir pool rose, even as recurring channel maintenance was performed. Degradation occurred between 2010 and 2012 as the reservoir pool declined. Less sediment removal and berm repair was required during 2011–2012 compared to 2005–2010 because of differences in the reservoir pool elevation and hydrology. The Temporary Channel planform has not changed during recurring maintenance and the cross section plots illustrate the variable depth and morphology that is typical of alluvial rivers.

Conclusions

The Rio Grande fluvial system upstream of Elephant Butte Reservoir is highly dynamic and behaves with a great deal of complexity. The primary drivers of water discharge (Figure 6) and sediment load (Figure 7), coupled with the primary control of base level elevation (Figure 9 and Figure 10), exhibit a large degree of variability. Channel bed adjustment is a function of sediment imbalance, which generally depends on the relative magnitude of upstream sediment supply and effects from the downstream reservoir (Park et al., 2012). An imbalance between sediment supply and sediment transport capacity is the prevailing condition that necessitates continuous channel adjustments over space and time (Figure 4 and Figure 5). Equilibrium or stability over a period of several years is not a reasonable outcome for this reach, owing to the variable nature of the drivers and controls. As the pool elevation of Elephant Butte Reservoir rises or falls, the slope of the Rio Grande is forced to respond (Figure 13). The river's response to fluctuations in base level and delta formation has controlled the channel elevation upstream of the reservoir (Figure 15 and Figure 16). The rate and magnitude of bed elevation changes is highly dependent on proximity to the reservoir pool and upstream water and sediment discharge (Levish, 2012).

Significant aggradation is the most defining historical characteristic of the Rio Grande upstream of Elephant Butte Reservoir (Makar and AuBuchon, 2012). This aggradation is primarily caused by low valley and channel slopes combined with a relatively high sediment load (Levish, 2012). During wet periods with a full reservoir, the reach experiences high levels of aggradation. Aggradation appears to slow in upstream reaches as the reservoir pool elevation drops, and degradation is initiated when a high flow event occurs when the reservoir is low. Degradation is likely to continue for a period of time as the river adjusts to the initial reservoir recession, and the bed may eventually stabilize if the reservoir pool remains at a constant low elevation for several years. The dominant aggradational trend will resume when the reservoir begins to rise. Adaptive management is likely the most appropriate strategy for this reach, given that the design life of any maintenance approach will be greatly reduced due to fluctuations in the upstream water discharge and sediment load and the downstream base level control (reservoir pool elevation) (Reclamation, 2012).

The Temporary Channel has been adaptively maintained every year since initial construction in response to channel adjustments that were caused by changes to the primary geomorphic drivers

and control. Initial excavation was likely responsible for increasing the local slope within the upper reservoir delta by about 8–12%, but some sinuosity was incorporated into the design so that the constructed channel length was within 1% of the 1972 channel length. A common assumption has been that Temporary Channel construction caused a headcut and ensuing upstream migration of a degradation wave from 2005 to 2008. However, a knickpoint existed in 1999 prior to construction and moved about three miles upstream by 2004 in response to the falling reservoir pool. Geomorphic concepts and analyses show that all three of the primary causes of channel degradation existed naturally in 2005: (1) a recently and rapidly lowered base level (reservoir pool) elevation, (2) a high magnitude, long duration flow event, and (3) a reduction in upstream sediment supply due to the Tiffany sediment plug. Levish (2012) concludes that Temporary Channel construction may have initiated and temporarily increased the rate of channel lowering, but this elevation change would have eventually occurred in response to the lower reservoir pool elevation. Riverbed degradation is a concern because of the potential relationship between thalweg elevation and groundwater elevation, which could impact riparian vegetation. Groundwater elevation is complex, highly variable, and appears to be primarily a function of river discharge (or river water surface elevation) and nearby groundwater controls (i.e., LFCC and ponded areas). River thalweg elevation trends over time and space can influence, but may not directly correspond to, trends in groundwater elevation.

As riverbed degradation upstream of the Temporary Channel began in 2005, bed elevation within the lower and middle portions of the Temporary Channel increased in response to a rising reservoir pool. Temporary Channel aggradation continued through 2010 with the river adjusting to an increased pool elevation. Recurring channel maintenance was performed every year during this time period, yet the average thalweg elevation increased 3 feet between 2004 and 2010. Then, about 0.5 feet of average degradation occurred from 2010 to 2012 in response to lowering of the reservoir pool. The thalweg elevation immediately upstream of the reservoir pool mirrors temporal reservoir pool elevation trends, while the riverbed further upstream responds later in time at an attenuated rate. Recurring maintenance actions attempt to maintain channel capacity, so the likely effect is a partial reduction in aggradation rate during some years. However, in a dynamic and complex system, data analysis verifies that the primary drivers (water and sediment discharge) and control (base level) dominate any effects from recurring channel maintenance. The riverbed elevation within the Temporary Channel (and nearby upstream reaches) is primarily controlled by the rate, magnitude, and duration of reservoir pool elevation fluctuations, in addition to the primary drivers. The scale of Temporary Channel maintenance actions is quite small compared to fluctuations in the other geomorphic drivers and controls. Using data from previous years, no correlation can be made between adaptive maintenance actions and geomorphic effects; whereas, there are clearly significant geomorphic effects that are caused by upstream water discharge, sediment load, and downstream reservoir pool elevation.

Acknowledgements

The work of Tracy Owen (2012), Paula Makar and Jonathan AuBuchon (2012), and Dan Levish (2012) provided an excellent foundation for many sections of this report. Jonathan AuBuchon, Ann Demint, and Mark Nemeth reviewed this document and offered several helpful comments and suggestions that improved the final report. Jason Casuga assisted with project coordination and also provided many useful suggestions. Vincent Benoit created the location maps shown in Appendix B. Anders Lundahl of the New Mexico Interstate Stream Commission (NMISC) reviewed the report and provided valuable clarification regarding the groundwater monitoring well locations. Well data used in the Groundwater Analysis section is courtesy of NMISC.

References

Bauer, T. 2004. Bed Material Data Collection Trip Report Rio Grande, New Mexico, July and August 2004. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado. 17 pp.

_____. 2007. 2006 Bed Material Sampling on the Middle Rio Grande, New Mexico. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado. 44 pp.

_____. 2009. Evolution of Sediment on the Middle Rio Grande, New Mexico. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado.

Biedenharn, D.S., C.C. Watson, C.R. Thorne. 2008. Fundamentals of Fluvial Geomorphology, chapter 6 in E.D. Garcia Sedimentation Engineering (Manual 110) Processes, Measurements, Modeling, and Practice, American Society of Civil Engineering (ASCE), Reston, Virginia.

Davis, W.M. 1895. The Development of Certain English Rivers. Journal of Geography, v. 5. p. 127–146.

Ferrari, R.L. 2008. Elephant Butte Reservoir 2007 Sedimentation Survey. Technical Report SRH-2008-4. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado. 153 pp.

Happ, S.C. 1948. Sedimentation in the Middle Rio Grande Valley, NM. Geological Society of America Bulletin 59(12). p. 1191–1216.

Hilldale, R. 2001. Trip Report – Middle Rio Grande Drilling Operations. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado.

_____. 2003. Middle Rio Grande Substrate Exploration. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado.

Julien, P.Y. 1998. Erosion and Sedimentation. Cambridge University Press, Cambridge, United Kingdom. 280 pp.

Knighton, D. 1998. Fluvial Forms and Processes: A New Perspective. Arnold, London England and Oxford University Press, New York, New York. 383 pp.

Lai, S.Y.J., and H. Capart. 2008. Response of Hyperpycnal Deltas to a Steady Rise in Base Level. Proceedings of the 5th IAHR Symposium on River, Coastal, and Estuarine Morphodynamics, edited by C.M. Dohmen-Janssen and S.J.M.H. Hulscher, Taylor and Francis, London. p. 57–62.

Lane, E.W. 1955. Design of Stable Channel. Transactions of the ASCE, Vol. 120. p. 1234–1279.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial Processes in Geomorphology. Dover Publications, New York, New York. 522 pp.

Levish, D.R. 2012. Elephant Butte Channel Maintenance: Geomorphic Effects. Technical Memorandum No. 86-68330-2012-15. Bureau of Reclamation, Technical Service Center, Seismotectonics and Geophysics Group, Denver, Colorado. 7 pp.

Makar, P. 2013. Personal Communication. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado.

Makar, P., and J. AuBuchon. 2012. Channel Conditions and Dynamics of the Middle Rio Grande River. Bureau of Reclamation, Technical Service Center, Denver, Colorado, and Upper Colorado Region, Albuquerque Area Office, Albuquerque, New Mexico. 94 pp.

Owen, T.E. 2012. Geomorphic Analysis of the Middle Rio Grande – Elephant Butte Reach, New Mexico. M.S. Thesis, Colorado State University, Fort Collins, Colorado. 186 pp.

Park, K., Bender, T.R., and P.Y. Julien. 2012. North Boundary of Bosque del Apache National Wildlife Refuge to Elephant Butte Reservoir Literature Review and Conceptual Assessment. Colorado State University Engineering Research Center, Department of Civil Engineering, Fort Collins, Colorado. 35 pp.

Reclamation. 1981. Restoration of the Low Flow Conveyance Channel. Bureau of Reclamation, Upper Colorado Region, Albuquerque Area Office, Middle Rio Grande Project, Albuquerque, New Mexico. 25 pp.

_____. 2012. Middle Rio Grande River Maintenance Program Comprehensive Plan and Guide. Bureau of Reclamation, Upper Colorado Region, Albuquerque Area Office, Middle Rio Grande Project, Albuquerque, New Mexico. 202 pp.

Schumm, S.A. 1977. The Fluvial System. John Wiley and Sons, New York. 338 pp.

Schumm, S.A., M.D. Harvey, and C.C. Watson. 1984. Incised Channels: Morphology , Dynamics and Control. Water Resources Publications. Littleton, Colorado. 200 pp.

Strand, R.I., and E.L. Pemberton. 1982. Reservoir Sedimentation Technical Guideline for Bureau of Reclamation. U.S. Bureau of Reclamation, Denver, Colorado. 48 pp.

Tetra Tech. 2010. River Mile 80 to River Mile 89 Geomorphic Assessment and Hydraulic and Sediment-Continuity Analyses. Prepared for the Bureau of Reclamation, Albuquerque, New Mexico. 121 pp.

Vogt, B. 2003. The Arroyo Problem in the Southwestern United States. http://geochange.er.usgs.gov/sw/impacts/geology/arroyos/, accessed September 2011.

Watson, C.C., D.S. Biedenharn, C.R. Thorne. 1999. Demonstration Erosion Control Design Manual. U.S. Army Engineer Research and Development Center. Vicksburg, Mississippi.

_____. 2007. Stream Rehabilitation. Cottonwood Research, LLC. Fort Collins, CO. 266 pp.

Wohl, E. 2007. G 652 Fluvial Geomorphology Class Notes. Colorado State University, Fort Collins, CO.

Appendix A: Thalweg Profiles

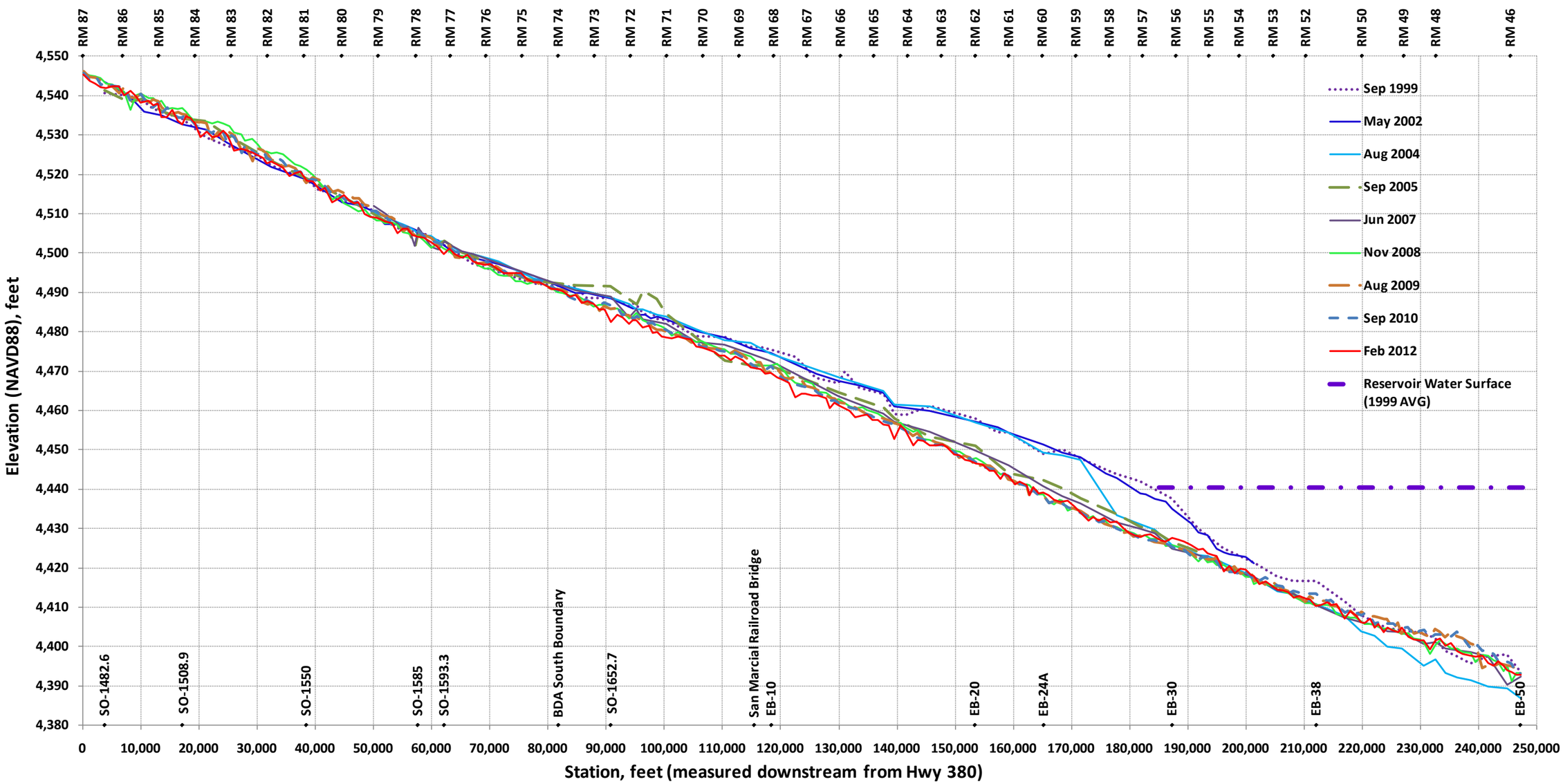


Figure A - 1. Thalweg Profile from Highway 380 Bridge to the Narrows (river miles on secondary x-axis use 2002 delineation)

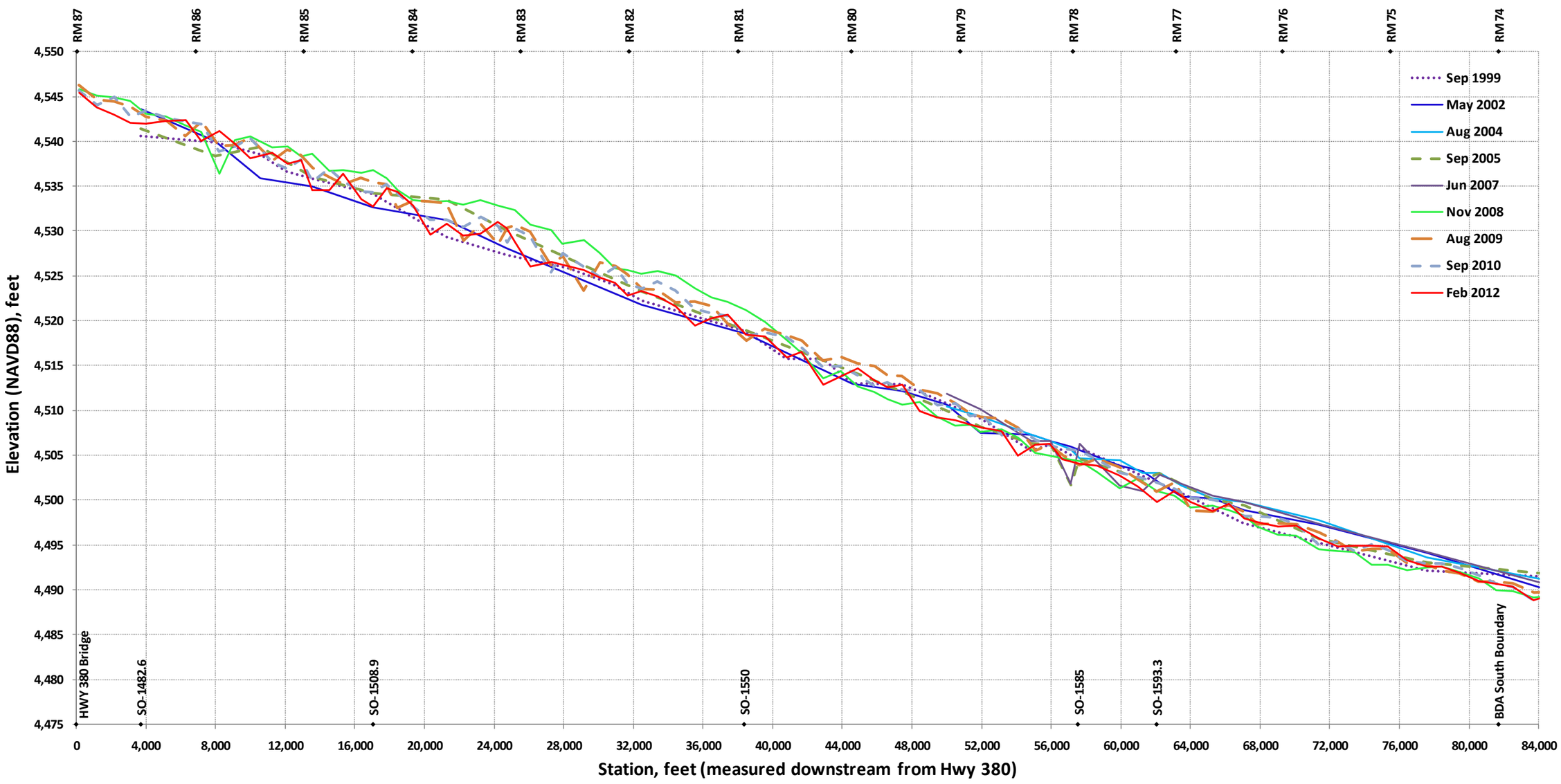


Figure A - 2. Thalweg Profile from Highway 380 Bridge to BDANWR South Boundary (river miles on secondary x-axis use 2002 delineation)

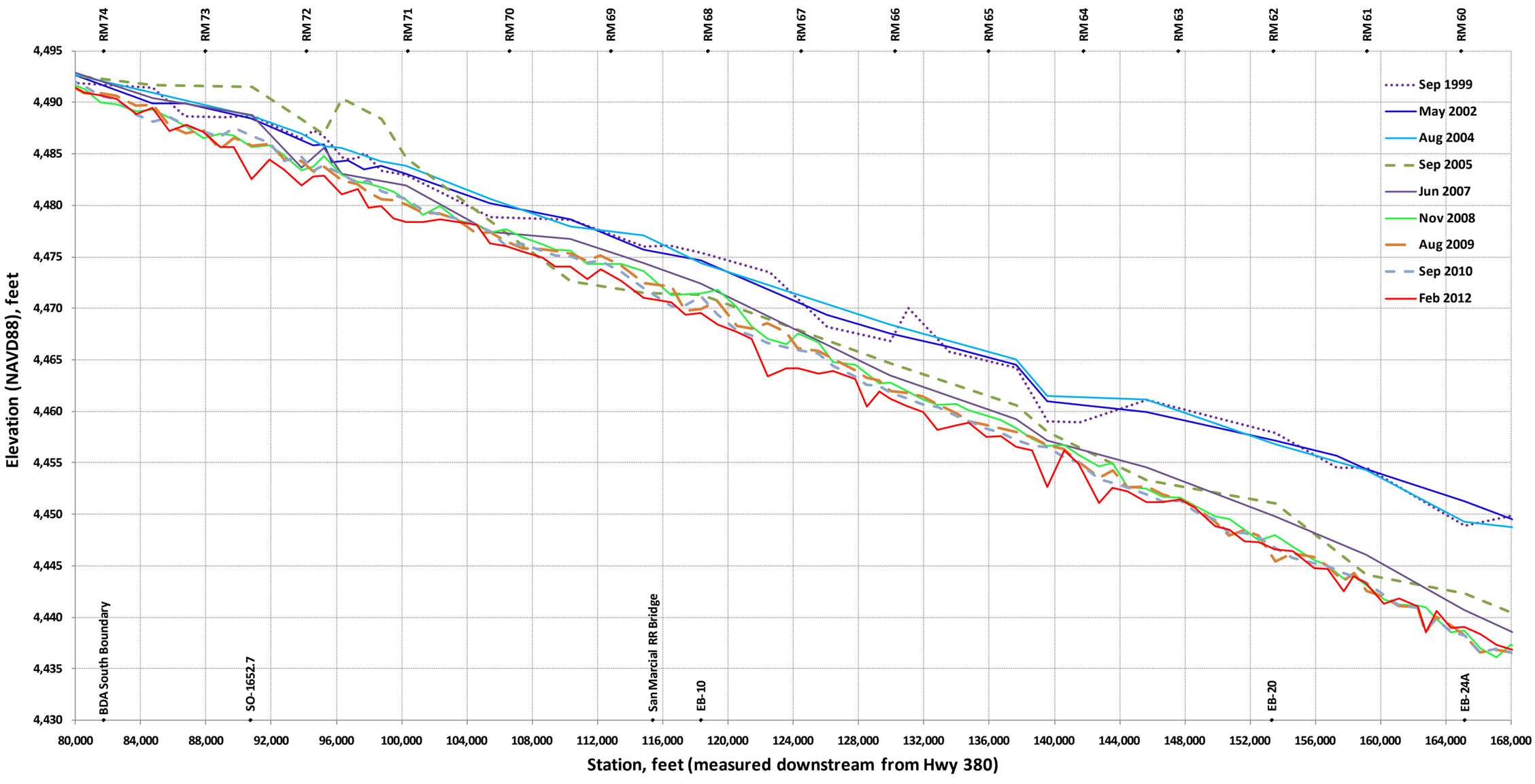


Figure A - 3. Thalweg Profile from BDANWR South Boundary to RM 60 (river miles on secondary x-axis use 2002 delineation)

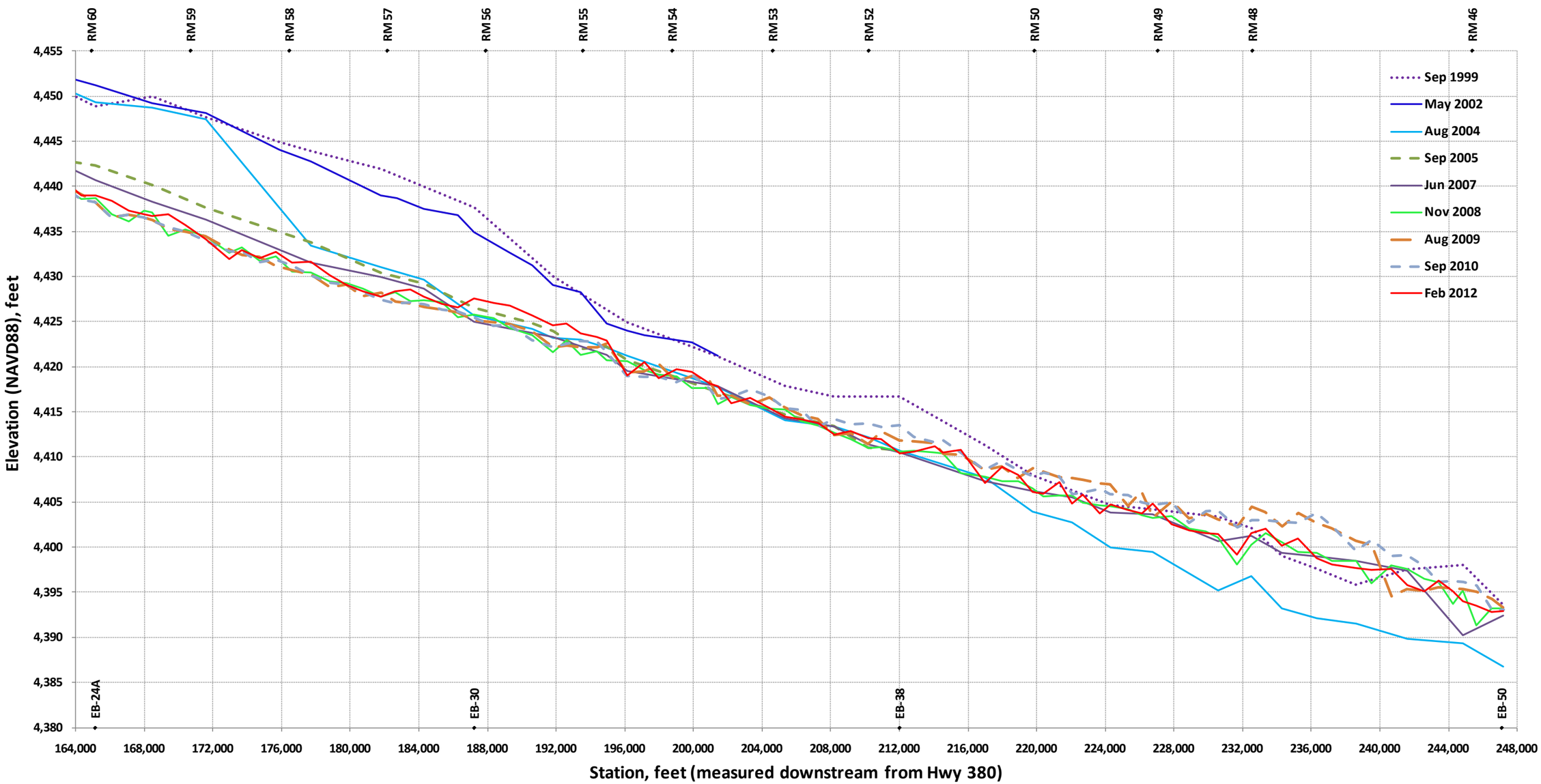
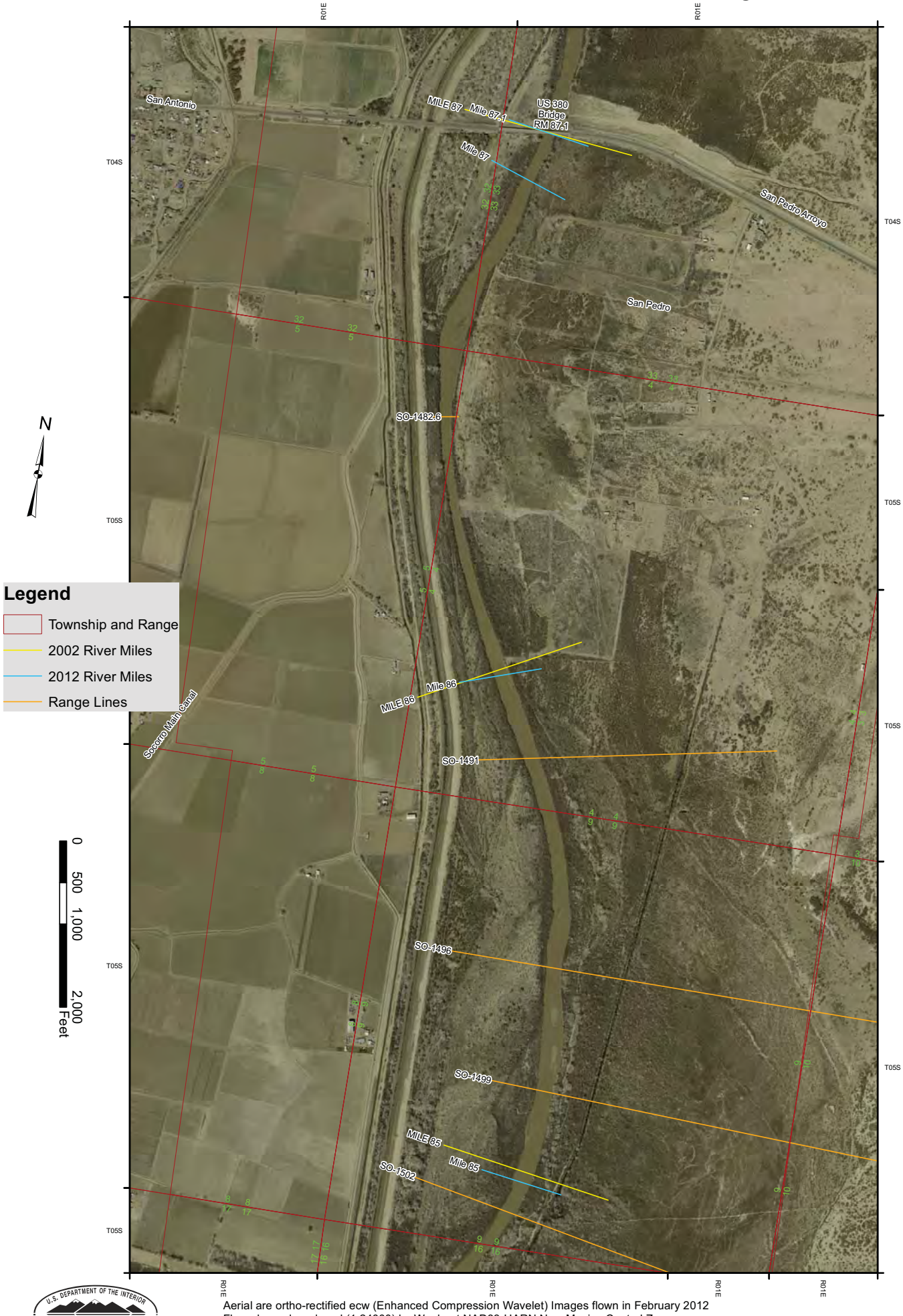


Figure A - 4. Thalweg Profile from RM 60 to the Narrows (river miles on secondary x-axis use 2002 delineation)

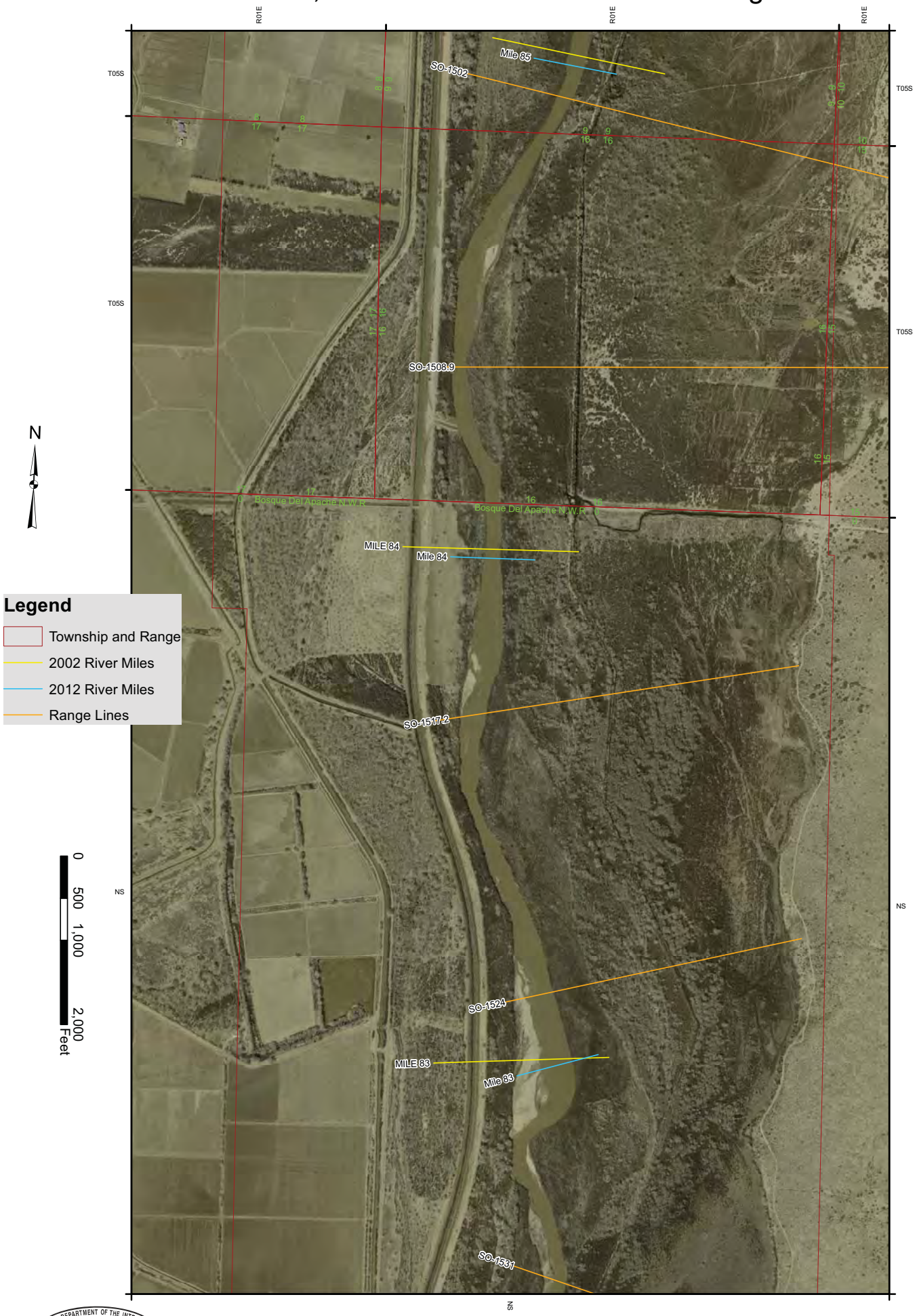
Appendix B: River Miles and Rangelines Location Map

Middle Rio Grande, New Mexico: River Miles and Rangelines



Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines

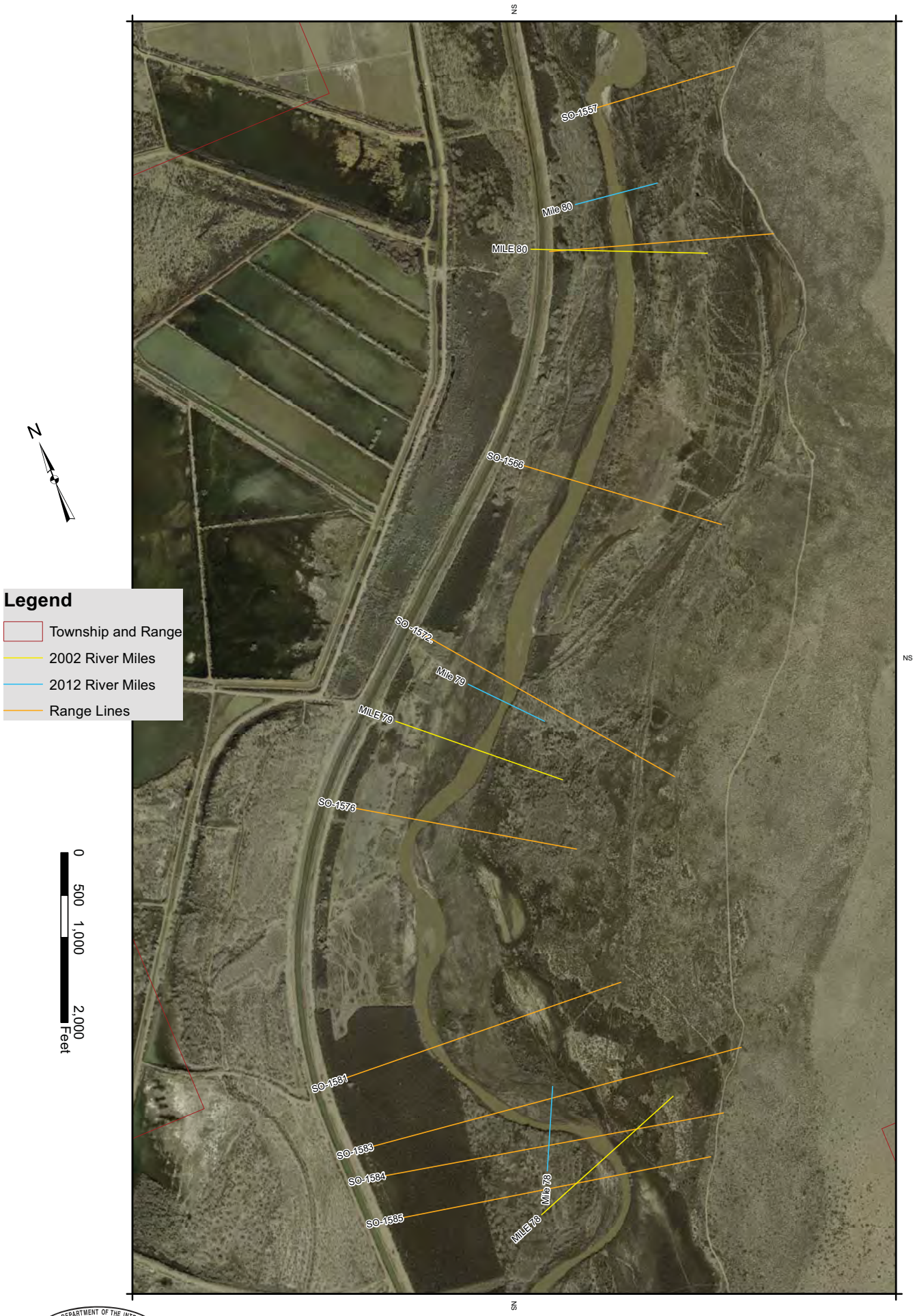


Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines

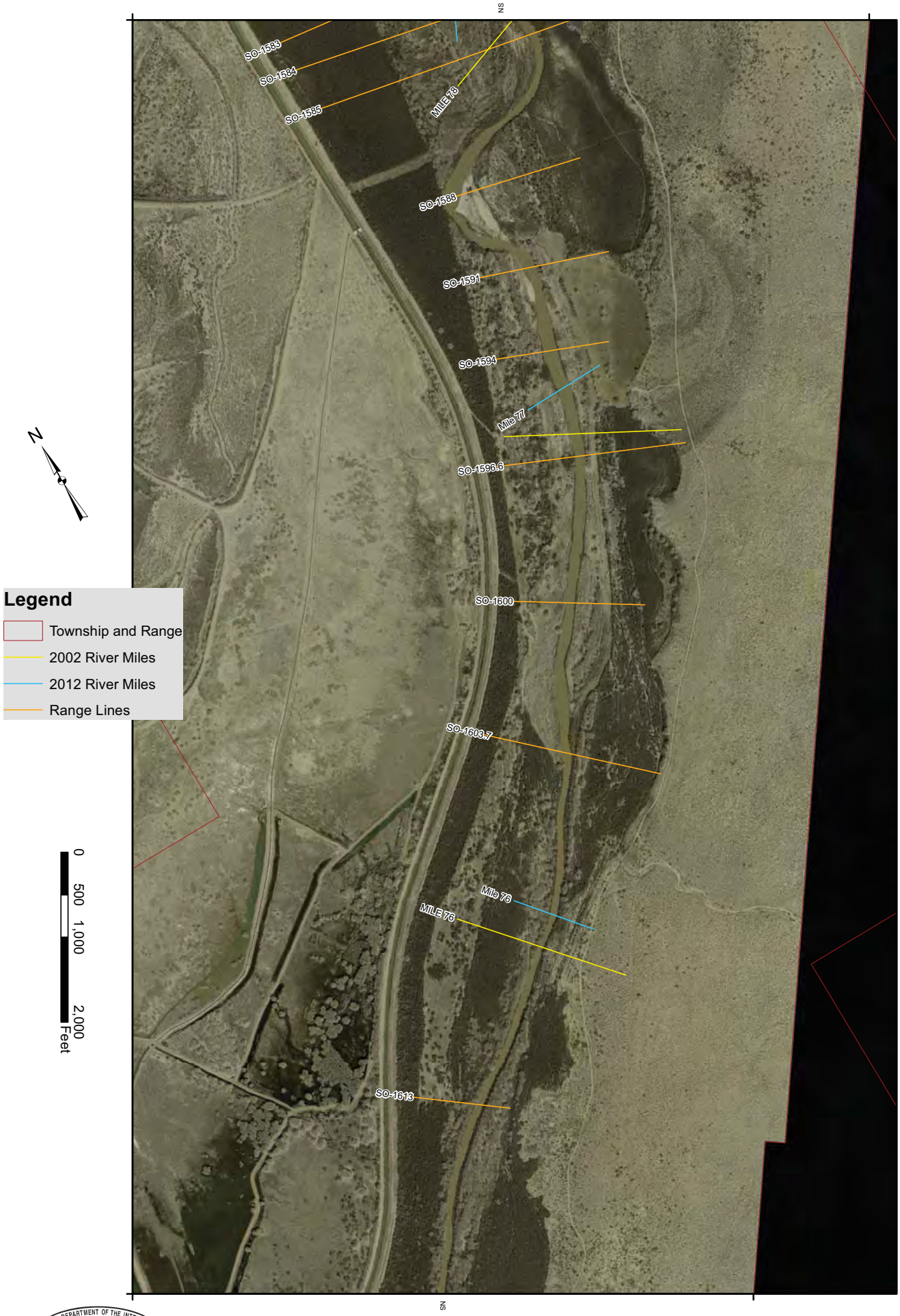
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



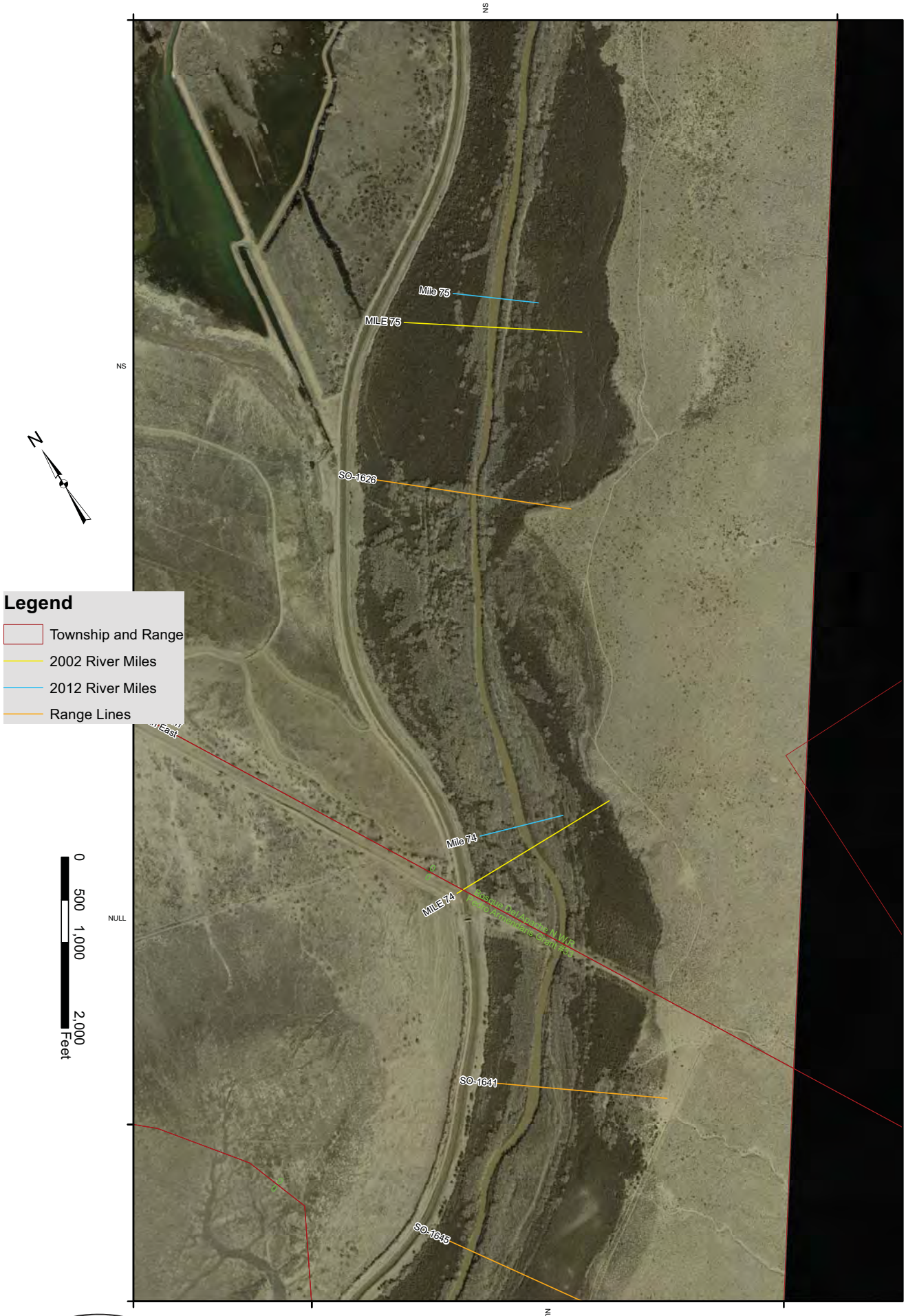
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



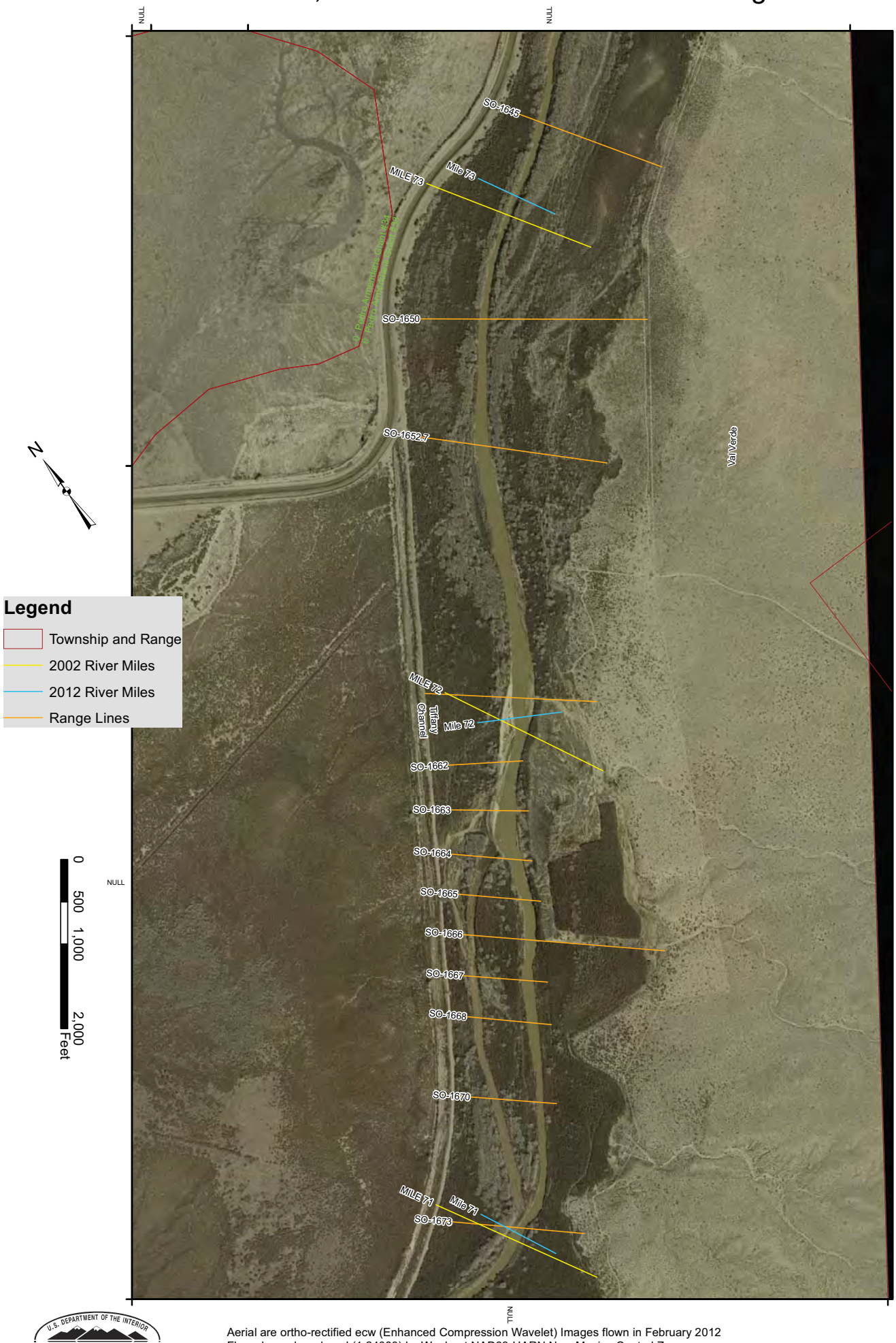
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



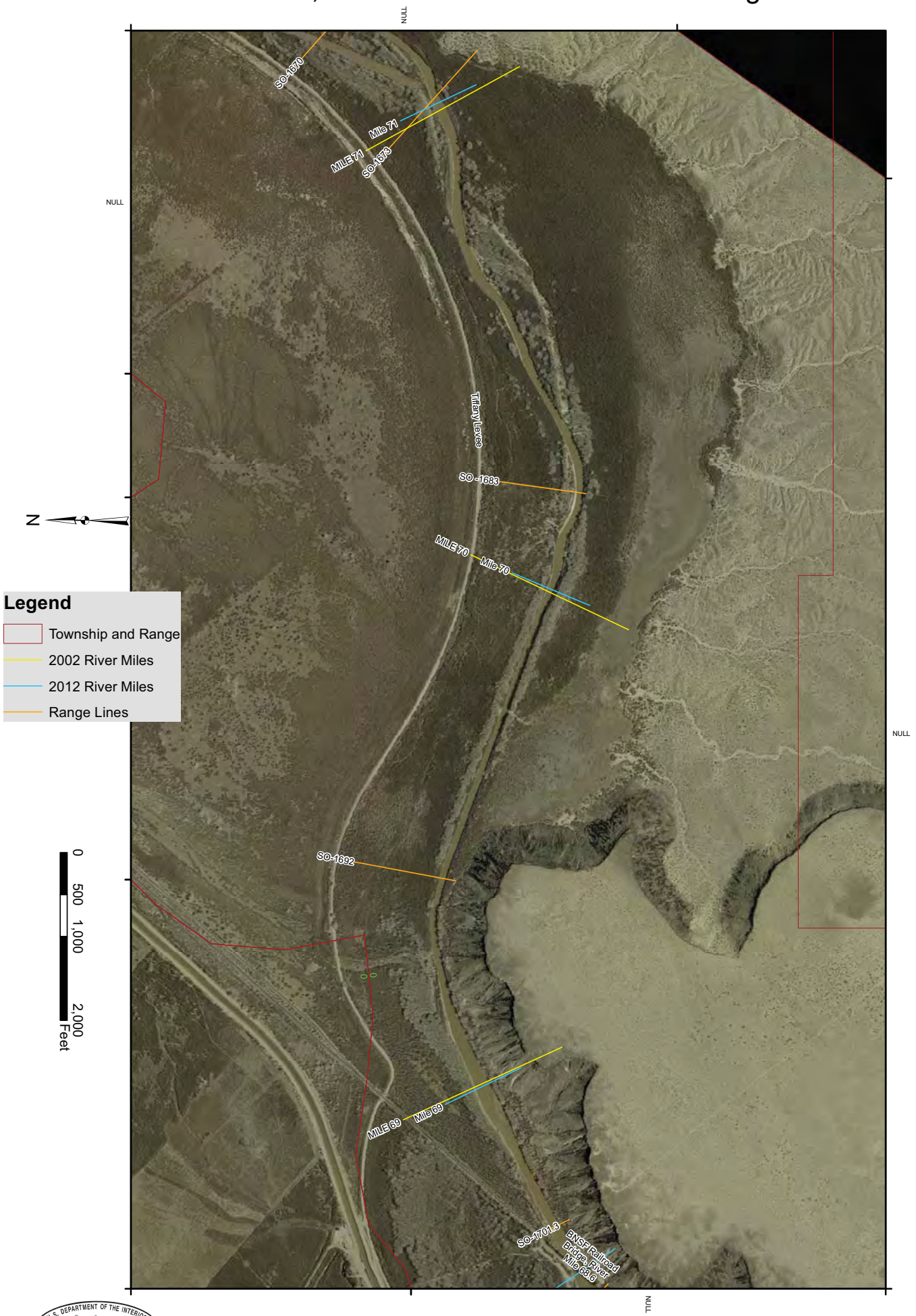
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



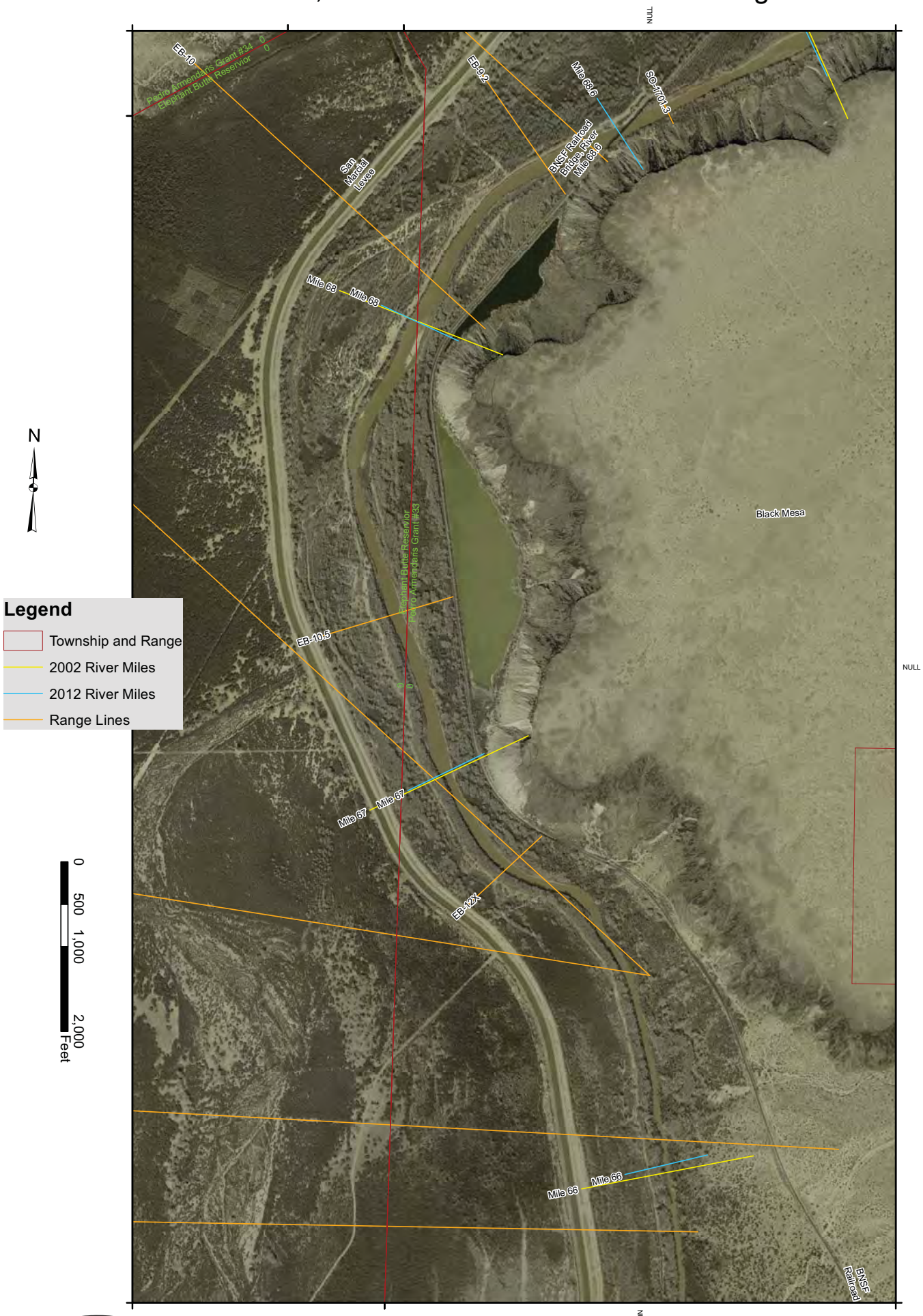
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



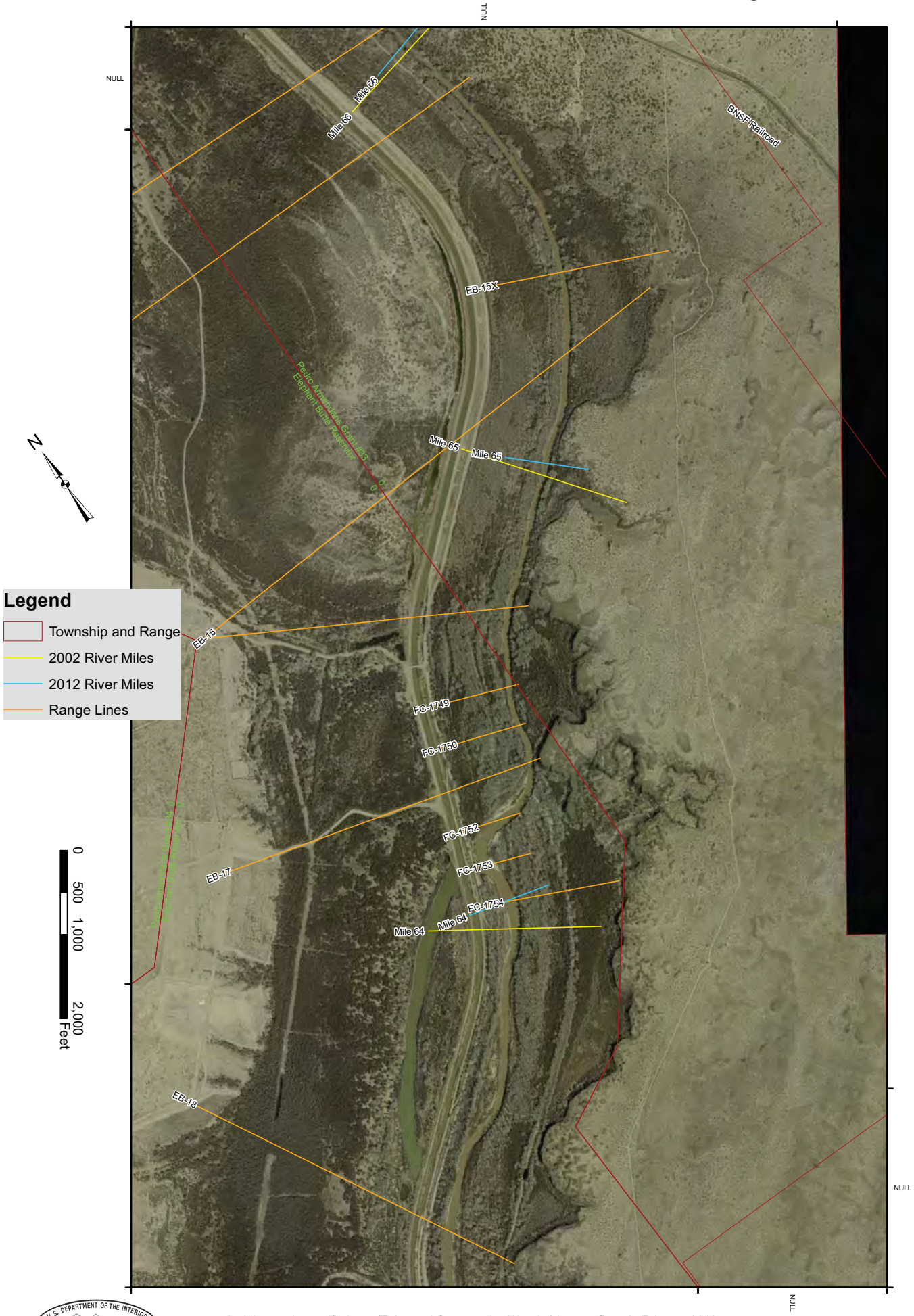
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



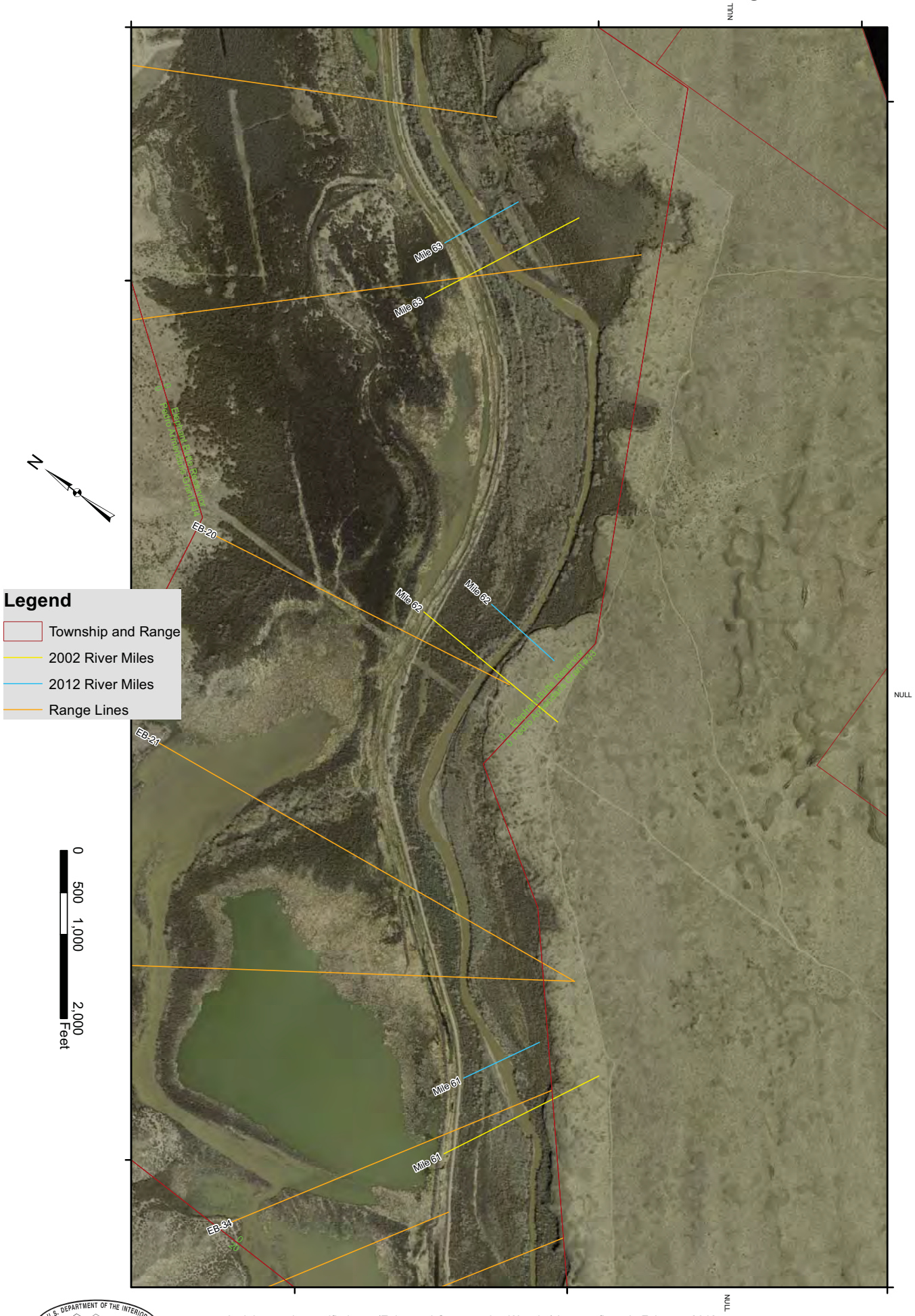
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



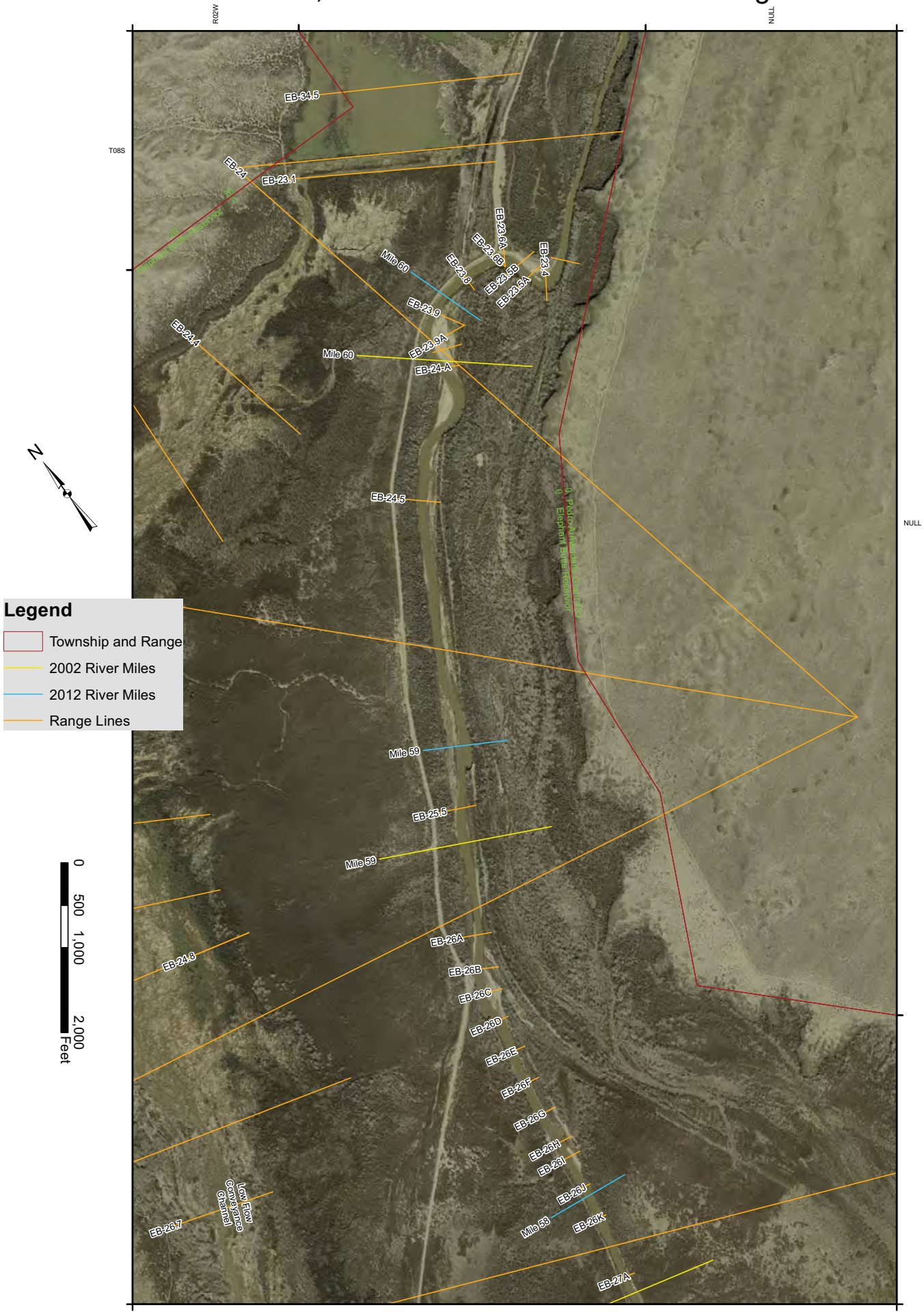
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



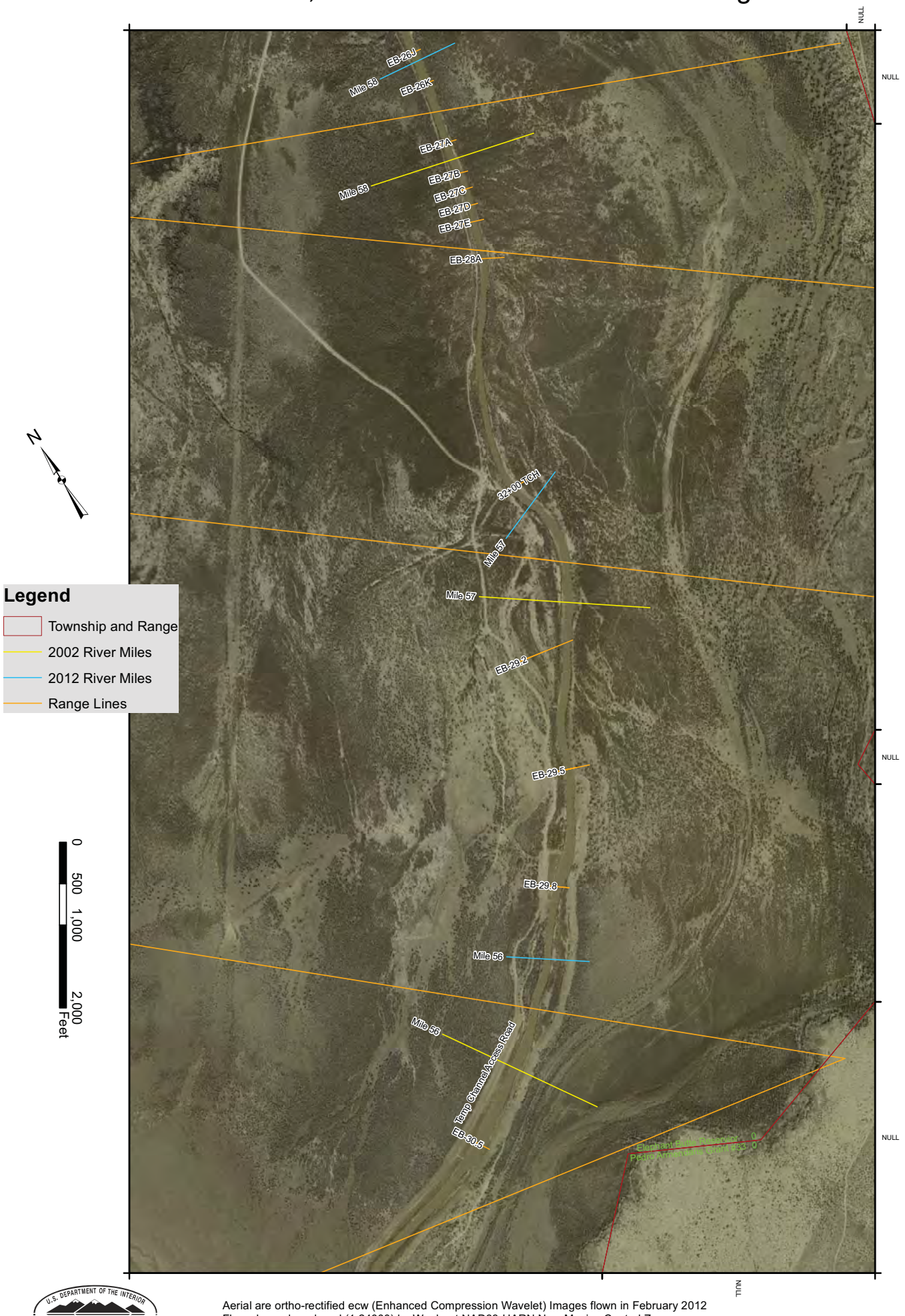
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



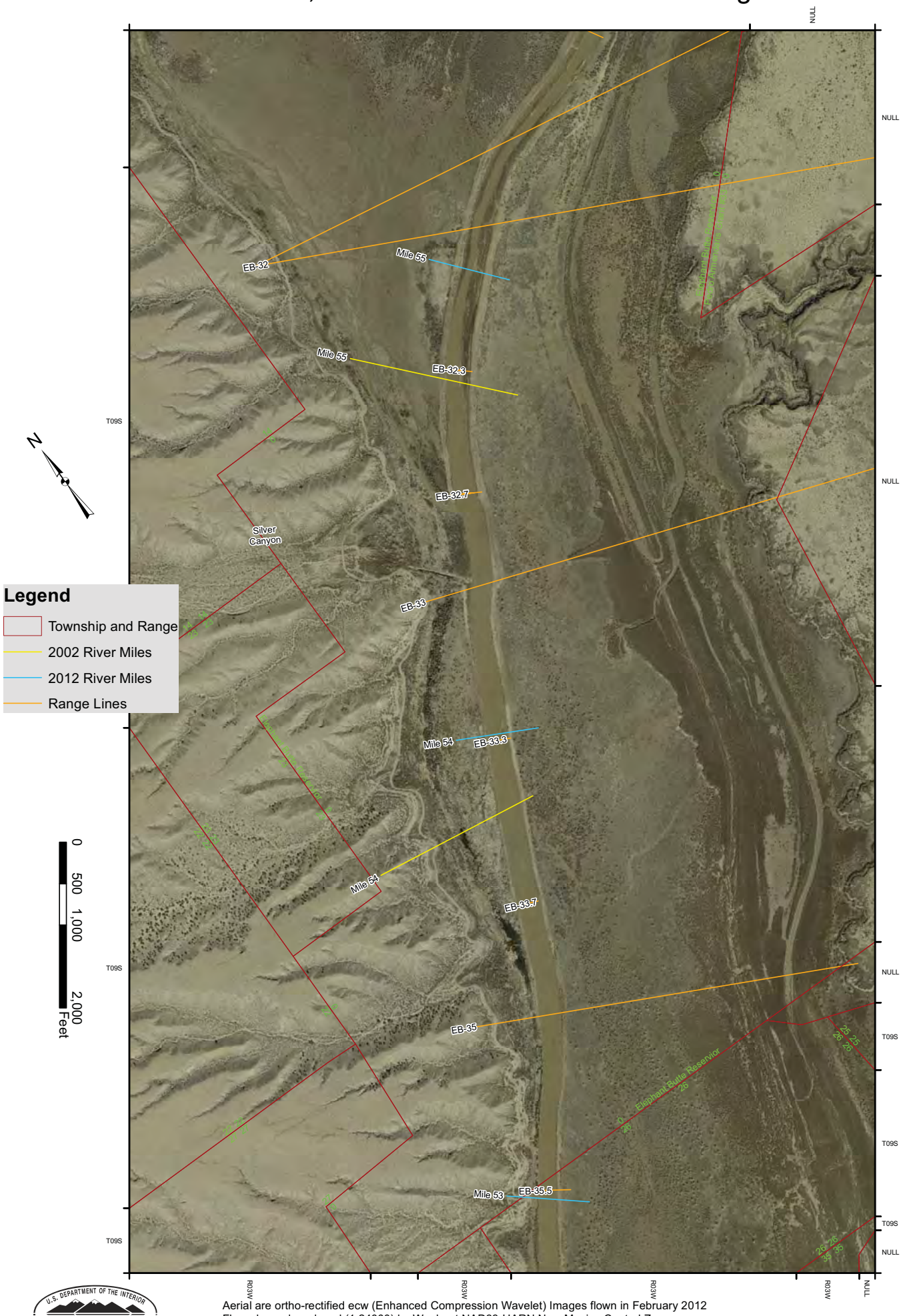
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



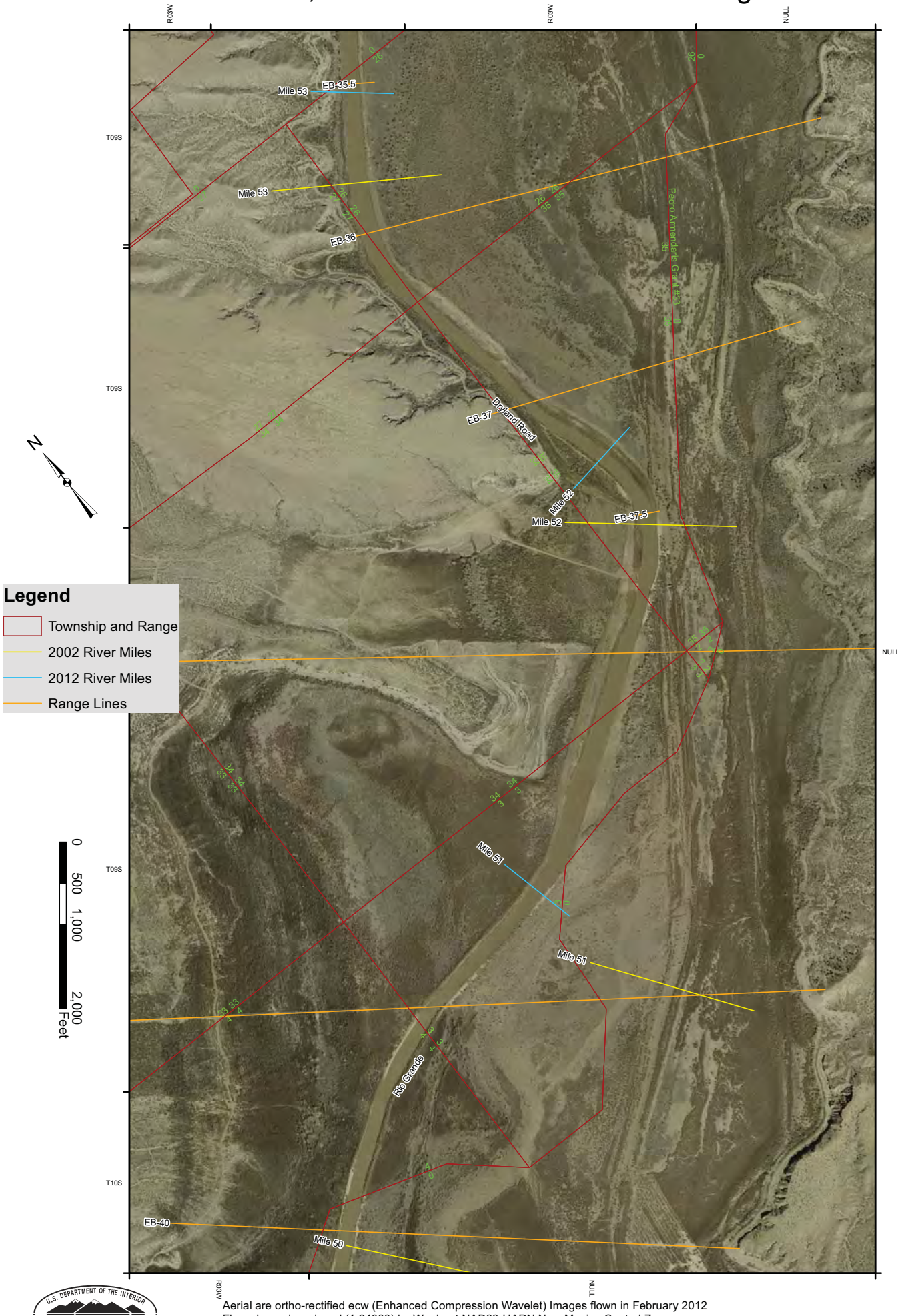
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



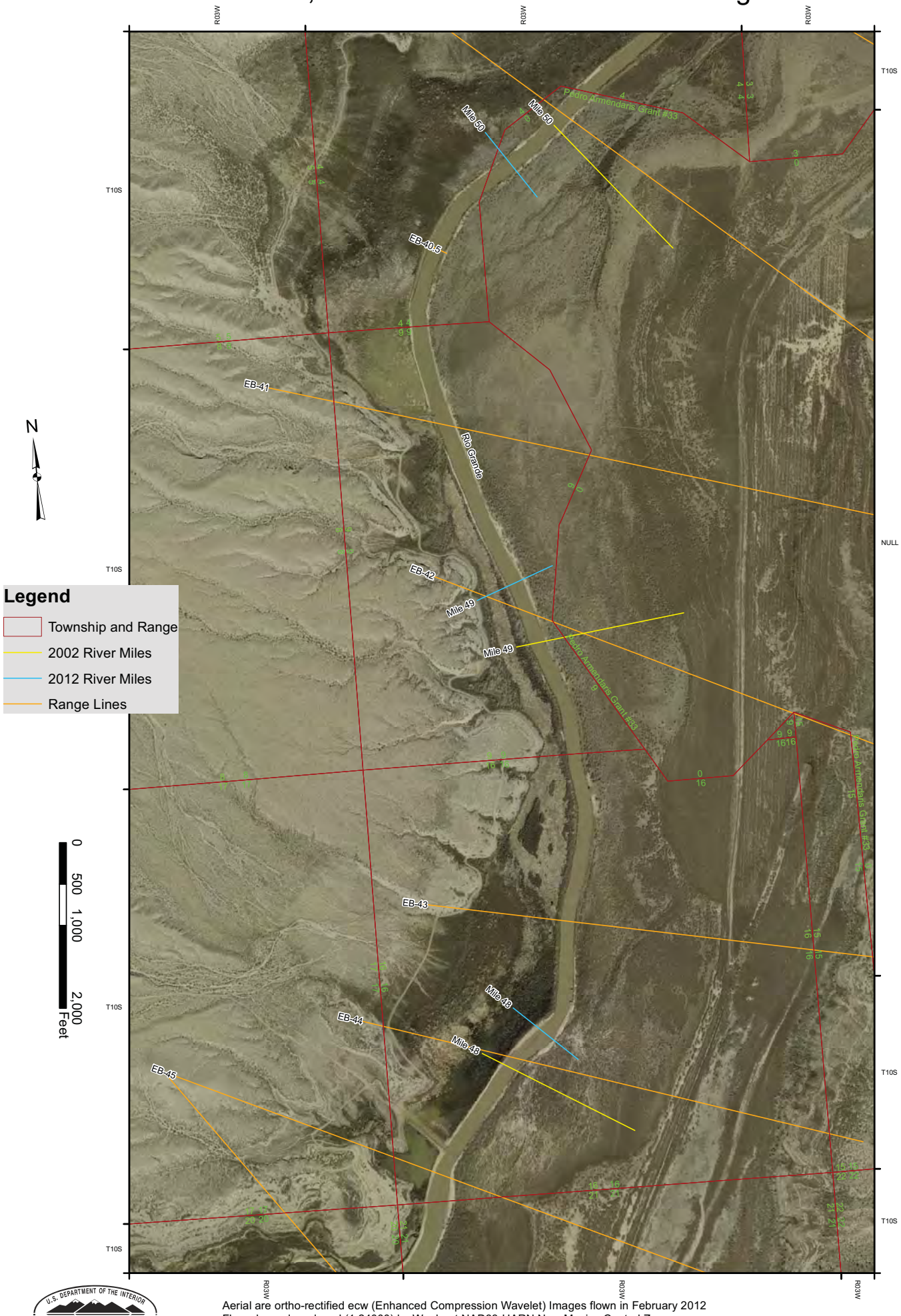
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



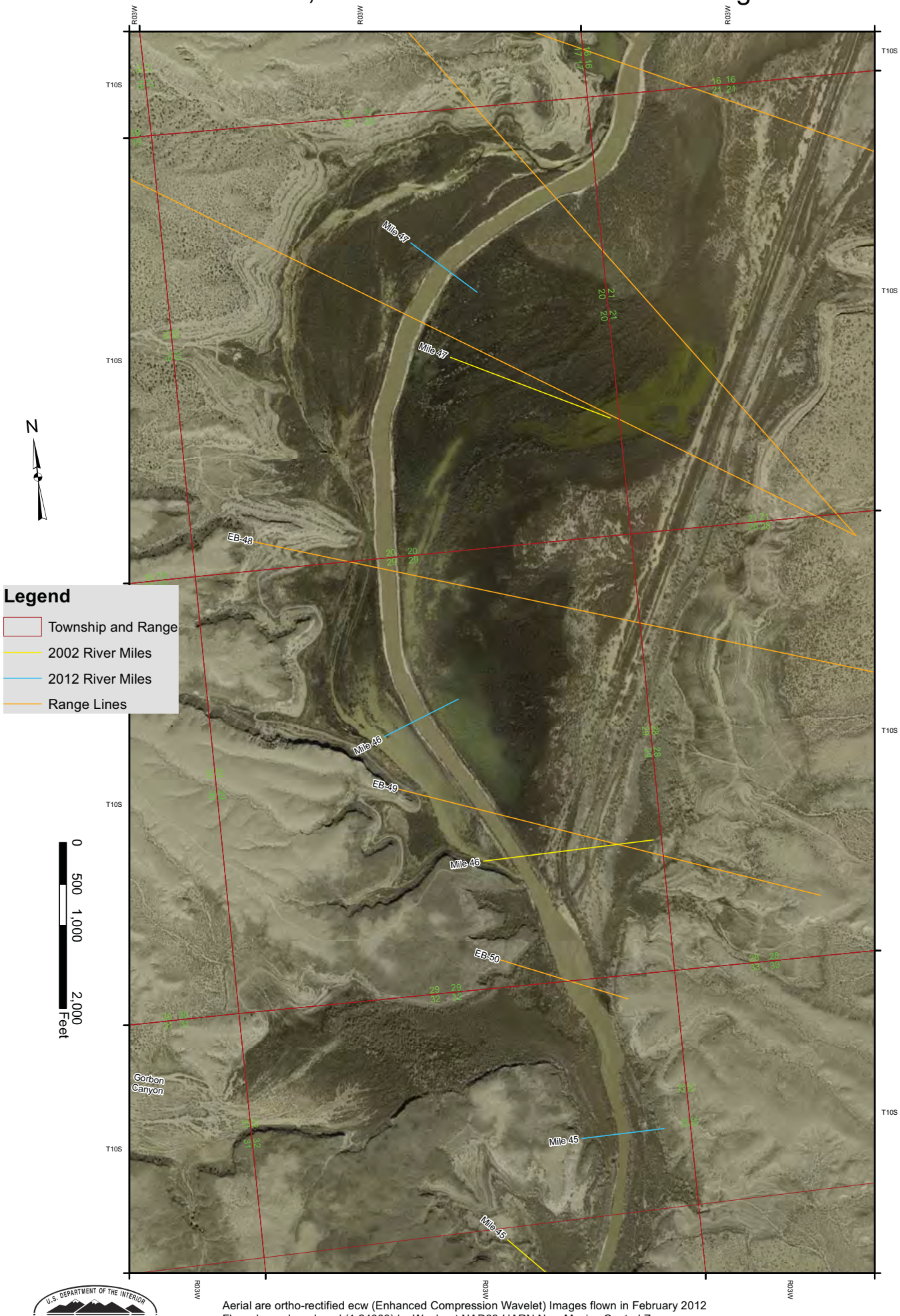
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



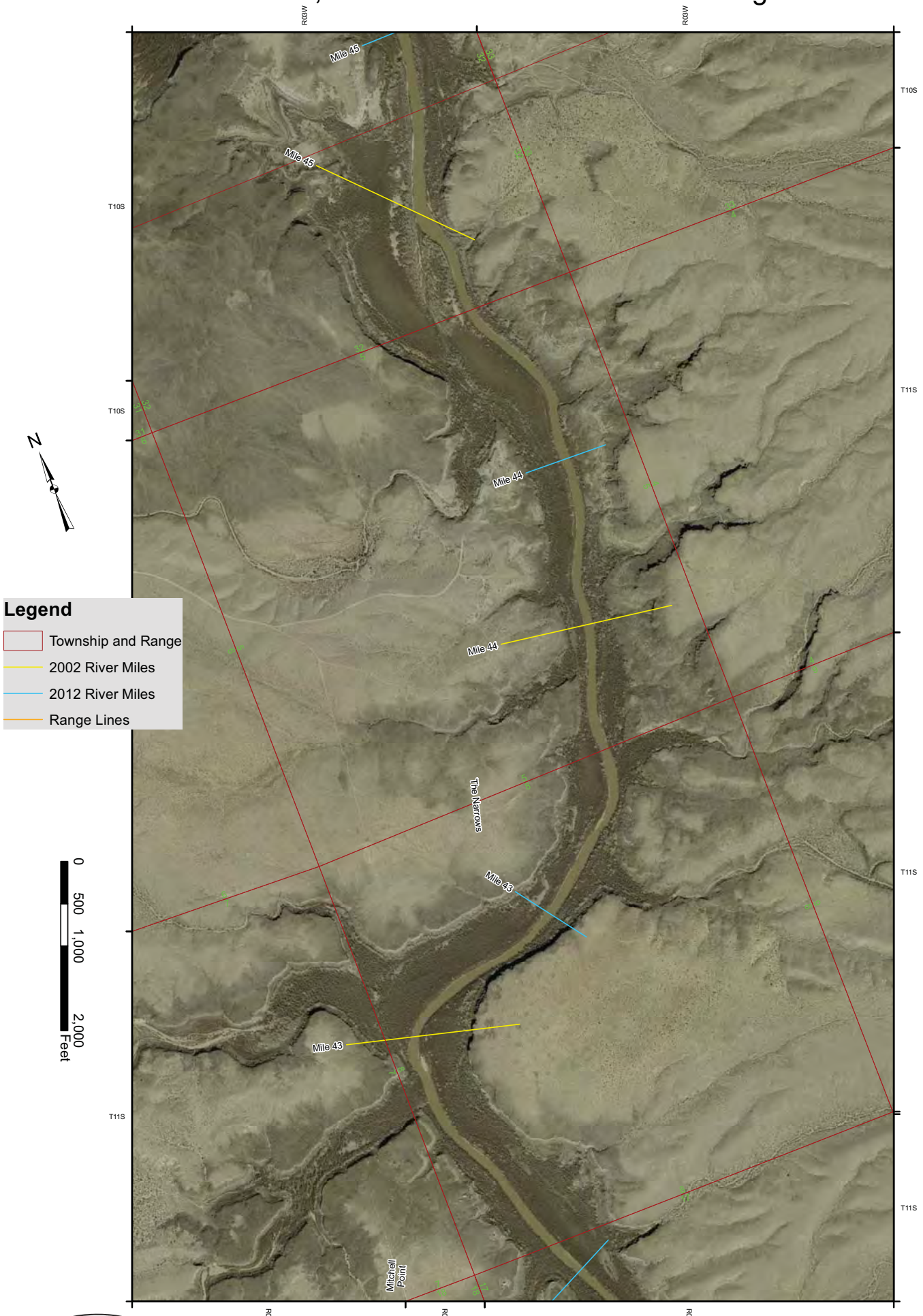
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



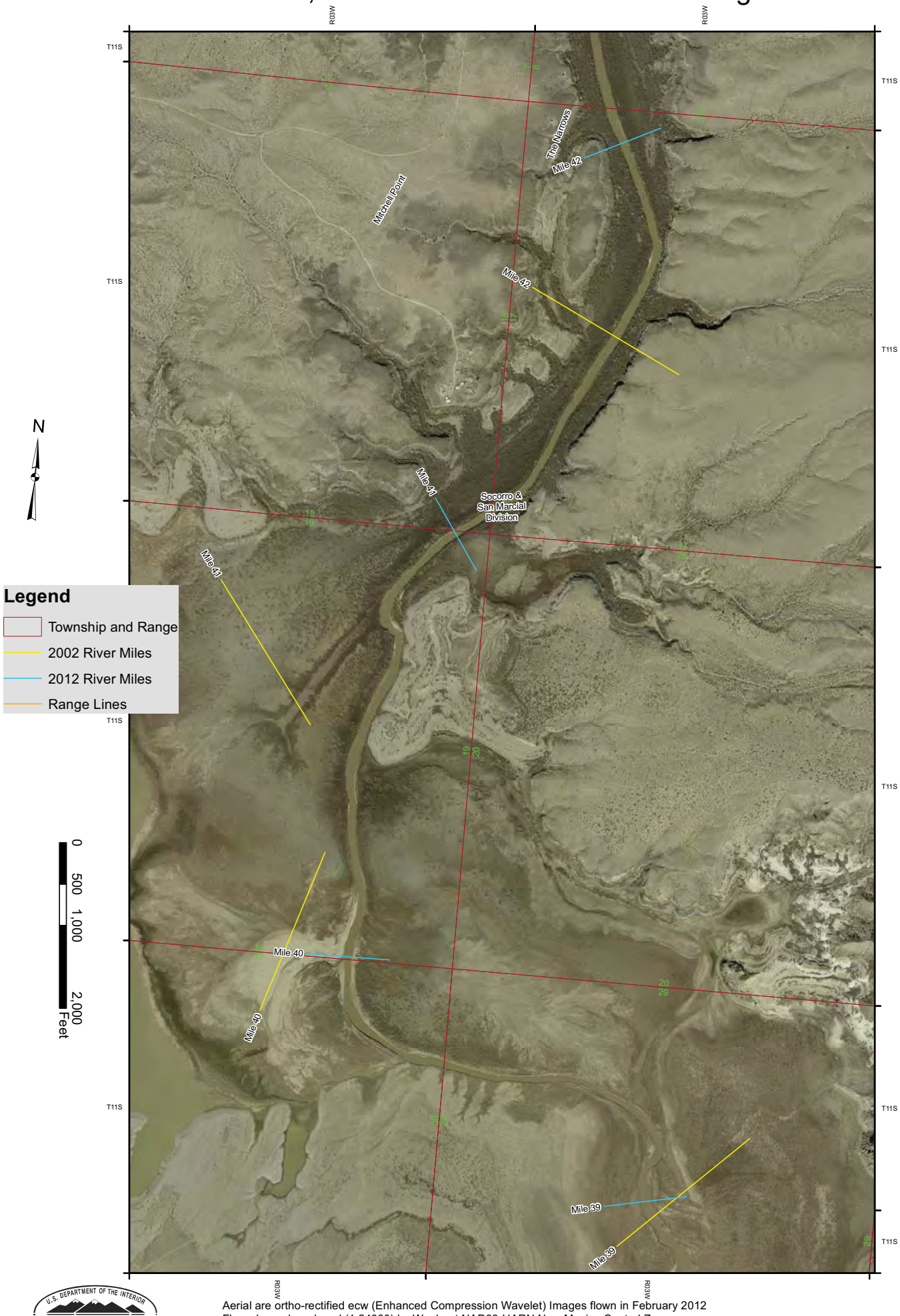
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



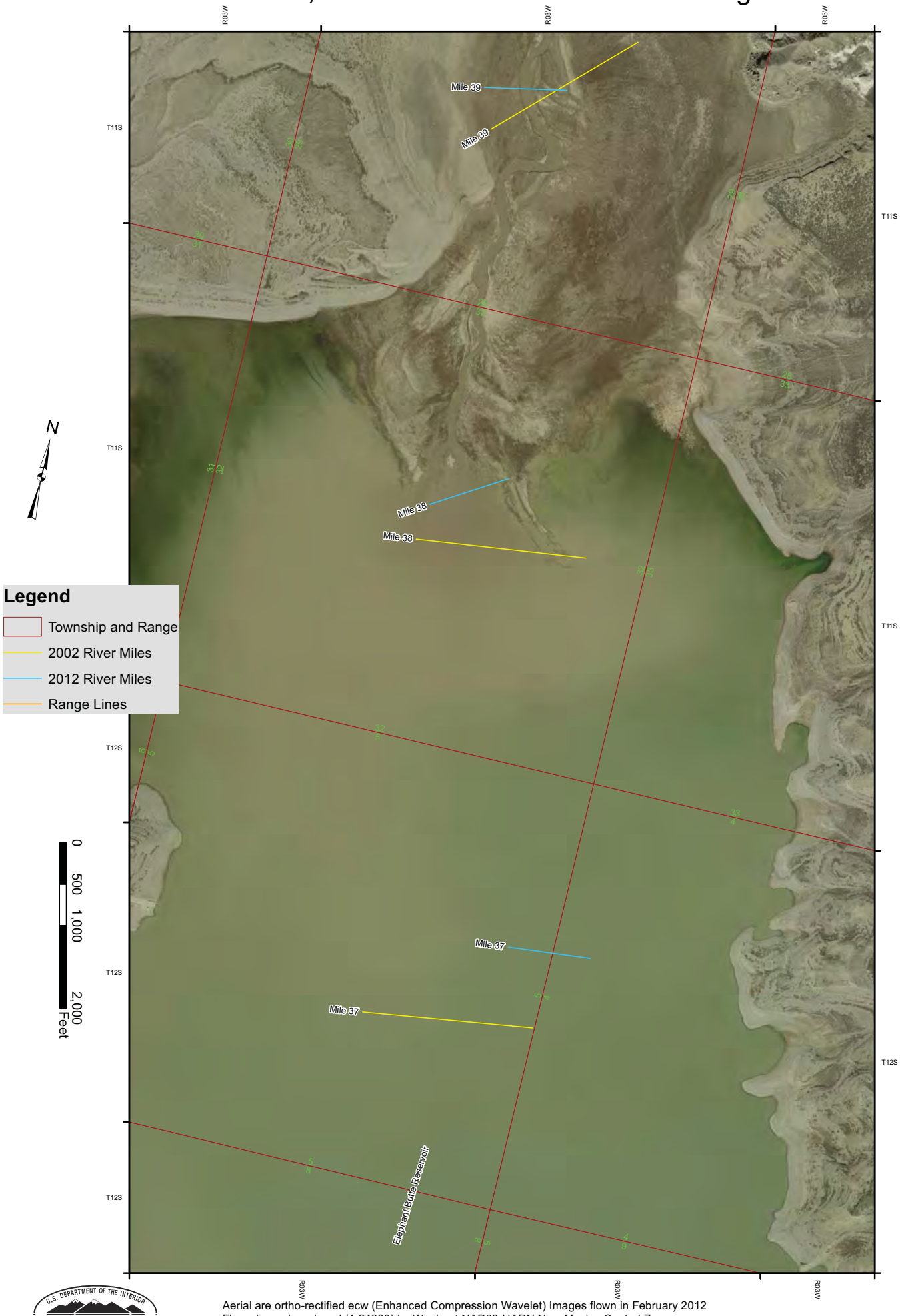
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



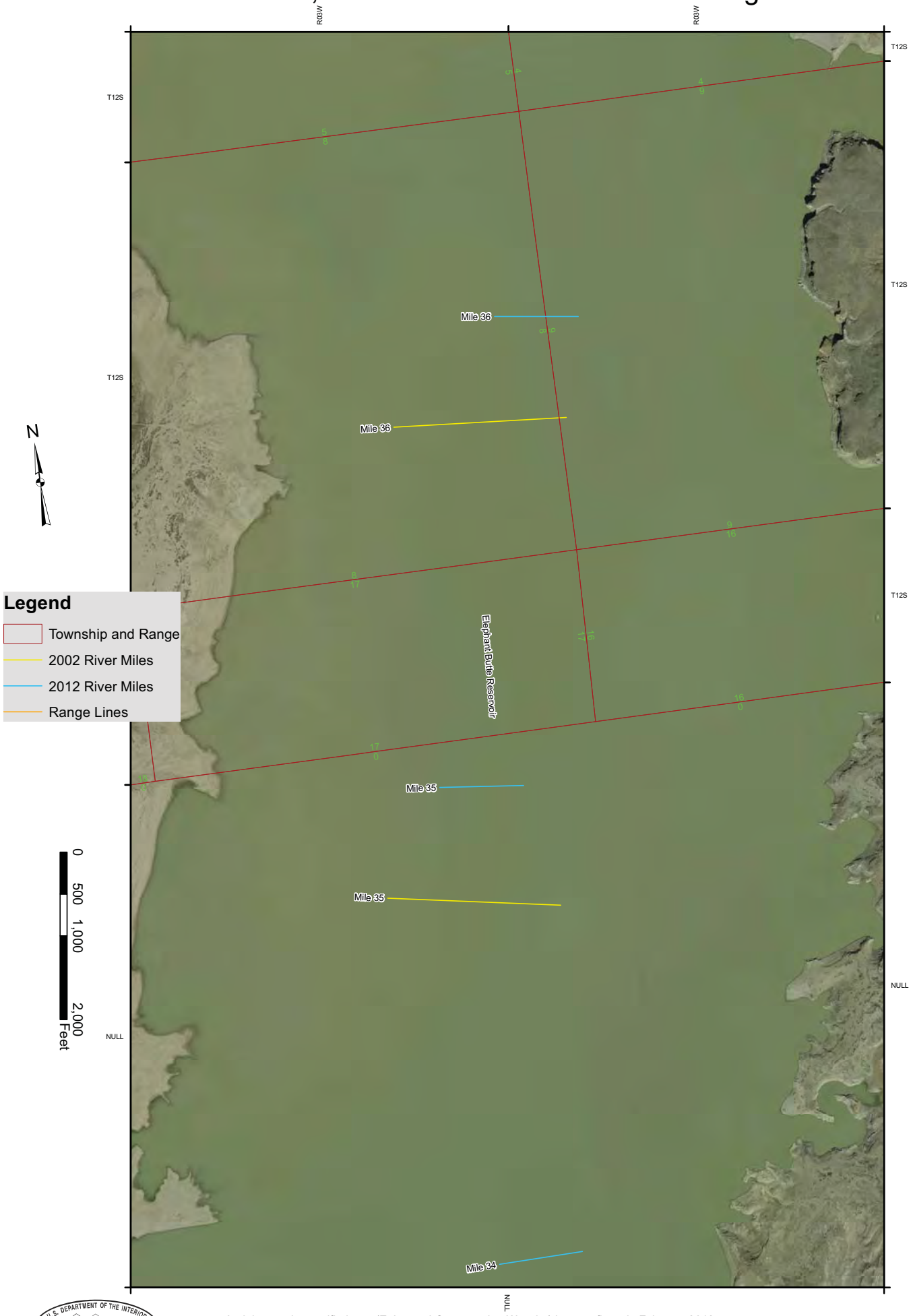
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



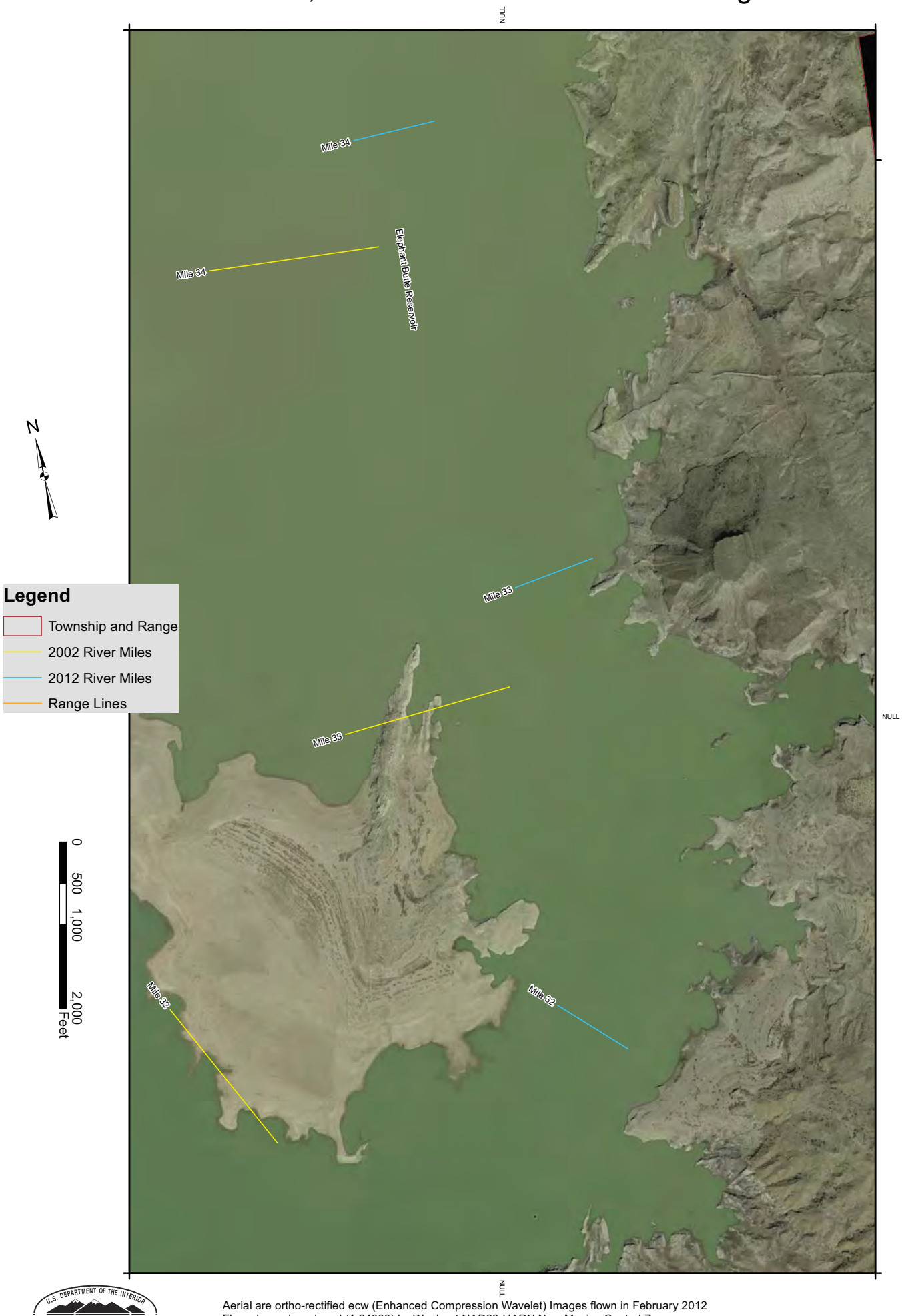
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



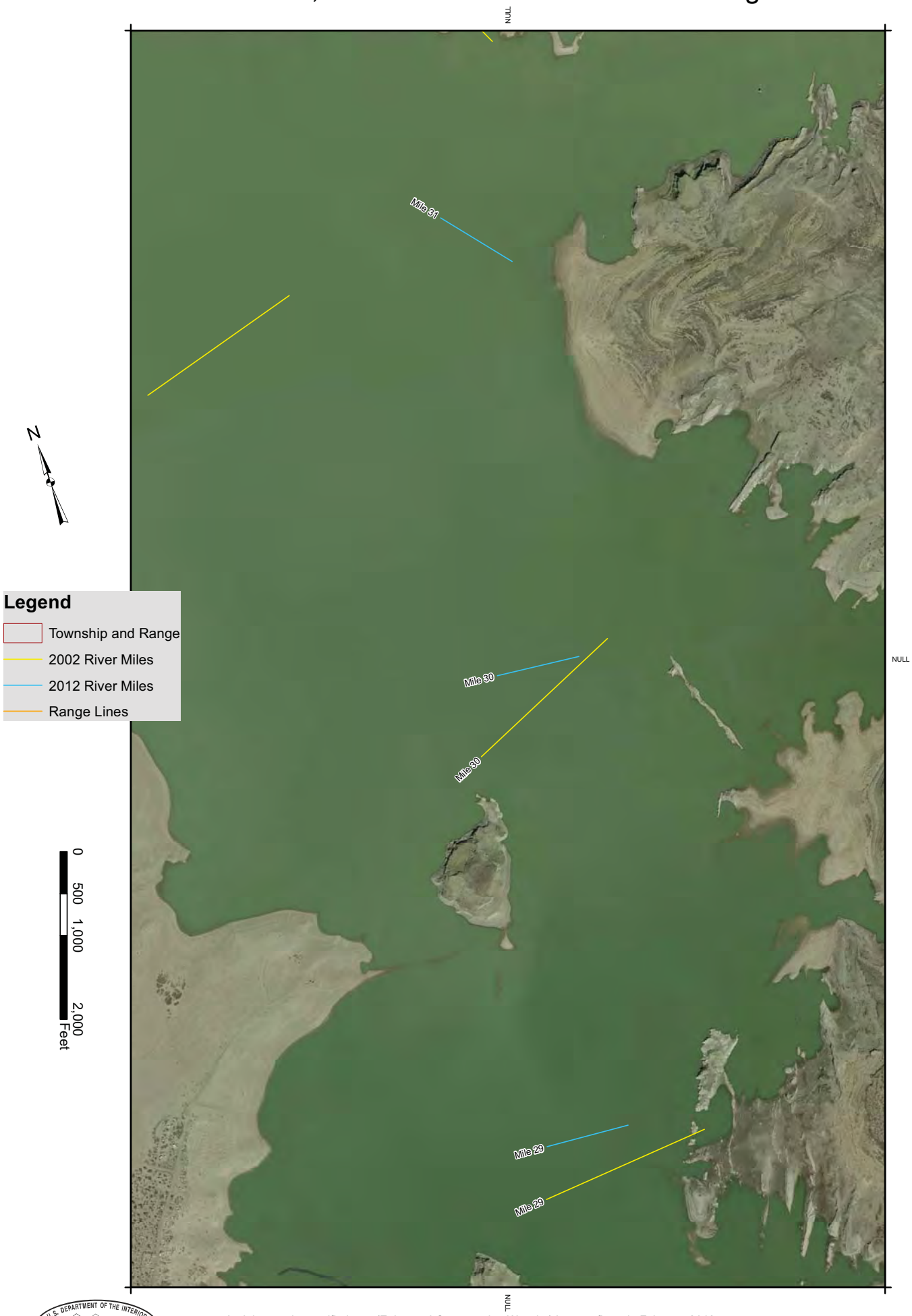
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



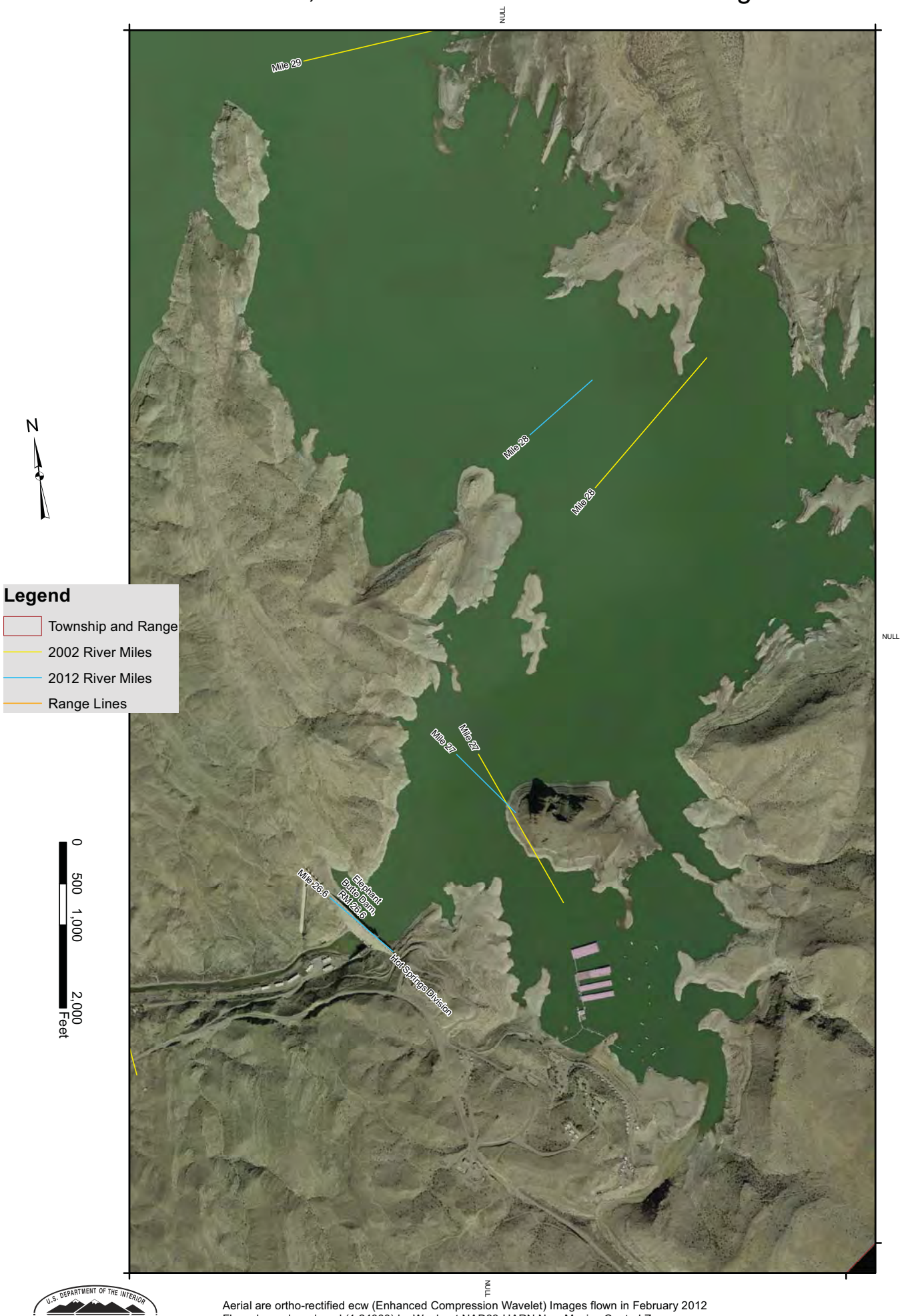
Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.

Middle Rio Grande, New Mexico: River Miles and Rangelines



Aerial are ortho-rectified ecw (Enhanced Compression Wavelet) Images flown in February 2012
Flown by and produced (1:24000) by Woolpert NAD83-HARN New Mexico Central Zone.
All line locations are from end point coordinates provided by Surveying Services, Inc.
PLSS information obtained from RGIS website, represents data collected by the BLM.
Produced by the Bureau of Reclamation.