RIO GRANDE CANALIZATION PROJECT
WATER BUDGET STUDY
Final Report
December 6, 2013

Appendix H

Unsteady HEC-RAS Modeling

Page Intentionally Blank

Table of Contents

List of Tables ii
List of Figures iii
1.0 Introduction 1
1.1 Study area 1
1.2 Purpose 1
2.0 HEC-RAS Model Development 2
2.1 Previous Studies 2
2.2 HEC-RAS Model Inputs 2
2.2.1 Geometry 2
2.2.2 Initial Conditions and Boundary Conditions 3
2.2.3 Computation Inputs 7
2.2.4 Computational Time 7
2.3 Model Calibration 7
2.3.1 Steady HEC-RAS Model with Updated Topography 8
2.3.2 Unsteady HEC-RAS Model: Initial Validation and Calibration 8
2.3.3 Unsteady HEC-RAS Model: Calibration with Seepage and Groundwater Return Flow 9
2.3.4 Comparison to Previous Seepage Studies 9
2.4 Unsteady HEC-RAS Model: Baseline Sensitivity Analyses 10
2.4.1 Sensitivity to Changes in K_{sat} 10
2.4.2 Sensitivity to Changes in Groundwater Inputs 10
2.4.3 Sensitivity to Changes in to River Sediment Thickness 11
2.5 Unsteady HEC-RAS Model: Hypothetical Irrigation Release Pulses 11
2.6 Unsteady HEC-RAS Model: Hypothetical Irrigation Releases Sensitivity Analyses 12
2.7 Unsteady HEC-RAS Model: Final Results with Return Flows 13
2.7.1 Results With Return Flows 13
2.7.2 Comparison of Results - Without and With Return Flows 13
2.8 Unsteady HEC-RAS Model: 2010 – 2012 Results with Return Flows 13
3.0 References 14
4.0 Tables 15
5.0 Figures 31

List of Tables

Table H-1. RGCP Segments 17
Table H-2. EBID River Gage River Station Table 17
Table H-3. Groundwater Monitoring Wells Utilized in HEC-RAS Model 18
Table H-4. Average Groundwater Depth at Groundwater Monitoring Wells Utilized in HEC-RAS Model 19
Table H-5. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions and Groundwater Interflow, March 31 to September 14, 2012 20
Table H-6. Comparison of Flow Volume, Gaged Hydrograph vs. Calibrated HEC-RAS Model Hydrograph 20
Table H-7. USGS Seepage Measurements 21
Table H-8. Sensitivity Analysis – K_{sat} Parameter Inputs 22
Table H-9. Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat} 22
Table H-10. Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat} 22
Table H-11. Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in Average Groundwater Depth 23
Table H-12. Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in River Sediment Thickness 23
Table H-13. Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in River Sediment Thickness 23
Table H-14. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions and Groundwater Interflow, Delayed Single-Pulse (S1) Hydrograph 24
Table H-15. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions and Groundwater Interflow, Normal Single-Pulse (S2) Hydrograph 24
Table H-16. S1, Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat} 25
Table H-17. S1, Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat} 25
Table H-18. S2, Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat} 25
Table H-19. S2, Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat} 25
Table H-20. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions, Returns, and Groundwater Interflow, March 31 to September 14, 2012 26
Table H-21. Comparison of Channel Seepage Results, Unsteady HEC-RAS Modeling without and with Return Flows, March 31 to September 14, 2012 26
Table H-22. Comparison of Flow Volumes, HEC-RAS Model Hydrographs without and with Return Flows, March 31 to September 14, 2012 26
Table H-23. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions and Groundwater Interflow, January 1, 2010 to September 14, 2012 27
Table H-24. HEC-RAS Modeling – File Summary 28

List of Figures

Figure H-1. Location of the Rio Grande Canalization Project 33
Figure H-2. HEC-RAS Model Coverage and Key Locations 34
Figure H-3. Caballo Release 2012 (Baseline) hydrograph - provided by the Rio Grande Project Allocation Committee. 35
Figure H-4. Caballo Release 2010-2012 Hydrograph – 2010 and 2011 provided by the USBR, 2012 (Baseline) provided by the Rio Grande Project Allocation Committee. 36
Figure H-5. S1 (Delayed Single-pulse) hydrograph, provided by the Rio Grande Project Allocation Committee. 37
Figure H-6. S2 (Normal Single-pulse) Hydrograph, provided by the Rio Grande Project Allocation Committee. 38
Figure H-7. Diversion Hydrographs at Percha Dam, Leasburg Dam, and Mesilla Dam, 2010 - 2012 .. 39
Figure H-8. Comparison of 2012 Caballo Release, Hypothetical Hydrographs, and Diversion Hydrographs at Percha Dam, Leasburg Dam, and Mesilla Dam 40
Figure H-9. Adjustment to 2012 Diversion Hydrographs at Percha Dam and Mesilla Dam for Delayed Single-Pulse (S1) 41
Figure H-10. Adjusted 2012 Diversion Hydrographs at Percha Dam and Mesilla Dam for Delayed Single-Pulse (S1) 42
Figure H-11. Adjustment to 2012 Diversion Hydrographs at Mesilla Dam for Normal Single-Pulse (S2) 43
Figure H-12. Adjusted 2012 Diversion Hydrograph at Mesilla Dam for Normal Single-Pulse (S2) 44
Figure H-13. Return Hydrographs at Nemexas Drain, West Drain, East Drain, Del Rio Drain, and La Mesa Drain 45
Figure H-14. Monitoring Well Locations 46
Figure H-15. HEC-RAS Groundwater Interflow Schematic 47
Figure H-16. HEC-RAS Groundwater Input Time Series Example Using EBID Well MES20R 48
Figure H-17. HEC-RAS Channel Invert and Average Groundwater Elevation Profiles 49
Figure H-18. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Sibley Arroyo. 50
Figure H-19. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Jaralosa Arroyo. 51
Figure H-20. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Yeso Arroyo. 52
Figure H-21. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Angostura Arroyo. 53
Figure H-22. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Rincon Arroyo. 54
Figure H-23. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Reed Arroyo. 55
Figure H-24. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Bignell Arroyo. 56

Figure H-25. Comparison of measured flow at the Leasburg gage and the hydrograph predicted by the initial HEC-RAS unsteady flow model with diversions for the period between March 31 and September 14, 2012. 57
Figure H-26. Comparison of measured flow at the Mesilla gage and the hydrograph predicted by the initial HEC-RAS unsteady flow model with diversions for the period between March 31 and September 14, 2012. 58
Figure H-27. Comparison of measured flow at the El Paso gage and the hydrograph predicted by the initial HEC-RAS unsteady flow model with diversions for the period between March 31 and September 14, 2012. 59
Figure H-28. Comparison of measured flow at the Leasburg gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions and groundwater interflow (seepage and groundwater return flow) for the period between March 31 and September 14, 2012........ 60
Figure H-29. Comparison of measured flow at the Mesilla gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions and groundwater interflow (seepage and groundwater return flow) for the period between March 31 and September 14, 2012........ 61
Figure H-30. Comparison of measured flow at the El Paso gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions and groundwater interflow (seepage and groundwater return flow) for the period between March 31 and September 14, 2012........ 62
Figure H-31. Baseline 2012 Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat} 63
Figure H-32. Baseline 2012 Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat} 64
Figure H-33. Baseline 2012 Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in Sediment Thickness........ 65
Figure H-34. Baseline 2012 Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in Sediment Thickness........ 66
Figure H-35. Comparison of Delayed Single-Pulse Hydrographs predicted by the initial HEC-RAS unsteady flow model with groundwater and diversions at Leasburg, Mesilla, and El Paso........ 67
Figure H-36. Comparison of Normal Single-Pulse Hydrographs predicted by the initial HEC-RAS unsteady flow model with groundwater and diversions at Leasburg, Mesilla, and El Paso........ 68
Figure H-37. Delayed Single-Pulse Hydrograph (S1) Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat} 69
Figure H-38. Delayed Single-Pulse Hydrograph (S1) Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat} 70
Figure H-39. Normal Single-Pulse Hydrograph (S2) Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat} 71
Figure H-40. Normal Single-Pulse Hydrograph (S2) Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat} 72

Figure H-41. Comparison of measured flow at the Leasburg gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions, return flows, and groundwater interflow (seepage and groundwater return) for the period between March 31 and September 14, 2012 73
Figure H-42. Comparison of measured flow at the Mesilla gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions, return flows, and groundwater interflow (seepage and groundwater return) for the period between March 31 and September 14, 2012 74
Figure H-43. Comparison of measured flow at the El Paso gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions, return flows, and groundwater interflow (seepage and groundwater return) for the period between March 31 and September 14, 2012 75

Page Intentionally Blank

1.0 INTRODUCTION

1.1 STUDY AREA

The Rio Grande Canalization Project (RGCP) is a 106.8-mile-long[1] river corridor that conveys Rio Grande flows from Caballo Dam in Sierra County, New Mexico, to the American Dam in El Paso County, Texas. Flow releases from the upstream Elephant Butte and Caballo Dams are conveyed by the RGCP for use in irrigation, water supply and also to meet the requirements of equitable distribution of the Rio Grande waters with Mexico based on the Convention of May 21, 1906, entitled “Equitable Distribution of the Waters of the Rio Grande.”

The hydraulic modeling discussed in this appendix covers the RGCP from Caballo Dam at the upstream end (River Station 5646+39.1) to a point just above American Dam at the downstream end (River Station 0+00.457). The study reach is shown in Figure H-1 and the major components or landmarks are shown in schematically in Figure H-2. The RGCP is subdivided into the following segments:

- Segment 1 - Caballo Dam to Leasburg River Cable metering station
- Segment 2 - Leasburg River Cable metering station to Mesilla Dam
- Segment 3 - Mesilla Dam to the Anthony metering station
- Segment 4 - Anthony metering station to the Below American Dam gage.

The lengths for each segment are summarized in Table H-1.

1.2 PURPOSE

This appendix documents the development of a one-dimensional (1-D) hydraulic model for the RGCP using the USACE Hydrologic Engineering Center (HEC) River Analysis Software (RAS) version 4.1. The HEC-RAS model was used to estimate water-surface elevations for unsteady flows that were based on reservoir releases, diversions, and returns, and to estimate losses or gains to the channel flows from groundwater interactions.

The following sections summarize previous studies, model development, steady-state model calibration for known discharges and water-surface elevations, and unsteady model calibration to observed outflow hydrographs during the 2012 irrigation season (March 21 through September 14; Figure H-3). The calibrated model is then used to evaluate actual outflow hydrographs from Caballo Reservoir in 2010 through 2012 (January 1, 2010 through September 14, 2012; Figure H-4) and two hypothetical outflow hydrographs: Delayed Single-Pulse Hydrograph (S1) shown in Figure H-5, and the Normal Single-pulse Hydrograph (S2) shown in Figure H-6. The hypothetical hydrographs are evaluated during the irrigation season in 2012.

[1] The reported length of the RGCP varies from 105.4 miles for the reach between Percha Dam and American Dam (USIBWC 2012a) to 106.8 miles for the Reach between Caballo Dam and American Dam (RGPAC 2012). Unless otherwise noted, references to the RGCP in this appendix refer to the longer reach.

2.0 HEC-RAS MODEL DEVELOPMENT

2.1 PREVIOUS STUDIES

Mussetter Engineering Incorporated (MEI), which is now Tetra Tech/MEI, prepared HEC-RAS modeling of the RGP for the USIBWC in 2007 (MEI and Riada 2007). USIBWC provided a revised version of the model, dated 2008, for use as a starting point in this analysis. The 2008 USIBWC model is understood to be the most recent hydraulic model that covers the project reaches and was updated based on proposed levee improvements within the project reach.

2.2 HEC-RAS MODEL INPUTS

The steady-state version of the 2008 USIBWC model was used for initial calibrations based on known discharges and known water-surface elevations. For purposes of the channel seepage analysis, the 2008 USIBWC model was expanded to include unsteady inflows and outflows, and a component for seepage (groundwater interaction). Changes to the model inputs are summarized in the sections below.

In performing the conversion, Tetra Tech noted a number of data-entry errors that prohibited a complete execution of the unsteady-flow runs. Some of these errors may have resulted from changing to an unsteady approach or from running the model with the most recent version (version 4.1) of the HEC-RAS software. The input files and resulting error files were reviewed and the input data was corrected.

2.2.1 Geometry

Cross Sections

The geometry inputs for the 2012 modeling were updated to incorporate LiDAR-based, bare-earth, 1-meter DEM topography that was developed by Tetra Tech for the USIBWC in August 2011. The 1-meter DEM was originally provided in the UTM coordinate system but was re-projected to New Mexico State Plane NAD83 coordinates. The original elevations were in meters (NAVD88) and were converted to feet (NAVD88). The updated topography covered the area from the Doña Ana County boundary south to American Dam (River Station 5259+28 to 0+00.457). The updated topography did not cover the RGP reach from Caballo Dam south to the Doña Ana County line (River Station 5646+39.1 to 5259+28).

The updated LiDAR topography did not include bathymetric data and did not accurately define the channel invert below the water surface at the time of LiDAR survey. Channel invert elevations were manually adjusted so that the steady-flow calibration of the new model reasonable matched surveyed water-surface elevations.

River Stationing

River Station (RS) distances were changed to reflect the distance to the next downstream RS. Erroneous values were identified and corrected by comparison with the geographically referenced RS.

Bank Stations, Levees, and Ineffective Flow Features

Bank stations were adjusted to match the geomorphic top-of-bank at each cross section. Existing levees and/or ineffective flow features within each cross-section were understood to be current as updated by the USIBWC and were not modified.

Inline Structures

The USIBWC 2008 model included inline structures for Percha Dam, Leasburg Dam, and Mesilla Dam. The inline structures in the 2008 IBWC model were used without modification.

2.2.2 Initial Conditions and Boundary Conditions

Initial Conditions

Initial flow conditions were specified at each cross section. Initial flows inputs were generally 25 cfs, but were varied between 20 cfs and 30 cfs to allow for optimization of split flows for the initial backwater calculations.

Upstream Boundary Condition

The upstream boundary condition was specified as an inflow hydrograph. For the baseline modeling and the sensitivity analyses, the inflow hydrograph was the 2012 release from Caballo Dam, as provided by the Rio Grande Project Water Allocation Committee (RGPAC). The inflow hydrograph for 2010-2012 analysis included the 2010 and 2011 hydrographs provided by the USBR and the 2012 hydrograph from the RGPAC. Plots of the 2012 and 2010 – 2012 Caballo releases are shown in Figure H-3 and Figure H-4 respectively. Raw data for Caballo Dam outflows are shown in **Appendix B, Table B-4.** Flow data that was processed to account for missing flows and spurious data are summarized in **Appendix B, Table B-5**.

Hydraulic analyses were also conducted for a delayed single-pulse hydrograph (Release Scenario S1) and a normal single-pulse hydrograph (Release Scenario S2). Plots of the hypothetical inflow hydrographs provided by the RGPAC and are included in Figure H-5 and Figure H-6 respectively.

Each of the inflow hydrograph records included a minimum flow value of 25 cfs to provide numerical stability for the unsteady-flow computations.

Downstream Boundary Condition

The downstream boundary condition in the 2008 USIBWC model was based on a rating curve for flows over the crest of American Dam, which is coded as cross section 0+00.457. The rating-curve boundary condition proved unstable during preliminary modeling and was therefore replaced with a normal-depth boundary condition using a friction slope of 0.005 feet/feet, which is consistent with the average bed slope in the reach and with previous models.

Internal Boundary Condition - Diversions

The flow diversions at Percha Dam, Leasburg Dam, and Mesilla Dam were modeled as inflow hydrographs using negative values to replicate the flow diverted out of the system. The combined diversion hydrographs at each structure are based on USBR records from January 1, 2010 through July 31, 2012, and gage records downloaded from the EBID website for August 1, 2012 through September

14, 2012 (**Appendix B, Table B-3**). The diversion hydrographs for 2010 through 2012 are plotted (as positive values) in Figure H-7.

Figure H-8 compares the diversion hydrographs for the 2012 season with the inflow hydrographs from Caballo Dam, the delayed single-pulse hydrograph (Release Scenario S1), and a normal single-pulse hydrograph (Release Scenario S2).

In the HEC-RAS unsteady method, it is important that the diversions match up with the inflow hydrographs. Otherwise, there is a potential that seepage component (discussed below) will dry out the channel and the computations will fail. There were three instances where this issue required adjustments to the diversion inputs.

1) Initial runs for the 2012 Caballo release showed model failure in mid-May, which resulted from a diversion at Percha Dam that started during a no-release period at Caballo Dam (see circled note on Figure H-8). The problem was addressed by shifting the Percha Dam diversion between May 16, 2012 and July 7, 2012 two days into the future so that it better matched the outflow from Caballo Dam.

2) The delayed single-pulse hydrograph (Release Scenario S1) does not provide inflow between March 31, 2012 and May 30, 2012 and the HEC-RAS unsteady flow computations are based entirely on the minimum inflow value of 25 cfs. The April and May diversions at Percha Dam and Mesilla Dam exceed the minimum flow and effectively dry out the channel, resulting in a computational failure. To address this problem, the diversions flows between March 31 and May 31 were set to zero and the loss in diversion volume was made up by uniformly increasing the diversion flows between May 31, 2012 and September 14, 2012. At Percha Dam the diversion flows prior to May 30, 2012 totaled 8,290 acre-feet and were made up by adding 39.1 cfs/day to the Percha diversion between May 31, 2012 and September 14, 2012. At Mesilla Dam the diversion flows prior to May 30, 2012 totaled 4,580 acre-feet and were made up by adding 26.1 cfs/day to the Mesilla diversion between May 31, 2012 and September 14, 2012. The diversion adjustments are shown graphically in Figure H-9. The adjusted diversions at Percha Dam and Mesilla Dam, and the diversion at Leasburg Dam, which requires no adjustment, are compared against the delayed single-pulse hydrograph (Release Scenario S1) in Figure H-10.

3) In the normal single-pulse hydrograph (Release Scenario S2) the 2012 diversion flows exceed the S2 inflows during two periods: June 6, 2012 to June 10, 2012 and July 25, 2012 to August 14, 2012. As a result, initial model runs were unbalanced with outflows exceeding inflows during these periods. To address this problem, the diversion flows at Mesilla Dam from June 5, 2012 to June 12, 2012 and July 24, 2012 to August 14, 2012 were adjusted so that they did not exceed the S2 inflows. The flow reduction, which totaled 25,437 acre-feet was accounted for by adding 242 cfs/day to the Mesilla diversion from April 12, 2012 to June 19, 2012 and from June 19, 2012 and July 14, 2012. The adjustments are shown graphically in Figure H-11. The adjusted diversion at Mesilla Dam, and the diversions at Percha Dam and Leasburg Dam, which require no adjustment, are compared against the delayed single-pulse hydrograph (Release Scenario S2) in Figure H-12.

Internal Boundary Condition - Returns (Irrigation Drains)

Irrigation return flow records are only available at five locations along the RGCP (Figure H-1):

- La Mesa Drain – Segment 2
- Del Rio Drain – Segment 3
- Nemexas Drain – Segment 4
- East Drain – Segment 4
- West Drain – Segment 4

The irrigation return flows modeled as lateral inflow hydrographs based on EBID records from January 1, 2010 through September 14, 2012 (**Appendix B, Table B-1**). The irrigation return flows hydrographs for 2010 through 2012 are plotted (as positive values) in Figure H-13.

Internal Boundary Condition - Groundwater Interflow

Once the initial model and surface water inputs were running within the desired tolerance, groundwater interflow was added as an additional boundary condition to estimate channel seepage and groundwater return flow.

Twenty-eight monitoring wells along the RGCP were selected from data provided by the USGS and EBID (See **Appendix A** to the main report). Well locations and well data are summarized in Figure H-14 and Table H-3.) Each well is assigned to a segment of the river that is bounded by upstream and downstream cross sections in the HEC-RAS model. The river segments assigned to each well were selected by geographic proximity to the wells. The resulting lengths of the 28 river segments vary from 0.8 miles to 12.2 miles.

Groundwater interactions in the HEC-RAS model are computed using the Darcy Equation:

$$Q = K_s * \frac{dh}{dx} * A, where\ A = \frac{T_{us} + T_{ds}}{2} * L$$

Where Q = interflow (ft^3/day), h = depth (feet) from water-surface elevation to the ground water elevation, x = the horizontal distance to the well (feet), A = area (feet^2), and K_{sat} = saturated hydraulic conductivity of the stream sediments (feet/day). Area A is calculated from T_{us} = flow top width upstream, T_{ds} = flow top width (feet) downstream, L = distance (feet) from the downstream cross section to the upstream cross section.

Alternatively, the Darcy Equation can be written:

$$Q = K_s * \frac{dh}{dy} * A, where\ A = \frac{T_{us} + T_{ds}}{2} * L$$

Where Q = interflow (ft^3/day), h = depth (feet) from water-surface elevation to the ground water elevation, y = the vertical thickness (feet) of river sediments, K_{sat} = saturated hydraulic conductivity of the river sediments (feet/day), and A is the same as above.

Inputs for HEC-RAS groundwater interflow include:

- Time series of groundwater elevations at the selected monitoring wells along the RGCP. Erroneous data and gaps within the groundwater well stage-time series were interpolated within HEC-RAS model using the *interpolate-missing-values* feature.
- Distance from the well to the low-flow channel (X) or the thickness of the stream sediments (y) if the groundwater elevations are available at the river.
- Saturated hydraulic conductivity (K_{sat}) was treated as a calibration parameter and was varied on a reach by reach basis to match surface flows in the HEC-RAS model with recorded gage data. The initial value of K_{sat} was 0.114 feet/day. This is consistent with the initial "vertical hydraulic conductivity" (K') that was used for conductance calculations in the URGWOM Technical Completion Report (USACE 2012). A copy of the relevant page from the URGWOM Technical Completion Report is included in **Appendix M.**

The top-width parameters are obtained from the cross sections at the upstream and downstream limit of each well and the length parameter is the channel distance between the bounding cross sections.

In preliminary runs, the wells were coded according to their location on the floodplain and the distance parameter dx was based on the horizontal distance to the well, which varies from 150 to 6,400 feet (Table H-3). Given that changes in surface and groundwater elevations were generally within about 10 feet, the resulting gradient dh/dx was quite low and led to unreasonable values of K_{sat} during initial calibration. It was also noted that groundwater levels at distant wells may not interact with, or be entirely representative of groundwater levels at the channel.

Consequently, the groundwater interflow approach was modified to assume that groundwater elevations could be characterized at the river and the groundwater interflow inputs were changed to the vertical approach in which the gradient dh/dy is based on the vertical thickness (feet) of the river sediments. For this analysis, the thickness of the river sediments was assumed to be 5 feet. This is consistent with the initial "riverbed thickness" used for the conductance calculations in the URGWOM Technical Completion Report (USACE 2012). A copy of the relevant page from the URGWOM Technical Completion Report is included in **Appendix M.**

The depth to groundwater at a given location was estimated using measured groundwater levels collected at RGCP restoration sites in June and July 2010 (USIBWC, 2010). The averages of the measured depths below the river bed at each site varied from 2.1 to 4.7 feet, and are summarized in Table H-4. The average for the overall reach was about 3 feet. The variation in groundwater depth (i.e., the time series) over the irrigation season was developed by applying the temporal pattern (i.e., the change depth) of the groundwater hydrographs at each well to this initial depth from the restoration site that corresponded to each well. Typical well records show an increase in groundwater levels between March 31 and September 14 and the average depth would typically occur near the end of June, when the 2010 groundwater depths were measured in the field. For simplicity, it is assumed that average depth within the groundwater hydrographs would correspond with the average depth for each well as shown in Table H-4. This approach is summarized graphically in Figure H-15 and a plot of a typical well input using EBID Well MES20R is shown in Figure H-16.

It is important to note that the groundwater elevation data assigned to a given river segment is associated with the downstream cross section, and does not vary within the segment. Thus, the depth to groundwater within a river segment can vary greatly from the downstream end to the upstream end. A profile comparing the HEC-RAS channel invert to the average groundwater levels (3 feet below the channel invert at the downstream cross section) are shown in Figure H-17.

Internal Boundary Condition - Gates

An internal boundary for a gate was included to allow for flow diversions at Mesilla Dam. Gate operation was not included within the unsteady-flow simulations, rather the gates were set open to 14 feet to allow the passage of the incoming flow. This simplification limits the accuracy of water-surface elevations in a short reach affected by backwater upstream of Mesilla Dam, but was appropriate for purposes of developing the groundwater interflow estimates. The combined diversions to the Eastside and Westside Canals and to the Del Rio Lateral were coded separately in as negative lateral inflows at Mesilla Dam.

2.2.3 Computation Inputs

Time Step

The computational time step was computed as 3.2 minutes based on the average channel cross-sectional spacing (482 feet) divided by the average velocity (2.5 feet/second) from the steady-flow calibration run. A rounded value of 3 minutes was adopted as the maximum time step for model computation. For some of the models, time steps as low as 15 seconds were required for numerical stability.

Tolerances

The allowable water-surface tolerance was set at 0.5 feet for numerical stability purposes and to reduce the model execution run times.

2.2.4 Computational Time

The computation time for the HEC-RAS unsteady analyses varied from about 1 hour for models based on the 2012 irrigation season to 3.5 hours for analyses based on the 2010 thorough 2012 records.

2.3 MODEL CALIBRATION

Model calibration was conducted at several steps along the model development process. The steps where calibration of the model occurred are listed below and discussed in the following sections.

- Development of a steady-flow model with updated topography.
- Development of an unsteady-flow model with upstream inflows and diversions.
- Development of the unsteady-flow model with upstream inflows, diversions, and groundwater interflow.

A list of the HEC-RAS input files is provided in Table H-24.

2.3.1 Steady HEC-RAS Model with Updated Topography

The steady-flow model included the updated topography and a range of steady-state discharges that vary from 1,560 cfs to 3,750 cfs. The discharges were selected to bracket the gaged flows at selected locations along the river.

The model was calibrated to measured water-surface elevations that were obtained at 12 sites during the 2007 survey (MEI and Riada 2007). Seven of those sites – Sibley Arroyo, Jaralosa Arroyo, Yeso Arroyo, Angostura Arroyo, Rincon Arroyo, Reed Arroyo, and Bignell Arroyo – are in areas where updated topography was incorporated into the model. In addition to the measured sites, the water-surface profiles from the 2008 USIBWC model were utilized to verify results along the portions of the study reach where surveyed water-surface elevations were not available. Since this is the primary change in the 2012 RGCP modeling effort, the following steady-flow calibrations focused on the 7 measured sites. The seven measured sites named for the nearest arroyo confluence are: Sibley, Jaralosa, Yeso, Angostura, Rincon, Reed, and Bignell. Calibration profile plots for the steady-flow calibration run each of the seven sites are plotted in Figure H-18 through Figure H-24.

The calibrated water-surface elevations in the steady-flow analysis were generally within 0.5 feet of observed water-surface elevations or water-surface elevations computed in the previous modeling by MEI and Riada (2007) and USACE et al. (2009). At two locations – Rincon Arroyo and Bignell Arroyo – the calibrated water surface elevations were within 1 foot of the observed water surface elevations. Given the differences between the 2007 measured data and the water-surface elevations predicted by the 2007 modeling (MEI and Riada, 2007), the updated steady-state model was considered reasonably calibrated and the geometry was deemed adequate to progress to the unsteady and groundwater interflow models.

2.3.2 Unsteady HEC-RAS Model: Initial Validation and Calibration

The HEC-RAS unsteady flow models are calibrated using the 2012 upstream irrigation release from Caballo Dam (Figure H-3) and the 2012 diversions at Percha Dam, Leasburg Dam, and Mesilla Dam (Figure H-7). Given the difficulties in obtaining numerically stable unsteady flows, this initial step did not include irrigation returns or seepage. The 2012 year shows two irrigation release pulses and will represent the baseline scenario.

The initial unsteady flow model calibration was based on EBID and USGS gage-measured hydrographs from March 31, 2012 through September 14, 2012. The gage locations and the corresponding HEC-RAS Rivers Station are provided in Table H-2. After reviewing the gage data, the calibrations were based on visual comparison of hydrographs calculated by HEC-RAS with gaged hydrographs at three EBID gages: Leasburg River Cable, Mesilla Dam, and El Paso. Results are shown respectively in Figure H-25, Figure H-26, and Figure H-27. The Haynor, Picacho, and Anthony metering stations were not used to calibrate the HEC-RAS model because the data at these gages is believed to be suspect (Dr. Al Blair, pers. comm., November 2012).

The plots show that the calculated flows from the HEC-RAS model generally match the gaged outflows in time, but are noticeably higher than the gage flows during the irrigation season. This difference highlights the lack of outflow/inflow model input that represents channel seepage, irrigation returns, or groundwater return flow.

2.3.3 Unsteady HEC-RAS Model: Calibration with Seepage and Groundwater Return Flow

The unsteady surface flow model was modified to account for seepage and groundwater return to the main channel by using the groundwater interflow option. The groundwater interflow option is a simplified algorithm that simulates flow into and out of the main channel. The groundwater aquifer is assumed to be very large and is not affected by the volume of groundwater interflow predicted by the model.

As previously noted, the groundwater interflow approach using the Darcy equation was based on the head difference between the surface water elevation and the groundwater elevation, and the vertical thickness (assumed to be 5 feet) of the riverbed sediments. The temporal variation in groundwater depth (i.e., the time series) was developed by transposing the temporal pattern from adjacent wells on the floodplain. The approach is summarized schematically in Figure H-15 and an example time series input is shown in Figure H-16.

Calibration using K_{sat}

The calibration for K_{sat} was initiated using the rate (0.114 feet/day) adopted for the initial "vertical hydraulic conductivity" (K') that was used for conductance calculations in the URGWOM Technical Completion Report (USACE 2012). The values of K_{sat} were adjusted within each segment to improve the visual match of the HEC-RAS outflows with the aforementioned gages at Leasburg, Mesilla, and El Paso. The plots of the HEC-RAS hydrographs with the best visual match are shown Figure H-28, Figure H-29, and Figure H-30 respectively. The calibrated values of K_{sat} for this "baseline" model are listed below:

- Segment 1 = 0.150 feet/day
- Segment 2 = 0.664 feet/day
- Segment 3 = 0.664 feet/day
- Segment 4 = 0.664 feet/day

Groundwater interflow (seepage and return flow) results for the baseline model are provided in Table H-5. The overall seepage rates for the entire RGCP vary from 22.4 cfs (44.5 acre-feet per day) to 353.7 cfs (701.5 acre-feet per day), and average 228.3 cfs (452.9 acre-feet per day).

The 2012 flow volumes at the gages are compared with flow volumes in the calibrated hydrographs in Table H-6. For the Leasburg gage, the modeled flow volume (304,940 acre-feet) is 5% greater than the measured flow volume (289,851 acre-feet). For the Mesilla gage, the modeled flow volume (175,017 acre-feet) is 12% greater than the measured flow volume (155,718 acre-feet). For the El Paso gage, the modeled flow volume (144,297 acre-feet) is 13% greater than the measured flow volume (128,071 acre-feet).

2.3.4 Comparison to Previous Seepage Studies

USGS Seepage Studies

Between 1988 and 2007, the USGS conducted a series of seepage investigations (USGS 1988-2007) along specific segments of channels and drains located within the Rio Grande watershed, including segments of the Rio Grande. In general, the investigations were conducted at times when flows in the channels/drains were low in magnitude. The results, summarized in Table H-7 indicate that net losses in the streamflows due to seepage occur only along the Rio Grande. The channels and drains included in the study show negative seepage values where inflows exceeded seepage. Seepage estimates are not only dependent upon the magnitude of inflows into the system, but also upon the time of the year that seepage occurs—particularly relative to preceding flows which would have a direct effect on achieving a steady-state seepage rate within and along the channel cross-section.

The USGS estimates indicate that along the 62.4-mile-long study reach, seepage rates range from as little as 7.2 cfs (14.3 acre-feet per day) to as much as 40.3 cfs (79.9 acre-feet per day). Ignoring the flow rates and time of the year, if these seepage rates are assumed applicable along the entire 106.8-mile-long river corridor of the Rio Grande Canalization Project, then seepage estimates would range from about 12.3 cfs (24.5 acre-feet per day) to about 69 cfs (136.8 acre-feet per day). The rates estimated by the USGS are comparable with the minimum seepage rate (22.4 cfs, 44.5 acre-feet per day) for the calibrated model (Table H-5). However, it should be noted that the seepage values from the USGS analyses were performed during a period with full allocation of project water, in which seepage rates are controlled by the conveyance in the agricultural drainage system. During times of extreme drought, such as the 2010 through 2012 period, the groundwater elevations are below the inverts of the canals and seepage is not affected by the drainage system.

RGPAC Seepage Estimates

The 2012 Draft Report (RGPAC 2012) includes a seepage estimate of 275 acre-feet per day for 2011 and 359 acre-feet per day for 2012 along a 106.8-mile-long reach of the same segment of the Rio Grande. These rates are roughly comparable with the average seepage rate (228.3 cfs, 452.9 acre-feet per day) for the calibrated model (Table H-5).

2.4 UNSTEADY HEC-RAS MODEL: BASELINE SENSITIVITY ANALYSES

2.4.1 Sensitivity to Changes in K_{sat}

In accordance with the Scope of Work (USIBWC 2012a and 2012b) a sensitivity analysis was performed to evaluate the effects of changes in K_{sat} on the groundwater interflow. Three separate HEC-RAS models were run with K_{sat} increasing by 10%, 20%, and 30% over the base values, and three models were run with K_{sat} decreasing by 10%, 20%, and 30%. The K_{sat} values for the baseline model and the six sensitivity models are summarized in Table H-8.

The sensitivity between channel seepage volume and the percent change in K_{sat} is shown in Table H-9 and the between percent change in seepage volume and the percent change in K_{sat} is shown in Table H-10. The results are shown graphically in Figure H-31 and Figure H-32 respectively.

2.4.2 Sensitivity to Changes in Groundwater Inputs

A sensitivity analysis was performed to evaluate the effects of changes in average groundwater depth on the groundwater interflow. An additional HEC-RAS model was run with a 50% increase in the average depth to groundwater at each well location (see Table H-3 and Table H-4). This increases the overall average depth in the RGCP from about 3 feet to about 4.5 feet. A similar model was run to decrease the overall average ground water depth by 50%, to give an overall average of about 1.5 feet. Results are summarized in Table H-11 and show essentially no change in the seepage at all four segments. Given that the depth to groundwater only changes by ±1.5 feet from the baseline value of about 3 feet, and the depth of irrigation flows in the river channel typically from between 5 feet and 10 feet, the value for h (depth from water-surface elevation to the ground water elevation) may only vary from 11.5% (1.5 feet/13 feet) to 19% (1.5 feet/8 feet),[2] with similar variation to the gradient dh/dy in the Darcy equation. In addition, given that groundwater elevations are fixed and result in very large values for h at the upper end of a reach[3], the variation in dh/dy can be fairly insignificant.

2.4.3 Sensitivity to Changes in to River Sediment Thickness

A sensitivity analysis was performed to evaluate the effects of changing the assumed thickness of the river sediment (y) on the groundwater interflow. An initial run looked at a 100% increase to give a sediment thickness of 10 feet, and found that total seepage is fairly sensitive to this parameter. Additional runs were performed to evaluate sediment thicknesses of 3 feet (-40%) and 8 feet (+60%)[4]. The sensitivity between channel seepage volume and the percent change in river sediment thickness are summarized on an absolute basis in Table H-12 and a percentage basis in Table H-13. Seepage volume in HEC-RAS is much more sensitive to changes in the thickness of the river sediment, largely because changes in the thickness (y) affect the denominator of the Darcy gradient dh/dy with no corresponding effect on "h". Example calculations[5] show that a 40% decrease in y will increase the gradient by 66%; likewise a 60% increase in y will decrease seepage by about 38%; and a 100% increase in y will decrease seepage by about 50%. These examples are reflected in sensitivities for Segment 1 in Table H-13, but are gradually reduced in Segments 2, 3, and 4, where diversion losses play a greater role.

2.5 UNSTEADY HEC-RAS MODEL: HYPOTHETICAL IRRIGATION RELEASE PULSES

In accordance with the Scope of Work (USIBWC 2012a and 2012b) the calibrated HEC-RAS model was used to analyze two hypothetical irrigation release scenarios from the upstream reservoirs to predict the impact on channel seepage and other water budget components.

The analyses were conducted for a delayed single-pulse hydrograph (Release Scenario S1 from May 29, 2012 through September 14, 2012) and a normal single-pulse hydrograph (Release Scenario S2 from March 31, 2014 through September 14, 2012) provided by the RGPAC. Plots of the inflow hydrographs are included in Figure H-5 and Figure H-6 respectively.

---

[2] This is a rough approximation, the actual variation would depend on how temporal and spatial changes in the groundwater depth compare against temporal and spatial changes in flow depth.

[3] See Internal Boundary Condition - Groundwater Interflow in Section 2.2.2.

[4] Models with sediment thicknesses of 7.5 feet and 2.5 feet (±50%) were attempted but the HEC-RAS models would not run correctly.

[5] Given dh/dy = 13/5 = 2.6. A 40% decrease in y gives dh/dy = 13/3 = 4.33. The ratio of 4.33/2.6 = 1.66 which corresponds to a 66% increase.

The analyses were based on the calibrated HEC-RAS model that included the adjusted surface flow diversions[6] and the groundwater interflow with the calibrated values of K_{sat}. The comparisons between the S1 and S2 scenarios were based on the "no-return-flow" modeling for consistency with sensitivity analyses described under Section 2.4. As noted in Section 2.7.2, the addition of return flows makes little difference in the seepage results. Plots of the routed S1 and S2 hydrographs are shown in Figure H-35 and Figure H-36.

Seepage results for the delayed single-pulse hydrograph (Release Scenario S1) and a normal single-pulse hydrograph (Release Scenario S2) shown in Table H-14 and Table H-15. For Release Scenario 1, the overall seepage rates vary from 25.1 cfs (49.7 acre-feet per day) to 425.6 cfs (844.1 acre-feet per day), and average 306.1 cfs (607.1 acre-feet per day). For (Release Scenario 2) the overall seepage rates vary from 22.0 cfs (43.6 acre-feet per day) to 373.9 cfs (741.7 acre-feet per day), and average 222.3 cfs (441.0 acre-feet per day). While the minimum, maximum, and average seepage rates under the S2 Scenario are less than those under the S1 Release Scenario, total volume of seepage in the S2 Release Scenario (74,087 acre-feet) is roughly 11% more than the total volume in the S1 Release Scenario (66,786 acre-feet). The higher volume for the S2 Release Scenario results from a longer release period (168 days) versus the 110-day release period under the S1 Release Scenario.

2.6 UNSTEADY HEC-RAS MODEL: HYPOTHETICAL IRRIGATION RELEASES SENSITIVITY ANALYSES

In accordance with the Scope of Work (USIBWC 2012a and 2012b) a sensitivity analysis was performed to evaluate the effects of changes in K_{sat} on the groundwater interflow based on the two hypothetical irrigation release scenarios described in the previous section. Three separate HEC-RAS models were run with K_{sat} increasing by 10%, 20%, and 30% over the base values, and three models were run with K_{sat} decreasing by 10%, 20%, and 30%, resulting in a total of twelve separate models (six models for each scenario). The K_{sat} values for the baseline model and the six sensitivity models are summarized in Table H-8.

The sensitivity for Scenario S1 between channel seepage volume and the percent change in K_{sat} is shown in Table H-16 and the between percent change in seepage volume and the percent change in K_{sat} is shown in Table H-17. The results are shown graphically in Figure H-37 and Figure H-38 respectively.

The sensitivity for Scenario S2 between channel seepage volume and the percent change in K_{sat} is shown in Table H-18 and the between percent change in seepage volume and the percent change in K_{sat} is shown in Table H-19. The results are shown graphically in Figure H-39 and Figure H-40 respectively.

The results for both hypothetical irrigation release scenario sensitivity analyses were found to be similar to the baseline condition sensitivity analysis.

[6] See the "Internal Boundary Condition - Diversions" heading under Section 2.2.2 and Figure H-10.

2.7 UNSTEADY HEC-RAS MODEL: FINAL RESULTS WITH RETURN FLOWS

2.7.1 Results With Return Flows

The calibrated baseline modeling was finalized by adding the irrigation returns shown in Figure H-13. The resulting hydrographs at the Leasburg, Mesilla, and El Paso gages are shown in Figure H-41, Figure H-42, and Figure H-43. Groundwater interflow (seepage) results for the HEC-RAS unsteady modeling with diversions, irrigation returns, and groundwater interflow are provided in Table H-20. Total seepage over the entire RGCP varies from 22.4 cfs (44.5 acre-feet per day) to 356.8 cfs (707.6 acre-feet per day), and averages 230.8 cfs (457.9 acre-feet per day).

2.7.2 Comparison of Results - Without and With Return Flows

Total seepage volumes over the project reach, without and with return flows, are compared in Table H-21. When the return flows are added, the total seepage increases are 0 acre-feet (Segment 1), 65 acre-feet (Segment 2), 243 acre-feet (Segment 3) and 531 acre-feet (Segment 4), with a total difference of 839 acre-feet along the overall RGCP. On a percentage basis, seepage increases by 3.4 percent in Segment 4, where most of the return flows are concentrated, but is only 1.1 percent overall.

The 2012 flow volumes with and without return flows at the Leasburg, Mesilla, and El Paso gages are compared in Table H-22. The volume differences vary from 1% at Mesilla to 6% at El Paso. There are no return flows measured at the Leasburg gage so the difference is zero.

2.8 UNSTEADY HEC-RAS MODEL: 2010 – 2012 RESULTS WITH RETURN FLOWS

The calibrated baseline modeling parameters were applied to an HEC-RAS model for the period between January 1, 2010 and September 14, 2012. Groundwater interflow (seepage) results for the HEC-RAS unsteady modeling with diversions, irrigation returns, and groundwater interflow are provided in Table H-23. Total seepage over the entire RGCP for the 2010-2012 period varies from 14 cfs (27.7 acre-feet per day) to 362.9 cfs (719.9 acre-feet per day), and averages 182.3 cfs (361.6 acre-feet per day). Since the model is run continuously from 2010 through 2012, the seepage results are influenced by the minimum flows required to keep the model running through the non-irrigation seasons. Adjustments to account for additional seepage are discussed in Section 9.9 of the main report and are made in **Appendix B, Table B-6**.

3.0 REFERENCES

Mussetter Engineering, Inc. and Riada Engineering, Inc., 2007. *Revised Draft Baseline Report: Rio Grande-Caballo Dam to American Dam FLO-2D Modeling, New Mexico and Texas*. Contract No. DACW47-03-D-0005, Delivery Order 0012, submitted to U.S. Army Corps of Engineers, Albuquerque, New Mexico.

Rio Grande Project Allocation Committee, March 2012. *Analysis of River Conveyance Efficiency for Initial Release of Project Water Delivery to Acequia Madre Canal in 2012*.

U.S. Army Corps of Engineers (USACE), 2012. Technical Completion Report Development of Riverware Model of the Rio Grande for Water Resources Management in the Paso Del Norte Watershed (URGWOM Report). Sponsored by U.S. Army Corps of Engineers, Gulf Coast Cooperative Ecosystem Studies Unit. Submitted by: Zhuping Sheng (PI), Texas A&M University System; Phillip J. King (Co-PI), New Mexico State University; Christopher Brown (Co-PI), New Mexico State University; Ari Michelsen and Binayak Mohanty (Co-PI), Texas A&M University System; and Alfredo Granados (Co-PI), Universidad Autónoma de Ciudad Juárez, México.

U.S. Army Corps of Engineers, Mussetter Engineering, Inc. and Riada Engineering, Inc., 2009. Conceptual Restoration Plan and Cumulative Effects Analysis, Rio Grande – Caballo Dam to American Dam, New Mexico and Texas. Prepared for International Boundary and Water Commission, United States and Mexico, United States Section, March.

US Geological Survey. 1988-2007. Rio Grande Basin – Rio Grande Seepage Investigations 1988-2007, provided via email correspondence with USGS, 2012

US Geological Survey. 1984-2011. Monitoring Well Data, email correspondence with USGS, 1984-2011, provided via email correspondence with USGS, 2012

US International Boundary and Water Commission. 2010. USIBWC Rio Grande Canalization Project River Restoration Depths to Groundwater at Restoration Sites

US International Boundary and Water Commission. 2012a. Scope of Work for the Rio Grande Canalization Project (RGCP) Water Budget Study.

US International Boundary and Water Commission. 2012b. Scope of Work for the Rio Grande Canalization Project (RGCP) Water Budget Study - Modification 1.

Reference websites:

EBID Water Resource Information System Data: http://www.ebid-nm.org/wris2008/RTUInventory-ShowCategories.asp

NRCS Web Soil Survey: http://websoilsurvey.nrcs.usda.gov/app/

4.0 TABLES

Page Intentionally Blank

Table H-1. RGCP Segments

Segment	Upstream Limit (HEC-RAS RS)	Downstream Limit (HEC-RAS RS)	Length (miles)
Segment 1	Caballo Dam (HEC-RAS RS = 564639)	Leasburg Cable metering station (HEC-RAS RS = 317830.3)	46.7
Segment 2	Leasburg Cable metering station (HEC-RAS RS = 317830.3)	Mesilla Dam (HEC-RAS RS = 207690.8)	20.8
Segment 3	Mesilla Dam (HEC-RAS RS = 207690.8)	Anthony metering station (HEC-RAS RS = 101318.5)	20.1
Segment 4	Anthony metering station (HEC-RAS RS = 101318.5)	American Dam (HEC-RAS RS = 0.457)	19.2
Total	**Caballo Dam (HEC-RAS RS = 564639)**	**American Dam (HEC-RAS RS = 0.457)**	**106.8**
Note 1) The total length computed from the HEC-RAS river stationing (564639 feet – 0.457 feet) is 106.9 miles. Segments lengths are scaled proportionally to give an overall length of 106.8 miles.			

Table H-2. EBID River Gage River Stations

Source	River Stations	Gage Name
EBID	564639.1	Caballo Dam
EBID	390175.1	Haynor Bridge
EBID	**317830.3**	**Leasburg River Cable**
EBID	236225.7	Picacho River
EBID	**197199.5**	**River Below Mesilla Dam**
EBID	101318.5	Anthony River
USGS	**9006.36**	**El Paso**
USGS	NA	American Canal
USGS	NA	Below American Dam

Vales in **bold** were used in calibration

Table H-3. Groundwater Monitoring Wells Utilized in HEC-RAS Model

Well ID	Data Source	Distance to River (feet)	Adjacent RS	RS Range	
				Upstream RS	Downstream RS
Segment 1					
RIN_10R	EBID	2100	534874.3	562627.5	534874.3
RIN_1R	EBID	2000	509363.4	534874.3	509363.4
RIN_9R	EBID	6000	494334.2	509363.4	494334.2
RIN2R	EBID	2700	476438.1	494334.2	476438.1
RIN8R	EBID	1300	458197.4	476438.1	458197.4
RIN7R	EBID	2000	430594.6	458197.4	430594.6
RIN5R	EBID	1700	403856.3	430594.6	403856.3
RIN12R	EBID	2700	392345.7	403856.3	392345.7
RIN13R	EBID	2700	377330.4	392345.7	327958.8
Segment 2					
MES41R	EBID	200	318326.5	327958.8	318326.5
MES43R	EBID	5500	295323.6	318326.5	295323.6
MES20R	EBID	4300	283320.3	295323.6	283320.3
MES15R	EBID	2200	257224.2	283320.3	257224.2
MES12R	EBID	3200	237725	257224.2	237725
32174510649: 2501 to 2503	USGS	150	235729.4	237725	235729.4
MES48R	EBID	1500	217711.2	235729.4	207690.8
Segment 3					
321237106: 2001 to 2003	USGS	200	197699.4	207640.7	197699.4
MES13R	EBID	2500	193308	197699.4	193308
MES8R	EBID	2200	183225.7	193308	183225.7
MES7R	EBID	6400	177179.9	183225.7	177179.9
MES6R	EBID	4600	157166.3	177179.9	157166.3
MES23R	EBID	5000	127272.1	157166.3	127272.1
MES32R	EBID	4300	110942.2	127272.1	110942.2
MES39R	EBID	4400	101318.5	110942.2	101318.5
Segment 4					
31571210636: 1801 to 1802	USGS	200	81333.4	101318.5	81333.4
ISC7	EBID	9900	52953.6	81333.4	52953.6
ISC5	EBID	400	38058	52953.6	38058
ISC4	EBID	1100	10483.5	38058	418.27

Table H-4. Average Groundwater Depth at Groundwater Monitoring Wells Utilized in HEC-RAS Model

Well ID	Associated USIBWC Restoration Site(s)[1]	Average Groundwater Depth (ft)[2]
Segment 1		
RIN_10R	Trujillo and Jaralosa	-2.1
RIN_1R	Trujillo and Jaralosa	-2.1
RIN_9R	Jaralosa and Yeso Arroyo	-3.4
RIN2R	Crow Canyon and Placitas Arroyo	-3.2
RIN8R	Crow Canyon and Placitas Arroyo	-3.2
RIN7R	Rincon Siphon and Angostura Arroyo	-2.4
RIN5R	Angostura Arroyo	-4.7
RIN12R	Angostura Arroyo	-4.7
RIN13R	Angostura Arroyo	-4.7
Segment 2		
MES41R	Shalem County	-4.1
MES43R	Shalem County	-4.1
MES20R	Shalem County	-4.1
MES15R	Shalem County and Leasburg Extension Lateral WW8	-2.4
MES12R	Leasburg Extension Lateral WW8 to Clark Lateral	-2.3
32174510649: 2501 to 2503	Leasburg Extension Lateral WW8 to Clark Lateral	-2.3
MES48R	Mesilla Valley St. Park	-2.1
Segment 3		
321237106: 2001 to 2003	Mesilla Valley St. Park and Berino	-2.6
MES13R	Mesilla Valley St. Park and Berino	-2.4
MES8R	Mesilla Valley St. Park and Berino	-2.6
MES7R	Mesilla Valley St. Park and Berino	-2.6
MES6R	Mesilla Valley St. Park and Berino	-2.6
MES23R	Berino and Vinton	-2.2
MES32R	Berino and Vinton	-2.2
MES39R	Berino and Vinton	-2.2
Segment 4		
31571210636: 1801 to 1802	Vinton and Valley Creek	-2.1
ISC7	Vinton and Valley Creek	-2.1
ISC5	Nemexas Siphon	-2.4
ISC4	Anapra	-3.4

[1]USIBWC Rio Grande Canalization Project River Restoration Depths to Groundwater at Restoration Sites in June/July 2010 (USIBWC, 2010).
[2]Depth in feet below channel.

Table H-5. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions and Groundwater Interflow, March 31 to September 14, 2012

	Segment 1	Segment 2	Segment 3	Segment 4	Total
	Channel Seepage (cfs)				
Minimum	6.9	5.3	5.5	4.7	22.4
Maximum	65.4	137.4	91.7	89.0	353.7
Average	41.7	88.5	50.6	47.4	228.3
	Channel Seepage (acre-feet per day)				
Minimum	13.8	10.4	10.9	9.4	44.5
Maximum	129.8	272.6	181.9	176.5	701.5
Average	82.7	175.6	100.5	94.1	452.9
	Total Seepage (acre-feet)				
Total	13,901	29,505	16,876	15,802	76,084

Positive values represent seepage out of the channel
Negative values indicate groundwater flow into the channel

Table H-6. Comparison of Flow Volume, Gaged Hydrograph vs. Calibrated HEC-RAS Model Hydrograph

River Station	Gage	Gage (acre-feet)	HEC-RAS output (acre-feet)	Difference (acre-feet)	Difference (%)
317830.3	Leasburg	289,851	304,940	15,089	5%
197199.5	Below Mesilla	155,718	175,017	19,299	12%
9006.36	El Paso	128,071	144,297	16,226	13%

Table H-7. USGS Seepage Measurements

Reach Description — Rio Grande	Dates of Investigation	Streamflow Estimate	Seepage Estimate	Evaporation Estimate
Rio Grande				
62.4-mile-long reach from downstream of Leasburg Dam to El Paso, Texas	Jan 5 - 6, 1988	95 to 194 cfs	26.1 cfs	Negligible
62.4-mile-long reach from downstream of Leasburg Dam to El Paso, Texas	Jan 10 - 11, 1989	33 to 122 cfs	7.2 cfs	Negligible
62.4-mile-long reach from downstream of Leasburg Dam to El Paso, Texas	Feb 24 - 25, 2004	2 to 10 cfs (many dry segments)	17.2 cfs (with side inflows of 26.8 cfs)	Negligible
62.4-mile-long from downstream of Leasburg Dam to El Paso, Texas	Feb 23, 2005 March 4, 2005	0.0 to 18 cfs	40.3 cfs (w/side inflows of 38.9 cfs)	Negligible
62.4-mile-long reach from downstream of Leasburg Dam to El Paso, Texas	Feb 14 - 15, 2006	0.0 to 22 cfs	36.2 cfs (w/ side inflows of 52.4 cfs)	Negligible
62.4-mile-long reach from downstream of Leasburg Dam to El Paso, Texas	Feb 13 - 14, 2007	13 to 39 cfs	36.4 cfs (w/side inflows of 46.5 cfs)	Negligible
11.0-mile-long reach from Fairview Lane Bridge in Espanola, New Mexico, to gaging station at Otowi Bridge near San Ildefonso, New Mexico	Sept 29, 2004	460 to 500 cfs	5.0 cfs (w/ inflow of 10.6 cfs)	N/A
East Drain				
11.5-mile-long reach from near Vado, New Mexico, to the Rio Grande near Anthony, Texas	Feb 15 - 16, 2000 Aug 22 - 23, 2000	0.4 to 40 cfs	-2.11 to -9.8 cfs	N/A
Montoya Drain				
6.7-mile-long reach from near Cañutillo, Texas, to the Rio Grande at Sunland Park, New Mexico	Feb 6 - 7, 2001 Aug 28 - 29, 2001	0.0 to 88 cfs	-4.1 to -2.4 cfs	N/A
Nemexas Drain				
18.8-mile-long reach from near Chamberino, New Mexico to the junction with the Montoya Drain, El Paso, Texas	Feb 12-13, 2002 Aug 29 - 30, 2002	0.0 - 71 cfs	-9.8 to -32.9 cfs	N/A
West Drain				
23.7-mile-long reach from near San Miguel, New Mexico, to junction at Nemexas Drain near Santa Teresa, New Mexico	Feb 24 - 26, 2003 Aug 25 - 27, 2003	0.0 - 11 cfs	-8.4 to -4.3 cfs	N/A

Source: (USGS 2012)

Table H-8. Sensitivity Analysis – K_{sat} Parameter Inputs

Percent Change in K_{sat}	K_{sat} Segment 1	K_{sat} Segments 2, 3, and 4
-30%	0.105	0.4648
-20%	0.120	0.5312
-10%	0.135	0.5976
0%	**0.150**	**0.6640**
10%	0.165	0.7304
20%	0.180	0.7968
30%	0.195	0.8632

Table H-9. Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat}

Percent Change in Ks	Seepage Volume (Acre-Feet)				
	Segment 1	Segment 2	Segment 3	Segment 4	Total
-30%	9,769	21,024	12,490	12,000	55,283
-20%	11,151	23,924	14,036	13,373	62,484
-10%	12,528	26,787	15,516	14,655	69,486
0%	**13,901**	**29,505**	**16,876**	**15,802**	**76,084**
10%	15,271	32,291	18,224	16,903	82,689
20%	16,636	35,041	19,508	17,914	89,099
30%	17,999	37,653	20,679	18,802	95,133

Table H-10. Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat}

Percent Change in K_s	Percent Change in Seepage				
	Segment 1	Segment 2	Segment 3	Segment 4	Total
-30%	-29.7%	-28.7%	-26.0%	-24.1%	-27.3%
-20%	-19.8%	-18.9%	-16.8%	-15.4%	-17.9%
-10%	-9.9%	-9.2%	-8.1%	-7.3%	-8.7%
0%	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
10%	9.9%	9.4%	8.0%	7.0%	8.7%
20%	19.7%	18.8%	15.6%	13.4%	17.1%
30%	29.5%	27.6%	22.5%	19.0%	25.0%

Table H-11. Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in Average Groundwater Depth

Overall Average Groundwater Depth (ft)[1]	Percent Change in Average Groundwater Depth	Seepage Volume (acre-feet)				
		Segment 1	Segment 2	Segment 3	Segment 4	Total
1.5	-50%	13,882	29,506	16,867	15,914	76,169
3.0	**0%**	**13,901**	**29,505**	**16,876**	**15,802**	**76,084**
4.5	50%	13,902	29,505	16,876	15,802	76,085

[1]Average of groundwater depths below the Rio Grande Invert through the RGCP. Based on June/July 2010 data shown in Table H-4.

Table H-12. Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in River Sediment Thickness

River Sediment Thickness (ft)	Percent Change in Average Groundwater River Sediment Thickness	Seepage Volume (acre-feet)				
		Segment 1	Segment 2	Segment 3	Segment 4	Total
3	-40%	22,965	47,128	24,523	21,400	116,016
5	**0%**	**13,901**	**29,505**	**16,876**	**15,802**	**76,084**
8	60%	8,732	18,878	11,316	10,937	49,863
10	100%	6,997	15,220	9,258	9,035	40,510

Table H-13. Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in River Sediment Thickness

River Sediment Thickness (ft)	Percent Change in Average Groundwater River Sediment Thickness	Percent Change in Seepage				
		Segment 1	Segment 2	Segment 3	Segment 4	Total
3	-40%	65%	60%	45%	35%	52%
5	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**
8	60%	-37%	-36%	-33%	-31%	-34%
10	100%	-50%	-48%	-45%	-43%	-47%

Table H-14. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions and Groundwater Interflow, Delayed Single-pulse (S1) Hydrograph

	Segment 1	Segment 2	Segment 3	Segment 4	Total
	Channel Seepage (cfs)				
Minimum	7.6	6.5	6.1	5.0	25.1
Maximum	74.5	159.0	98.9	96.3	425.6
Average	56.4	116.8	68.2	64.7	306.1
	Channel Seepage (acre-feet per day)				
Minimum	15.0	12.8	12.1	9.9	49.7
Maximum	147.8	315.3	196.1	191.0	844.1
Average	111.9	231.7	135.2	128.3	607.1
	Total Seepage (acre-feet)				
Total	12,305	25,491	14,873	14,117	66,786

Positive values represent seepage out of the channel
Negative values indicate groundwater flow into the channel

Table H-15. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions and Groundwater Interflow, Normal Single-pulse (S2) Hydrograph

	Segment 1	Segment 2	Segment 3	Segment 4	Total
	Channel Seepage (cfs)				
Minimum	6.9	5.2	5.2	4.7	22.0
Maximum	66.5	140.0	93.9	91.0	373.9
Average	42.9	87.6	47.4	44.4	222.3
	Channel Seepage (acre-feet per day)				
Minimum	13.6	10.3	10.4	9.3	43.6
Maximum	131.9	277.7	186.2	180.5	741.7
Average	85.2	173.8	94.0	88.0	441.0
	Total Seepage (acre-feet)				
Total	14,309	29,207	15,792	14,780	74,087

Positive values represent seepage out of the channel
Negative values indicate groundwater flow into the channel

Table H-16. S1, Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat}

Percent Change in Ks	Seepage Volume (Acre-Feet)				
	Segment 1	Segment 2	Segment 3	Segment 4	Total
-30%	8,645	18,122	10,903	10,564	48,234
-20%	9,867	20,637	12,292	11,829	54,625
-10%	11,087	23,122	13,631	13,046	60,886
0%	**12,305**	**25,491**	**14,873**	**14,117**	**66,786**
10%	13,520	27,922	16,115	15,186	72,743
20%	14,727	30,277	17,277	16,171	78,452
30%	15,938	32,611	18,411	17,095	84,055

Table H-17. S1, Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat}

Percent Change in K_s	Percent Change in Seepage				
	Segment 1	Segment 2	Segment 3	Segment 4	Total
-30%	-29.7%	-28.9%	-26.7%	-25.2%	-27.3%
-20%	-19.8%	-19.0%	-17.4%	-16.2%	-17.8%
-10%	-9.9%	-9.3%	-8.3%	-7.6%	-8.6%
0%	**0.0%**	**0.0%**	**0.0%**	**0.0%**	0.0%
10%	9.9%	9.5%	8.4%	7.6%	8.9%
20%	19.7%	18.8%	16.2%	14.5%	17.5%
30%	29.5%	27.9%	23.8%	21.1%	25.0%

Table H-18. S2, Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat}

Percent Change in Ks	Seepage Volume (Acre-Feet)				
	Segment 1	Segment 2	Segment 3	Segment 4	Total
-30%	10,057	20,827	11,701	11,214	53,799
-20%	11,479	23,693	13,140	12,495	60,807
-10%	12,895	26,520	14,520	13,698	67,633
0%	**14,309**	**29,207**	**15,792**	**14,780**	**74,087**
10%	15,718	31,956	17,067	15,840	80,581
20%	17,120	34,601	18,242	16,789	86,752
30%	18,522	37,242	19,437	17,729	92,931

Table H-19. S2, Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat}

Percent Change in K_s	Percent Change in Seepage				
	Segment 1	Segment 2	Segment 3	Segment 4	Total
-30%	-29.7%	-28.7%	-25.9%	-24.1%	-27.4%
-20%	-19.8%	-18.9%	-16.8%	-15.5%	-17.9%
-10%	-9.9%	-9.2%	-8.1%	-7.3%	-8.7%
0%	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
10%	9.8%	9.4%	8.1%	7.2%	8.8%
20%	19.6%	18.5%	15.5%	13.6%	17.1%
30%	29.4%	27.5%	23.1%	20.0%	25.4%

Table H-20. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions, Returns, and Groundwater Interflow, March 31 to September 14, 2012

	Segment 1	Segment 2	Segment 3	Segment 4	Total
	Channel Seepage (cfs)				
Minimum	6.9	5.3	5.5	4.8	22.4
Maximum	65.4	140.7	92.6	91.3	356.8
Average	41.7	88.7	51.4	49.0	230.8
	Channel Seepage (acre-feet per day)				
Minimum	13.8	10.4	10.9	9.4	44.5
Maximum	129.8	279.0	183.6	181.0	707.6
Average	82.7	176.0	101.9	97.2	457.9
	Total Seepage (acre-feet)				
Total	13,901	29,570	17,119	16,333	76,923

Positive values represent seepage out of the channel
Negative values indicate groundwater flow into the channel

Table H-21. Comparison of Channel Seepage Results, Unsteady HEC-RAS Modeling without and with Return Flows, March 31 to September 14, 2012

	Segment 1	Segment 2	Segment 3	Segment 4	Total
	Total Seepage (acre-feet)				
Without Returns	13,901	29,505	16,876	15,802	76,084
With Returns	13,901	29,570	17,119	16,333	76,923
Difference	0	65	243	531	839
Percent Difference	0.0%	0.2%	1.4%	3.4%	1.1%

Table H-22. Comparison of Flow Volumes, HEC-RAS Model Hydrographs without and with Return Flows, March 31 to September 14, 2012

River Station	Gage	HEC-RAS Output No Returns (acre-feet)	HEC-RAS Output With Returns (acre-feet)	Difference (acre-feet)	Difference (%)
317830.3	Leasburg	304,940	304,939	0	0%
197199.5	Below Mesilla	175,017	176,835	1,818	1%
9006.36	El Paso	144,297	153,604	9,307	6%

Table H-23. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions and Groundwater Interflow, January 1, 2010 to September 14, 2012

	Segment 1	Segment 2	Segment 3	Segment 4	Total
	Channel Seepage (cfs)				
Minimum	5.2	4.4	-0.7	5.1	14.0
Maximum	70.7	142.8	86.7	94.8	362.9
Average	30.0	69.3	39.2	43.8	182.3
	Channel Seepage (acre-feet per day)				
Minimum	10.3	8.8	-1.4	10.0	27.7
Maximum	140.3	283.3	172.0	188.1	719.9
Average	59.6	137.5	77.7	86.8	361.6
	Total Seepage (acre-feet)				
Total	58,853	135,827	76,813	85,786	357,280

Positive values represent seepage out of the channel
Negative values indicate groundwater flow into the channel

Table H-24. HEC-RAS Modeling – File Summary

Model	Period	Project Filename	Plan/Unsteady Flow Name	Unsteady Flow Name
Flow Release at Caballo Dam, Diversions at Percha, Leasburg, and Mesilla Dams, No Return Flows				
Baseline	2012	Baseline_Cal_GW_Div_NR.prj	Baseline_Cal_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows
Baseline - No Seepage	2012	Baseline_Cal_NoGW_Div_NR.prj	Baseline_Cal_NoGW_DIV_noRet	Calibrated baseline model for 2012, with no return flows and no seepage
Baseline Ks x 1.1	2012	Baseline11_Cal_GW_Div_NR.prj	Baseline11_Cal_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, increase Ks by 10%
Baseline Ks x 1.2	2012	Baseline12_Cal_GW_Div_NR.prj	Baseline12_Cal_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, increase Ks by 20%
Baseline Ks x 1.3	2012	Baseline13_Cal_GW_Div_NR.prj	Baseline13_Cal_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, increase Ks by 30%
Baseline Ks x 0.9	2012	Baseline09_Cal_GW_Div_NR.prj	Baseline09_Cal_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, decrease Ks by 10%
Baseline Ks x 0.8	2012	Baseline08_Cal_GW_Div_NR.prj	Baseline08_Cal_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, decrease Ks by 20%
Baseline Ks x 0.7	2012	Baseline07_Cal_GW_Div_NR.prj	Baseline07_Cal_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, decrease Ks by 30%
Baseline GW x 0.5	2012	Baseline_Cal_GW05_Div_NR.prj	Baseline_Cal_GW05_DIV_noRet	Calibrated baseline model for 2012, with no return flows, decrease baseline depth of groundwater hydrographs by 50%
Baseline GW x 1.5	2012	Baseline_Cal_GW15_Div_NR.prj	Baseline_Cal_GW15_DIV_noRet	Calibrated baseline model for 2012, with no return flows, increase baseline depth of groundwater hydrographs by 50%
Baseline dy x 0.6	2012	Baseline_Cal_dy06_Div_NR.prj	Baseline_Cal_dy06_DIV_noRet	Calibrated baseline model for 2012, with no return flows, decrease river sediment thickness (dy) by 40%, from 5 feet to 3 feet
Baseline dy x 1.6	2012	Baseline_Cal_dy16_Div_NR.prj	Baseline_Cal_dy16_DIV_noRet	Calibrated baseline model for 2012, with no return flows, increase river sediment thickness (dy) by 60%, from 5 feet to 8 feet
Baseline dy x 2.0	2012	Baseline_Cal_dy20_Div_NR.prj	Baseline_Cal_dy20_DIV_noRet	Calibrated baseline model for 2012, with no return flows, increase river sediment thickness (dy) by 100%, from 5 feet to 10 feet
S1	2012	S1_GW_Div_NR.prj	S1_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S1)
S1 Ks x 1.1	2012	S1_11_GW_Div_NR.prj	S1_11_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S1), increase Ks by 10%
S1 Ks x 1.2	2012	S1_12_GW_Div_NR.prj	S1_12_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S1), increase Ks by 20%
S1 Ks x 1.3	2012	S1_13_GW_Div_NR.prj	S1_13_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S1), increase Ks by 30%
S1 Ks x 0.9	2012	S1_09_GW_Div_NR.prj	S1_09_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S1), decrease Ks by 10%
S1 Ks x 0.8	2012	S1_08_GW_Div_NR.prj	S1_08_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S1), decrease Ks by 20%
S1 Ks x 0.7	2012	S1_07_GW_Div_NR.prj	S1_07_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S1), decrease Ks by 30%

All models are based on the “Rio Grande, Canalization Reach-2012-US” geometry file.

Table H-24. HEC-RAS Modeling – File Summary

Model	Period	Project Filename	Plan/Unsteady Flow Name	Unsteady Flow Name
Flow Release at Caballo Dam, Diversions at Percha, Leasburg, and Mesilla Dams, No Return Flows (cont.)				
S2	2012	S2_GW_Div_NR.prj	S2_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Normal Single Pulse Model (S2)
S2 Ks x 1.1	2012	S2_11_GW_Div_NR.prj	S2_11_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S2), increase Ks by 10%
S2 Ks x 1.2	2012	S2_12_GW_Div_NR.prj	S2_12_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S2), increase Ks by 20%
S2 Ks x 1.3	2012	S2_13_GW_Div_NR.prj	S2_13_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S2), increase Ks by 30%
S2 Ks x 0.9	2012	S2_09_GW_Div_NR.prj	S2_09_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S2), decrease Ks by 10%
S2 Ks x 0.8	2012	S2_08_GW_Div_NR.prj	S2_08_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S2), decrease Ks by 20%
S2 Ks x 0.7	2012	S2_07_GW_Div_NR.prj	S2_07_GW_DIV_noRet	Calibrated baseline model for 2012, with no return flows, using Delayed Single Pulse Model (S2), decrease Ks by 30%
Flow Release at Caballo Dam, Diversions at Percha, Leasburg, and Mesilla Dams, and Groundwater Interaction, With Return Flows				
Baseline - With Returns	2012	baseline_Cal_GW_Div_WR.prj	baseline_Cal_GW_DIV_withRet	Calibrated baseline model, with return flows
Baseline 2010-2012 - With Returns	2010-2012	2010-2012_GW_Div_WR.prj	2010-2012_GW_DIV_withRet	Calibrated model run for 2010-2012, with return flows

All models are based on the “Rio Grande, Canalization Reach-2012-US” geometry file

Page Intentionally Blank

5.0 FIGURES

Page Intentionally Blank

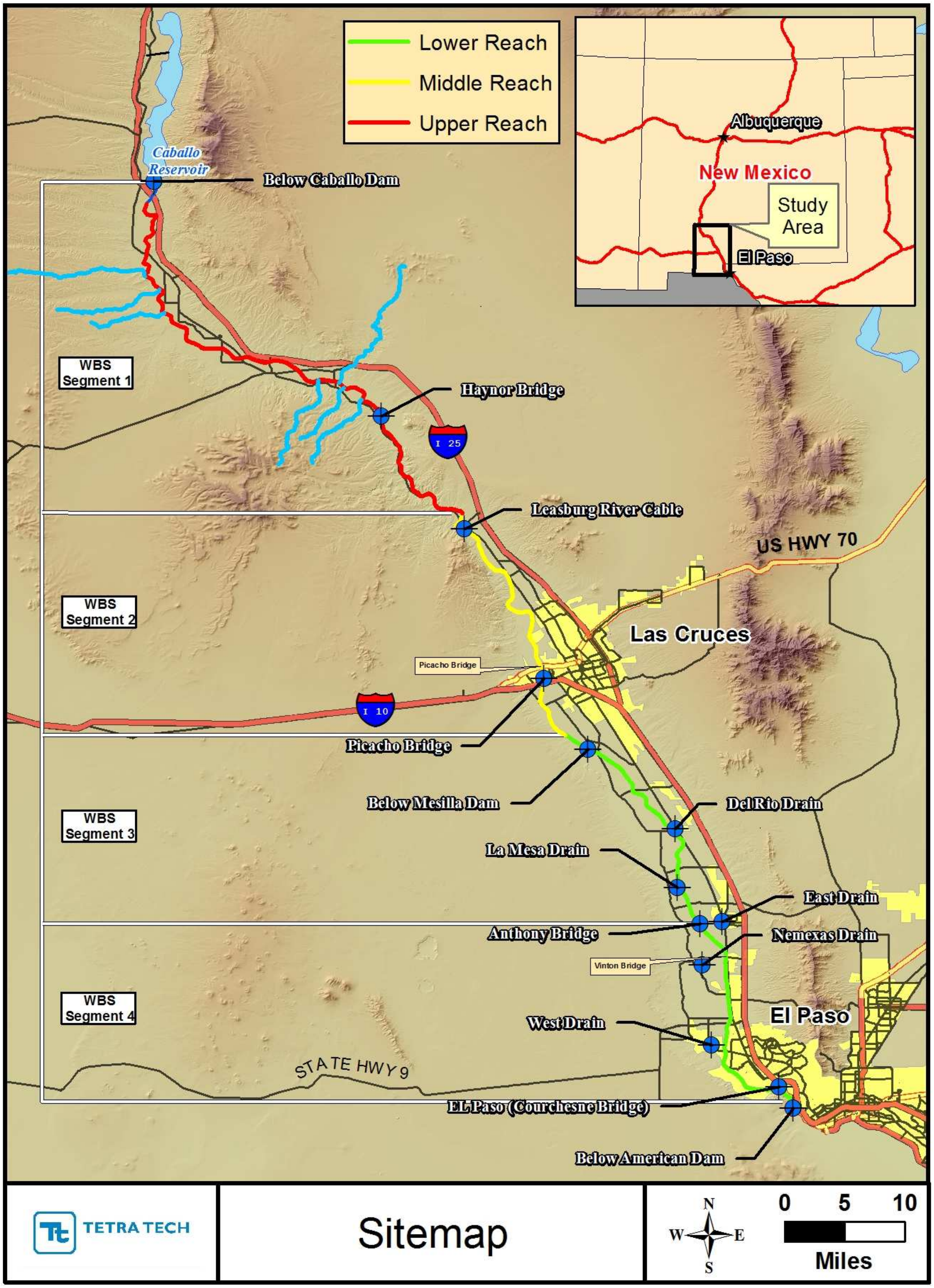


Figure H-1. Location of the Rio Grande Canalization Project

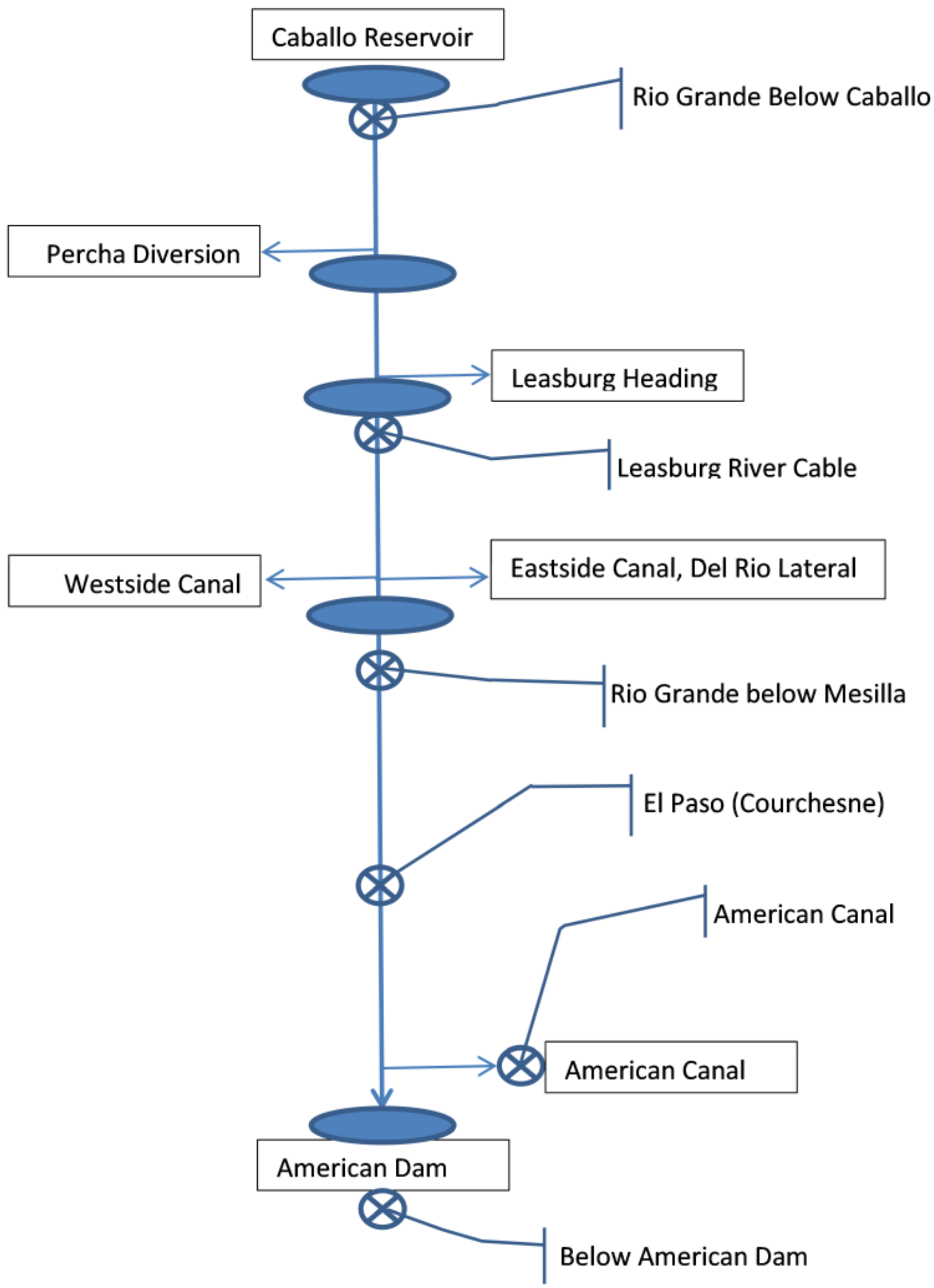


Figure H-2. HEC-RAS Model Coverage and Key Locations

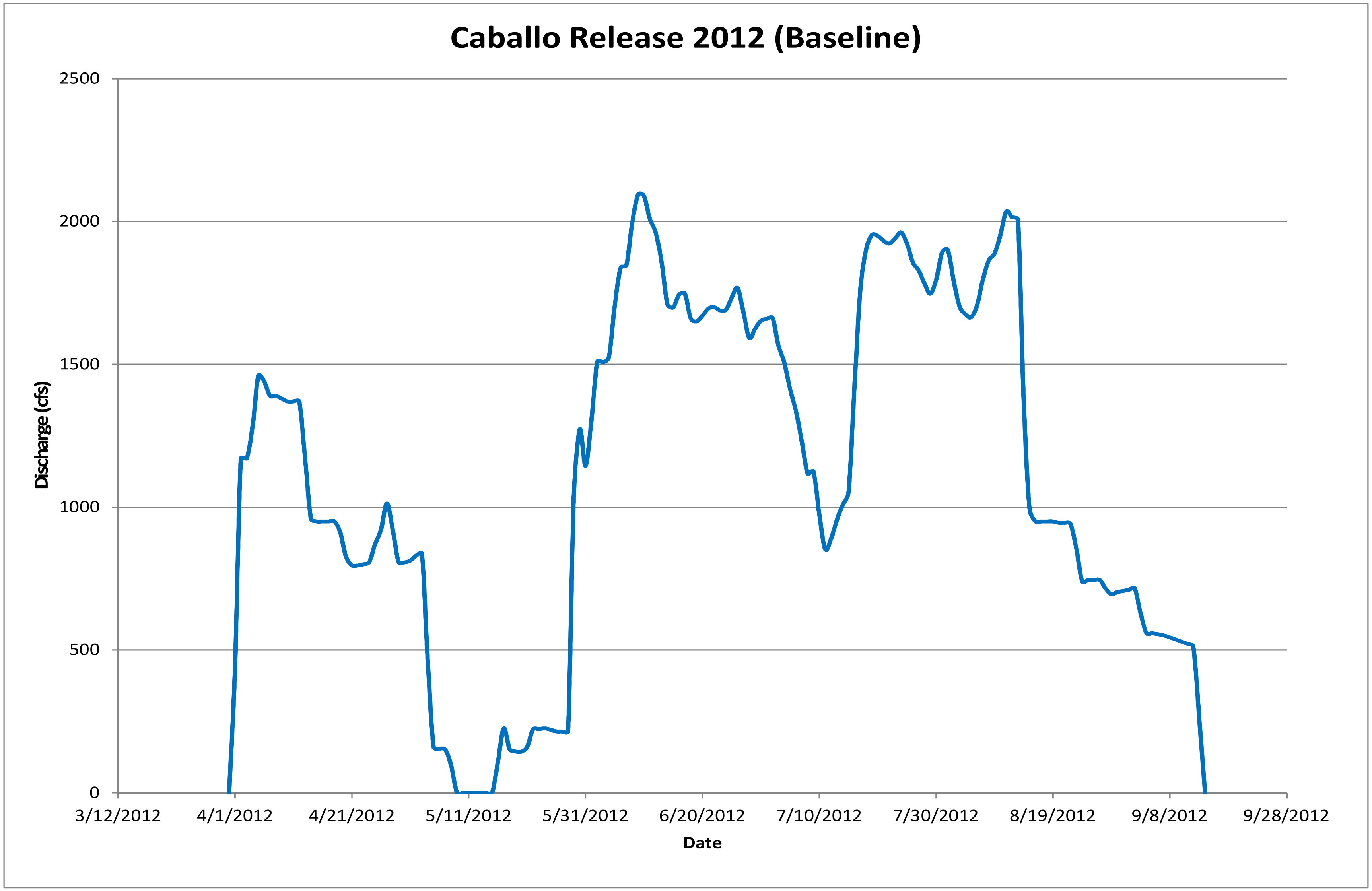


Figure H-3. Caballo Release 2012 (Baseline) hydrograph - provided by the Rio Grande Project Allocation Committee

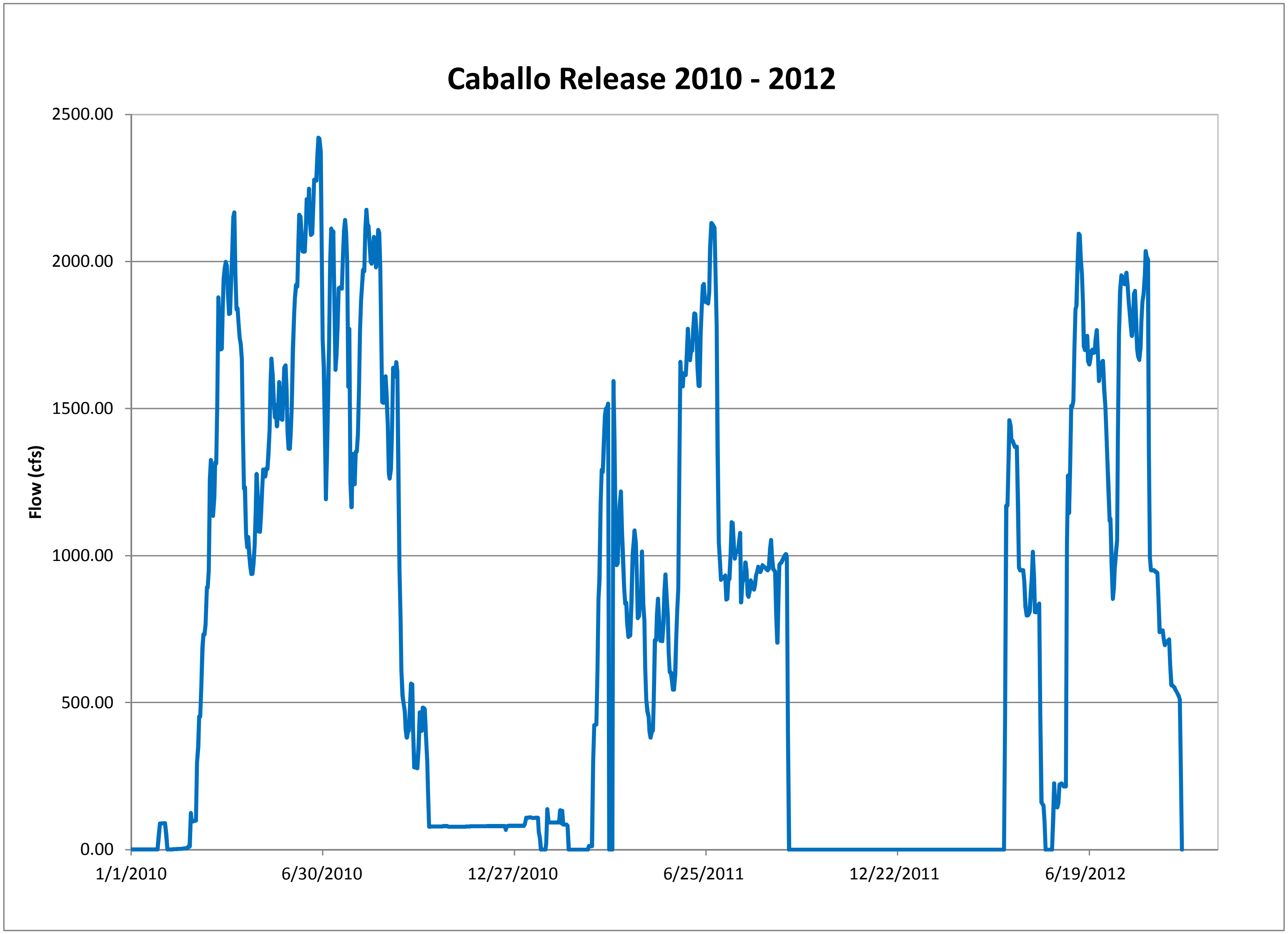


Figure H-4. Caballo Release 2010-2012 Hydrograph – 2010 and 2011 provided by the USBR, 2012 (Baseline) provided by the Rio Grande Project Allocation Committee

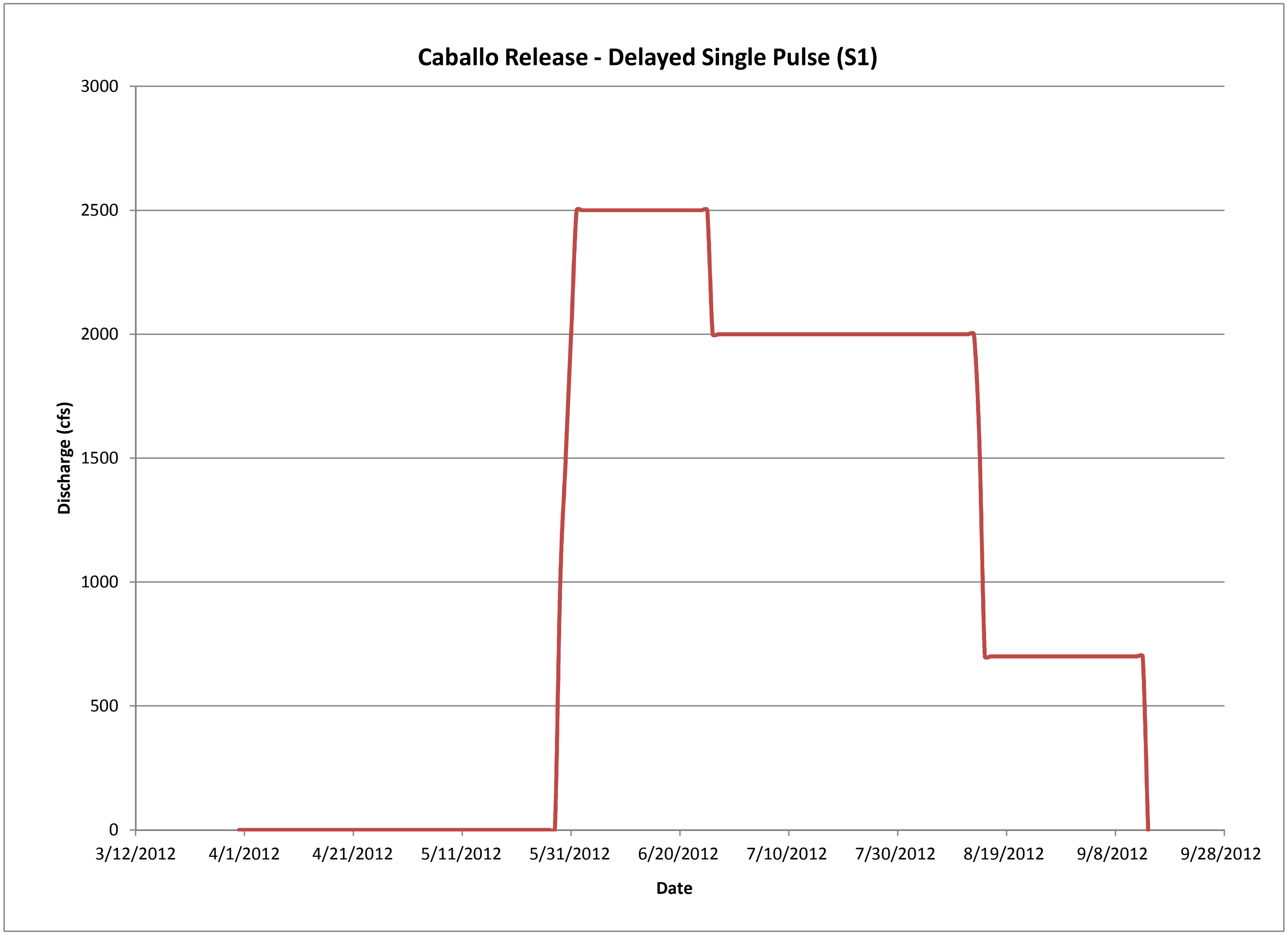


Figure H-5. S1 (Delayed Single-pulse) hydrograph, provided by the Rio Grande Project Allocation Committee

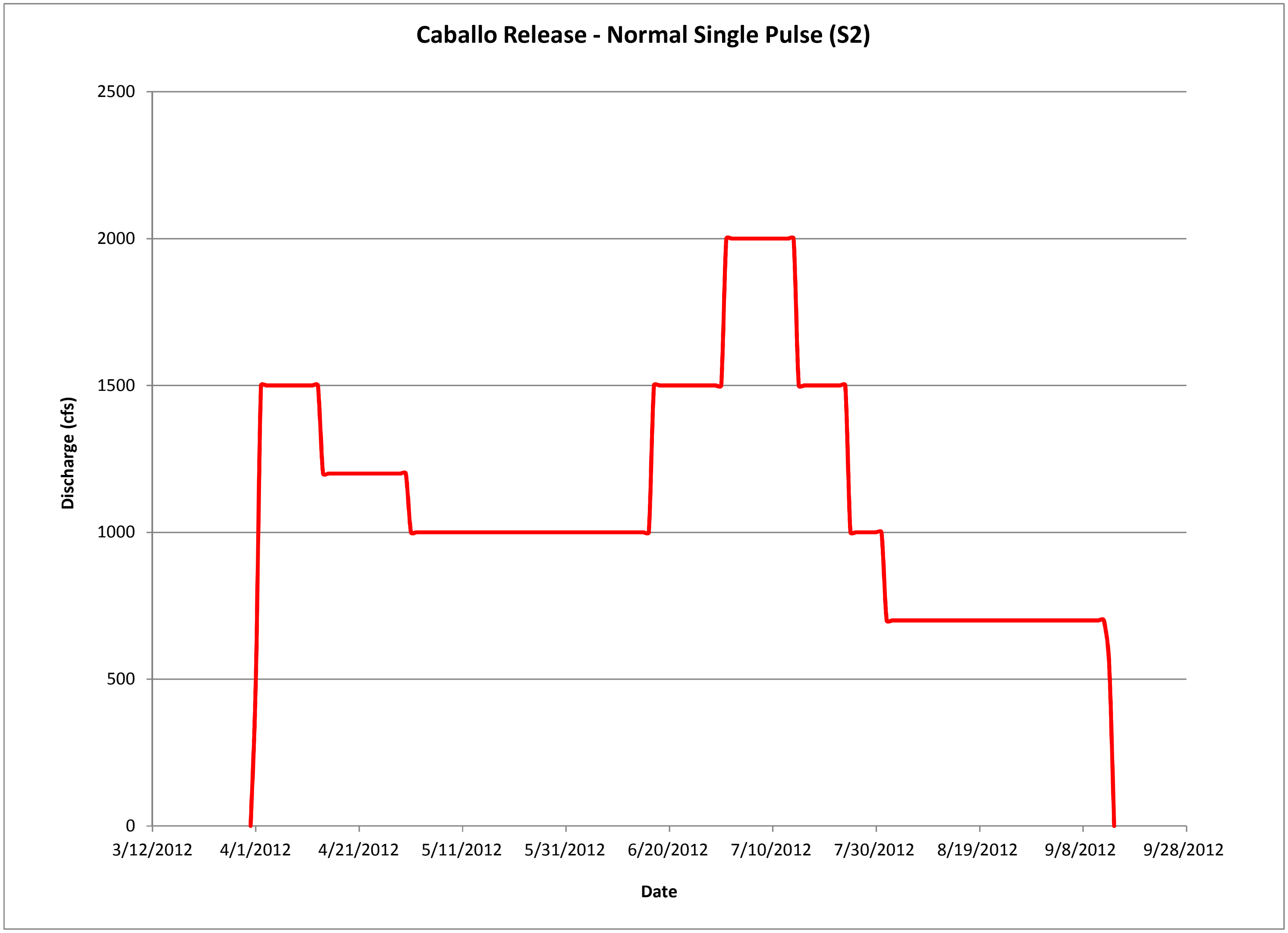


Figure H-6. S2 (Normal Single-pulse) Hydrograph, provided by the Rio Grande Project Allocation Committee

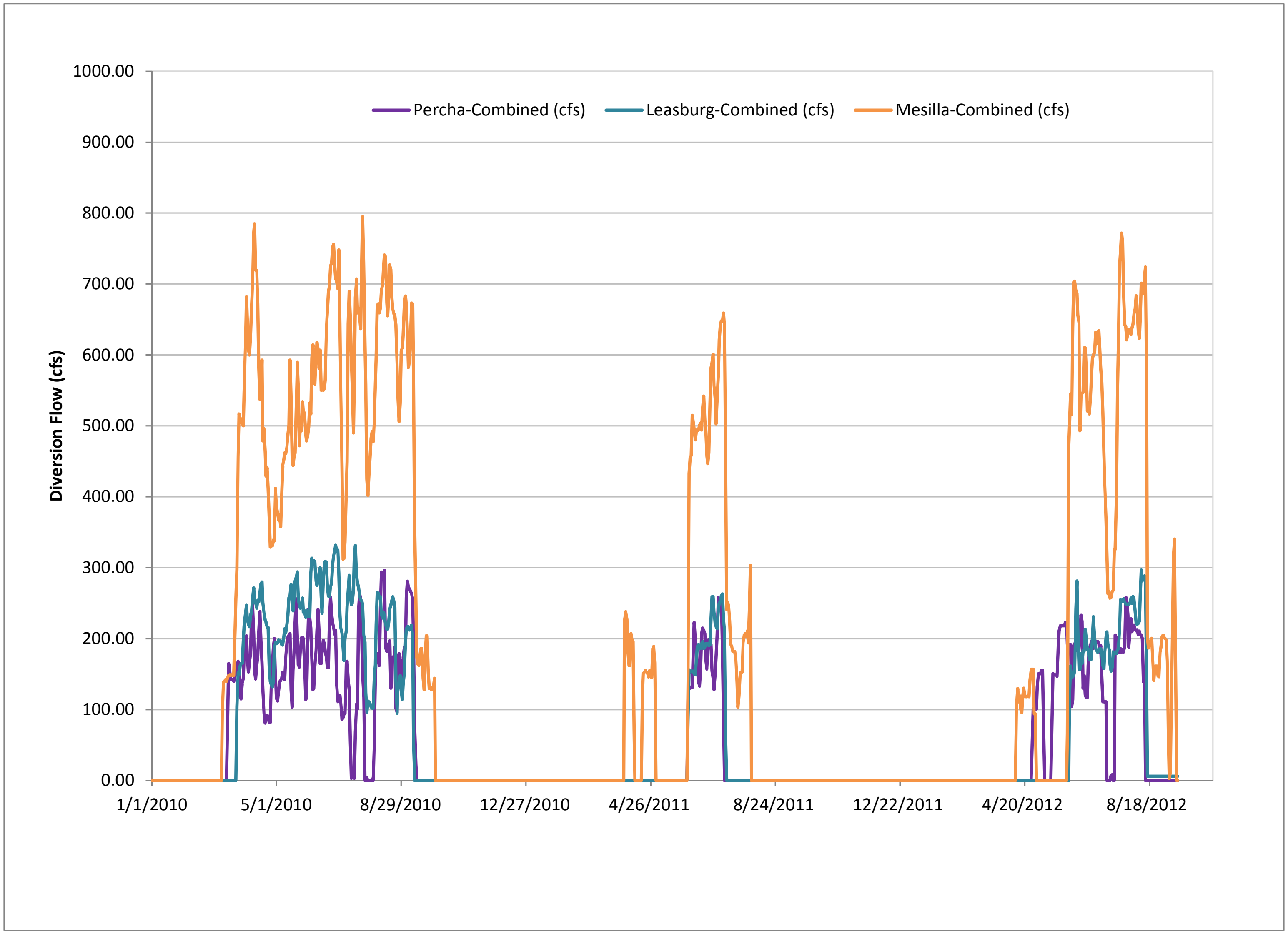


Figure H-7. Diversion Hydrographs at Percha Dam, Leasburg Dam, and Mesilla Dam, 2010 - 2012

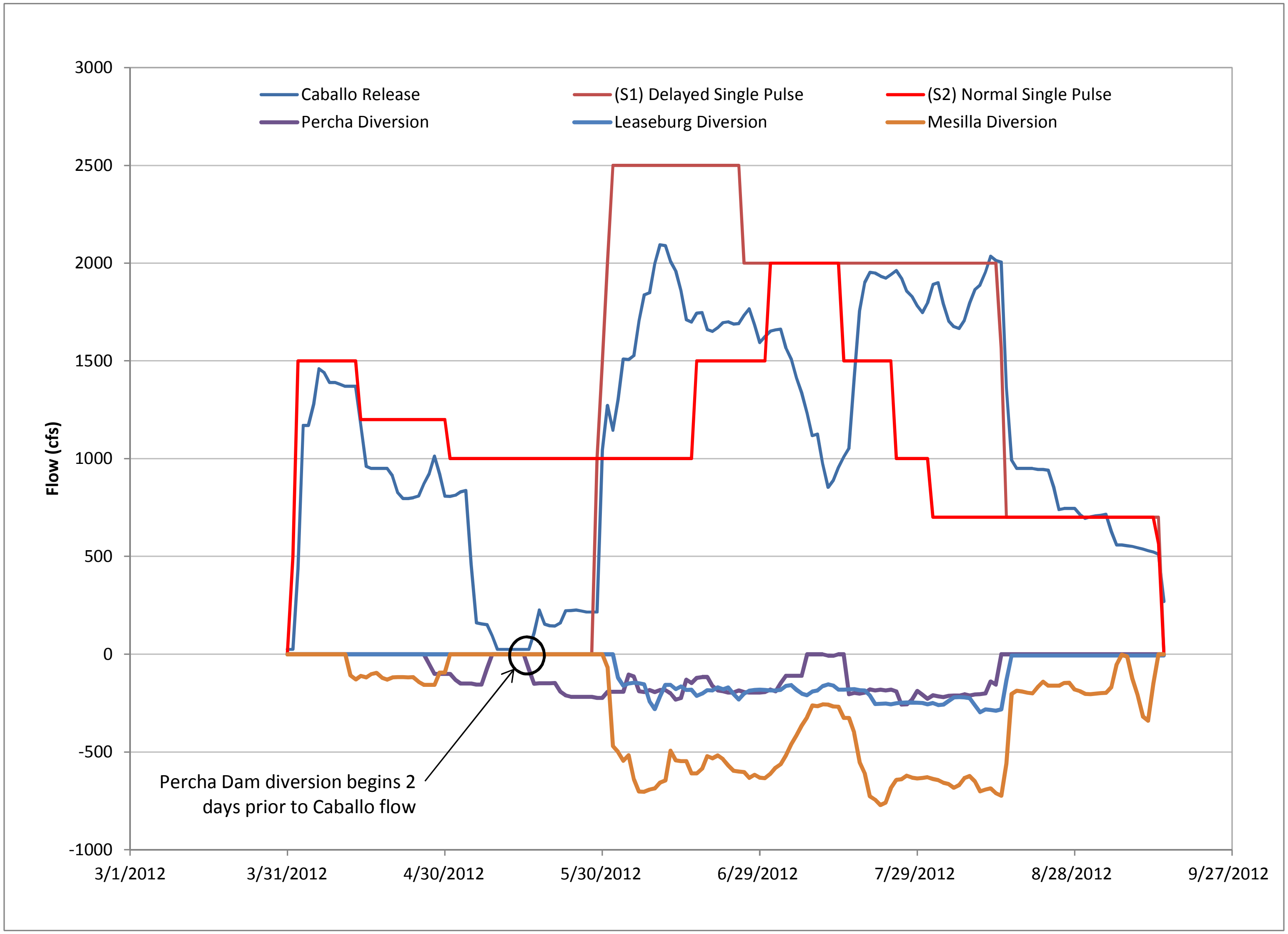


Figure H-8. **Comparison of 2012 Caballo Release, Hypothetical Hydrographs, and Diversion Hydrographs at Percha Dam, Leasburg Dam, and Mesilla Dam**

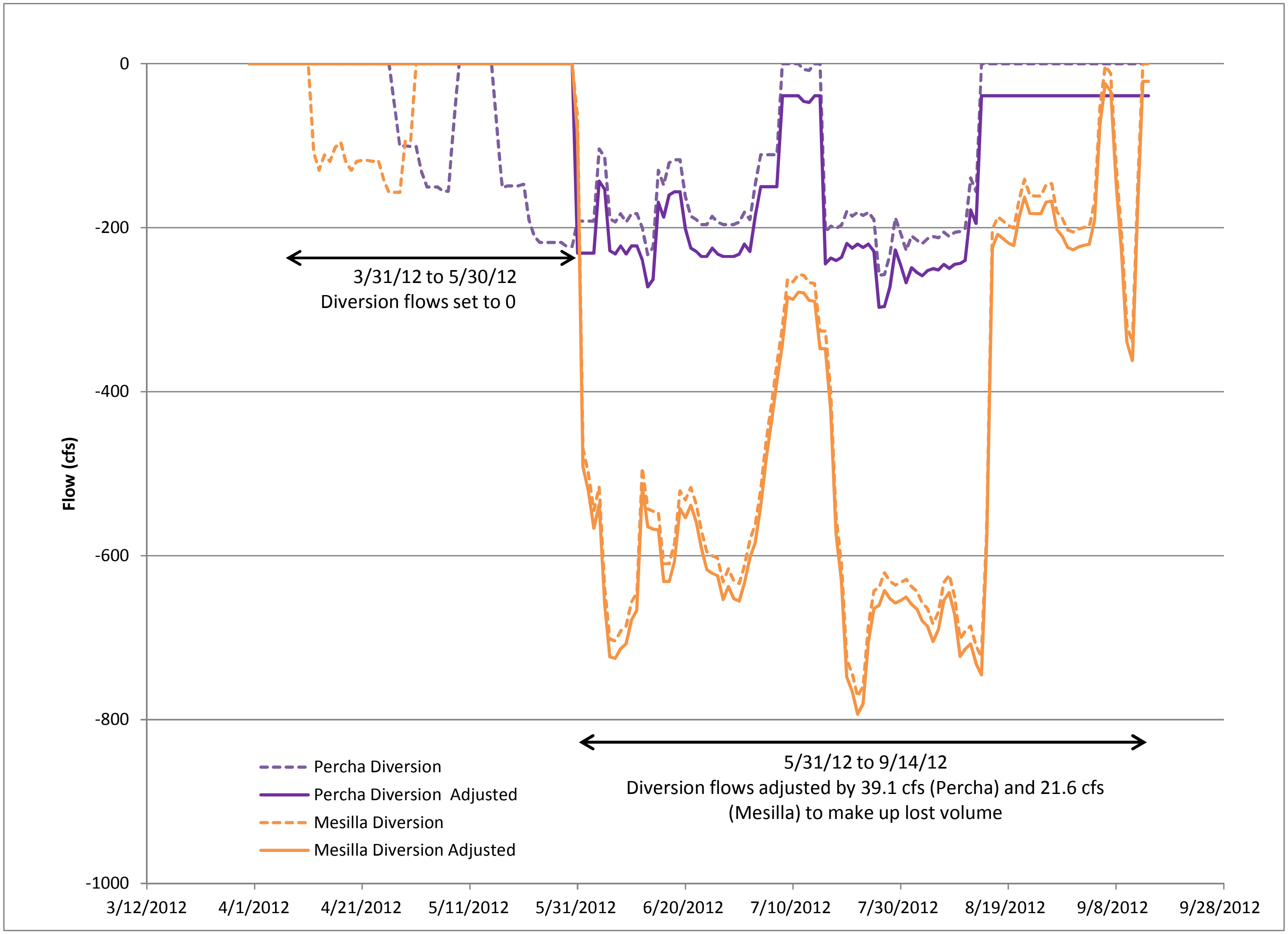


Figure H-9. Adjustment to 2012 Diversion Hydrographs at Percha Dam and Mesilla Dam for Delayed Single-Pulse (S1)

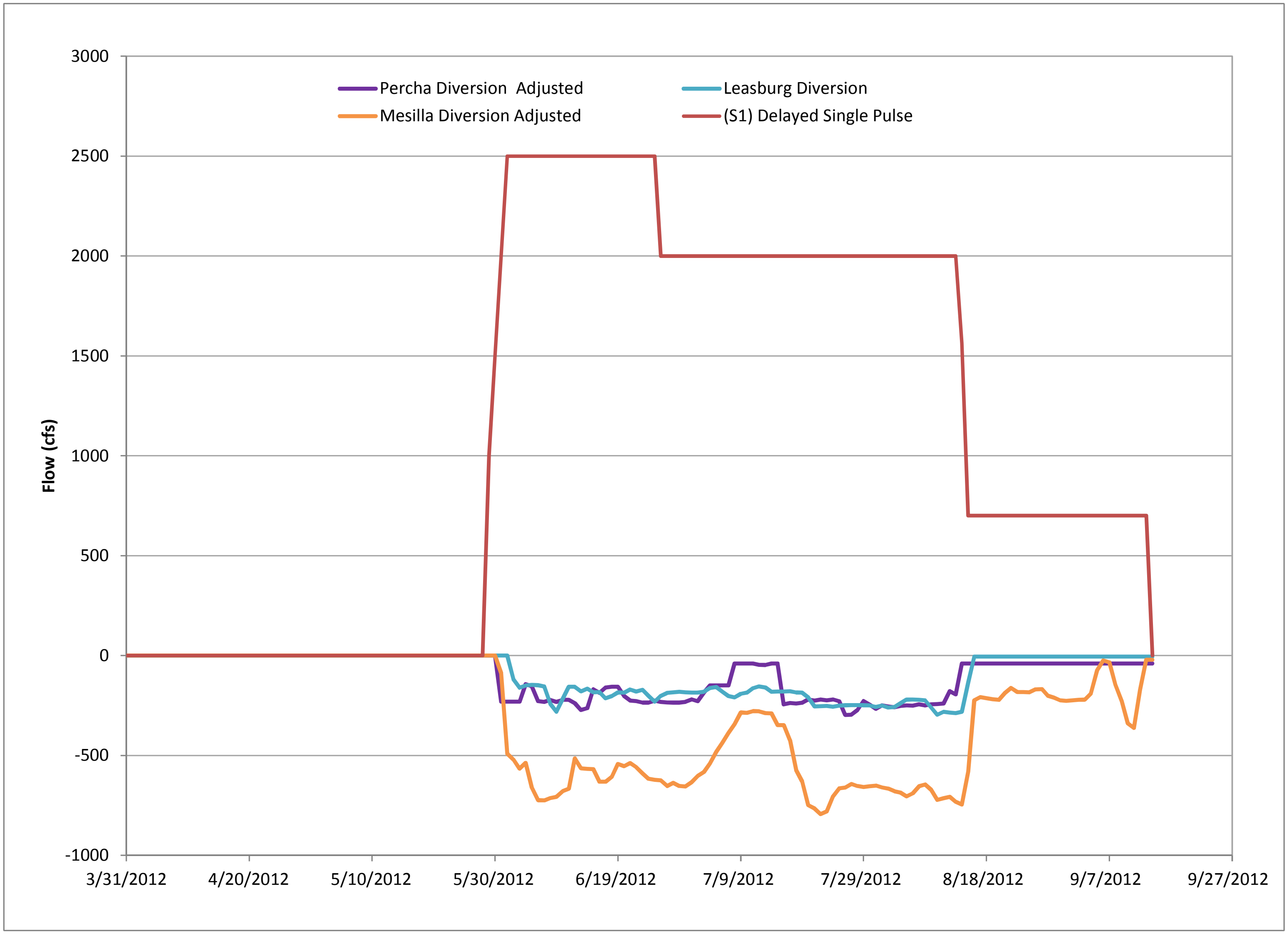


Figure H-10. Adjusted 2012 Diversion Hydrographs at Percha Dam and Mesilla Dam for Delayed Single-Pulse (S1)

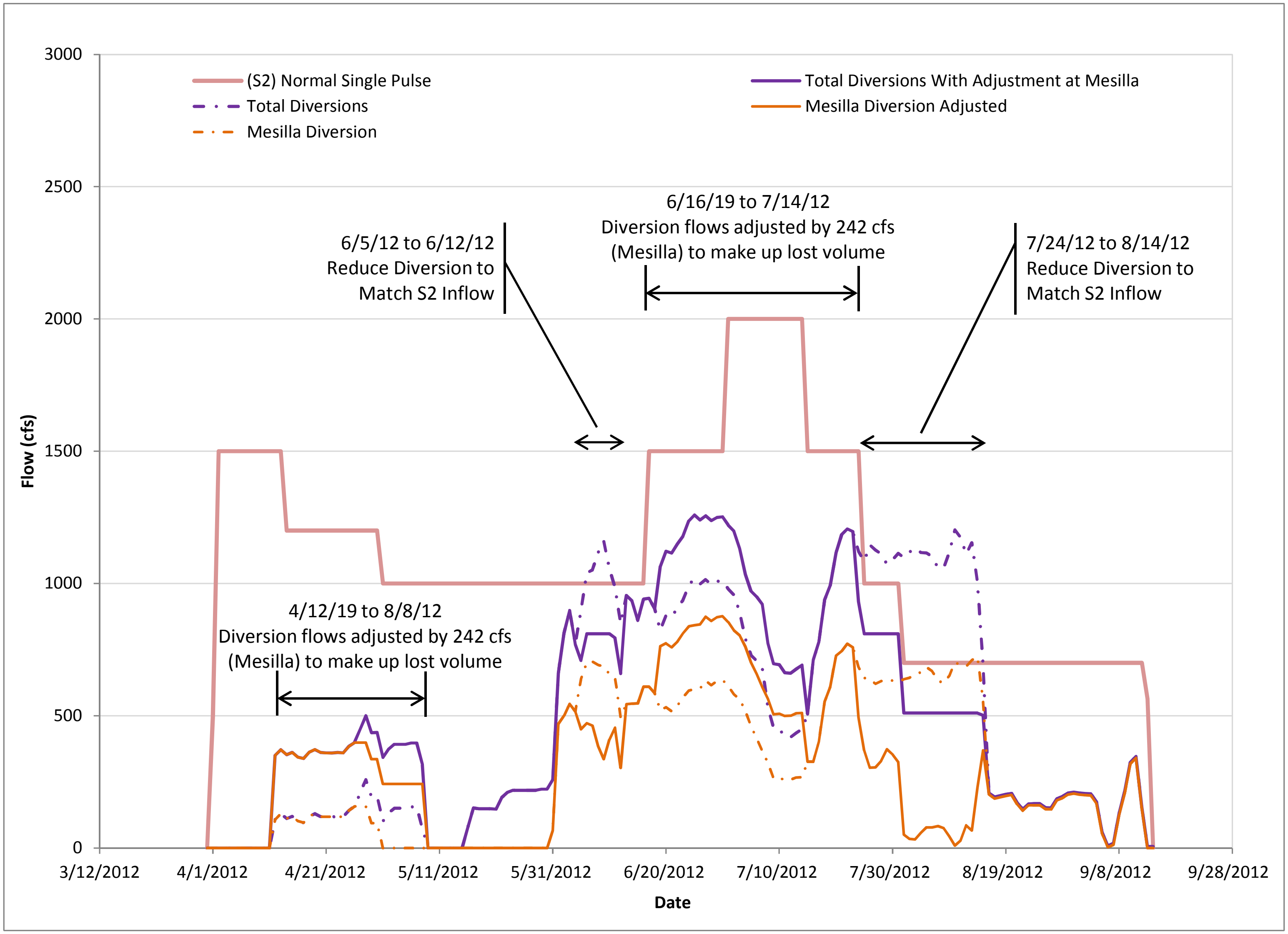


Figure H-11. Adjustment to 2012 Diversion Hydrographs at Mesilla Dam for Normal Single-Pulse (S2)

(Note: Diversion flows in this plot are shown as positive for direct comparison with S2 Hydrograph)

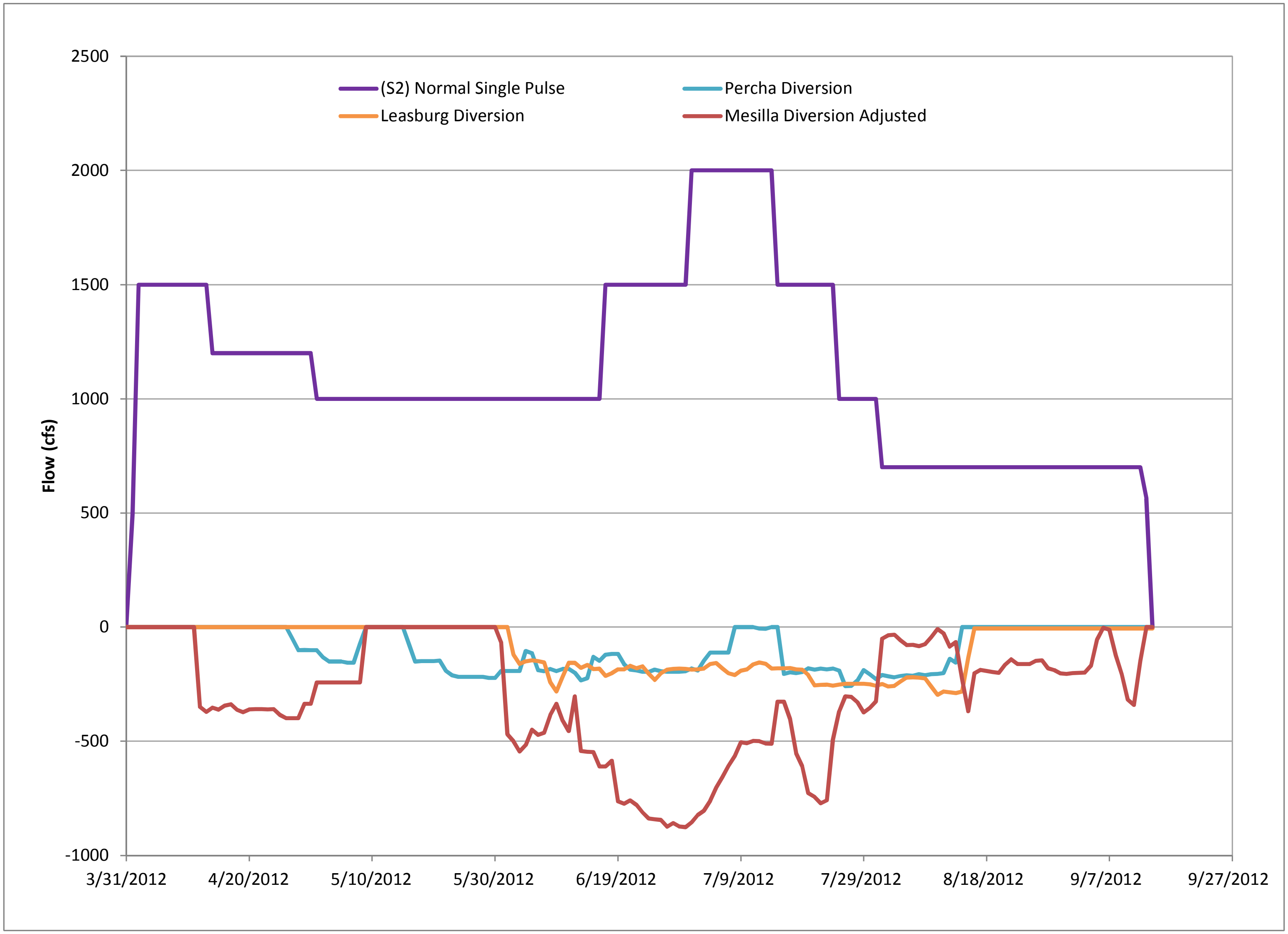


Figure H-12. Adjusted 2012 Diversion Hydrograph at Mesilla Dam for Normal Single-Pulse (S2)

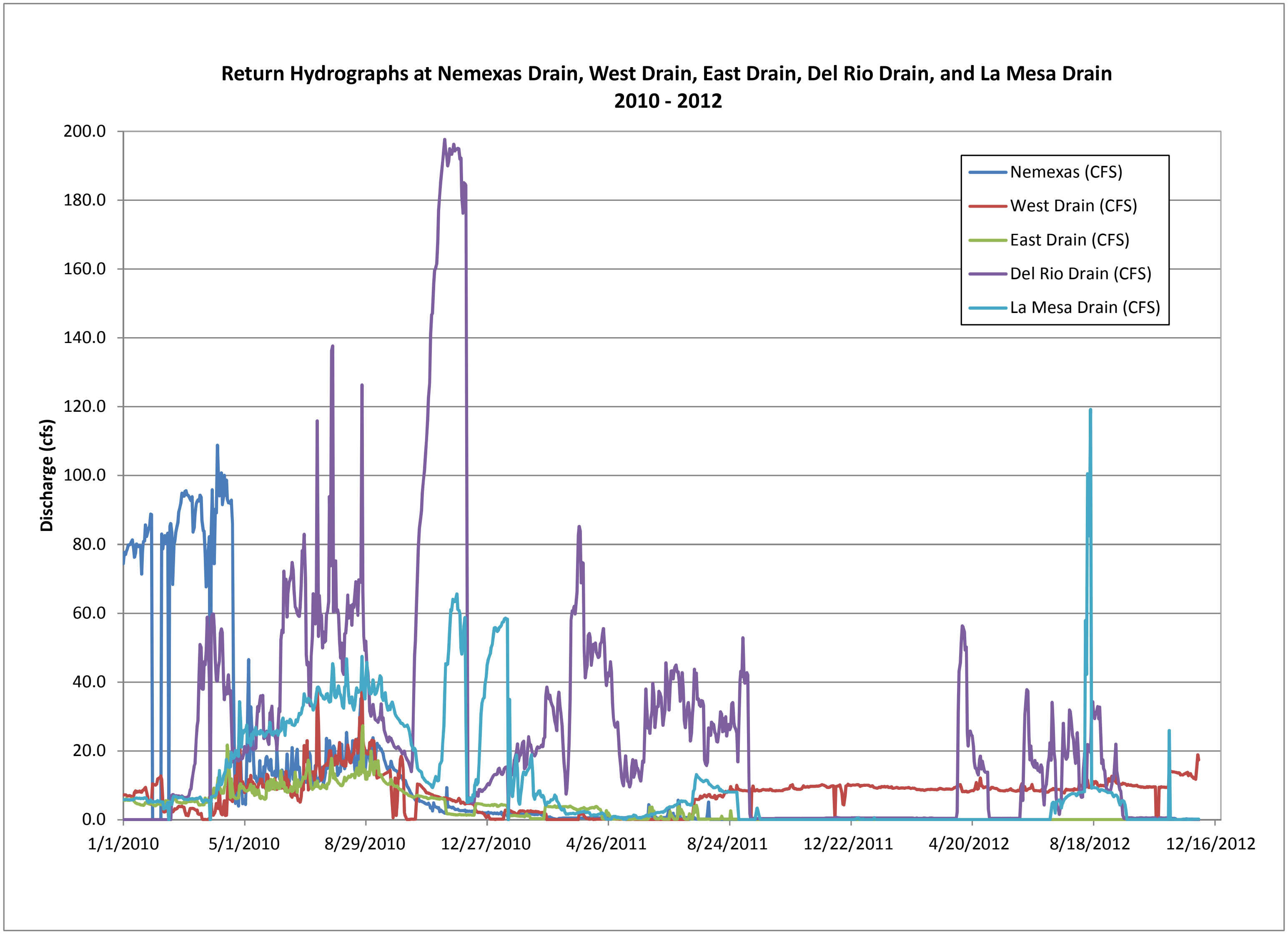


Figure H-13. Return Hydrographs at Nemexas Drain, West Drain, East Drain, Del Rio Drain, and La Mesa Drain

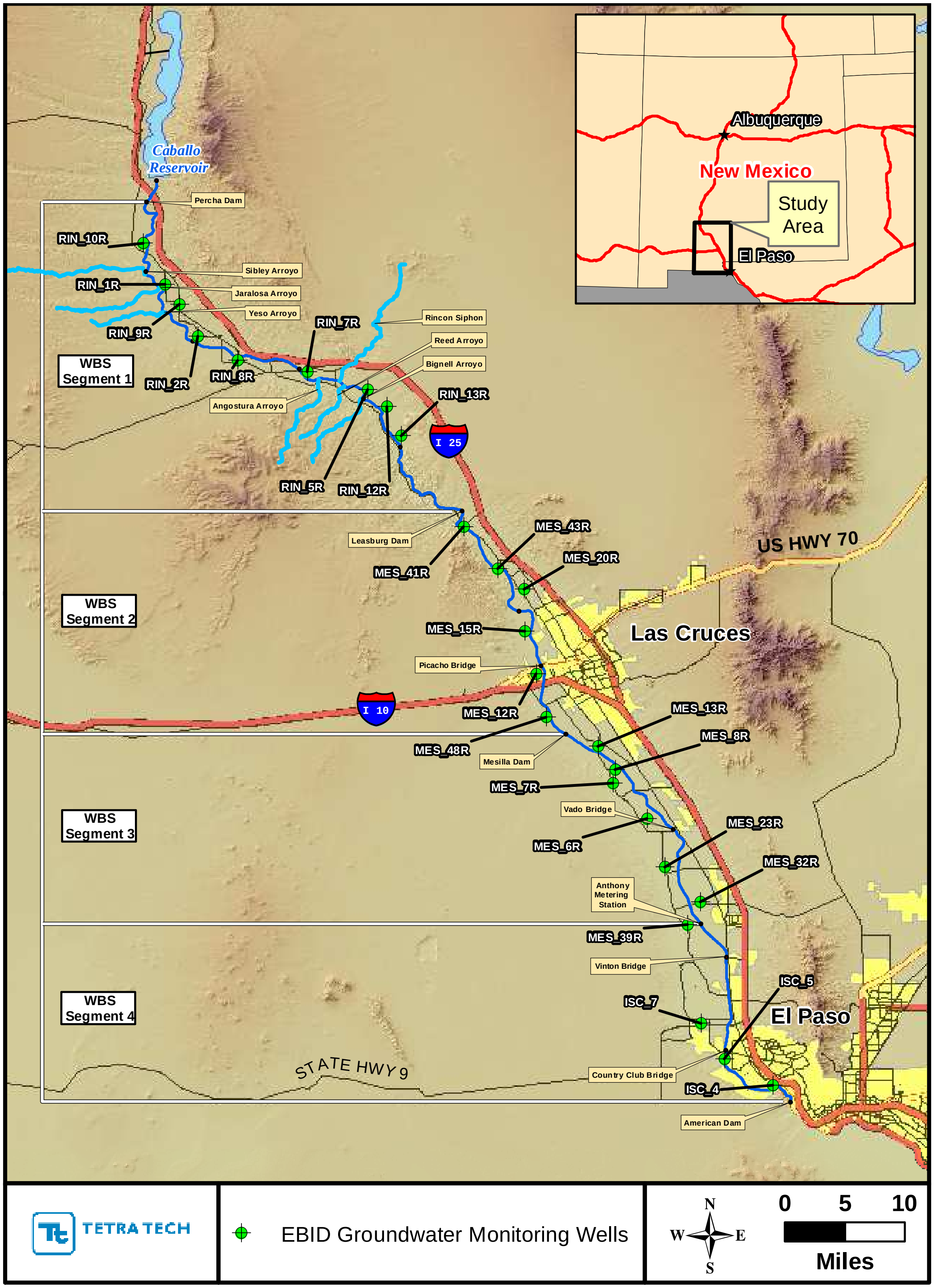
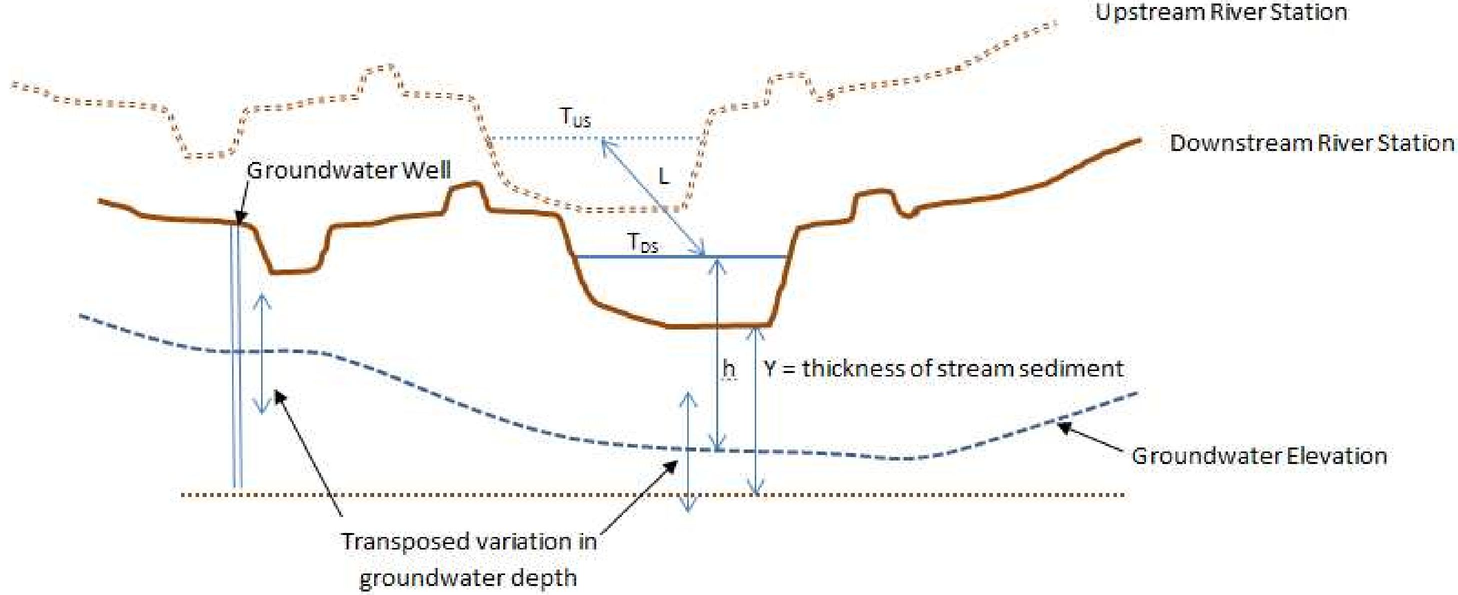


Figure H-14. Monitoring Well Locations



The Darcy Equation as applied by HEC-RAS is written:

$$Q = K_s * \frac{dh}{dy} * A \quad where \quad A = \frac{T_{us} + T_{ds}}{2} * L$$

Where Q = groundwater interflow (ft^3/day), h = depth (ft) from water surface elevation to the ground water elevation, y = thickness (ft) of river sediments, A = area (sf), T_{us} = flow top width upstream, T_{ds} = flow top width (ft) downstream, L = distance (ft) from the downstream cross section to the upstream cross section, and K_s = saturated hydraulic conductivity of the stream sediments (feet/day). Note that y should vary with changes in the groundwater elevation. However, since HEC-RAS only allows a single input for this parameter, it is taken as the thickness of the streambed sediment.

Figure H-15. HEC-RAS Groundwater Interflow Schematic

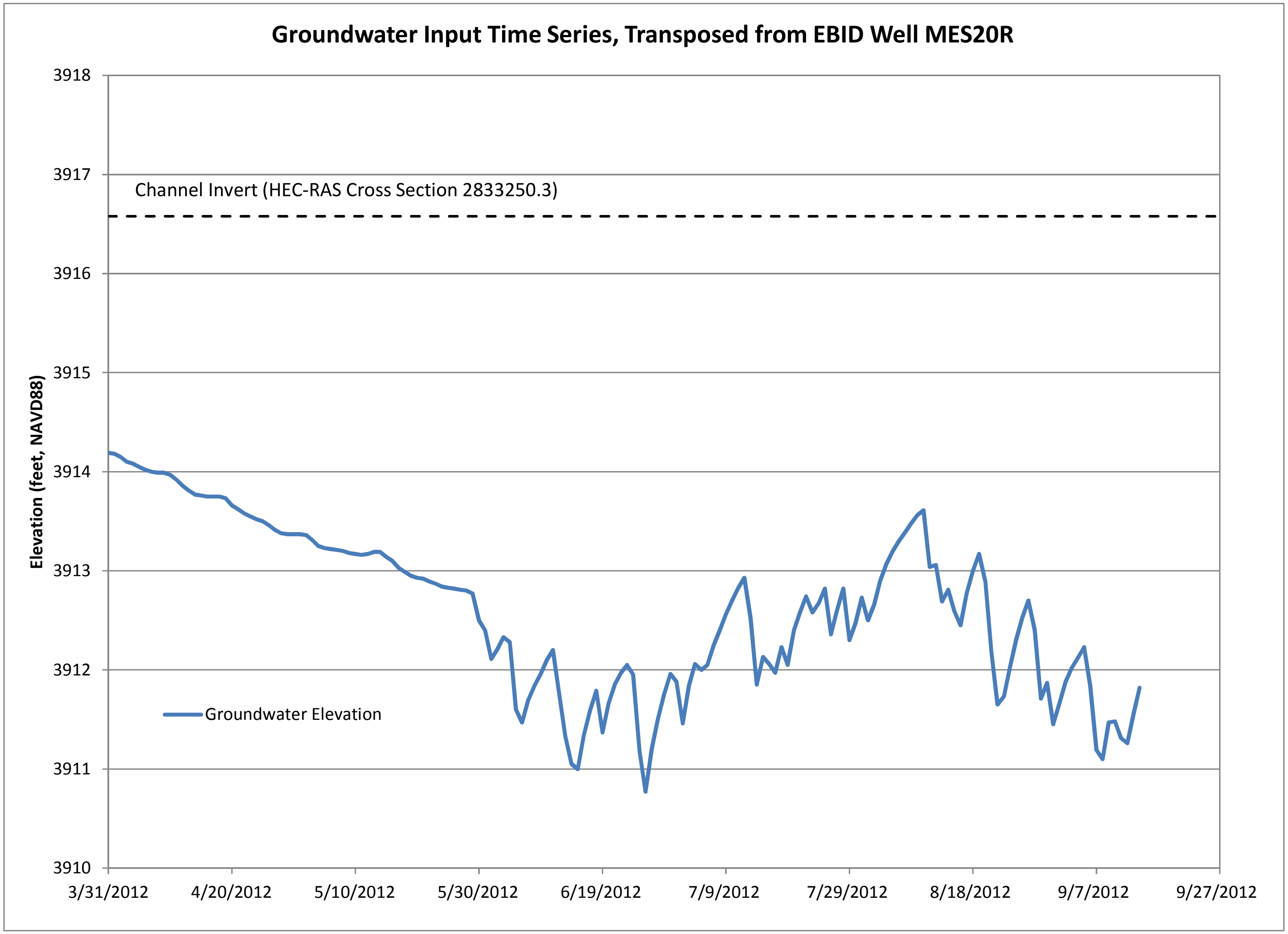


Figure H-16. HEC-RAS Groundwater Input Time Series Example Using EBID Well MES20R

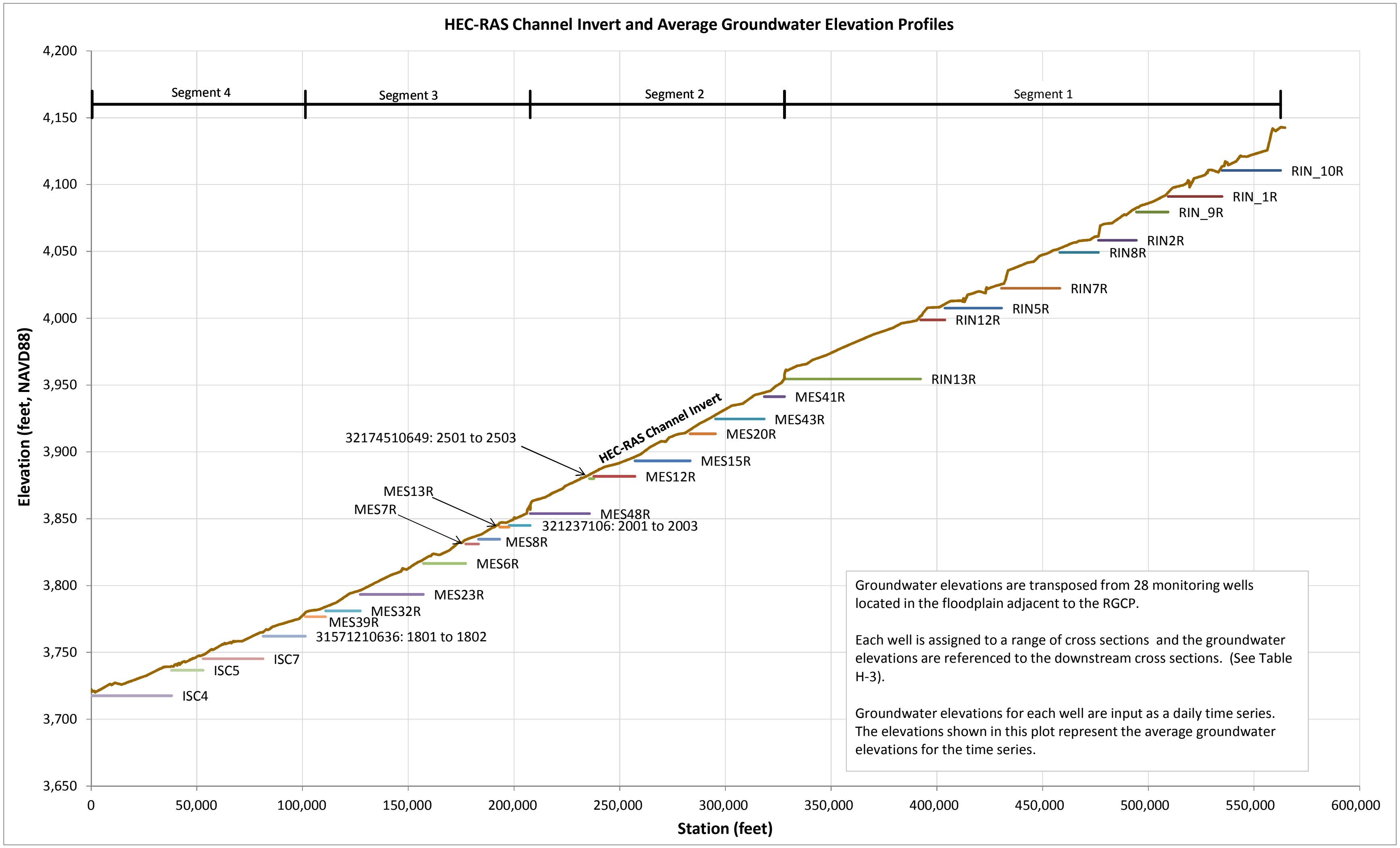


Figure H-17. HEC-RAS Channel Invert and Average Groundwater Elevation Profiles

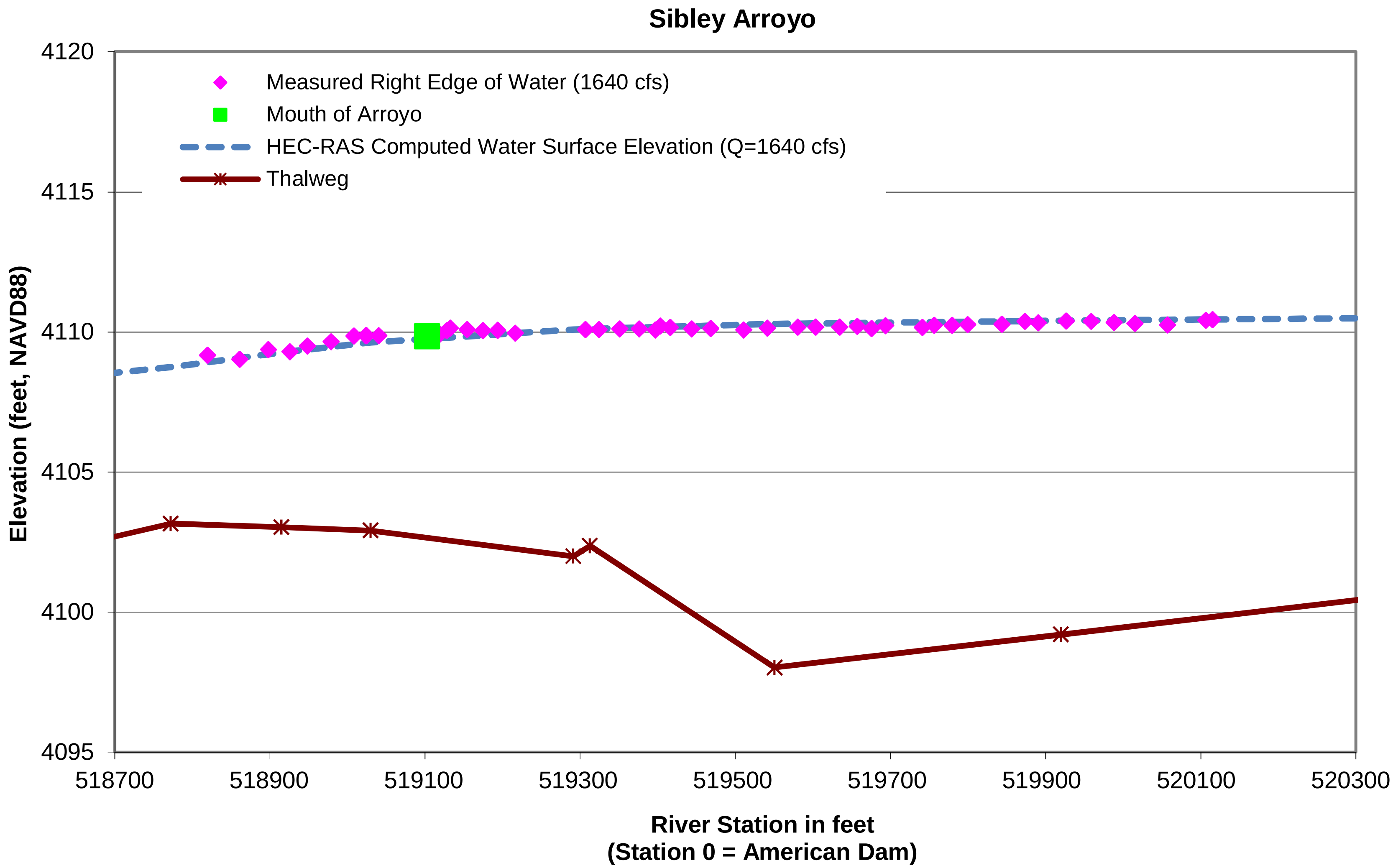


Figure H-18. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Sibley Arroyo.

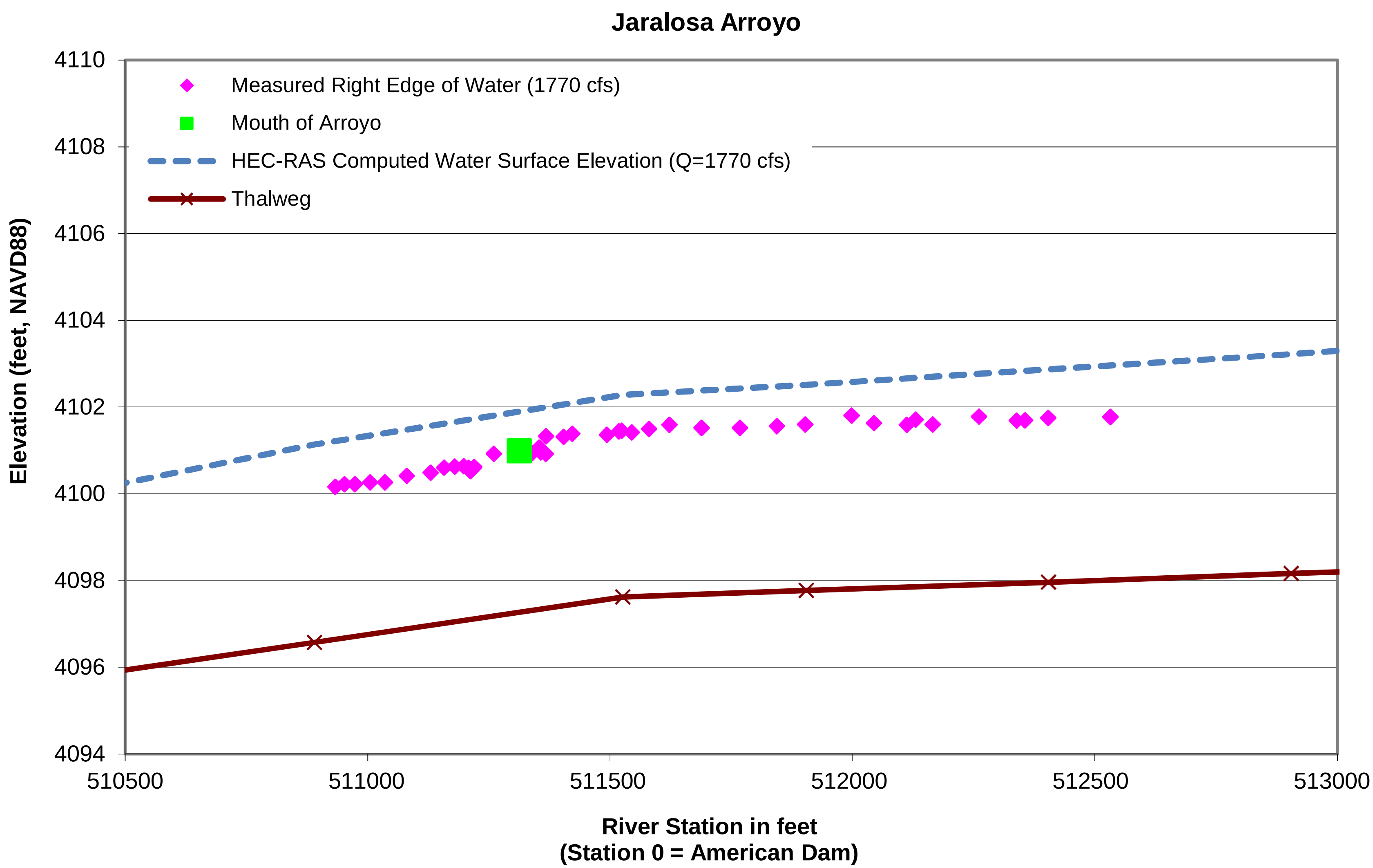


Figure H-19. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Jaralosa Arroyo

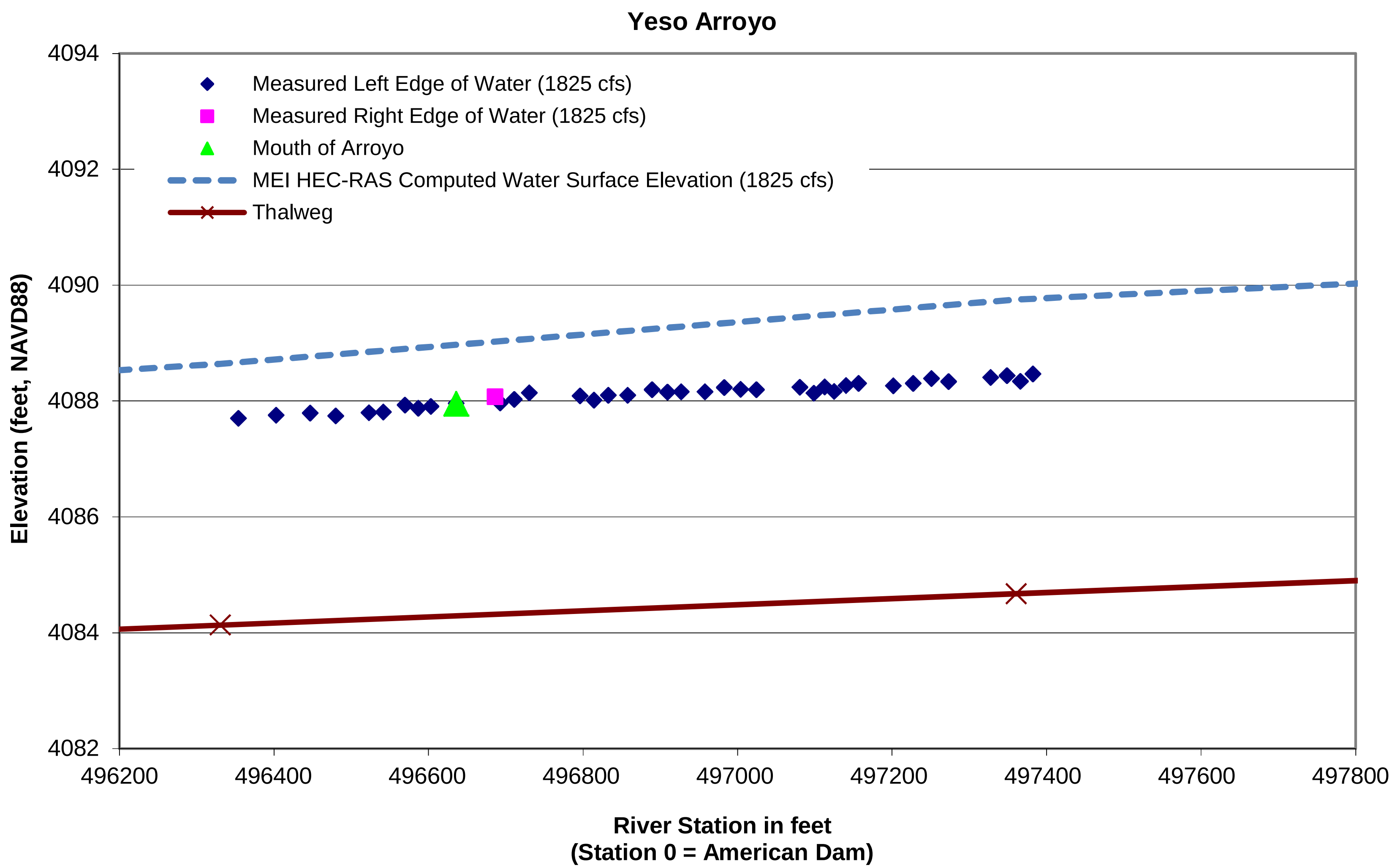


Figure H-20. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Yeso Arroyo

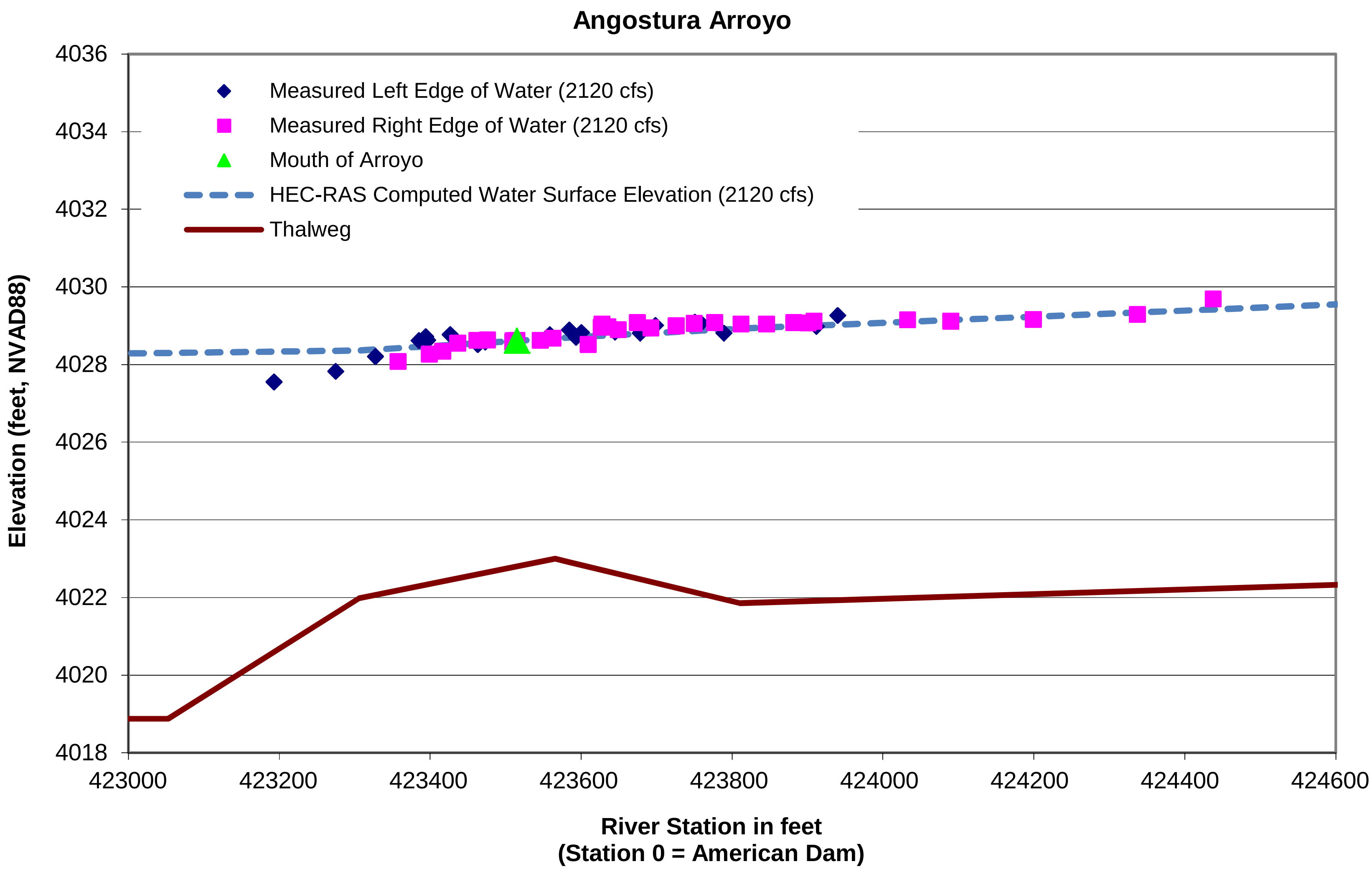


Figure H-21. **Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Angostura Arroyo**

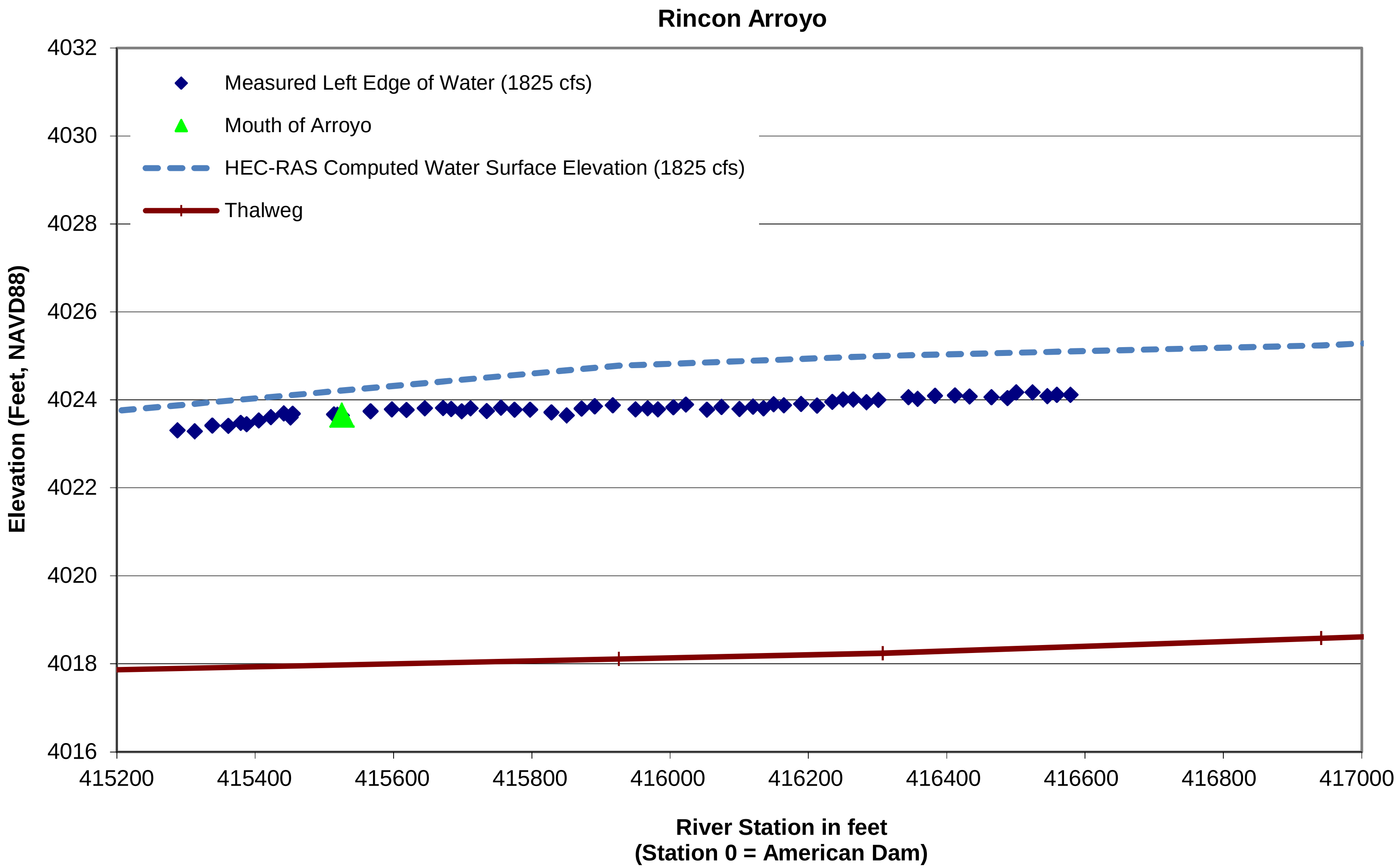


Figure H-22. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Rincon Arroyo

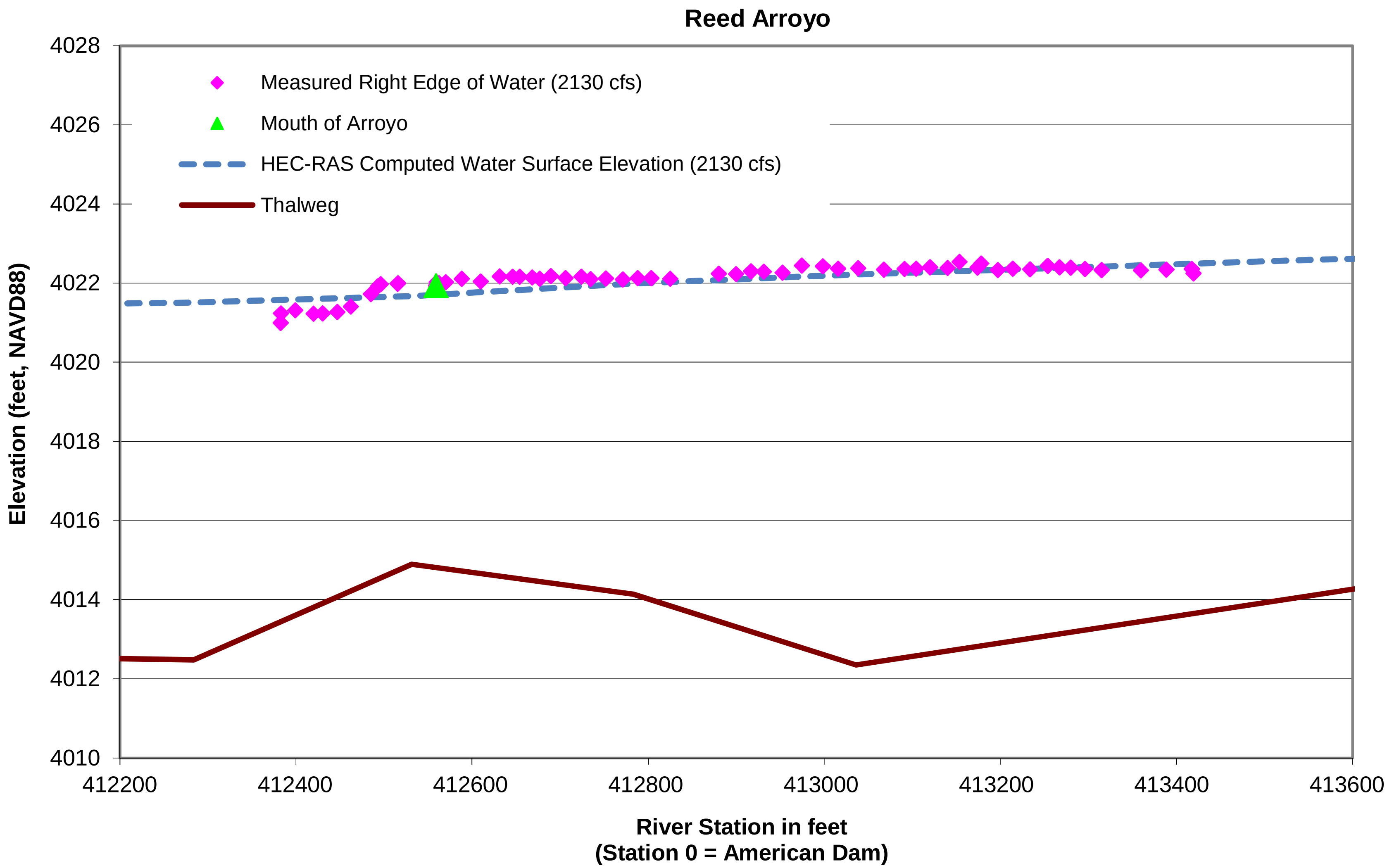


Figure H-23. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Reed Arroyo

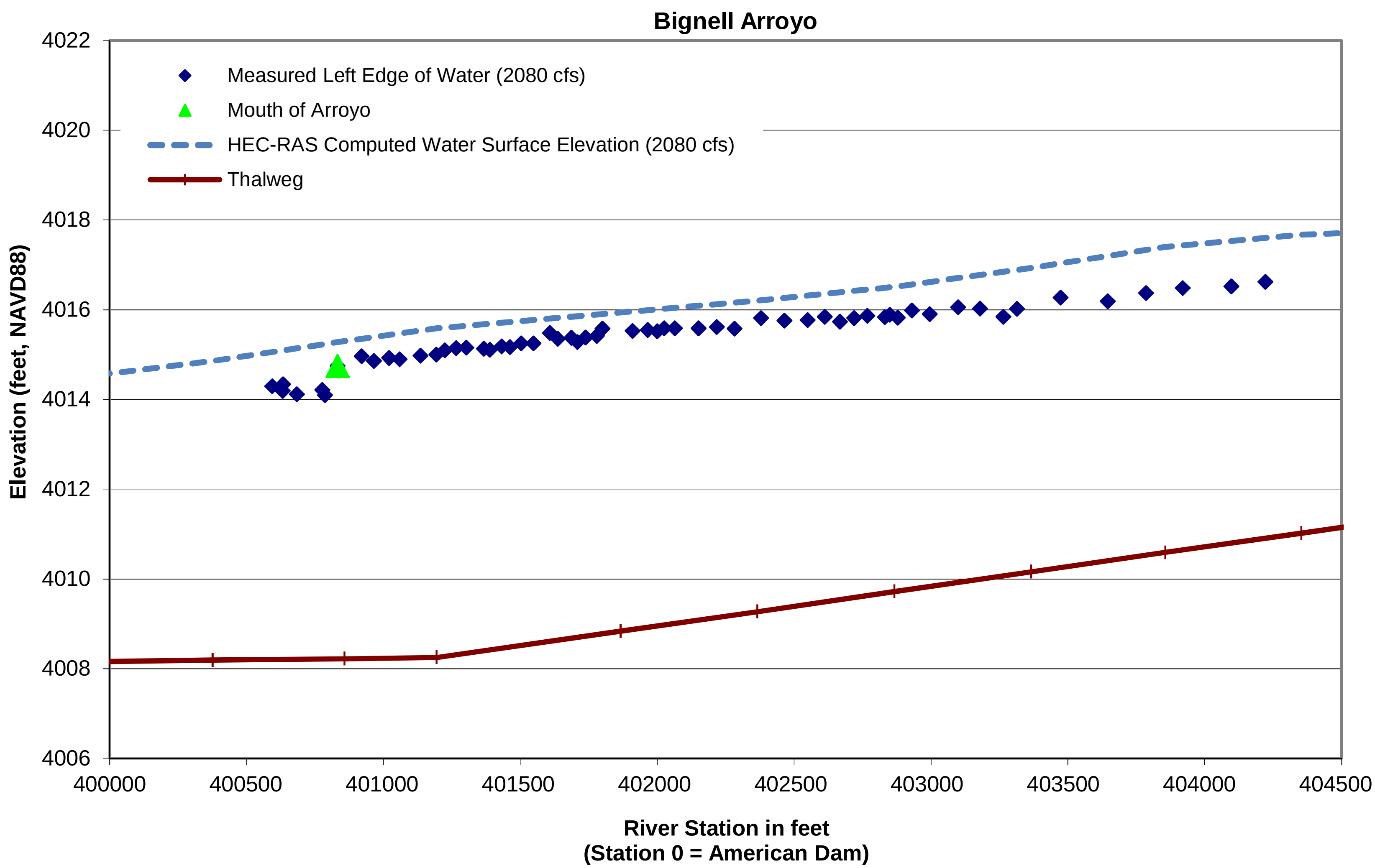


Figure H-24. Comparison of measured and predicted water-surface elevations from the steady-state HEC-RAS model in the vicinity of Bignell Arroyo

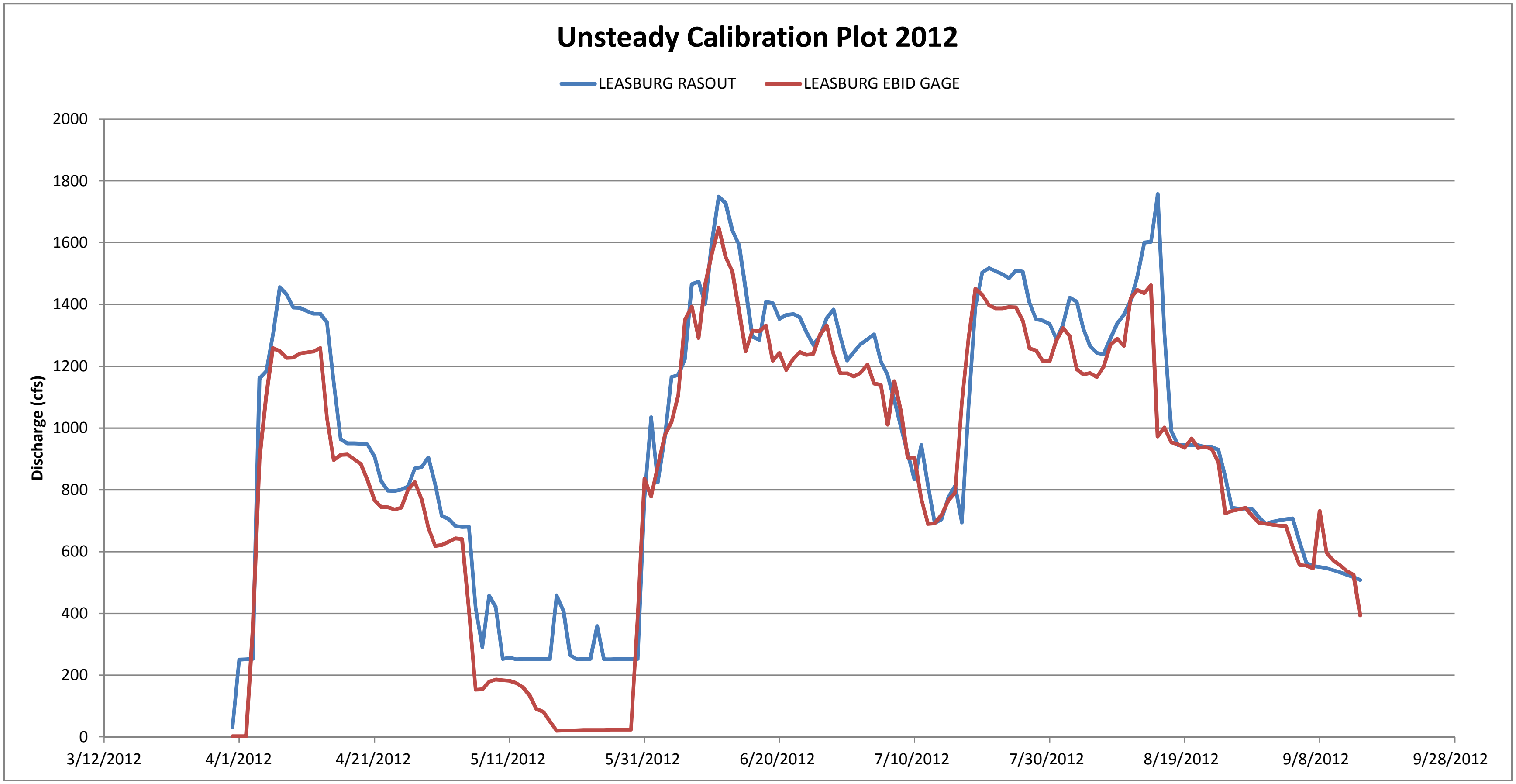


Figure H-25. Comparison of measured flow at the Leasburg gage and the hydrograph predicted by the initial HEC-RAS unsteady flow model with diversions for the period between March 31 and September 14, 2012

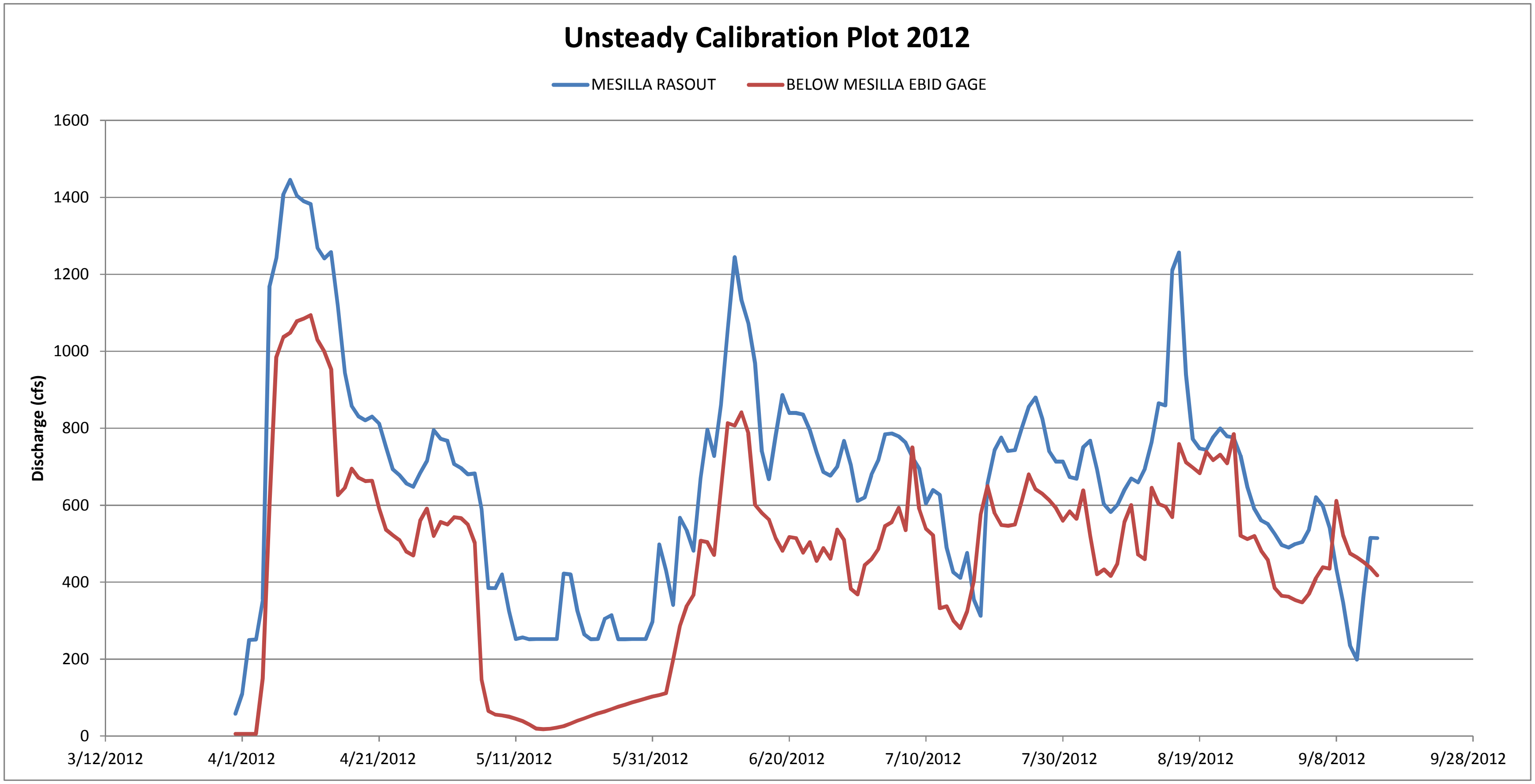


Figure H-26. Comparison of measured flow at the Mesilla gage and the hydrograph predicted by the initial HEC-RAS unsteady flow model with diversions for the period between March 31 and September 14, 2012

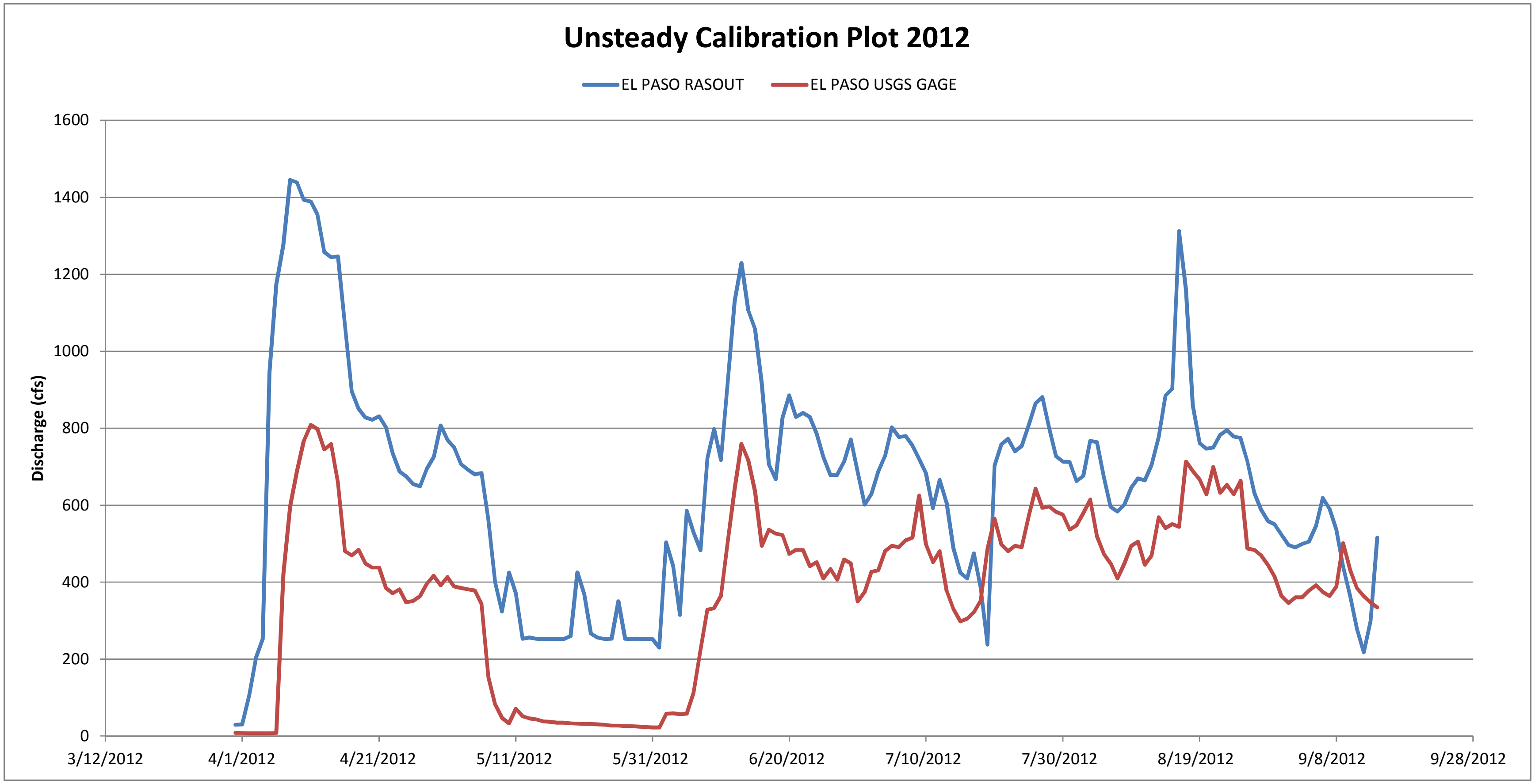


Figure H-27. **Comparison of measured flow at the El Paso gage and the hydrograph predicted by the initial HEC-RAS unsteady flow model with diversions for the period between March 31 and September 14, 2012**

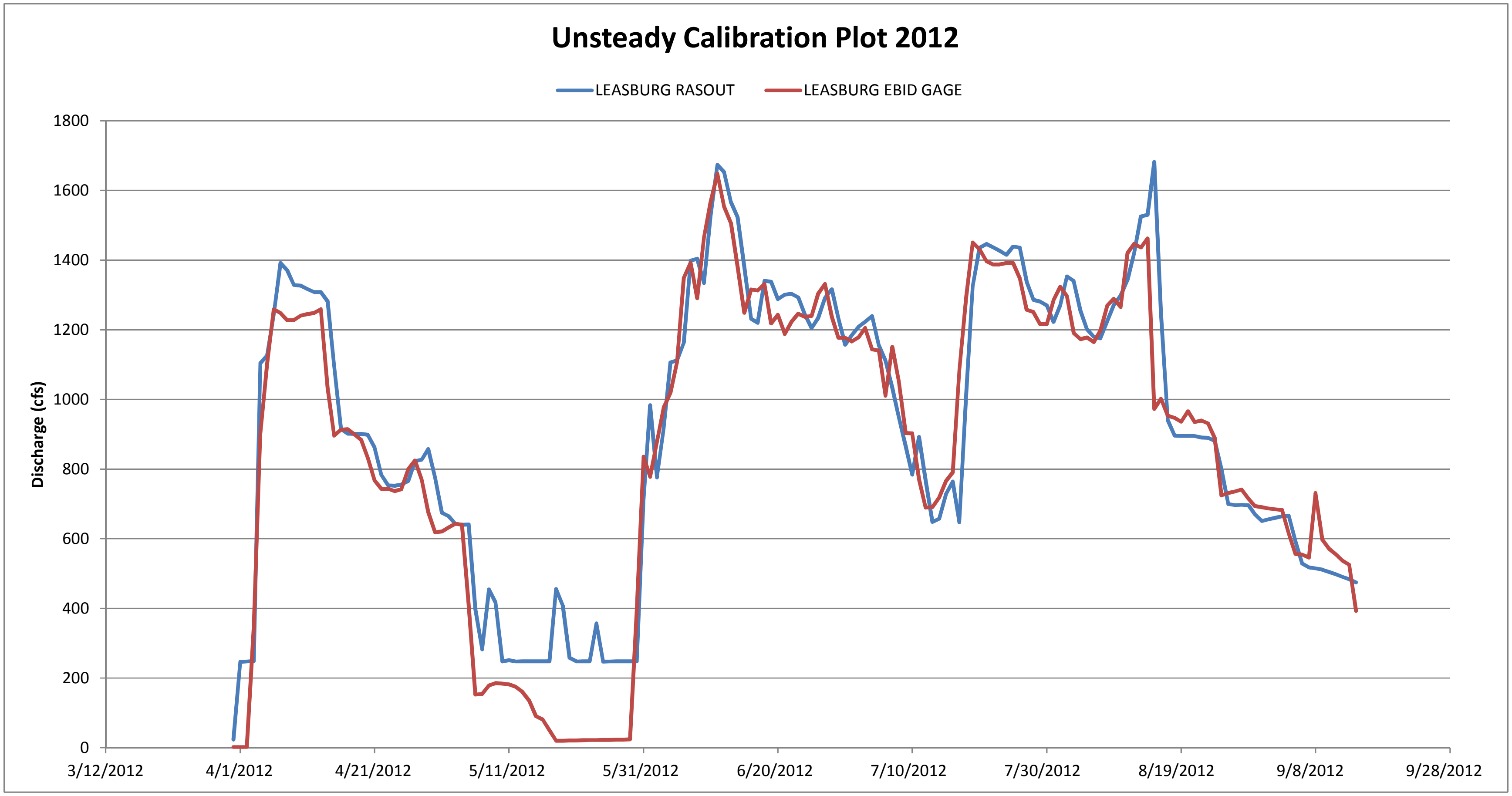


Figure H-28. Comparison of measured flow at the Leasburg gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions and groundwater interflow (seepage and groundwater return flow) for the period between March 31 and September 14, 2012

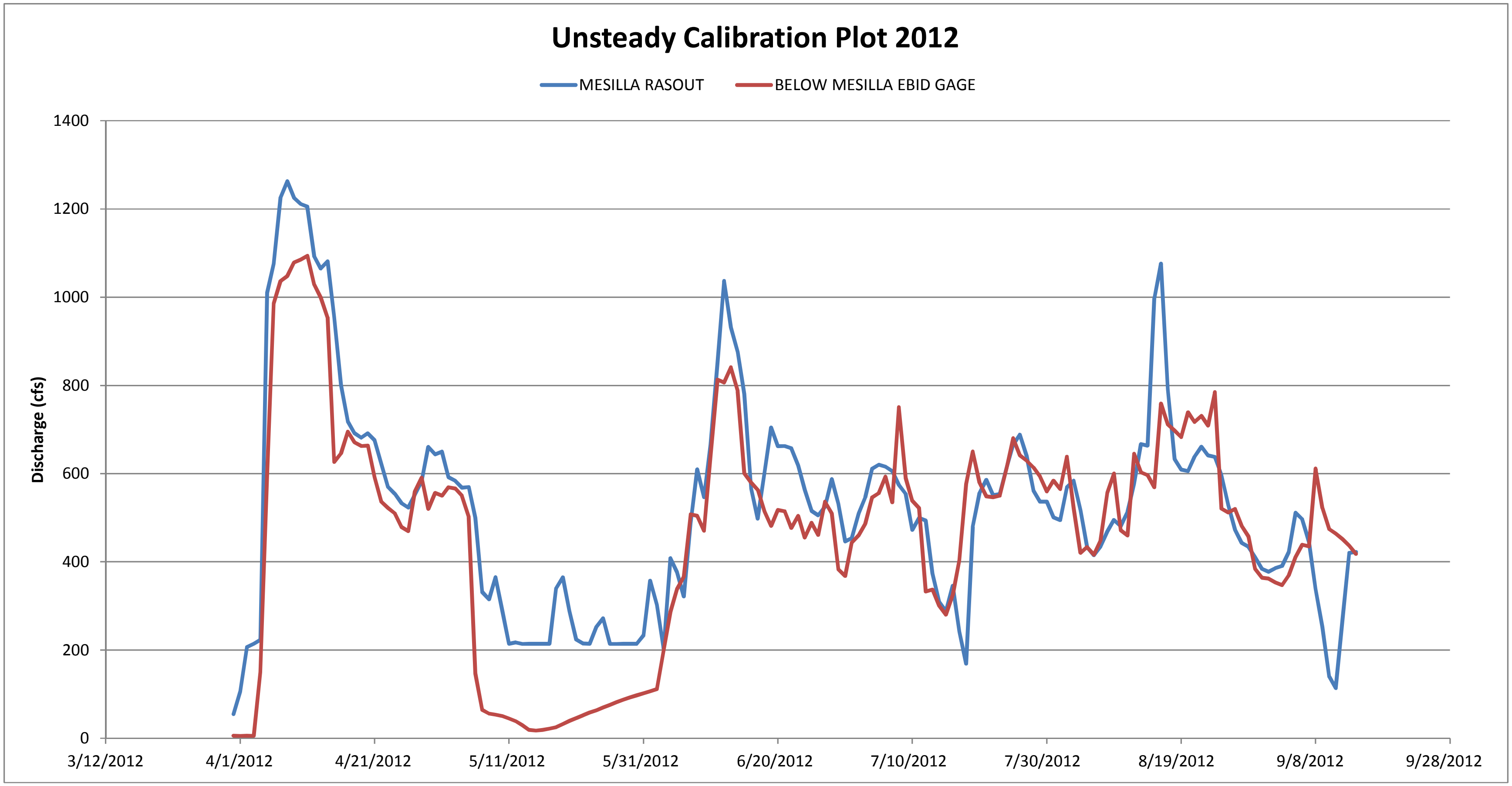


Figure H-29. Comparison of measured flow at the Mesilla gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions and groundwater interflow (seepage and groundwater return flow) for the period between March 31 and September 14, 2012

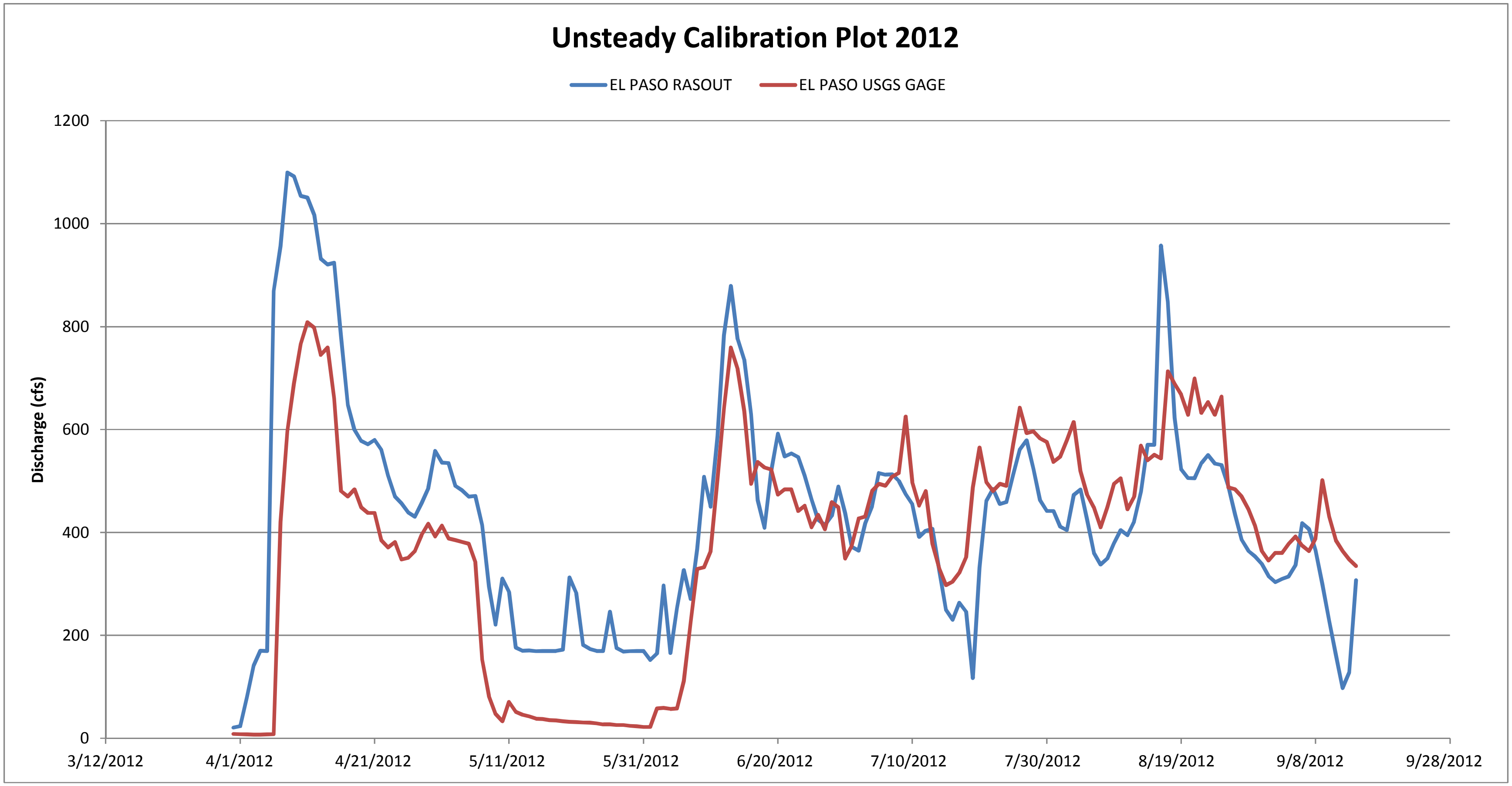


Figure H-30. Comparison of measured flow at the El Paso gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions and groundwater interflow (seepage and groundwater return flow) for the period between March 31 and September 14, 2012

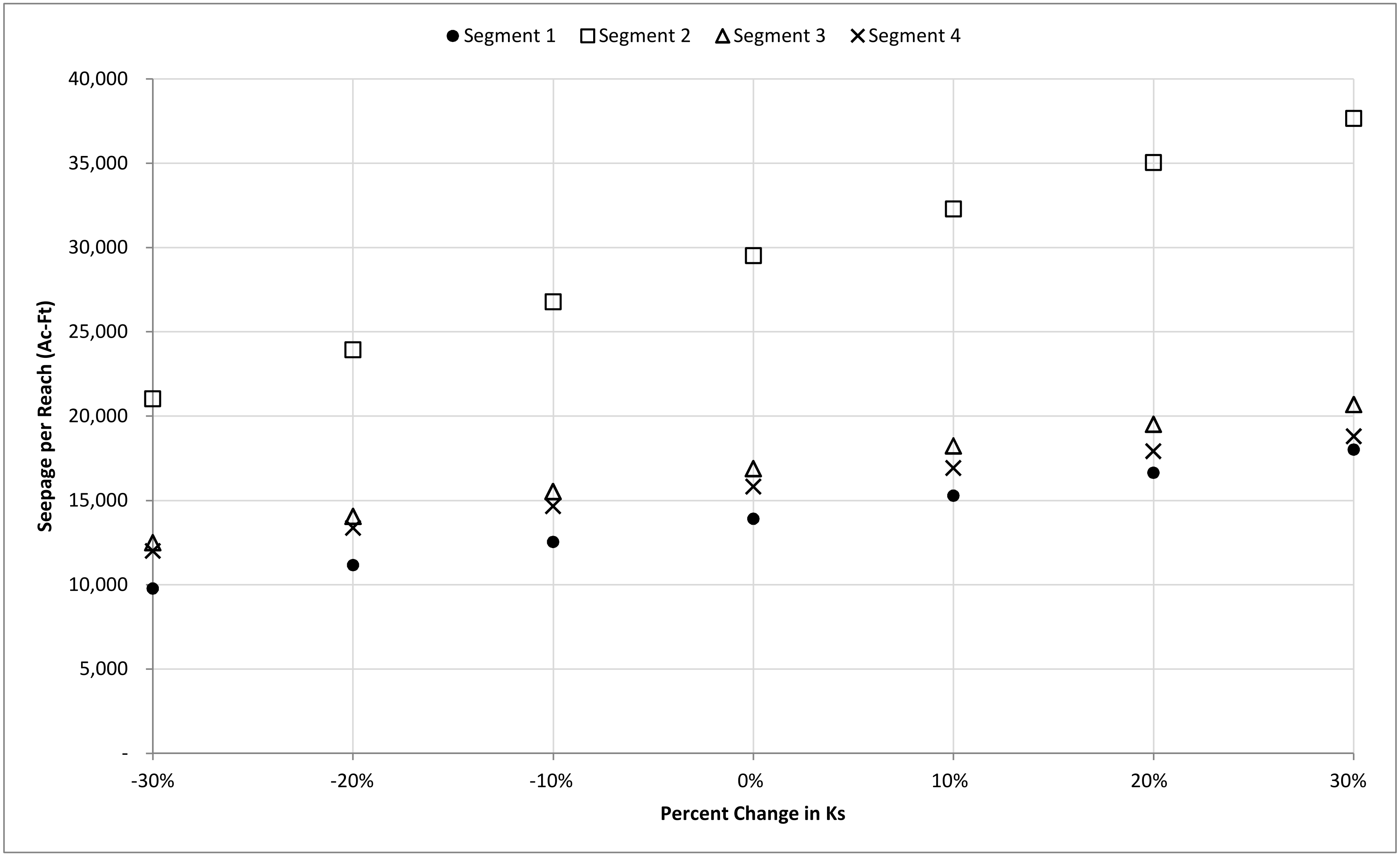


Figure H-31. Baseline 2012 Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat}

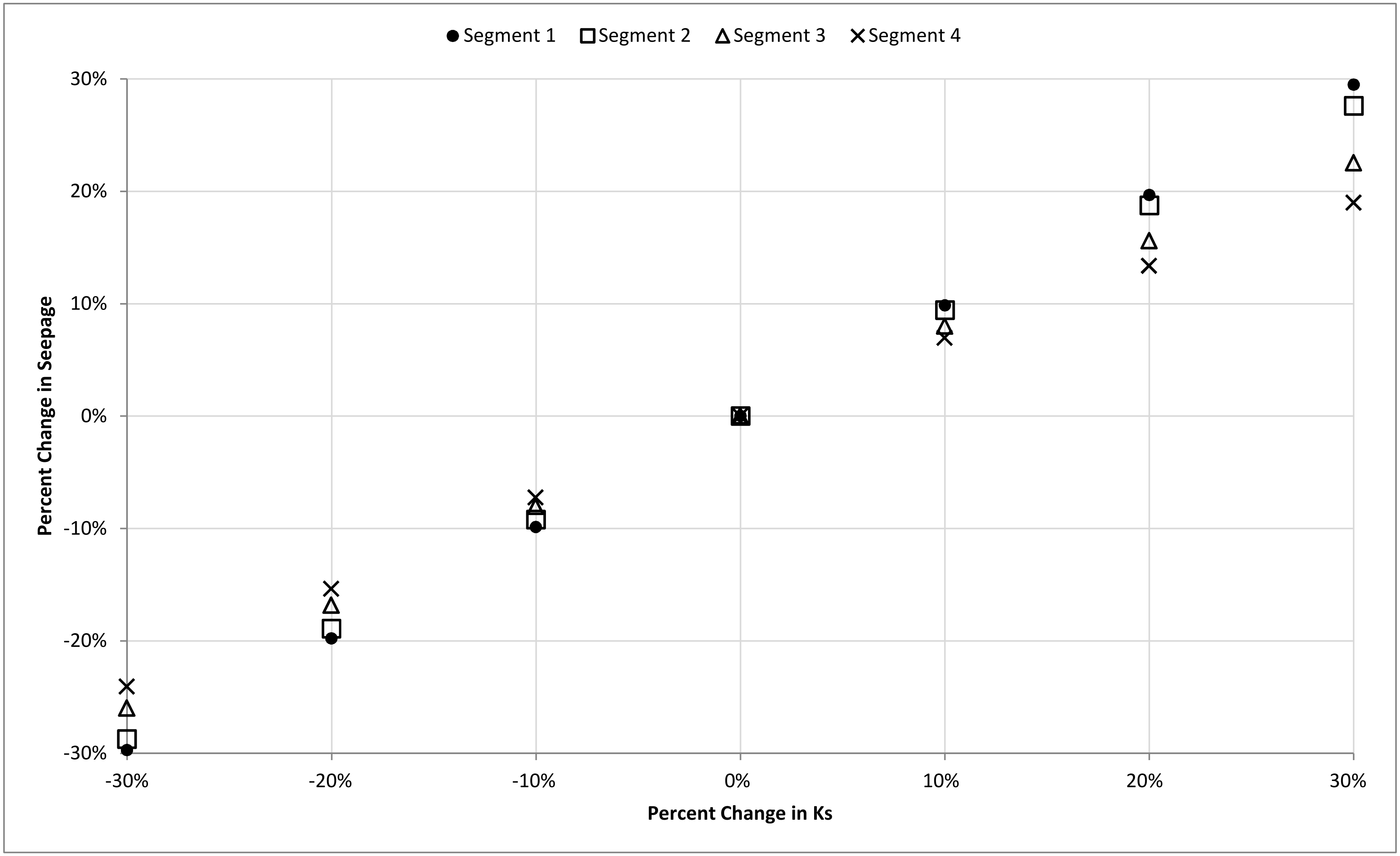


Figure H-32. Baseline 2012 Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat}

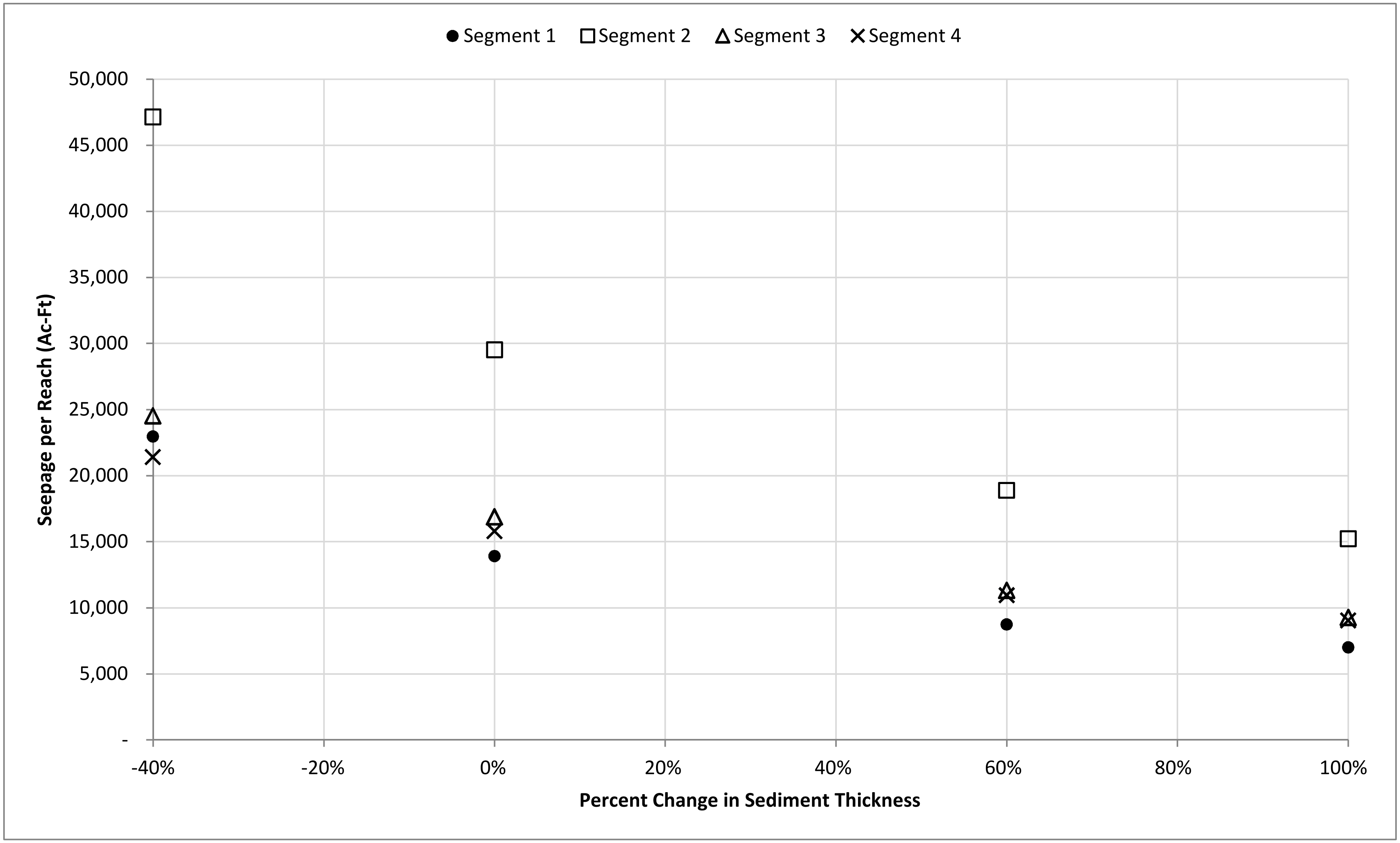


Figure H-33. Baseline 2012 Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in Sediment Thickness

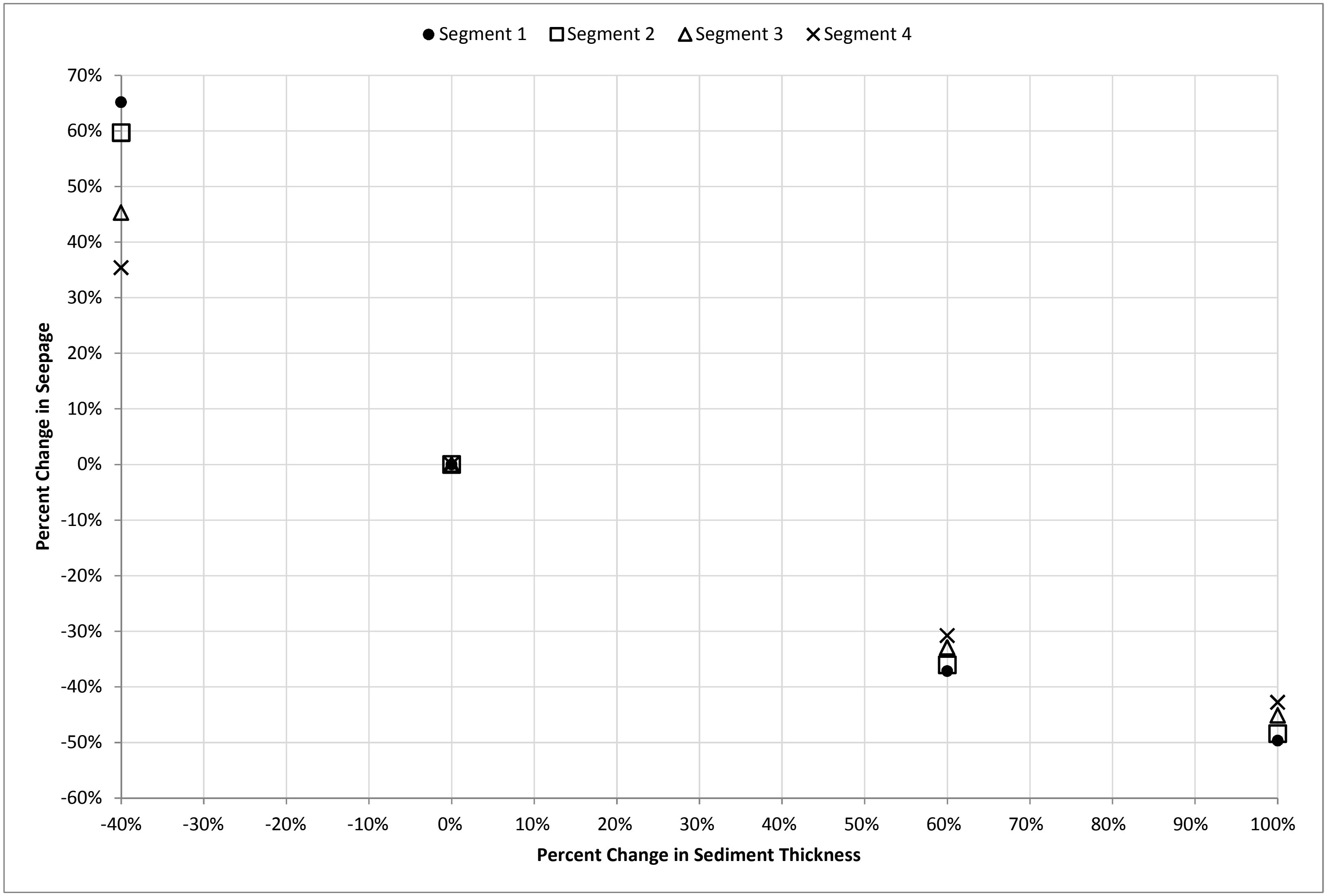


Figure H-34. Baseline 2012 Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in Sediment Thickness

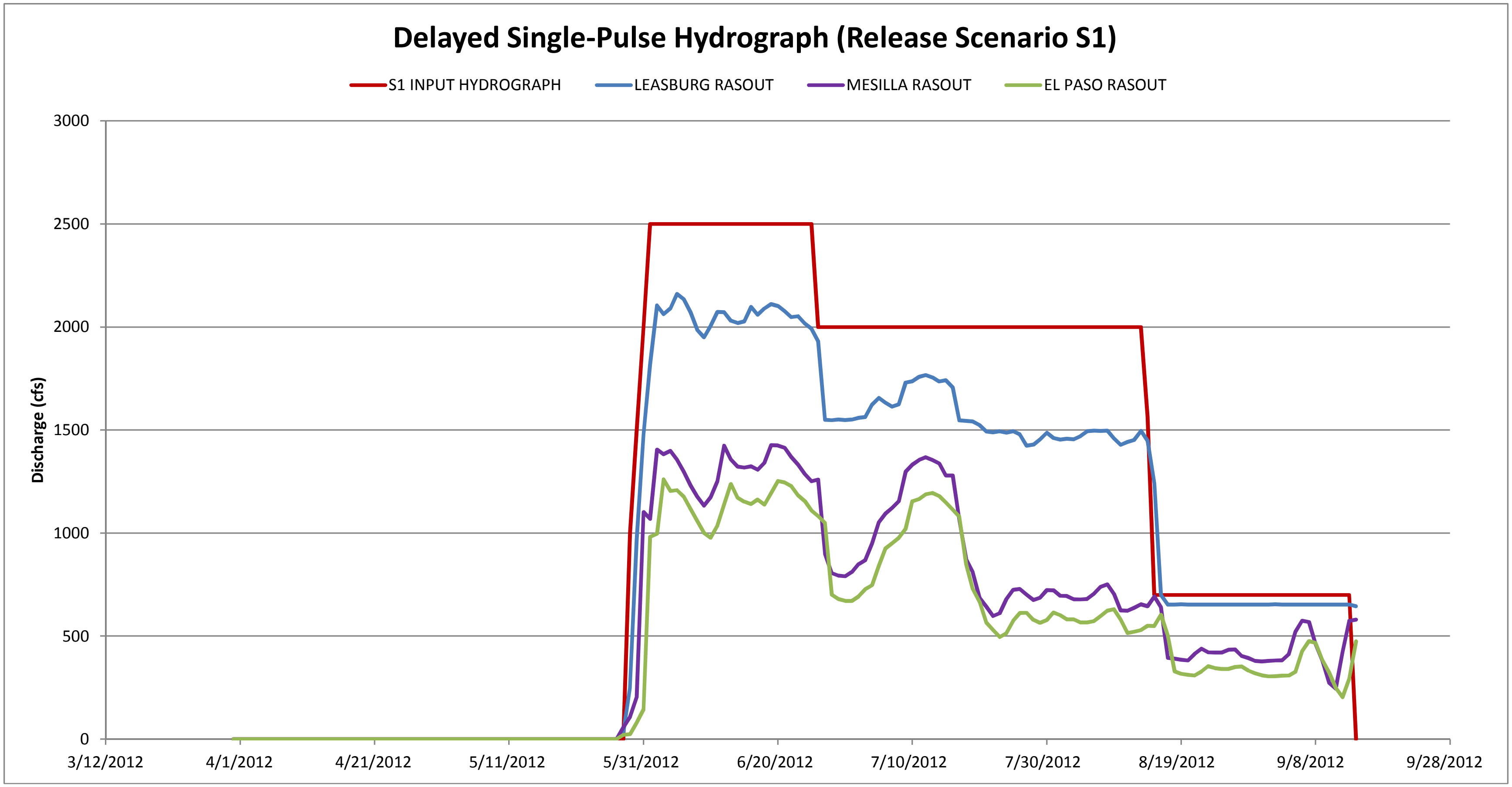


Figure H-35. Comparison of Delayed Single-Pulse Hydrographs predicted by the initial HEC-RAS unsteady flow model with groundwater and diversions at Leasburg, Mesilla, and El Paso

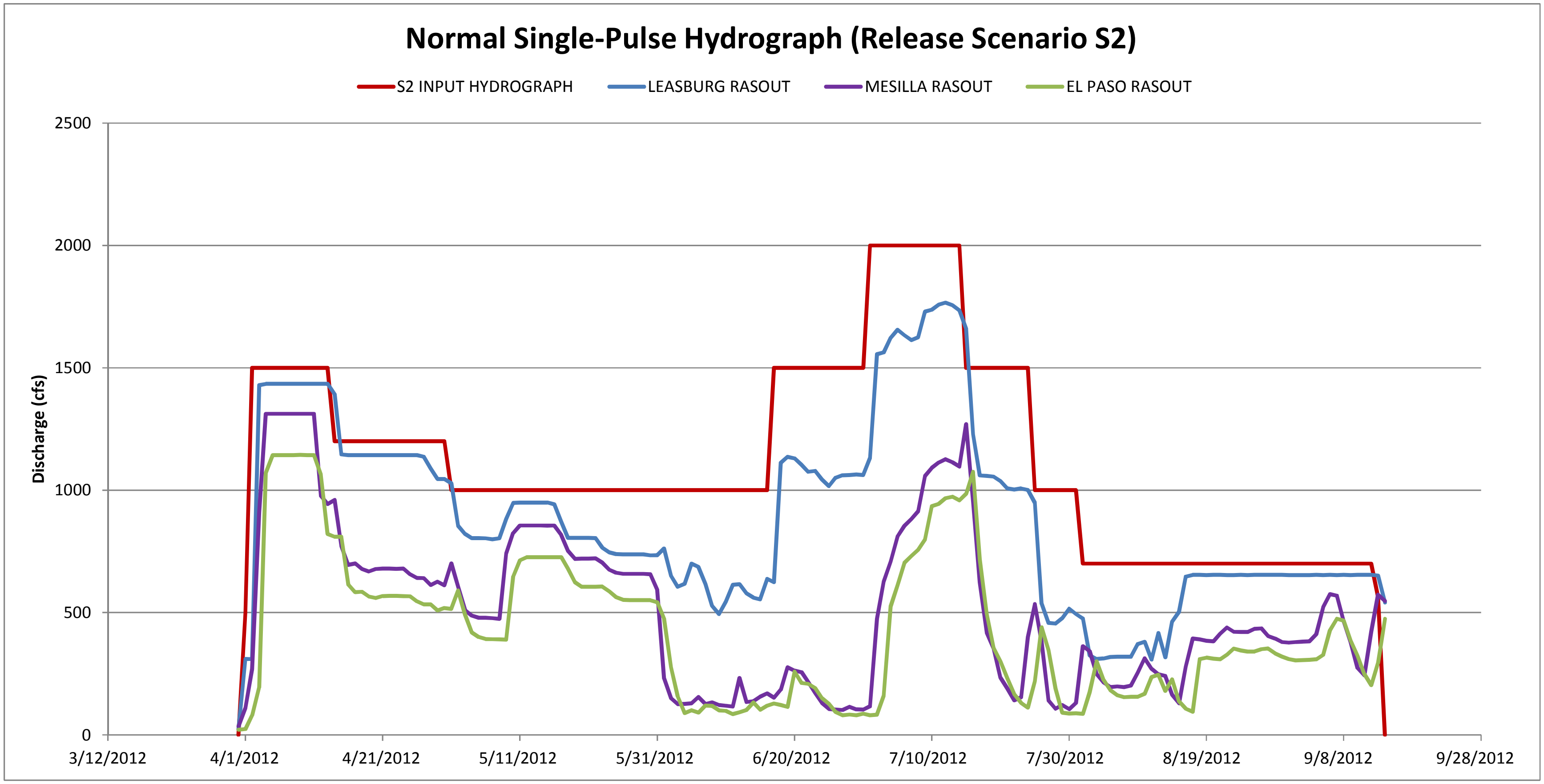


Figure H-36. Comparison of Normal Single-Pulse Hydrographs predicted by the initial HEC-RAS unsteady flow model with groundwater and diversions at Leasburg, Mesilla, and El Paso

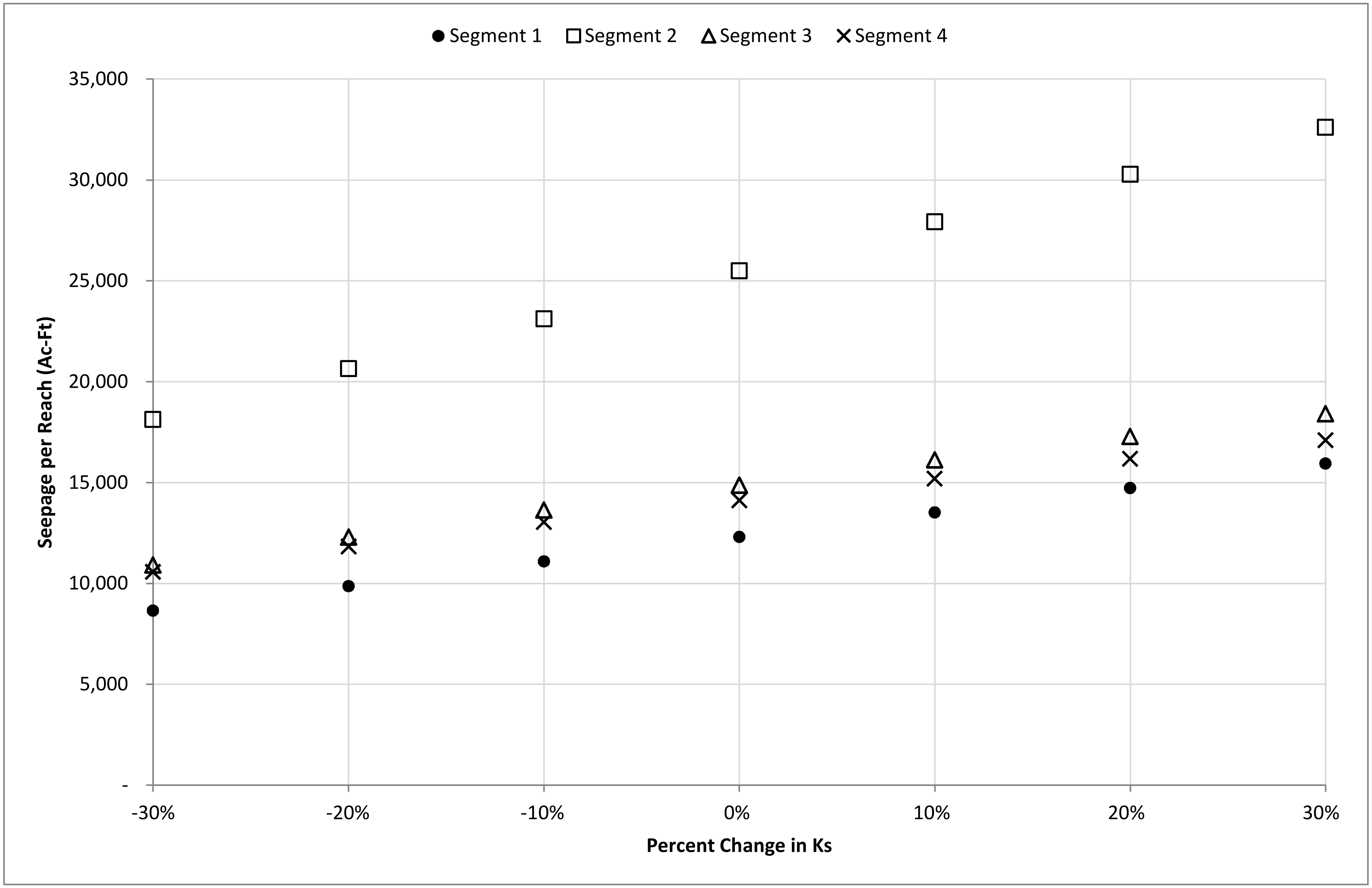


Figure H-37. **Delayed Single-Pulse Hydrograph (S1) Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat}**

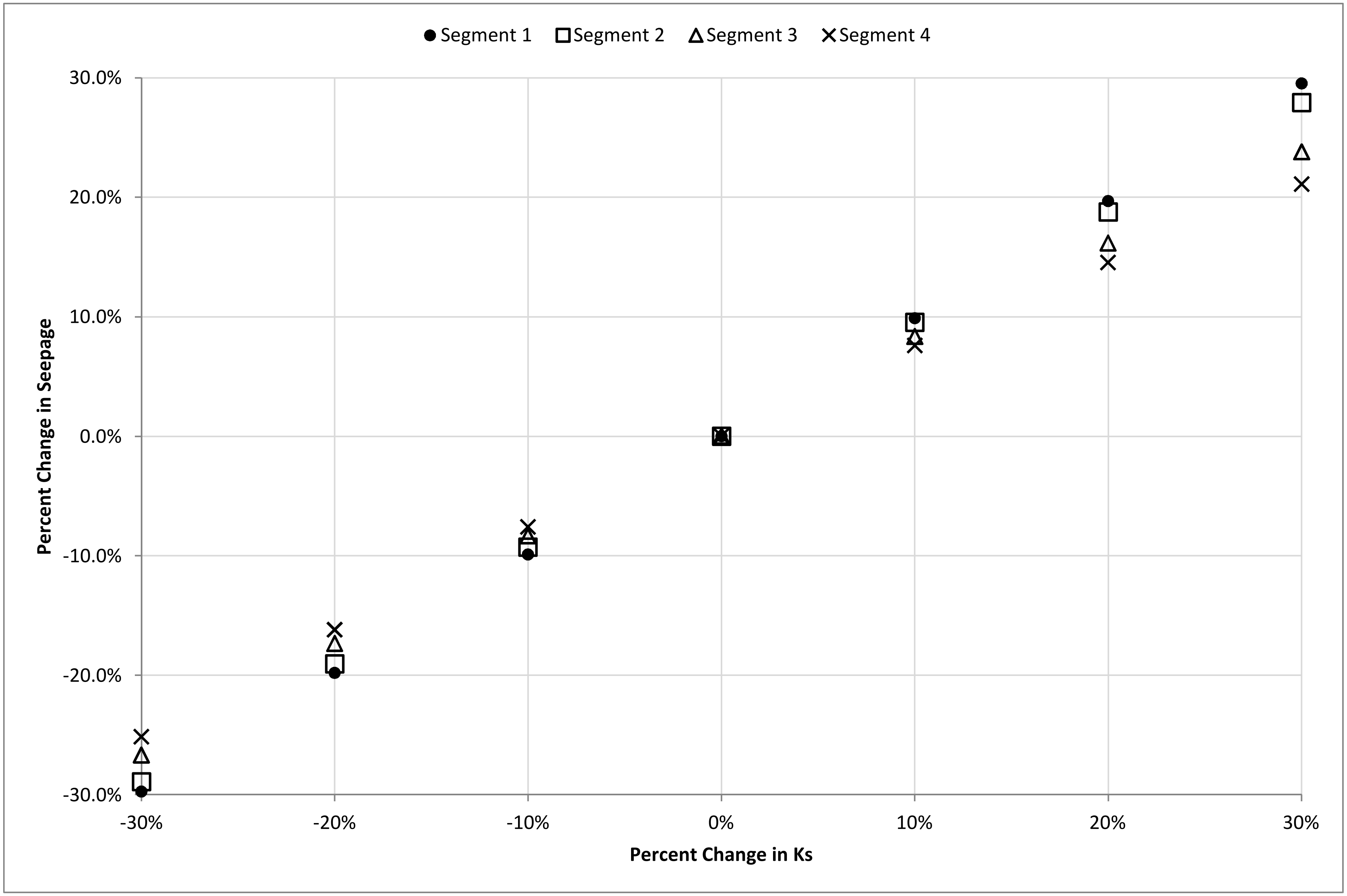


Figure H-38. Delayed Single-Pulse Hydrograph (S1) Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat}

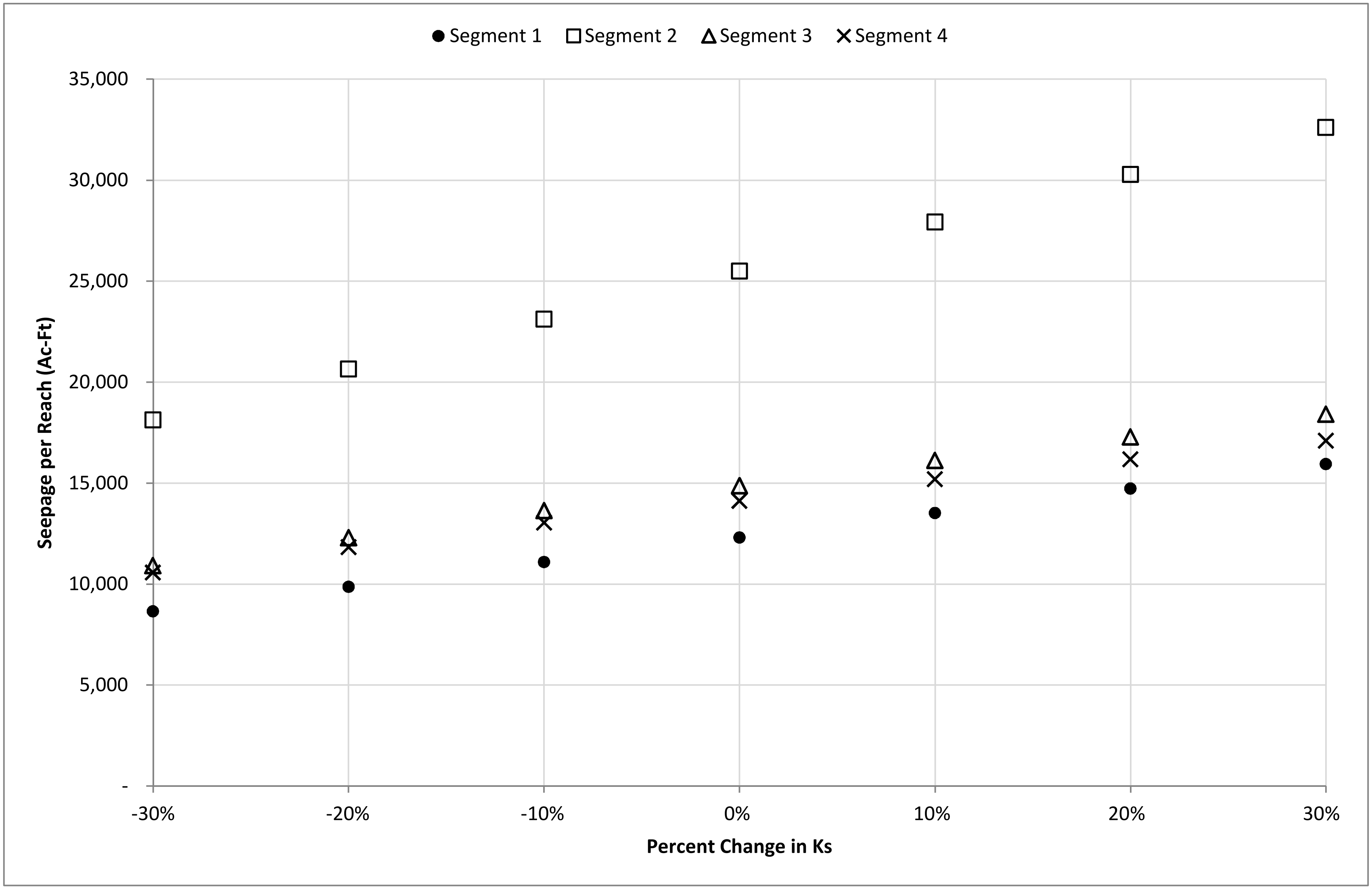


Figure H-39. Normal Single-Pulse Hydrograph (S2) Sensitivity Analyses Results, Absolute Change in Seepage vs. Percent Change in K_{sat}

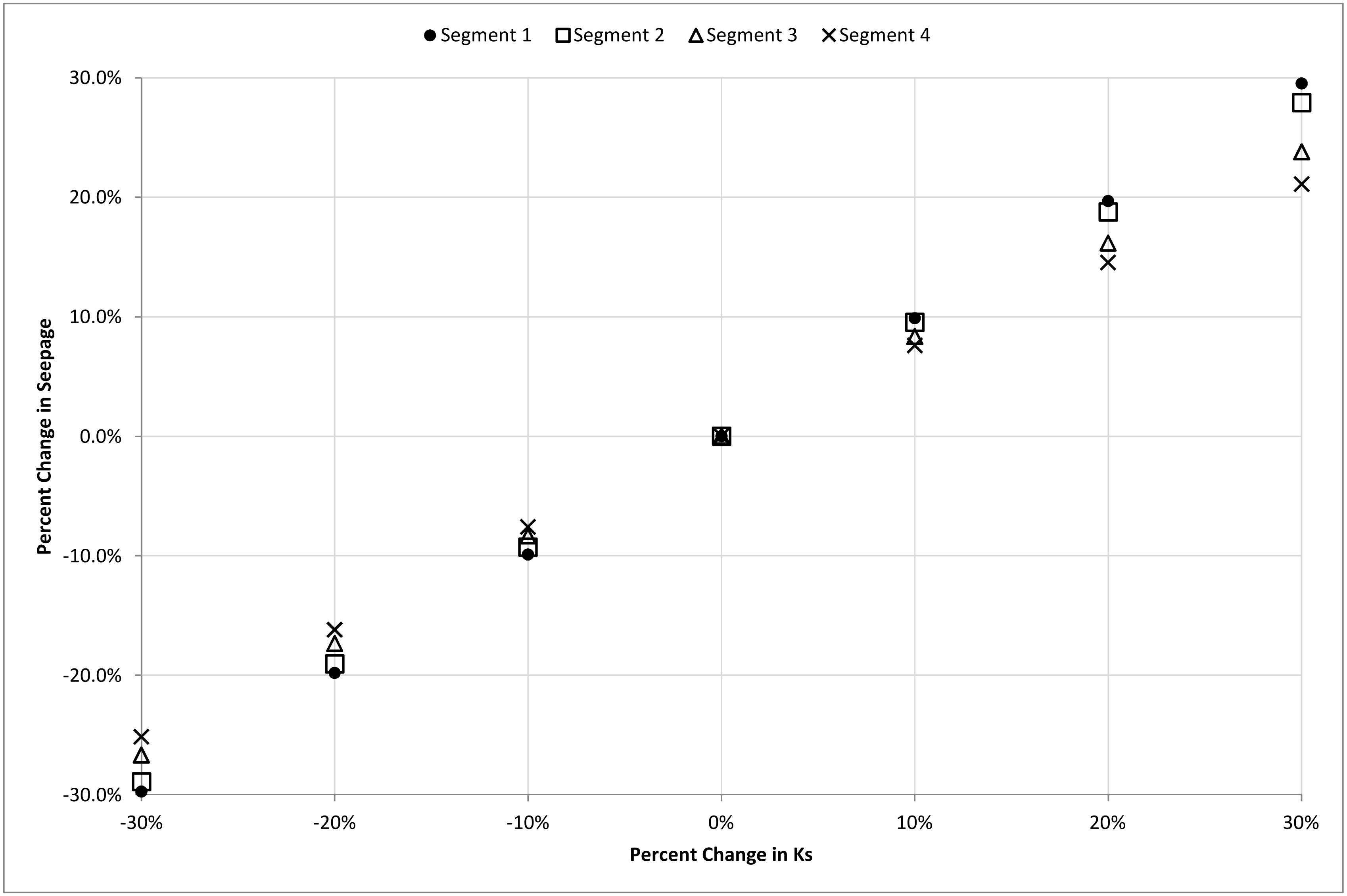


Figure H-40. Normal Single-Pulse Hydrograph (S2) Sensitivity Analyses Results, Percent Change in Seepage vs. Percent Change in K_{sat}

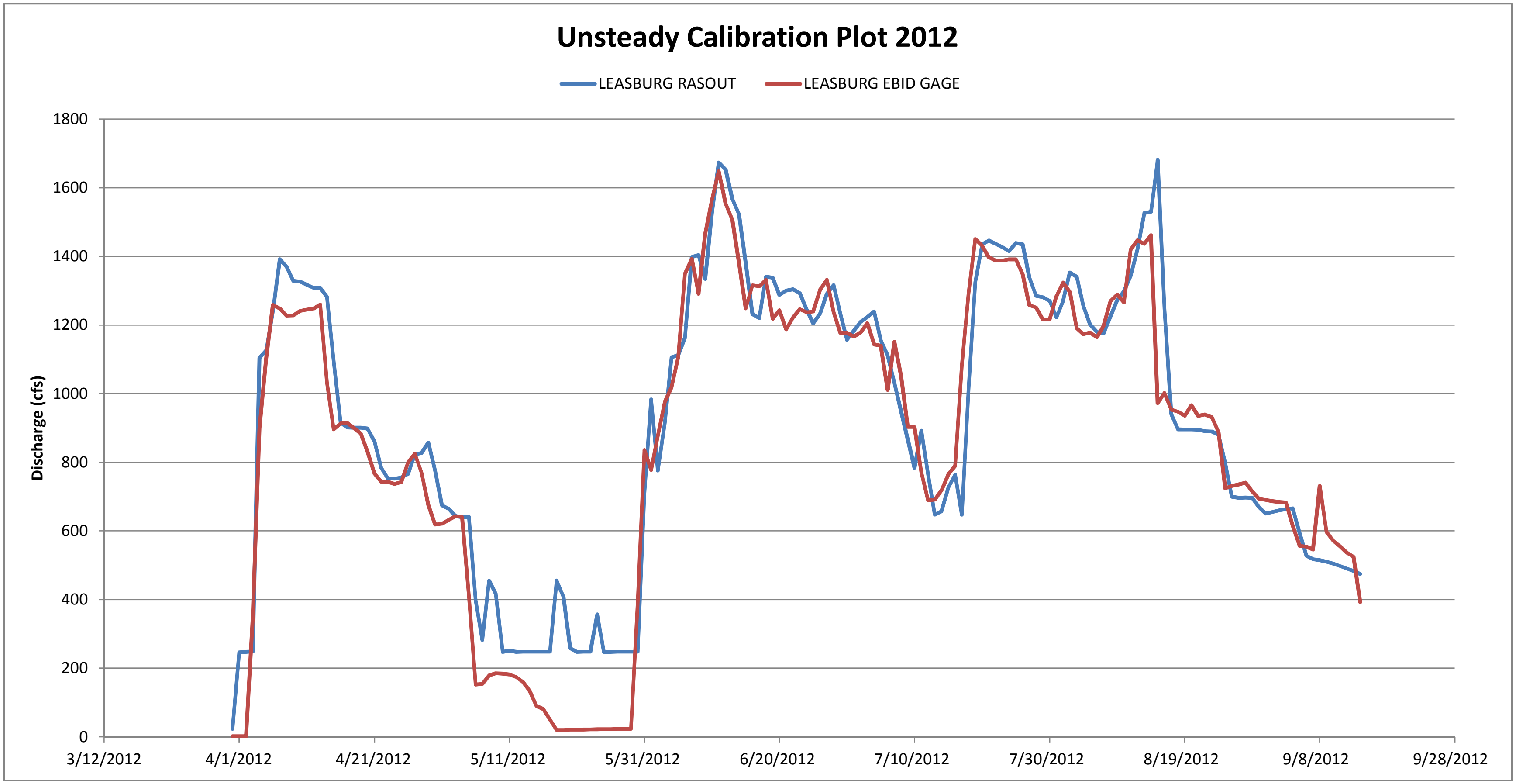


Figure H-41. **Comparison of measured flow at the Leasburg gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions, return flows, and groundwater interflow (seepage and groundwater return) for the period between March 31 and September 14, 2012**

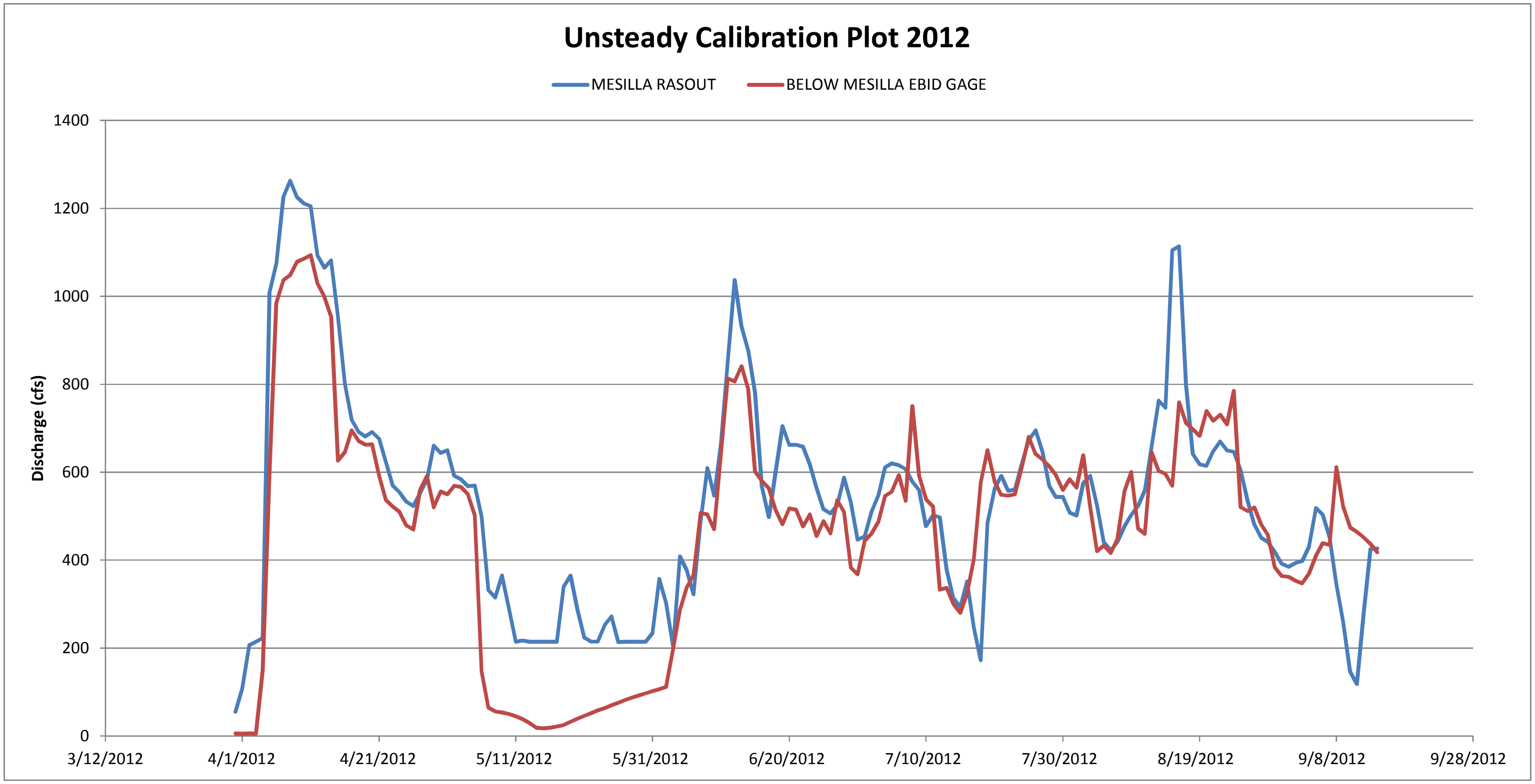


Figure H-42. Comparison of measured flow at the Mesilla gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions, return flows, and groundwater interflow (seepage and groundwater return) for the period between March 31 and September 14, 2012

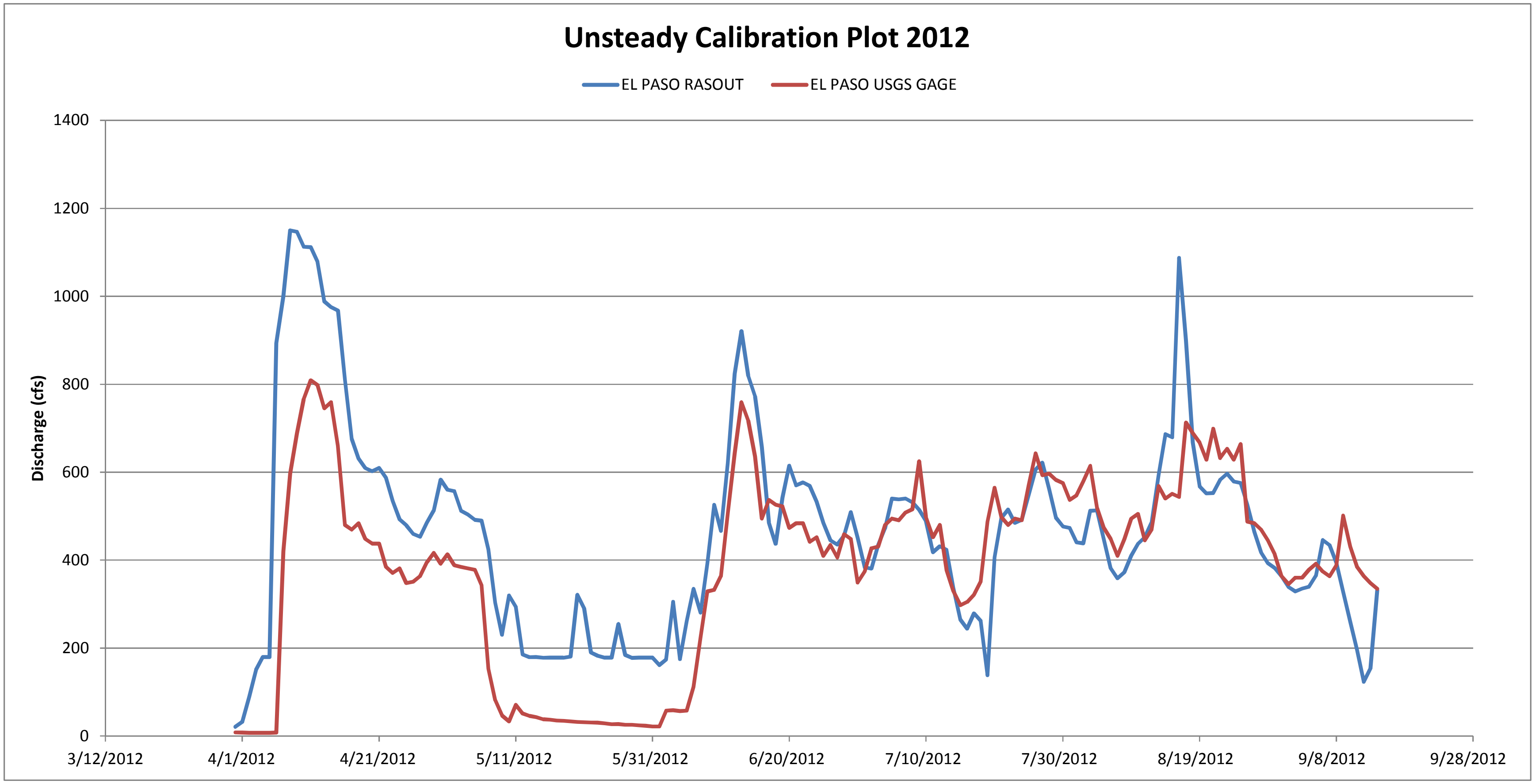


Figure H-43. **Comparison of measured flow at the El Paso gage and the hydrograph predicted by the HEC-RAS unsteady flow model with diversions, return flows, and groundwater interflow (seepage and groundwater return) for the period between March 31 and September 14, 2012**