PRELIMINARY ANALYSIS OF CHANNEL SEEPAGE AND WATER BUDGET COMPONENTS ALONG THE RIO GRANDE CANALIZATION PROJECT

Final Report

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Executive Summary

ES-1. Background

The Rio Grande Canalization Project (RGCP) is a narrow river corridor that extends 105.4 miles from Percha Dam at River Mile (RM) 105.4 in Sierra County, New Mexico, to American Dam at RM 0 in El Paso, Texas (USIBWC et al., 2004; Figure ES-1). The RGCP was constructed between 1938 and 1943 to facilitate compliance with the 1906 convention between the United States and Mexico, and to properly regulate and control, to the fullest extent possible, the water supply for use of the two countries as provided by the treaty (USIBWC, 2004). Major elements of the project included acquisition of Right of Way (ROW) for the river channel and adjoining floodways (8,332 acres), improvement of the alignment and efficiency of the river channel conveyance for water delivery, and flood-control measures that extended through the Rincon and Mesilla Valleys of New Mexico and El Paso Valley in Texas. As part of the RGCP, a deeper main channel was dredged to facilitate water delivery for irrigation. Flood protection levees were placed along two-thirds of the length of the RGCP where the channel was not confined by hillslopes or canyon walls (e.g., Selden Canyon). A number of NRCS sediment/flood-control dams were built between 1969 and 1975 on tributary arroyos to control flooding and sediment delivery to the RGCP from about 300 square miles of drainage basin downstream of Percha Dam.

The 2010 through 2012 period marks one of the most significant drought periods that have affected Caballo Dam water releases for irrigation purposes, with increasing drought severity in each of the years. In 2012, US irrigators requested that the release be delayed to mid- to late-May to insure adequate water supplies during summer months, while Mexico required water deliveries during the normal period (March through September). The primary purpose of this study is to determine the extent to which the amount of Rio Grande Project (RGP) water would be available for diversion to US irrigators and for delivery to Mexico under different release scenarios compared to the actual 2012 release.

To evaluate the differences in the amount of water that would be available for diversion or delivery to the various stakeholders (the Elephant Butte Irrigation District, the El Paso County Water Improvement District Number 1, and Mexico), water budget analyses were carried out by comparing the various inflows and outflows to the RGCP and the local basin under a range of conditions. A water budget study is an accounting of the water volumes within a defined study area, which is the RGCP. The inflows and outflows into the study area are calculated for a fixed time interval (i.e., daily). If the inflows exceed the outflows, there is an increase in the storage of water within the RGCP during that time interval, whereas if the outflows exceed the inflows, a decrease in storage is indicated. The **RGCP-scale channel water budget analysis** focused on the water budget components that directly affect the channel and adjacent floodplain, while the **local-basin-scale water budget analysis** focused on the inflows and outflows that affect the portion of the basin that is directly affected by irrigation. To prepare input for the water budget analyses, hydraulic modeling was developed and calibrated to the double pulse release that occurred in the **2012 baseline year**. The 2012 release followed two years of dry conditions and should therefore represent conditions where stream-groundwater interactions are relatively limited, thereby improving model calibration. Once calibrated, the models were executed over the 2010 through 2012 period to provide input to the water budget analyses of the overall study period. Other input to the water budget analyses included inflows and outflows that were measured, estimated, or extracted from

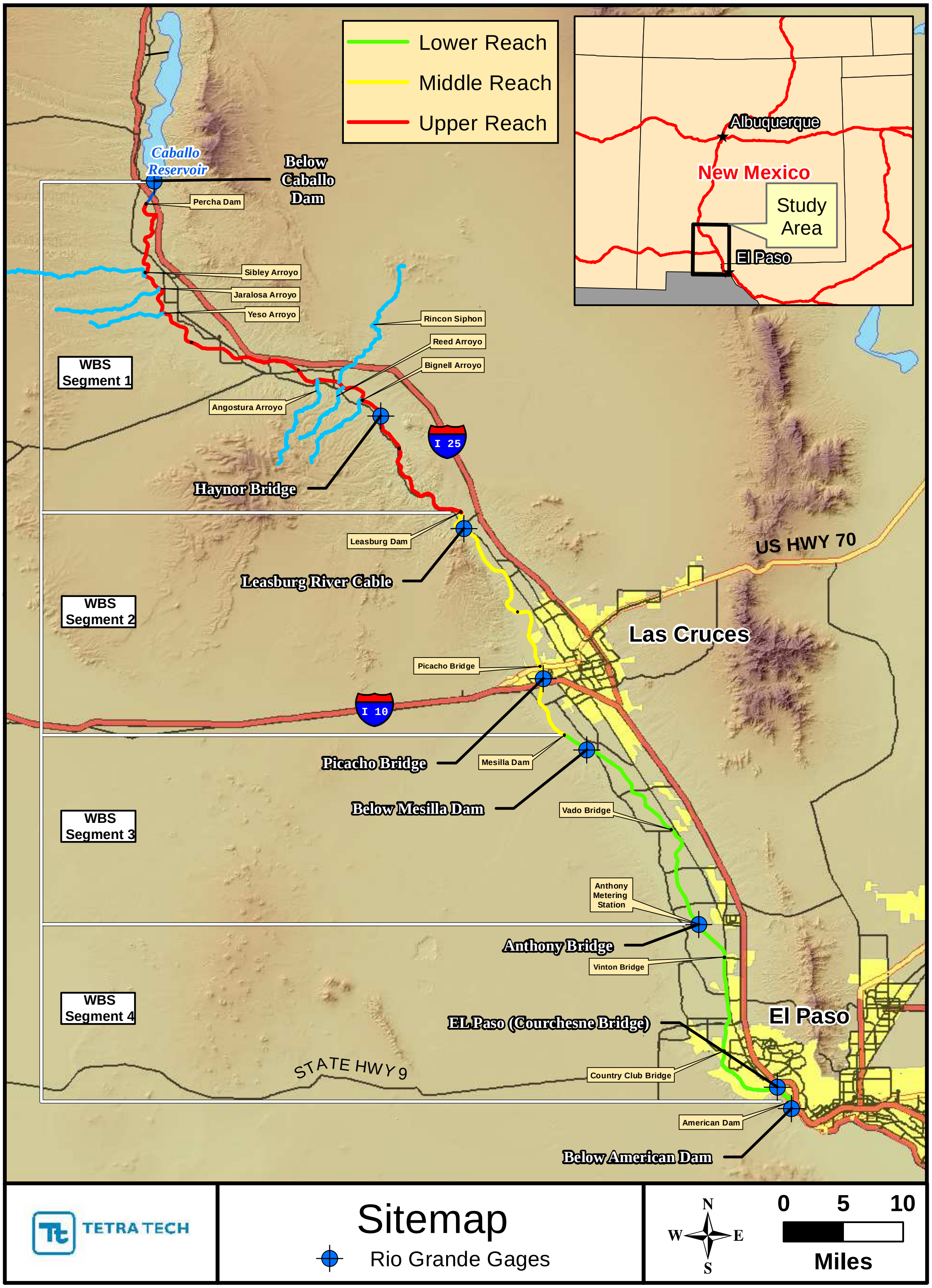

Figure ES-1. Location of the Rio Grande Canalization Project (adapted from USACE, 2007)

an existing groundwater model (SSPA, 2007). Of particular interest to this study is channel seepage, which refers to the water that is infiltrated into the underlying aquifer and thereby lost from the surface water supply. The hydraulic models and associated water budget analyses were then developed for two hypothetical release scenarios that were developed by the Rio Grande Project Allocation Committee (RGPAC). These release scenarios maintained the volume of water that was released during the 2012 double-pulse release, and included the **S1 delayed single pulse release** (May 29 through September 14) and the **S2 normal single pulse release** (March 31 through September 14). A comparison of the water budget components under the S1 and S2 release scenarios to those from the baseline (actual double pulse) release scenario provides an ability to assess the expected differences in water that is available for diversion or delivery. A more detailed discussion of the study purpose, approach, and analysis is provided in the following sections.

ES-2. Study Purpose

As discussed above, the primary purpose of this report is to estimate the difference in the amount of RGP water supply available for diversion to Elephant Butte Irrigation District (EBID), El Paso County Water Improvement District Number 1 (EPCWID No. 1), and Mexico under two proposed release scenarios compared to the actual 2012 release. During 2012, RGP water was released from Caballo Reservoir for delivery in the vicinity of El Paso, Texas in two pulses. Because of the need to conserve water as a result of the extreme drought and a limited water supply due to depleted reservoir storage, EPCWID No. 1 and EBID proposed that RGP water only be released in a delayed single pulse. This report documents the amount of RGP water that was released, diverted from the Rio Grande, infiltrated to seepage and lost to evaporation, and compares this baseline condition to the hypothetical situation if the same amount of water had been released in a single pulse as either a delayed (Scenario S1) or normal (Scenario S2) release.

To quantify the differences between the water release, the diverted waters, seepage rates, and losses to evaporation, an evaluation of the water budget components was carried out for the ongoing 2010 to 2012 drought period along the RGCP (Figure ES-1). In general, the water budget analysis at the RGCP scale involves the hydrologic domain that includes the river and adjacent floodplain, and the groundwater zone located beneath the river-floodplain area. The RGCP-scale channel water budget was performed on four segments of the RGCP, including (1) Caballo Dam to Leasburg River Cable metering station, (2) Leasburg River Cable to Mesilla Dam, (3) Mesilla Dam to the Anthony metering station, and (4) Anthony metering station to the Below American Dam gage. A separate evaluation of the water budget components was carried out within the local basin for the same period. This study is intended to help the stakeholders to manage single or double water release timings and volumes during years of water scarcity. The hypothetical releases that were evaluated included a normal single pulse release (Scenario S2) and delayed single pulse release (Scenario S1) from Caballo Reservoir. This study was carried out according to the USIBWC Scope of Work dated June 13, 2012 and Modification No. 1.

ES-3. Water Budget Data and Information

Data that was available for this study generally included reservoir evaporation data from Elephant Butte and Caballo Reservoirs, river and canal gage data, precipitation data, groundwater well data, and groundwater pumping data. The USIBWC, the U.S. Bureau of Reclamation (USBR), the EBID, the El Paso

County Water Improvement District no. 1 (EPCWID No. 1), the New Mexico Office of the State Engineer (NMOSE) and the New Mexico Interstate Stream Commission (NMISC) are responsible for the majority of this data. The majority of the data was either provided by these agencies or downloaded from the agency websites.

In addition to data that was used for the study, previously developed models, information from previous studies, and existing literature was also used to prepare the water budget analysis. A HEC-RAS model of the RGCP that was developed by Tetra Tech (formerly Mussetter Engineering, Inc.; MEI and Riada, 2007) in 2007 was determined to be the most representative model of the overall reach, and was modified for this study. The FLO-2D model that was developed for that study was also modified for this study. The operational 2007 MODFLOW groundwater model was provided by the NMOSE and the results from this model were used for the groundwater components of the analysis. Although a large number of documents were reviewed for this study, of primary importance are the Rio Grande Project Allocation Committee's Draft reports entitled "Analysis of River Conveyance Efficiency for Initial Release of Project Water for Delivery to Acequia Madre Canal in 2012" (RGPAC, 2012a) and "Analysis of Multi-Year Drought and D2 Linear Regression Equation" (RGPAC, 2012b).

One of the main purposes of this study is to investigate seepage, which is not fully understood due lack of seepage studies under drought conditions. Channel seepage, delivery of water through canals and laterals, irrigation of project acreage, and return flows recharge the unsaturated zone and the aquifer. Groundwater pumped from the aquifer is used to irrigate the crops and it is believed that only a small portion of the channel seepage should be considered a loss to the overall water budget through evaporation from the unsaturated zone. It is important to note that even though only a portion of the seepage may be entirely lost to the system on a regional basis, any seepage will likely not be used by the surface water entity for which this volume of water is intended, so it is lost to that entity.

ES-4. HEC-RAS Analysis

To quantify the channel seepage, hydraulic modeling was developed using the HEC-RAS software programs. The previously developed model (MEI and Riada, 2007) that was updated by USIBWC and obtained for this study was updated to reflect the 2011 LiDAR-based topographic mapping. Because portions of the channel bathymetry were underwater at the time of the 2011 LiDAR survey, the bathymetry of the model cross sections was adjusted as part of the steady-state HEC-RAS model calibration process.

Once the steady-state model was calibrated, this model was converted to an unsteady flow model by coding in the upstream hydrologic boundary condition (release from Caballo Dam), specifying the other unsteady input (time steps and tolerances, among other items), and insuring numerical stability. Diversion outflows measured at Percha, Leasburg, Mesilla and American Dams were added to the model. However, in an effort to simplify the unsteady flow analyses, the relatively minor return flows from Del Rio Drain, La Mesa Drain, East Drain, Nemexas Drain, and West Drain were not added until after the calibration was completed.

The HEC-RAS groundwater interflow option, which uses the Darcy Equation to estimate seepage or groundwater return flow, was also added to the model. This option requires specification of the horizontal distance to the groundwater well from the main channel and time series of the groundwater well elevations, which were input to the model based on representative EBID and USGS groundwater well data. Initial model runs indicated that unrealistic saturated hydraulic conductivity (K_{sat}) values would be required to predict reasonable seepage rates due to the long horizontal distance to the wells. The model was therefore adjusted to set a zero horizontal distance to the groundwater table. The depth to groundwater was based on a previous analysis of groundwater depths at USIBWC restoration sites. It varies throughout the reach but averages approximately 3 feet.

The model was calibrated by iteratively adjusting the K_{sat} input parameters over a reasonable range of values. Data from the NRCS National Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/) indicate that the bed material below the Rio Grande was uniformly identified as Riverwash, which has *initial* K_{sat} values that range from 1.2 to 4.1 feet/day. Results from the HEC-RAS modeling indicate that a steady-state K_{sat} value of 0.15 feet/day in Segment 1 results in reasonable calibration results. This K_{sat} value is consistent with the *initial* K_{sat} values shown in the NRCS data and with K_{sat} values previously used along the RGCP and in similar environments as identified in the literature. Hydraulic conductivity (K_{sat}) values of 0.664 feet/day are necessary in Segments 2, 3 and 4 to achieve reasonable calibration, which is in alignment with the conductivity values that were applied to the drains in the URGWOM model (K_{sat} = 0.641; USACE, 2012).

A comparison of the HEC-RAS modeling results to measured hydrographs indicates that seepage rates appear to have been higher than the predicted rates over the first two months of the 2012 release. The model results also indicate that the total volume of seepage is about 76,923 acre-feet over the entire 2012 release, with seepage rates that were similar to the USGS seepage estimates during normal flow (non-drought) years (USGS, 2012).

ES-5. FLO-2D Analysis

The existing FLO-2D model (MEI and Riada, 2007) was also updated and revised to estimate the seepage that occurred in 2012. This model is different than the HEC-RAS model in that it uses the Green-Ampt method to simulate channel infiltration, and the model code was updated specifically for this project to incorporate a varying K_{sat} value over the simulation. This modification was necessary to account for the initial abstractions that occur during the initial phases of the Caballo release, which were apparently very high in 2012. In addition, the model incorporates spatially and temporally varying K_{sat} values that were identified for seven separate reaches (Segment 1 was subdivided at Haynor Bridge, Segment 2 was subdivided at Picacho Bridge, and Segment 4 was subdivided at Courchesne Bridge). The temporally varied K_{sat} was used to account for the initially high infiltration rates into dry soil. This model appears to calibrate reasonably well to the 2012 release hydrograph at a variety of gages along the RGCP. Results from this model indicate that initial K_{sat} values would range from 0.36 to 2.5 feet/day, and would decay to between 0.08 and 1.4 feet/day. Results also indicate that of the approximately 372,000 acre-feet of water released from Caballo Dam during the period of overall simulation (i.e., the 2012 baseline simulation), about 108,600 acre-feet would be infiltrated and about 26,800 acre-feet would be lost to evaporation.

ES-6. Evaporation Analysis

An evaluation of reservoir (pan) evaporation data reveals that when comparing actual (calculated) to predicted values the changes in evaporative losses are relatively minor for both the Elephant Butte Reservoir and the Caballo Reservoir—especially for Release Scenario S2 (Normal Single Pulse). Accordingly, from the preceding analysis it is concluded that for current conditions using either Release Scenario S1 (Delayed Single Pulse) or Release Scenario S2 (Normal Single Pulse) results in only minor differences in lake evaporation loss at Elephant Butte and Caballo Reservoirs—and particularly for Release Scenario S2 (Normal Single Pulse).

ES-7. RGCP-Scale Channel Water Budget Analysis

The components for the channel (RGCP scale) water budget for each of the four segments discussed above includes the upstream inflow, downstream outflow, surface-water inflows (precipitation, stormwater runoff and irrigation return flows), surface-water outflows (diversions and evapotranspiration), and groundwater interflows (seepage, groundwater return flows and floodplain/ irrigation-based recharge).

The water budget calculations were performed by first assembling the measured inflows and outflows on a mean daily-flow basis for the study period between January 1, 2010, and November 30, 2012. The measured data include the upstream inflow, measured irrigation return flows at the drains and spillways, measured water treatment plant effluent discharges, and diversions into canals. It should be noted that because the data collected at the Anthony metering station is not believed to report accurate flow measurements, the outflow from Segment 3 and the inflow to Segment 4 was obtained from the HEC-RAS modeling.

Once the measured values were input to the spreadsheet, information from an existing groundwater (MODFLOW) model that was prepared by S.S. Papadopoulos and Associates, Inc. (SSPA, 2007) was entered into the spreadsheet. This information includes groundwater return flow (that portion of the groundwater return flow that is directly returned to the bed of the river) and floodplain recharge. Estimated values for precipitation-derived flow, ungaged in-channel stormwater flow, evapotranspiration (based on the sum of the riparian evapotranspiration predicted by the MODFLOW model and the estimated surface water evaporation), and unauthorized diversions were entered into the spreadsheet along with the estimated channel seepage rates from the HEC-RAS model.

The components of the RGCP-scale channel water budget equation that were derived from the MODFLOW model (SSPA, 2007) were limited to fluxes in the immediate vicinity of the floodplain. Five geographic zones were set up in this area, with four zones set along the channel and adjacent floodplain that correspond to the four water budget segments, and a fifth zone set along the perimeter of these zones to evaluate fluxes into and out of each zone. For the RGCP-scale channel water budget, information obtained from the MODFLOW model included fluxes that represent floodplain recharge, groundwater return flow to the Rio Grande, and riparian evapotranspiration.

ES-8. Local-Basin-Scale Water Budget Analysis

The water budget analysis at the local-basin-scale is similar to the analysis at the RGCP scale. The main difference is that it involves a hydrologic domain defined as a local basin that receives and delivers flow along the RGCP. For purposes of the local-basin-scale water budget, the local-basin domain was set at the approximate extents of the area that is irrigated along the RGCP. A single local-basin-scale water budget analysis was performed over the local basin that interacts with the RGCP by evaluating the surface-water and groundwater components. The surface-water components for the local-basin-scale water budget includes the upstream inflow, precipitation, surface-water pumping, groundwater return flow, the downstream channel outflow, groundwater recharge, and evapotranspiration. The groundwater components include the upstream groundwater inflow, groundwater recharge, pumping from the aquifer, groundwater return flow, and the downstream groundwater outflow. The groundwater recharge, groundwater return flow, and pumping components are included in the surface water and groundwater budgets, and have the same magnitude. However, for the surface water budget, the pumping and groundwater return flow components are inflows and the groundwater recharge is an outflow, whereas the opposite is the case for the groundwater budget.

The water budget calculations were performed by first assembling the measured inflows and outflows on a mean daily-flow basis for the study period between January 1, 2010, and November 30, 2012. The measured data include the upstream inflow, precipitation, pumping data, and the downstream outflow, Consistent with the RGCP-scale channel water budget analysis; the data assembly was performed in a Microsoft Excel spreadsheet to facilitate organization of the large amounts of data. Information from the existing MODFLOW groundwater model (SSPA, 2007) was entered into the spreadsheet. For the local-basin-scale water budget, the groundwater components were extracted from the portion of the model that generally represents the area that is irrigated. This information includes the upstream groundwater inflow, groundwater return flow, groundwater recharge, evapotranspiration, and the downstream groundwater outflow.

ES-9. Study Limitations

A number of limitations associated with the water budget analysis were identified during the development of this study. These limitations include:

- Groundwater flux information was extracted from the SSPA (2007) MODFLOW groundwater model, which does not include a simulation period that covers the 2010 through 2012 drought period that is being evaluated in this study. Differences between the predicted groundwater fluxes in 2004 that were adopted for use in this study could be significantly different than the actual fluxes that occurred during the drought period of interest.
- Measured groundwater data along the RGCP and adjoining groundwater basin is limited, especially along the Rio Grande and the primary canals and drains, where complex processes govern stream-groundwater interactions.
- Diversions were specified at three locations: Percha, Leasburg, and Mesilla Dams. However, it is understood that there are numerous diversions and irrigation return locations that are not entirely accounted for in this modeling effort. A recommendation would be to increase the number of data

collection facilities and add to a central database for the river system where the irrigation return flow data for all locations could be represented to improve the modeling effort. **The lack of available data representing inflows and outflows to the Rio Grande, as well as groundwater level and flux data, is the single most significant limitation to this study. Considering this lack of data and the complex processes that govern stream-groundwater interactions, along with the fact that the groundwater model (SSPA, 2007) does not include the 2010 through 2012 study period, the results of this study should be considered preliminary.**

- Use of a steady-state, saturated hydraulic conductivity (K_{sat}) value for the HEC-RAS models is a significant limitation of the resulting channel seepage estimates because the hydraulic conductivity changes at the beginning of the release, when dry antecedent moisture conditions control seepage rates, to during the remainder of the release, when saturated conditions control seepage.
- Evaporation along the RGCP is currently estimated by transposing the estimated evaporation rates from the USBR URGWOM (RiverWare) model of the Rio Grande upstream from Elephant Butte Reservoir. The existing RiverWare model along the RGCP (USACE, 2012) was not available for this study, and it is not known whether or not this model includes estimates for evaporation. If this model does include estimates of evaporation, these estimates should be used for the water budget analyses.
- Crop evapotranspiration was estimated using the 2004 consumptive use values presented in SSPA (2007). If consumptive use values become available for the 2010 through 2012 period, these values should be used to estimate crop evapotranspiration for this study.
- Considering the relatively long reach over which this study is being performed, comparing the various inflows and outflows on a daily basis can lead to misleading results under both the RGCP-scale channel water budget and the local-basin scale water budget. Even though the HEC-RAS and FLO-2D modeling account for routing effects and hydrograph translation, the water budget computations assume that the mean daily inflows and outflows are representative of an instantaneous point in time. While this may be appropriate under relatively steady flow conditions and reflect the overall interaction of the groundwater components over longer periods, daily comparisons during periods with rapidly changing releases from Caballo Dam (i.e., at the start or end of a release) may not reflect actual instantaneous changes to the water budget.
- Use of a water budget study of past conditions to predict future conditions may not be appropriate considering the highly variable and dynamic nature of the demands, supply, and availability of RGP water and water that is pumped from groundwater.

ES-10. Water Budget Analysis Results

Results from the RGCP-scale channel water budget for 2010 to 2012 were evaluated to assess the magnitudes of the individual components on the water budget, and to assess the change in-channel storage along each reach. The most significant components of the RGCP-scale channel water budget are the upstream inflow and downstream outflow. Diversions, irrigation return flows, and channel seepage are the next significant components, followed by in-channel stormwater flow. The remaining components are much less significant. The total annual volumes indicate that Segment 1 is a significantly losing segment, Segment 2 is a moderately gaining segment, Segment 3 shifts from a gaining segment in

2010 to a losing segment in 2011 and 2012, and Segment 4 is a gaining segment, especially in 2010. Although the predicted change in volume of channel storage is relatively high in each of the segments, the total change in volume is less than 15 percent of the upstream inflow in each of the segments at the end of the 3-year study period. An evaluation of the individual components on a daily and monthly basis indicates that the relative effects of the components vary from segment to segment.

Results from the local-basin-scale water budget analysis for the 2010 to 2012 period indicate that, similar to the RGCP-scale channel water budget, the upstream channel inflow and the downstream channel outflow are the most significant components. However, except for precipitation, groundwater inflow, and groundwater outflow, most of the other components are also very significant. The surface water budget indicates a net increase in surface-water storage of about 630,300 acre-feet over the 3-year study period, while the groundwater budget indicates a net decrease in groundwater storage of about 218,400 acre-feet. Although the resulting net storage appears to be unreasonably high for drought conditions, the baseline analysis does provide insight into the relative effects of the two hypothetical releases through a comparison with the results from the water budget analyses of these releases.

Under the hypothetical delayed pulse release (Scenario S1) and normal single-pulse release scenario (Scenario S2), results from the RGCP-scale channel water budget using the HEC-RAS model results indicate that, compared to baseline conditions, the hypothetical scenarios would generally result in different seepage and channel storage conditions in each of the segments by the end of the 2012 release. The total volume of seepage predicted by the HEC-RAS model of the baseline 2012 release (March 31 through September 14) is about 76,923 acre-feet, which is somewhat higher than the predicted seepage volume (359 acre-feet/day x 167 days = 59,953 acre-feet) presented in the Rio Grande Project Allocation Committee (RGPAC) Draft Report entitled, "Analysis of River Conveyance Efficiency for Initial Release of Project Water for Delivery to Acequia Madre Canal in 2012." Compared to baseline conditions, the total predicted seepage volume would decrease under Scenario 1 in each of the segments due to the shorter duration of the release, resulting in a significant decrease to seepage along the overall RGCP (about 66,800 acre-feet; Table ES-1). Compared to baseline conditions, the total seepage volume under Scenario S1 would decrease by about 10,100 acre-feet, which equates to a reduction of about 2.7 percent of the Caballo release (i.e., the seepage volume decreases from about 20.7 percent of the Caballo release under baseline conditions to about 18.0 percent of the Caballo release under Scenario S1). Under Scenario S2, the predicted seepage volumes are higher than the baseline condition in Segment 1 but are lower than baseline conditions in the remaining segments, resulting in a moderate reduction to seepage along the overall RGCP (74,087 acre-feet; Table ES-1). Compared to baseline conditions, the total seepage volume under Scenario S2 would decrease by 2,100 acre-feet, which equates to a reduction of about 0.8 percent of the Caballo release (i.e., the seepage volume decreases from about 20.7 percent of the Caballo release under baseline conditions to about 19.9 percent of the Caballo release under Scenario S2). Results from the RGCP-scale channel water budget indicate that, compared to baseline conditions, Scenario S1 would result in decreased channel storage in Segments 1 and 2, and increased channel storage in Segments 3 and 4, and a total decrease to channel storage along the overall RGCP. Compared to baseline conditions, the predicted channel storage volumes at the end of the release under Scenario S2 would also decrease in Segments 1 and 2 and would increase in Segments 3 and 4, but the total change in-channel storage along the overall RGCP would increase.

Table ES-1. Summary of predicted (HEC-RAS) seepage rates along the RGCP under the hypothetical release scenarios as compared to baseline (2012) conditions and as percentage of release volume. Also shown is the RGPAC estimate for 2012.

Release Scenario	Total Seepage (ac-ft)	Caballo Release (ac-ft)	Seepage as Percent of Caballo Release	Seepage as Percent of Baseline
Baseline Conditions*	76,923	372,028	20.7%	100%
Scenario S1: Delayed Single Pulse*	66,786	372,028	18.0%	86.8%
Scenario S2: Normal Single Pulse*	74,087	372,028	19.9%	96.3%
RGPAC Estimate (2012)	59,953	372,028	16.1%	77.9%

*Baseline conditions & Scenario S2 from April 1 to September 14; Scenario S1 from May 29 to September 14.

A similar analysis was conducted using the results from the calibrated FLO-2D modeling. The FLO-2D-based seepage results are presented in Table ES-2. Using this modeling platform, the total volume of seepage predicted for the baseline 2012 release (March 31 through September 14) is about 104,500 acre-feet, which is an increase of about 36 percent over the seepage volume predicted by the HEC-RAS model. The seepage volumes predicted by the FLO-2D model for the hypothetical release scenarios are also significantly larger than the estimates from the HEC-RAS modeling, with an increase of 26 percent under Scenario S1 and an increase of 41 percent under Scenario S2. Results from the FLO-2D modeling indicate that the total seepage volume would decrease significantly under Scenario S1, reducing by about 20,500 acre feet compared to baseline conditions. This reduction equates to about 5.5 percent of the Caballo Release. Under Scenario S2, the FLO-2D modeling indicates that the seepage volume would be about the same as that under baseline conditions.

Table ES-2. Summary of predicted (FLO-2D) seepage rates along the RGCP under the hypothetical release scenarios as compared to baseline (2012) conditions and as percentage of release volume. Also shown is the RGPAC estimate for 2012.

Release Scenario	Total Seepage (ac-ft)	Caballo Release (ac-ft)	Seepage as Percent of Caballo Release	Seepage as Percent of Baseline
Baseline Conditions*	104,546	372,028	28.1%	100.0%
Scenario S1: Delayed Single Pulse*	84,066	372,028	22.6%	80.4%
Scenario S2: Normal Single Pulse*	104,684	372,028	28.1%	100.1%
RGPAC Estimate (2012)	59,953	372,028	16.1%	57.3%

*Baseline conditions & Scenario S2 from April 1 to September 14; Scenario S1 from May 29 to September 14.

The local-basin-scale water budget analyses of the hypothetical scenarios indicates that the surface water storage would increase slightly under Scenario S1 compared to baseline conditions, but decrease slightly under Scenario 2, and that the scenarios would have an opposite effect on groundwater storage.

The estimated net storage (groundwater plus surface water) would increase slightly under Scenario S1, but decrease slightly under Scenario 2.

ES-11. Conclusions and Recommendations

Primary Conclusions

The following primary conclusions were developed as part of this study:

- The available data along the RGCP are not sufficient or is of insufficient quality to perform a detailed water budget analysis.
- Channel seepage was significant over the 3-year study period from 2010 to 2012. The HEC-RAS model indicates that the volume of seepage was about 22 percent of the volume released from Caballo Reservoir during this period, while the FLO-2D model indicates that the volume of seepage was about 17 percent of the volume released from Caballo Reservoir.
- Both the HEC-RAS model and FLO-2D model results are sensitive to the hydraulic conductivity input. The HEC-RAS model results are also sensitive to the sediment thickness input, while the FLO-2D model results are sensitive to the limiting storage depth input. Considering the differences between the Darcy equation as applied in HEC-RAS and the Green-Ampt methodology as applied in FLO-2D, a direct comparison of these two input parameters is not appropriate.
- The most significant components in the RGCP-scale water budget are the upstream inflow, diversions, downstream outflow, and channel seepage, in that order.
- The most significant components in the local-basin-scale surface-water budget are the upstream channel inflow, downstream channel outflow, pumping and groundwater recharge, in that order. The most significant components in the local-basin-scale groundwater budget are pumping, groundwater recharge, and groundwater return flow, in that order.

Recommendations for Best Water Management Practices for Future Years

Recommendations for best water management practices for future years include the following:

- A delayed single-pulse release should be considered during future years of drought.
- Considering that the 2011 pumping appears to have resulted in reduced groundwater levels in 2012 and the associated high degree of seepage that occurred during the beginning of the 2012 release, significant pumping from the aquifer similar to that which occurred in 2011 is not recommended. Instead, a more detailed investigation of the linkage between the 2011 pumping and groundwater levels and channel seepage in 2012 should be undertaken. The results from this investigation could then be used to determine upper limits of the pumping that would prevent overdraft of the aquifer.
- Water management improvements may also come in the form of methods to improve on-farm efficiency. These methods may include scientifically based scheduling of irrigation, increased use of tailwater return systems, and improvements to the irrigation systems. Examples of improved irrigation systems include improved furrows or changing from surface irrigation to pressurized systems.

Recommendations for Channel Conveyance Improvements

Recommendations for channel conveyance improvements include the following:

- Removal of vegetation along the channel banks that increases the hydraulic roughness and reduces the conveyance efficiency, provided this is accomplished within the framework of the USIBWC Record of Decision for River Management Alternatives for the Rio Grande Canalization Project (USIBWC, 2009). Areas that have dense salt cedar or other non-native woody vegetation should be considered high priority sites for vegetation removal, while areas where this vegetation does not significantly affect the hydraulic roughness should be considered low priority sites. Considering the need for improved riparian habitat (USIBWC et al., 2004), removal of native vegetation along overbanks and within the floodway should not be considered. It should be noted that at some locations (i.e., at confluences with arroyos), vegetation also grows along the channel bed margins, but this vegetation is typically grass and reeds so it does not appear to significantly affect the hydraulic roughness.
- Localized accumulations of sediment along the RGCP also appear to affect channel conveyance, and removal of these sediments would improve efficiency. The most significant deposits tend to occur upstream from the diversion dams and at the confluences of the tributary arroyos. Reducing the amount of sedimentation at the arroyo confluences could be achieved by reducing the amount of sediment that is delivered by the arroyos (i.e., using sedimentation basins in the arroyo watershed) or by mechanically removing the material from the RGCP channel.
- Similarly localized accumulations of sediment also appear to affect conveyance through the canal and drain system, especially in the downstream portion of the wasteways where water is returned to the Rio Grande. Mechanical removal of this material would improve the delivery of return flows, thereby increasing the overall efficiency of the RGCP system.
- Sedimentation could also be reduced by implementing the modified leases for grazing that would result in reduced erosion as identified in the EIS (USIBWC et al., 2004).
- Lining the RGCP with concrete would greatly improve the conveyance efficiency by reducing seepage and increasing flow velocities, but this option is probably not feasible due to cost constraints and ecological concerns. However, use of a synthetic impermeable membrane would limit seepage and may be more cost effective and more environmentally sensitive than the concrete lining.
- It may also be possible to identify reaches where irregularities in the banks could be smoothed to reduce energy losses and improve conveyance.

<u>Recommendations for Future Studies</u>

Recommendations for future studies include:

- The Water Budget analysis could be refined with additional well data to better define the groundwater profile along the RGCP.
- Updated groundwater modeling that includes the 2010 through 2012 drought period would provide better estimates of the groundwater components and would improve the accuracy of the study.

- It is also recommended that an analysis be carried out to determine the baseflow release rate prior to the irrigation release that would be necessary to reduce the very high seepage rates that are indicated by the FLO-2D model at the beginning of each pulse release.
- The project reach of the RGCP Water Budget Study could be extended farther downstream to include reaches of the Lower Rio Grande to better assess the effects of the various features along the extended reach. To assess these features, it is recommended that the water budget study reach be extended to the Fort Quitman gaging station.
- Although this analysis indicates that the reduced duration of a delayed single pulse release would result in reduced seepage volumes, the degree to which the delayed release would affect groundwater pumping prior to the release is not known. If groundwater pumping were to increase during the period prior to the release, the resulting reduction to groundwater levels could increase seepage rates during the release, thereby reducing the benefits of the delayed release that are indicated by this study. As such, it is recommended that a study be carried out to determine the degree to which the delayed release would affect groundwater pumping prior to the release, and assess how this change in pumping would affect seepage during the release.
- Both the HEC-RAS and FLO-2D models appear to reasonably replicate the measured hydrographs, and thus, reasonably predict channel seepage rates. However, because the FLO-2D model software that was revised for this study now includes the capability to incorporate spatial and temporal variability in hydraulic conductivity, the model platform is recommended for use in future studies.

<u>Recommendations to Improve Accuracy of Study and Suggested Water Management Investments</u>

Key recommendations to improve the accuracy of the study, which in some cases include suggested water management investments, include:

- A number of inflow/outflow locations are known to have gage information that was not available for this study. This information should be obtained and incorporated to improve the accuracy and completeness of the calculations.
- Improve the quality of the existing surface water gages along the river, at diversions, and at the return locations. Improvements to the accuracy of the gages could be achieved by increasing the frequency of gage measurements for calibration purposes. Of particular interest would be the river gages at Haynor, Picacho and Anthony.
- At locations where inflows or outflows to the river are not gaged, the accuracy of the water budget analysis could be improved by adding gages to these locations. Models for quantifying arroyo flows could also be developed. A few major arroyos could be instrumented to study the rainfall-runoff relationships and calibrated models could be developed for these arroyos. Models with similar parameters could then be used to calculate stormwater inflows from ungaged arroyos for the measured precipitation amounts. Models that will be developed by counties and cities adjoining the RGCP as part of the interior drainage analysis for the levee system can be used when they become available.

- In addition to the recommended updates to the groundwater modeling, updated groundwater data and information for the study period would benefit the accuracy of the groundwater-related components of the water budgets.

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List of Acronyms

CR	Caballo Reservoir
CRE	Caballo Reservoir Evaporation
DA	Drainage Area
DEM	Digital Elevation Model
EBID	Elephant Butte Irrigation District
EBR	Elephant Butte Reservoir
EBRE	Elephant Butte Reservoir Evaporation
EPCWID	El Paso County Water Improvement District
ET	Evapotranspiration
GW	Groundwater
HEC-RAS	Hydrologic Engineering Center – River Analysis System
LiDAR	Light Detection and Ranging
MEI	Mussetter Engineering Incorporated
NAD	North American Datum
NAVD	North American Vertical Datum
NMISC	New Mexico Interstate Stream Commission
NMOSE	New Mexico State Engineer's Office
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
RGCP	Rio Grande Canalization Project
RGP	Rio Grande Project
RGPAC	Rio Grande Project Allocation Committee
RS	River Station
URGWOM	Upper Rio Grande Water Operations Model
USACE	United States Army Corps of Engineers
USIBWC	United States International Boundary and Water Commission
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
WSE	Water Surface Elevation
WWTP	Wastewater Treatment Plant

Conversion Factors

SI Units	U.S. Customary Units
1 millimeter	0.0394 inches
1 meters	3.2808 feet
1 kilometer	0.6214 miles
1 hectares	2.4711 acres
1 cubic-meter/second (cms)	35.315 cubic feet/second (cfs)
1 micro-meter/second	0.02835 feet/day

U.S. Customary Units	SI Units
1 inch	25.4 millimeters
1 foot	0.3048 meters
1 mile	1.6093 kilometers
1 acre	0.4047 hectares
1 cubic foot/second (cfs)	0.0283 cubic-meter/second (cms)
1 foot/day	3.5273 micro-meters/second

Common Conversions	
1 gallon/day	1.5472 x 10^{-6} cubic-feet/second
1 cubic-foot/second	646,320 gallons/day
1 acre-foot/day	0.5042 cubic-feet/second
1 cubic-foot/second	1.9835 Acre-feet/day

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1.0 INTRODUCTION

1.1 STUDY BACKGROUND

1.1.1 The Rio Grande Canalization Project

The United States Section of the International Boundary and Water Commission (USIBWC) Rio Grande section of the Rio Grande Canalization Project (RGCP) is a narrow river corridor that extends 105.4 miles from Percha Dam at River Mile (RM) 105.4 in Sierra County, New Mexico to American Dam at RM 0 in El Paso, Texas (USIBWC et al., 2004). The RGCP reach is contained within the Lower Bioregion (Caballo Dam, NM to Candelaria, TX) geomorphic subreach of the Rio Grande (Fullerton and Batts, 2003). The RGCP was constructed between 1938 and 1943 under the authority of an Act of Congress approved June 4, 1936 (49 Stat. 1463), to facilitate compliance with the 1906 convention between the United States and Mexico, and to properly regulate and control, to the fullest extent possible, the water supply for use of the two countries as provided by the treaty (USIBWC et al., 2004). The 1936 Act authorized the construction, operation and maintenance of the RGCP in agreement with the Engineering Record Plan of December 14, 1935 (Baker, 1943; cited in USIBWC et al., 2004).

Major elements of the plan included acquisition of Right of Way (ROW) for the river channel and adjoining floodways (8,332 acres), improvement of the alignment and efficiency of the river channel conveyance for water delivery, and flood-control measures that extended through the Rincon and Mesilla Valleys of New Mexico and El Paso Valley in Texas. As part of the RGCP, a deeper main channel was dredged to facilitate water delivery for irrigation. Hydraulic capacity of the dredged channel ranged from 2,500 to 3,000 cfs in the Upper Rincon Valley, to less than 2,000 cfs in the Lower Mesilla Valley (USIBWC, 2001). In general, the dredged channel followed the alignment of the existing channel in most locations (5-percent reduction in-channel length), resulting in a small increase in the average river bed slope from 0.00073 (3.85 ft/mi) to 0.00074 (3.9 ft/mi). Canalization included riprapping portion of the channel banks to prevent lateral migration of the channel.

Flood protection levees, designed to provide a 100-year level of flood protection, were placed along two-thirds of the length of the RGCP (57 miles along the west side of the channel and 74 miles along the east side), where the channel was not confined by hillslopes or canyon walls (e.g., Selden Canyon). The width between the levees north of Mesilla Dam ranged from 750 to 800 feet, and it was a constant 600 feet downstream of Mesilla Dam. A number of NRCS sediment/flood-control dams were built between 1969 and 1975 on tributary arroyos to control flooding and sediment delivery to the RGCP from about 300 square miles of drainage basin downstream of Percha Dam. The NRCS dams in Broad Canyon, Green Canyon, Arroyo Cuervo and Berrenda/Jaralosa Arroyo control approximately one third of the drainage area between Percha and Leasburg Dams, and reduce the flood peak frequency by an estimated 40 percent (USACE and RTI, 1996). A recent evaluation of the project levees by MEI and Riada (2007) determined that the design freeboard would be encroached during the 100-year flood (i.e., the water surface would be within 3 feet of the levee crest) along 37 miles of levee in Doña Ana County and 12 miles of levee in El Paso County. The MEI and Riada (2007) study found that levee overtopping would occur during the 100-year event at several locations along the reach, with a total length of about 1 mile in Doña Ana County and about two miles in El Paso County. As a result of this study, USIBWC is currently in the process of raising the levees in the affected area.

1.1.2 Current Drought and Study Reasoning

The 2010 through 2012 period marks one of the most significant drought periods that have affected Caballo Dam water releases for irrigation purposes, with increasing drought severity in each of the years. The area around the RGCP experienced exceptional drought during the 2011 irrigation season and severe drought during the 2012 irrigation season. Copies of the U.S. Drought Monitor Maps (http://droughtmonitor.unl.edu/) for September 2010, 2011, and 2012 are shown in **Appendix K**. The drought conditions are apparent when actual storage volumes for Elephant Butte Reservoir and Caballo Reservoir are compared to design capacity. According to online datasets (http://www.usbr.gov/uc/elpaso/water/rgreports), the maximum storage in Elephant Butte Reservoir during 2010, 2011, and 2012 was approximately 600,000, 504,000, and 385,000 acre-feet, respectively, compared to a storage capacity of approximately 2,000,000 acre-feet. At Caballo Reservoir, with a storage capacity of approximately 332,000 acre-feet, the maximum storage during 2010, 2011, and 2012 was approximately 72,000, 63,000, and 24,000 acre-feet, respectively.

In 2012, US irrigators requested that the release be delayed by several months to insure adequate water supplies during summer months, while Mexico required water deliveries during the normal period (April through May), resulting in a double pulse release. In drought years, there is a benefit to maintaining a single short duration release. This will improve conveyance efficiency while minimizing channel seepage. In contrast, an initial release followed by a much later release will result in replenishment of the unsaturated (vadose) zone twice, potentially increasing channel seepage.

1.2 STUDY PURPOSE

The primary purpose of this report is to determine the difference in the amount of Rio Grande Project (RGP) (Figure 1) water supply available for diversion to Elephant Butte Irrigation District (EBID), El Paso County Water Improvement District (EPCWID No. 1), and Mexico in 2012 under one or more proposed release scenarios compared to a baseline of the actual project operations. During 2012, Rio Grande Project water was released from Caballo Reservoir for delivery in the vicinity of El Paso, Texas in two pulses. The first pulse was from April 1 through May 4 and a second pulse started on May 29 and terminated on September 13. Alternatively, because of the need to conserve water as a result of the extreme drought and a limited water supply, EPCWID No. 1 and EBID proposed that Rio Grande Project water only be released in single pulse water from May 29 through September 13. This report documents the amount of RGP water that was released, diverted from the Rio Grande, and lost to infiltration (seepage) and evaporation and compares this baseline condition to the hypothetical situation if the same amount of water had been released in a normal single pulse or delayed single pulse.

To quantify the differences between the water release, the diverted waters, and the seepage and evaporation, an evaluation of the water budget components was carried out for the ongoing 2010 to 2012 drought periods along the Rio Grande Canalization Project (RGCP), which extends from Percha Dam to American Dam over a distance of 105.4 miles. A separate evaluation of the water budget components was carried out within the local groundwater basin for the same period. Through a quantification and comparison of the relative magnitudes of the water budget components, this study is intended to help the stakeholders to manage release timings and volumes during years of water scarcity. As such, the actual water budget for the 2012 period was compared to the water budget under hypothetical releases that could have occurred in 2012. The hypothetical releases that were evaluated included a normal single pulse and delayed single pulse release from Caballo Reservoir, and were developed by the Rio Grande Project Allocation Committee (RGPAC).

1.3 WATER BUDGET ANALYSIS APPROACH

Water budget studies specific to drought conditions are lacking in the RGCP. Therefore, one of the purposes of this study is to investigate the volume of channel seepage, since it is not fully understood during periods of drought. This study develops **channel (RGCP-scale) water budgets** and **local-basin-scale water budgets** based on surface water and groundwater components for the period from January 1, 2010, through November 30, 2012. To assess the effects of different release schedules on the various water budget components, the amount of channel seepage in **normal single pulse (Scenario S2)** and **delayed single pulse (Scenario S1)** irrigation releases and the amount of evaporation associated with a normal or late irrigation release was estimated and compared to the water budget components for the actual double-pulse release that occurred in the **2012 baseline year**. As discussed in more detail below, the channel water budget (RGCP scale) was carried out by subdividing the RGCP reach into four segments. The Upper Reach (Caballo to Leasburg metering stations) and Middle Reach (Leasburg metering station to Mesilla Dam) as shown in Figure 1 are two segments. The Lower Reach in Figure 1 was split into the remaining two segments—a third segment from Mesilla to Anthony metering station, and a fourth segment from Anthony to downstream of American Dam. The local-basin-scale water budget analysis was carried out for the overall RGCP (Caballo Dam to American Dam), and includes the area that extends laterally to the approximate extents of the area that is affected by irrigation.

1.4 KEY STUDY LIMITATIONS

A number of limitations were identified during preparation of this study. Among the most important limitations are incomplete or unknown inflows and outflows to the RGCP and unknown stream-groundwater interactions, especially during periods of drought. **The lack of available data representing inflows and outflows to the Rio Grande, as well as groundwater level and flux data, is the single most significant limitation to this study. Considering this lack of data and the complex processes that govern stream-groundwater interactions, along with the fact that the groundwater model (SSPA, 2007) does not include the 2010 through 2012 study period, the results of this study should be considered preliminary.** Additional limitations of the study are outlined in Section 12.6.

2.0 STUDY AREA

The study area for the RGCP defined by the Scope of Work (USIBWC 2012a and 2012b) extends 105.4 miles from Percha Dam to American Dam. However, the surface-water modeling conducted under this study flow and a number of reference documents refer to a 106.8-mile-long project reach that extends from Caballo Dam to American Dam. Unless otherwise noted, all references to the RGCP in this report are in reference to the 106.8-mile-long section that extends to Caballo Dam.

As discussed in Section 9.0, the channel water budget study area at the RGCP scale is divided in four 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 reaches are summarized in Table 1. Points of interest along the study reach are shown in Figure 2. The local-basin-scale water budget study area covers the same reach of the RGCP, and generally covers the portion of the groundwater basin that is directly affected by irrigation.

3.0 RIO GRANDE PROJECT ALLOCATION COMMITTEE 2012 DRAFT REPORTS

On March 31, 2012, the Rio Grande Project Allocation Committee (RGPAC) prepared a Draft Report entitled, "Analysis of River Conveyance Efficiency for Initial Release of Project Water for Delivery to Acequia Madre Canal in 2012," referred to herein as the RGPAC Draft Report. The RGPAC Draft Report summarized the anticipated conveyance efficiency for a release of Project Water from Caballo Reservoir for delivery to the Acequia Madre Canal approximately 2.1 miles downstream of the American Diversion Dam.

Using data obtained from numerous measurements of flow in the Rio Grande during March and April of 2011, and including consideration for the fact that drought conditions along the Rio Grande are more extreme in 2012 than in 2011; the RGPAC Draft Report of river conveyance efficiency presented the following conclusions:

- It would take a release of 33,300 acre-feet of RGP water from Caballo Reservoir for the delivery to Mexico of their current RGP allocation of 12,275 acre-feet.
- The difference between the amount released and the amount diverted to Mexico was estimated to be 21,000 acre-feet.
- The diversion ratio, i.e., the ratio of the amount of water diverted to Mexico (12,275 acre-feet) to the amount of water released (33,000 acre-feet) is about 37 percent.
- The conveyance efficiency estimated to be less than 34 percent[1].
- A significant portion of the difference between the amount released and the amount diverted (i.e., about 21,000 acre-feet) would reduce future seepage in 2012 if a second release of RGP water were to follow the initial release within a few days.
- An alternative schedule was presented in the RGPAC Draft Report which proposed diversions of RGP Water for both EPCWID No. 1 and Mexico. That schedule proposed a release of 67,630 acre-feet of water for a diversion of 12,275 acre-feet to Mexico and 34,285 acre-feet to the EPCWID No. 1, with

[1] The RGPAC Draft Report does not explicitly state how this value was estimated.

a resulting diversion ratio ((12275+34285)/37630) of 69 percent and a conveyance efficiency of about 66 percent.[2]

3.1 CONVEYANCE EFFICIENCY

The RGPAC Draft Report indicates the amount of RGP Water released from Caballo Reservoir and flowing in the Rio Grande to the American Diversion Dam (a distance of 106.8 river miles) is diminished by (1) evaporation, (2) seepage, (3) channel storage, and (4) unauthorized diversions. The Draft Report characterizes the majority of the Rio Grande as being channelized from Caballo Dam to the American Diversion Dam, with a wetted surface width ranging from 150 to 400 feet and an average wetted surface width of approximately 240 feet. The RGPAC Draft Report also indicates that typical depths of flow along the Rio Grande are shallow; with exceptions for thalweg channels, which can be five feet, or more, in depth, but usually are only 20 to 30 feet in width.

The components that diminish the conveyance efficiency of the Rio Grande, as identified in the RGCAP Draft Report are summarized in the following sections.

3.1.1 Evaporation

The loss of water volume due to daily evaporation is presented in the RGPAC Draft Report as 26 acre-feet (rounded to the nearest whole acre-foot) for every 0.10 inches per day of water-surface evaporation. This estimate was determined by performing the following calculation:

Daily Evaporation = 106.8 mi x 5,280 ft/mi x 240 ft x 0.10 in./12 in. x 1 ac/43,560 sq. ft. = 26 acre-feet

3.1.2 Channel Storage

The magnitude of this loss was based on the fact that for water released from Caballo Reservoir, a certain amount of the release must accumulate as channel storage (i.e., the water must physically be stored above the bed and between the banks of the Rio Grande). Based on several hundred measured cross sections of the river and direct measurements made during previous releases of water, the RGPAC's estimate of the channel storage is 5,000 acre-feet for a release from Caballo Dam that is below a discharge rate of 1,000 cfs.

3.1.3 Channel Seepage

The RGPAC Draft Report points out that seepage of water through the bed and banks of the Rio Grande is typically made up of two phases: (1) a first phase of rapid rate of infiltration of water (typically referred to as Initial Abstraction) in order to fill the voids and porosity of the soil beneath and adjacent to the river upon initial release of flows, and (2) a second phase of steady-state seepage that occurs between 15 to 25 days later, when the seepage rate from the river becomes steady and does not change significantly from day-to-day.

The RGPAC Draft Report used the flow of water discharged from the Las Cruces Waste Water Treatment Plant into the Rio Grande just upstream of the Interstate Highway 10 to make an estimate of channel

[2] The RGPAC Draft Report does not explicitly state how this value was estimated.

seepage. The steady-state seepage rate downstream from the Wastewater Treatment Plant was estimated to be approximately 7.9 acre-feet per mile per day. Extrapolating this seepage rate for the 106.8 river miles between Caballo and American Dams would yield 847 acre-feet per day, or a daily average of 427 cfs. However, the RGPAC Draft Report notes that the seepage rate along this portion of the Rio Grande is likely greater than in other portions of the Rio Grande; thus extrapolation of this high seepage rate would likely overestimate the average steady-state seepage rate for the Rio Grande. Accordingly, the Draft Report suggested that the estimate for the average steady-state seepage rate for the entire 106.8 miles of the river for 2011 was 139 cfs, or 275 acre-feet per day; and for 2012 that estimate was 181 cfs, or 359 acre-feet per day. The Draft Report did not include any calculations for the seepage estimates in 2011 and 2012, so the source of these estimates is not known.

3.1.4 Unauthorized Diversions

The RGPAC Draft Report notes that during previous releases of RGP Water from Caballo Reservoir, various governmental agencies have observed unauthorized diversions of surface water from the Rio Grande. The Draft Report also indicates that, at the time of preparation of the report, there was no good estimate of the magnitude of these diversions; and that work is ongoing to estimate the amount of unauthorized diversions and to stop such diversions.

3.1.5 Return Flows

In addition to losses, the RGPAC Draft Report provides a 2011 estimate of return flows to the Rio Grande of 70 cfs (about 139 acre-feet per day) upstream of the American Diversion Dam.

3.2 RIO GRANDE PROJECT ALLOCATION COMMITTEE 2012 DRAFT REPORT CONCLUSIONS

The RGPAC Draft Report notes that because of the large number of changes in the amount of water flowing in the Rio Grande over time, it is difficult, and likely economically impossible, to determine the conveyance efficiency of the river on a reach-by-reach basis. Consequently, the overall fluvial system was analyzed in the report as a single-unit system by comparing the cumulative volume of water released (mass curve) to the cumulative volume of water diverted for authorized use.

The RGPAC Draft Report also noted that drought conditions along the Rio Grande are significantly worse in 2012 than they were in 2011. The RGPAC estimates that the Initial Abstraction for 2012 will be in the range of 30 percent greater than what occurred in 2011, and thus the corresponding conveyance efficiency of the Rio Grande will be significantly less during the initial release for 2012 than it was in 2011. Accordingly, the best estimate of the amount of water that would have been lost if the proposed release were carried out according to Table 8 presented in the Draft Report would be (1) an Initial Abstraction of 20,200 acre-feet (this includes channel storage), (2) a steady-state seepage of 5,400 acre-feet, (3) an evaporative loss of 1,500 acre-feet, (4) a loss below American Diversion Dam of 200 acre-feet, and (5) a net return of 6,000 acre-feet after the release is discontinued per the proposed release schedule. This leads to a net system-wide loss of 27,300 acre-feet, and net differential loss of 21,300 acre-feet (i.e., 20,200 acre-feet +5,400 acre-feet + 1,500 acre-feet + 200 acre-feet - 6,000 acre-feet).

3.3 ANALYSIS OF MULTI-YEAR DROUGHT AND D2 LINEAR REGRESSION EQUATIONS

This report provided an evaluation of the USBR's "D2 Equation" under multi-year drought conditions. The D2 Equation is a linear regression equation that predicts the annual amount of RGP Water available for diversion based on the amount of RGP Water that is released from storage at Caballo Dam based on measured volumes for the period between 1951 and 1978. The linear regression assumes that all data is not correlated, which is not correct during periods extreme drought conditions in multiple years because the volume that is available for diversion is affected by the volume that was released the previous year; thus, the regression equation is biased and in error during these periods.

The report included a summary of an evaluation of the period between 1954 and 1957 during which there was a release volume of less than 400,000 acre-feet, or three consecutive years with release volumes of this amount. The analysis indicated that a correction factor should be applied to the linear regression equation during this period that should also be applied during other periods when releases of less than 400,000 acre-feet occur over consecutive years. These correction factors decrease from 0.88 in the first consecutive year (i.e., the second year with a release of less than 400,000 acre-feet) to 0.78 in the second consecutive year to 0.75 for remaining years.

4.0 DATA COLLECTION AND DATA REVIEW

Data and information for the project, most of which was provided by the US International Boundary and Water Commission (USIBWC), included:

- Previous studies for the RGCP by the US Army Corps of Engineers, and the corresponding HEC-RAS and FLO-2D modeling,
- 2011 LiDAR-based 1-meter DEM topography ,
- Precipitation and Gage Data along the RGCP, and
- Data from stakeholders and public agencies.

Data to develop the water budget study were assembled from several sources. A table of the data assembled for the study is included in **Appendix A, Table A-1**. Hydraulic models and the associated modeling data, along with reports from previous hydraulic studies developed for the RGCP were provided by the USIBWC. River diversion and reservoir evaporation data, including flow releases from Caballo Reservoir, were provided by the US Bureau of Reclamation (USBR) to USIBWC. The USIBWC coordinated with the New Mexico State Engineer's Office (NMOSE) to provide groundwater modeling and the associated reports prepared in 2007. Available data from the El Paso County Water Improvement District No.1 (EPCWID No. 1) and the EBID were either provided by the USIBWC or were downloaded from the EBID website.

Data from the various EBID radio telemetry units that are available from the EBID website were downloaded by the USIBWC and Tetra Tech. These data included:

- Drains
- Monitoring wells
- River gage data
- Checks
- Dams
- Flumes
- Headings
- Irrigation wells
- Laterals
- Spillways
- Turnouts

A summary of EBID drain data is included in **Appendix B, Table B-1.** Data from the Del Rio Drain, East Drain, West Drain, La Mesa Drain, and Nemexas Drain were used to evaluate inflows to the river. The Rio Grande Operations Manual (USBR, 2010) indicates gage data are collected at 38 drain locations, but these data were not available for this study.

USIBWC provided historical river gage data for El Paso and for the summation of the gages at the American Canal and Below American Dam. The flows are summarized in (**Appendix B, Table B-2**).

USBR diversion data are summarized in **Appendix B, Table B-3** and include mean daily diversions at Percha, Arrey, Leasburg, Eastside, Westside, and Del Rio.

EBID river gage data included mean daily flow summaries for Rio Grande gages downstream of Caballo Dam, Haynor Bridge, Picacho, Leasburg Cable below Leasburg Dam, below Mesilla Dam, and at Anthony. The records at Haynor, Picacho, and Anthony are not considered as reliable and were not used in this study. EBID river gage data were available from the gaging station below Caballo. Raw data for Caballo Dam outflows are shown in **Appendix B, Table B-4.** Flow data that were processed to account for missing flows and spurious data are summarized in **Appendix B, Table B-5**. EBID Gage data are summarized in Table 2.

5.0 KEY ASSUMPTIONS

5.1 ELEVATION DATA

The vertical data for elevations in this report vary. The previous topographic mapping for the HEC-RAS model was in feet referenced to the North American Vertical Datum of 1988 (NAVD88). The 2011 LiDAR topography was also referenced to NAVD88, but required conversion from meters to feet before use in the hydraulic modeling. The vertical datum for other elevations in this report, including well data, is not known and was assumed to reference NAVD88.

5.2 GROUNDWATER INFORMATION

Estimates for selected groundwater components, including subsurface groundwater flows into and out of the Rio Grande, floodplain recharge, and evapotranspiration for riparian and agricultural areas were obtained from an existing MODFLOW groundwater model that was prepared by SSPA (2007). The data from the MODFLOW model represent irrigation and non-irrigation periods in 2003-2004, a period in which the Rio Grande was fully allocated and the inputs are not representative of the extreme drought conditions in 2010 through 2012. The analysis can be improved by using data that is representative of the drought period.

5.3 ACCURACY OF AVAILABLE DATA

Data that were directly used in this study was assumed to be accurate. As with any study that involves use of measured data to assess existing conditions or to predict future responses, the validity of the results presented in this study, while believed to be reasonable, is limited to the accuracy of the available data. In a number of cases, the measured data were not used or only used anecdotally since the reported data are believed to be inaccurate. Data that were not used because of the questionable accuracy have been identified.

6.0 EVALUATION OF DISTANCE BETWEEN WATER TABLE AND RIVER BED

A comparison of groundwater and riverbed elevations for 2010 through 2012 is provided in Table 3. Well locations are shown in Figure 3. The trends of the groundwater elevation shows a general lowering of the water table between 2010 and 2012 as would be expected during drought conditions. The groundwater elevation compared to the channel thalweg varies based on the linear distance between the well and the river. It is recognized that the well data included in this analysis only represents the local groundwater conditions in the vicinity of the wells and does not represent the variability between the wells, and that this analysis could be improved if additional well information near the Rio Grande were available.

Estimates of the distance between the water table and the riverbed along the RGCP channel were prepared using representative EBID well data and channel invert data from the unsteady HEC-RAS flow model (see Section 7.3). The results are shown in Table 4. Table 5 summarizes groundwater depths observed at USIBWC restoration sites during in June/July 2010 and shows how the depths were assigned to each well site for use in the HEC-RAS modeling.

7.0 CHANNEL SEEPAGE

7.1 GENERAL OVERVIEW OF SEEPAGE

Seepage along the RGCP is not entirely understood. A number of studies have been prepared to identify areas that are losing flow to seepage, or conversely areas that are gaining flow that is returned from groundwater. Most of the reviewed studies were not conducted during periods of prolonged drought, so the results of these studies may not reflect seepage conditions for the ongoing period of drought. In 1993, the USIBWC prepared a study of seepage between Picacho Bridge (near Las Cruces, NM) and Courchesne Bridge (El Paso, TX) for the USBR (USIBWC, 1993). This study included data that were collected between 1985 and 1992. Results from this study indicated that the entire study reach was losing flow during the overall study period, and only the reach between Vado Bridge and Canutillo Bridge experienced gains in 1992. A separate study (TRC, 2010) was prepared for the USIBWC to evaluate the depth to groundwater at 24 USIBWC restoration sites along the RGCP (Table 5). This study included groundwater depth measurements collected in June and July of 2010 along with measured well data, and indicated that almost all of the sites would be considered losing areas. The only areas that were identified as gaining were in the vicinity of the Rincon Siphon and at the Mesilla Valley Bosque site.

A review of recent aerial photography was carried out to identify reaches of the RGCP that could be gaining or losing reaches based on the degree of open water identified during the non-irrigation season. An initial review of the aerial photography that was collected as part of the 2011 LiDAR survey indicated that portions of the photography appeared to be collected during the period prior to the initial Caballo release, while other portions were collected during the initial phases of the release. Because it was unknown which portions of the photography were collected prior to the release, this set of photography was not used in the review. Instead, Google Earth™ imagery was reviewed, which included aerial imagery on November 9 and 26, 2011, and November 5, 2012. Reaches that were identified as wet but that are obviously affected by drain return flows were not considered to be gaining reaches. Similarly, wet reaches below the diversion dams were not considered to be gaining reaches because the local groundwater table was probably still draining the pool area above the dam. The resulting areas that were identified as possible gaining reaches included:

- A roughly 7-mile-long reach of intermittent flowing or ponded water located between Bignell Arroyo and Leasburg Diversion Dam.
- A 2.3-mile-long reach of intermittent flowing or ponded water located below Picacho Bridge.
- A 1.4-mile-long reach of intermittent flowing or ponded water located below the Mesilla Gage.
- A 0.9-mile-long reach of intermittent flowing or ponded water located below the Highway 28 Bridge.
- A 0.7-mile-long reach of intermittent flowing or ponded water located below the Anthony metering station.

Of the above locations that were identified as potential gaining reaches, the only one with a significantly long distance was that reach between Bignell Arroyo and Leasburg Diversion Dam. Because the degree to which return flows from pumping affect the conditions in the RGCP is unknown, it appears unlikely that there are any other reaches of significant distances that are truly a gaining reach since late 2011.

7.2 CHANNEL SEEPAGE ANALYSIS – FLO-2D MODELING

FLO-2D modeling of the RGCP was originally developed to estimate channel seepage in 2004 and was later updated to be compatible with the FLO-2D Version 2009. For this analysis, the FLO-2D modeling is updated to represent the 2011 topographic mapping and is calibrated to the 2012 Caballo release hydrograph provided by the Rio Grande Project Allocation Committee (Figure 4). This model is different than the HEC-RAS model in that it uses the Green-Ampt method to simulate channel infiltration, and the model code was updated specifically for this project to incorporate varying K_{sat} values over the simulation. This modification was necessary to account for the initial abstractions that occur during the initial phases of the Caballo release, which were apparently very high in 2012. In addition, the model includes spatially varied K_{sat} values that were identified for seven separate reaches (Segment 1 was subdivided at Haynor Bridge, Segment 2 was subdivided at Picacho Bridge, and Segment 4 was subdivided at Courchesne Bridge). This model appears to calibrate reasonably well to the 2012 release hydrograph at a variety of gages along the RGCP. Results from this model indicate that initial K_{sat} values would range from 0.36 to 2.5 feet/day, and would decay to between 0.08 and 1.4 feet/day. Results also indicate that of the approximately 190,000 acre-feet of water released by Caballo Dam during the period of simulation, about 69,700 acre-feet would be infiltrated and about 4,800 acre-feet would be lost to evaporation. The FLO-2D author (Dr. Jim O'Brien) updated the model code to report the predicted seepage rates as spatially varied time series for input to the water budget analysis. A summary of the FLO-2D modeling, the predicted seepage rates, and the associated water budget analysis is provided in **Appendices G1 through G5**.

It should be noted that even though the Haynor, Picacho, and Anthony gages are believed to be suspect, these gages were used during the calibration of the FLO-2D model to track the timing and overall shape of the hydrographs. A more detailed discussion of the use of these gages, and the implications of using these gages on the predicted seepage rates, is included in **Appendix G1**.

7.3 CHANNEL SEEPAGE ANALYSIS – UNSTEADY HEC-RAS MODELING

Channel seepage was estimated using the USACE Hydrologic Engineering Center (HEC) River Analysis Software (RAS), version 4.1. HEC-RAS is a one-dimensional hydraulic model that allows for steady and unsteady-flow analysis. The unsteady approach includes a groundwater interflow boundary condition that estimates seepage or inflows to the main channel using Darcy's equation (Figure 5).

Mussetter Engineering Inc. (MEI), which is now Tetra Tech, 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 the 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.

Appendix H summarizes data collection and 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. It should be noted that the Haynor, Picacho, and Anthony metering stations were not used to calibrate the HEC-RAS model because the data at these gages are believed to be suspect (Dr. Al Blair, pers. comm., November 2012). The calibrated model is then used to evaluate outflow hydrographs from Caballo Reservoir in 2010 through 2012, and two hypothetical outflow hydrographs: Delayed Single Pulse Hydrograph (S1) shown in Figure 6, and the Normal Single Pulse Hydrograph (S2) shown in

Figure 7. The hypothetical hydrographs are evaluated during the irrigation season in 2012.

7.3.1 Unsteady HEC-RAS Model Results: Caballo Reservoir Outflows

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). 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

By comparison, the final K_{sat} values from the FLO-2D modeling (**Appendix G1**) varied from 0.03 to 0.60 feet/day during the first pulse in 2012, and from 0.08 to 1.4 feet/day in the second pulse in 2012.

The modeled groundwater interflow results in the main channel (seepage and return flow) for the baseline model are provided in Table 6. The overall seepage rates for the entire RGCP vary from 22.4 cfs (44.5 acre-feet per day) to 356.8 cfs (707.6 acre-feet per day), and average 230.8 cfs (457.9 acre-feet per day). The total volume of seepage predicted by the HEC-RAS model of the baseline 2012 release (March 31 through September 14) without irrigation return flows is about 76,084 acre-feet, and is about 76,923 acre-feet based on the model with irrigation return flows. These estimates are somewhat higher than the predicted seepage volume (359 acre-feet/day x 167 days = 59,953 acre-feet) presented in the Rio Grande Project Allocation Committee (RGPAC) Draft Report entitled, "Analysis of River Conveyance Efficiency for Initial Release of Project Water for Delivery to Acequia Madre Canal in 2012." The 2012 flow volumes with and without returns are summarized in

Table 7. For the Leasburg gage, which is not affected by returns, the difference is zero. For the Mesilla gage, the modeled flow volume without returns (175,017 acre-feet) is 1 percent less than the modeled flow volume with returns (176,835 acre-feet). For the El Paso gage, the modeled flow volume without returns (144,297 acre-feet) is 6 percent less than the modeled flow volume with returns (153,604 acre-feet).

7.3.2 Unsteady HEC-RAS model Results: 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) and a normal single-pulse hydrograph (Release Scenario S2) provided by the RGPAC. Plots of the inflow hydrographs are included in Figure 6 and

Figure 7, respectively. Both of the hypothetical release scenarios have a release volume that is identical to the actual (baseline) 2012 release of 372,028 acre-feet.

Seepage results for the delayed single-pulse hydrograph (Release Scenario S1) and a normal single-pulse hydrograph (Release Scenario S2) are shown in Table 8 and Table 9. 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, the total volume of seepage in the S2 Release Scenario (74,087 acre-feet) is roughly 11 percent 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 (167 days) versus the 110-day release period under the S1 Release Scenario. Both of the hypothetical release scenarios result in reduced total seepage volumes compared to the baseline 2012 condition, which indicated a total seepage volume of about 76,084 acre-feet. The predicted cumulative seepage volumes under baseline conditions and for the hypothetical release scenarios are presented in Figure 8.

7.3.3 Comparison to Other 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 10, indicate that net reductions in the stream flows 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 6). 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.

A comparison of the HEC-RAS results to the USIBWC (1993) seepage study was also carried out to evaluate how the model-based seepage estimates compare with historical observations (Table 11). The gains and losses reported in the USIBWC (1993) are based on measured flows at the river, diversion, and wasteway gages as well as estimated wasteway discharges, so the reported gains and losses include all unknown inflows and outflows (i.e., channel seepage, evaporation, ungaged or unknown inflows and outflows, etc.), so they may not provide a direct comparison with the predicted seepage volumes from the HEC-RAS modeling. The values do, however, provide a range of gains and losses that can be used to check the reasonableness of the HEC-RAS results.

The USIBWC (1993) study was conducted jointly with the USBR, and includes estimated gains and losses based on 7 years of gage data from 1986 to 1992. The gages included in the study were located between Picacho Bridge and Courchesne Bridge, and provide estimates of gains and losses in the overall reaches from Picacho Bridge to Courchesne Bridge (1991 and 1992 only) and Mesilla Dam to Courchesne Bridge (1986 to 1992), as well as for the shorter subreaches from Picacho Bridge to Mesilla Dam, Mesilla Dam to Vado Bridge, Vado Bridge to Canutillo Bridge, and Canutillo Bridge to Courchesne Bridge. Results from the study indicate that the overall study reach from Picacho Bridge to Courchesne Bridge was a losing segment between 1991 and 1992, and that the reach between Mesilla and Courchesne Dams was a losing reach from 1986 to 1992, both of which are consistent with the HEC-RAS model results. A comparison of the seepage rates predicted by the HEC-RAS model and the losses reported in USIBWC, with normalized rates on a per-unit-mile basis, is presented in Table 11.

The comparison of the reported losses and predicted seepage rates on a subreach basis indicates that the maximum predicted seepage rate is significantly less than the maximum loss reported in USIBWC (1993). The average predicted seepage rates, however, appear to be more consistent with the reported losses. In the 1991 and 1992 period, the maximum losses reported in USIBWC (1993) between Picacho Bridge and Courchesne Bridge was 24.4 acre-feet/day/mile, which is significantly larger than the maximum seepage along the overall RGCP that is predicted by the HEC-RAS model (6.6 acre-feet/mi/day). However, the average seepage rates predicted by the HEC-RAS model in the RGCP are about 4.3 acre-feet/mi/day, compared to average loss rates of 1.3 acre-feet/mi/day as indicated in USIBWC (1993) from Picacho Bridge to Courchesne Bridge.

8.0 LAKE, CHANNEL, AND VADOSE-ZONE EVAPORATION ASSESSMENTS

As an element of the RGCP Scope of Work, an assessment of both lake and vadose (unsaturated) zone evaporation, relative to their impact on the Rio Grande Water Budget, was conducted. The trend in lake evaporation was, in large part, based upon data for the Elephant Butte Reservoir and the Caballo Reservoir. The trend in vadose-zone evaporation along the RGCP was based upon findings from a number of technical sources that were acquired from available documents, as well as from the conducting of a detailed Internet literature search of vadose-zone processes. Estimates of evaporation along the RGCP itself were developed using information from the existing Upper Rio Grande Water Operations Model (URGWOM). A discussion of the evaporation analysis is included in **Appendix I**.

8.1 EVAPORATION SUMMARY

As documented in Appendix I, additional water storage loss due to lake evaporation under either the Delayed Single Pulse Scenario (S1) or the Normal Single Pulse Scenario (S2) would be minor in magnitude at Caballo Reservoir and Elephant Butte Reservoir. Results are shown in Table 12.

9.0 CHANNEL WATER BUDGET CALCULATIONS – RIO GRANDE CANALIZATION PROJECT SCALE

As stated in the Scope of Work (USIBWC, 2012a and 2012b), the water budget is the scientific method for measuring or quantifying the amount of all water inflows and outflows, and resulting change in storage within a defined hydrologic domain over a time period. This water budget analysis is being completed for the period starting from January 1, 2010, and ending on November 30, 2012. The water budget analysis at the RGCP scale is described below. The water budget analysis at the local-basin scale is described in Section 10.0.

9.1 METHODOLOGY

In general, the channel water budget analysis at the RGCP scale involves the hydrologic domain that includes the river and adjacent floodplain, and the groundwater zone located beneath the river-floodplain area. The RGCP-scale channel water budget was performed on four segments of the RGCP:

- 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

As such, the components for the RGCP-scale channel water budget for each segment includes the upstream inflow, downstream outflow, surface-water inflows (precipitation, stormwater runoff and irrigation return flows), surface-water outflows (diversions and evapotranspiration), and groundwater interflows (seepage, return flows and floodplain recharge). The water budget calculations were performed by first assembling the measured inflows and outflows on a mean daily-flow basis for the study period between January 1, 2010, and November 30, 2012. The measured data include the upstream inflow, measured irrigation return flows at the drains and spillways, measured water treatment plant effluent discharges, and diversions into canals. The data assembly was performed in a Microsoft Excel spreadsheet to facilitate organization of the large amounts of data. Because a significant portion of the data was only available in instantaneous (30-minute) format, these data were converted to mean daily flows. In some cases, the instantaneous gage data included periods with no data. Because these periods were relatively short (typically less than 6 hours), the missing data were interpolated using the measured data that brackets the data gap. It should be noted that because the data collected at the Anthony metering station is not believed to report accurate flow measurements, the outflow from Segment 3 and the inflow to Segment 4 was obtained from the HEC-RAS modeling.

Once the measured values were input to the spreadsheet, information from an existing groundwater (MODFLOW) model that was prepared by SSPA (2007) was entered into the spreadsheet. This information includes groundwater return flow (including irrigation/drainage return flow) and floodplain recharge. Estimated values for precipitation-derived flow, ungaged in-channel stormwater flow, evapotranspiration (based on the sum of the riparian evapotranspiration predicted by the MODFLOW model and the estimated surface-water evaporation), and unauthorized diversion were entered into the spreadsheet along with the estimated channel seepage rates from the HEC-RAS model. The source of the water budget components are discussed in more detail in the following sections. The water budget was then computed using the RGCP-scale channel water budget equation, as discussed below.

9.2 RIO GRANDE CANALIZATION PROJECT – CHANNEL WATER BUDGET EQUATION

The RGCP-scale channel water budget provided in the Scope of Work (USIBWC, 2012a and 2012b) is shown in Figure 9. For a given time Δt, the RGCP-scale channel water budget equation is:

$$\Delta S_{ic} = (Q_{cus} + P_c + Q_{cin} + Q_{irf} + Q_{gwrf}) - (Q_{cds} + Q_{cs} + Q_{fpr} + ET + Q_{da} + Q_{du})$$

where:

ΔS_{ic} = in-channel change in storage
Q_{cus} = upstream dam release or inflow
P_c = precipitation
Q_{cin} = in-channel stormwater flow
Q_{irf} = irrigation return flow
Q_{gwrf} = groundwater return flow

Q_{cds} = downstream channel outflow
Q_{cs} = channel seepage
Q_{fpr} = floodplain recharge
ET = evapotranspiration
Q_{da} = diversions authorized
Q_{du} = diversions unauthorized

Estimates for each component of the RGCP-scale channel water budget equation are summarized in the following sections.

9.3 UPSTREAM DAM RELEASE OR INFLOW, Q_{CUS}

Upstream dam release inflow data to Segment 1 were obtained from the USBR gage below Caballo Dam (Gage No. 08362500). These data were obtained from the USBR, and are also available on the USGS surface-water website.

In addition to this gage, a number of other gages exist or have historically operated along the study reach (Figure 10, which also shows the locations of other gages considered in the analysis), as discussed below. Although these gages do not represent the upstream dam inflow, they could provide inflow data for segments or sub-segments of the water budget study, and were used to define other components of the water budget. Initial versions of the water budget study used the measured hydrographs at the Leasburg, Mesilla, and Anthony gages to define the upstream inflow to Segments 2, 3 and 4, respectively. However, because the reported flow data at the Anthony metering station are not believed to be accurate (Dr. Al Blair, pers. comm., November 2012), the hydrographs predicted by the hydraulic models were used at this location. Furthermore, it was necessary to use the hydrographs predicted by the hydraulic models at the other locations (Leasburg and Mesilla) for the water budget analyses of the hypothetical releases. To insure a direct comparison between the hypothetical and actual releases, the hydrographs predicted by the hydraulic models at the appropriate locations were used in the water budget analysis for all cases (actual and hypothetical) as the upstream inflow to Segments 2 through 4. However, the HEC-RAS model requires a 0.5-foot tolerance for numerical stability during periods of low flows that results erroneously high predicted baseflows during these periods (i.e., the model does not maintain flow continuity during periods of low flow). As such, the predicted flows from the 2010 to 2012 model were adjusted to remove these errors during periods of low flow. The adjustment was made by first identifying the obviously apparent, constant discharge that is over-predicted by the model during periods of low flow at each of the gaging stations. The mean measured discharge at the valid gaging stations was then computed for the baseflow periods, and the adjustment was made by subtracting the difference between the identified baseflow error and the mean measured discharge from the predicted (erroneous) baseflow. At the metering stations that are not believed to report accurate data (Haynor, Picacho, and Anthony), a nominal “measured” baseflow of 1 cfs was used in the adjustments. The baseflow adjustments range from 89 cfs at Haynor to 245 cfs at Leasburg, and progressively decrease in the downstream direction below Leasburg to 161 cfs at American Dam. The resulting hydrographs are presented in **Appendix B, Table B-6**.

To facilitate the adjustment of the erroneous baseflows, data from the EBID website were downloaded in varying increments depending on the type of information reported at each gage, since the EBID website apparently has limitations on the amount of data that can be reported. The data were combined into a master list of gage data that is found in **Appendix B, Table B-2**. USIBWC gage data were provided by the USIBWC. The USBR has compiled key data at EBID and EPCWID No. 1 gages, and these data were provided by the USBR. A summary of these river gages is as follows:

Segment 1

Below Caballo Dam 08362500—maintained by the USBR, USGS and USIBWC. Data were provided by the USBR. This gage represents the upstream inflow into Segment 1.

Hatch—maintained by EBID. No flow data were found for this metering station.

Haynor Bridge—maintained by EBID. Data were obtained from the EBID website; however, this gage does not appear to be well calibrated and the reported flows are not believed to be accurate (Dr. Al Blair, pers. comm., November 2012). As such, flow data at this gage were not used in this analysis.

Segment 2

Leasburg Gaging Station 08363500—maintained by the USBR. No data were obtained for this metering station.

Leasburg River Cable—maintained by EBID. Data were obtained from the USBR. This gage appears to have been installed as a replacement for the Leasburg gaging station. This gage represents the downstream outflow for Segment 1 and the upstream inflow into the Segment 2 for the water budget calculations.

Picacho River—maintained by EBID. Data were obtained from the EBID website; however, this gage does not appear to be well calibrated and the reported flows are not believed to be accurate (Dr. Al Blair, pers. comm., November 2012). As such, flow data at this gage were not used in this analysis.

Mesilla Dam—maintained by EBID. Gate operation data were obtained from the EBID website, but was not used in this study.

Segment 3

River below Mesilla Diversion Dam—maintained by EBID. Data was obtained from the EBID website. This was assumed to be the downstream outflow for Segment 2 and the upstream inflow for Segment 3 in the water budget calculations.

Vado Bridge—at SR 227. No data were found for this metering station.

Anthony—maintained by EBID. Data were obtained from the EBID website. This was assumed to be the downstream outflow for Segment 3 and the upstream inflow for Segment 4; however, this gage does not appear to be well calibrated and the reported flows are not believed to be accurate (Dr. Al Blair, pers. comm., November 2012). As such, flow data at this gage were not used in this analysis.

Segment 4

Vinton Bridge. No data were found for this metering station.

Canutillo Bridge—maintained by EBID. No data were found for this metering station.

At El Paso 08364000—maintained by USIBWC. Data were obtained from the USIBWC website.

Diversions from Rio Grande at the American Canal 08364500—maintained by the USIBWC. Data were obtained from the USIBWC website.

Below American Dam 08365000—maintained by the USIBWC. Data were obtained from the USIBWC website. This was assumed to be the downstream outflow for Segment 4 in the water budget calculations.

9.4 PRECIPITATION, P_C

Historic annual average rainfall data were developed from records at Caballo Reservoir, Hatch, Las Cruces, and El Paso (Figure 11) from the USBR and National Weather Service (NWS) records. The stations, periods of record, and the river segment they are applied to are summarized below. A table summarizing the average rainfall data is in **Appendix C, Table C-3**.

Location	Period of Record
Caballo (Segment 1)	11/01/38 - 12/31/05
Hatch (Segment 1)	02/01/31 - 02/29/00
Las Cruces (Segment 2 and 3)	04/01/59 - 12/31/05
El Paso (Segment 4)	07/01/47 - 08/31/12

Average-annual rainfall were compared to the sums of the monthly precipitation for each location and matched to within approximately one tenth of an inch. Daily precipitation data were not provided for this study and actual historic daily rates were not found, so the historic daily rainfall averages were used for the water budget calculations.

In 2010 and 2011, the annual precipitation at El Paso, Texas, amounted to 6.67 and 5.27 inches for each respective year. The long-term historical average at El Paso is 8.49 inches (period of record from July 1, 1947, to August 31, 2012). This difference reflects the current drought conditions along the RGCP. In 2010, 6.33 inches of precipitation fell at El Paso through September; and in 2011, 4.49 inches of precipitation fell (average of 5.42 inches of both years) at El Paso through September. In 2012, 5.83 inches of precipitation fell at El Paso through September. Thus, if it were available everywhere along the RGCP, the data from 2010 and 2011 would likely yield lower estimates of the contributions due to precipitation.

It was assumed that precipitation that results in runoff from the watershed runoff would be captured in the gage data obtained from the USIBWC, USGS, USBR, and EBID. The precipitation data were utilized in the water budget study only as an inflow for precipitation directly on the wetted river channel. For each year modeled, the average annual precipitation for each day (from Table C-3) was multiplied by the surface-water area developed for the HEC-RAS modeling effort. The surface-area calculations are included in **Appendix C, Table C-2.** The resulting flow (cfs) contributed by precipitation is summarized in **Appendix C, Table C-4.**

9.5 IN-CHANNEL STORMWATER FLOW, Q_{CIN}

This data includes treated effluent from wastewater treatment plants (WWTP), municipal stormwater flow into the river, and flow from arroyos with watersheds contributing flow the Rio Grande.

9.5.1 Effluent Discharges

Doña Ana County operates seven wastewater treatment plants, three of which discharge into the Rio Grande: Northwest, South Central Regional, and Sunland Park. The Rincon WWTP has ability to discharge into the Rio Grande, but currently sends all effluent to the Sunland Park WWTP. Discharge data from the Jacobs Hands WWTP were not available. Discharges for the Northwest El Paso WWTP were provided by EPCWID No. 1. Effluent discharges from WWTPs are summarized in **Appendix C, Table C-6.** Effluent discharges included in the water budget are summarized below:

Segment 1

Northwest WWTP (Salem)	0.035 MGD	0.05 cfs
Village of Hatch WWTP	0.30 MGD	0.46 cfs

Segment 2

Las Cruces	13.50 MGD	20.89 cfs
East Mesa Water Reclamation Facility	1.00 MGD	1.55 cfs

Segment 3

Santa Teresa	0.53 MGD	0.82 cfs
South Central Regional WWTP (La Mesa)	0.32 MGD	0.50 cfs

Segment 4

Sunland Park WWTP	1.7 MGD	2.63 cfs
Northwest El Paso WWTP	9.05 MGD	14.0 cfs

9.5.2 Municipal Stormwater Discharges

Municipal stormwater discharge locations consist of the following:

- Hatch—Discharge data are not available
- Las Cruces—Discharges into Rio Grande via the Las Cruces Outfall Channel. No discharge data form the City of Las Cruces were available for this study.
- Anthony—Discharge data are not available
- Sunland Park—Discharge data are not available
- Private Individuals—When data were assembled for the project, it was noted that there was reference to some drains that are owned by private individuals. No data for those private drains were obtained.

Doña Ana County has no flood-control facilities with discharge points directly into the river. All County flood-control facilities discharge into EBID irrigation wasteway or drain facilities.

9.5.3 Tributary Arroyos

Stormwater runoff in arroyos from watersheds contributing to flow in the Rio Grande was identified at 37 locations (USACE and RTI, 1996). Flow data were not available for the majority of the stormwater runoff locations, but measured (flume) data were available at Over Shot, Picacho, Rincon and Placitas Arroyos. Available data indicate that Placitas and Rincon Arroyos contributed significant storm flows during the 2010 and 2011 monsoon season. These data were incorporated into the water budget analysis. If additional data are obtained or if gages are installed on other arroyos in the future, the water budget study can be updated to include that information. For reference, the following locations were identified as locations where runoff enters the Rio Grande. Where available, the drainage area (DA) of the watershed contributing to the arroyos or the structures regulating the flow into the river is also identified (USACE and RTI, 1996).

Segment 1

- Trujillo Arroyo
- Montoyas Arroyo (DA = 23.0 sm)
- Tierra Blanca Arroyo (DA = 68.2 sm)
- Green Arroyo (Green Arroyo Dam; DA = 35.6 sm)
- Sibley Arroyo (DA = 27.2 sm)
- Jaralosa Creek (Jaralosa Creek Dam No. 4 and No. 5; DA = 6.8 sm)
- Arroyo Yeso
- Arroyo Cuervo (Crow Arroyo Dam; DA = 90.4 sm)
- Misc. 4A Basin
- Misc. 4 Basin
- Placitas Arroyo (currently gaged)
- Misc. 5 Basin
- Angostura Arroyo
- Rincon Arroyo (DA = 124.70 sm; currently gaged)
- Reed Arroyo (DA = 9.60 sm)
- Bignell Arroyo (Misc. 6 Basin; DA = 6.1 sm))
- Misc. 6 Basin (DA = 44.50 sm)
- Lytten Canyon (DA = 0.96 sm)
- Broad Canyon (Broad Canyon Dam – 68.0 sm)
- Buckle Bar Canyon
- Foster Canyon (DA = 11.0 sm)
- Faulkner Canyon (DA = 25.0 sm)
- Misc. 7 Basin (DA = 12.5 sm)

Segment 2

- Subarea 15 (DA = 3.4 sm)
- Arroyo Over Shot (currently gaged)
- Box Canyon
- Subarea 16 (DA = 3.8 sm)
- Subarea 17 (DA = 4.92 sm)
- Subarea 18 (DA = 2.8 sm)
- Subarea 19 (DA = 2.6 sm)
- Subarea 20 (DA = 3.0 sm)
- Doña Ana North Arroyo (DA = 2.1 sm)
- Doña Ana Arroyo (DA = 6.9 sm)
- Apache Canyon/Picacho Arroyo (currently gaged)
- Subarea 23 (DA = 0.87 sm)
- Subarea 24 (DA = 4.2 sm)

Segment 3

- None

Segment 4

- Subarea 206 (DA = 1.5 sm)
- Subarea 202 (DA = 1.78 sm)

- Subarea 204 (DA = 0.92 sm)
- Subarea 203 (DA = 1.24 sm)
- Subarea 301 (DA = 2.58 sm)
- Subarea 302 (DA = 2.2 sm)

9.5.4 Flood-control Dams

Other arroyos that are non-contributing were also identified for reference. Flood-control dams at 38 locations have gated outlets that discharge into irrigation facilities—irrigation canals or return channels (USACE and RTI, 1996). Flow from these watersheds is not considered directly contributing to the river and may already be included in the irrigation return flow information. The structures identified in this category include:

Segment 1

- Nordstrom Dams
- Underwood Dam
- Caballo Dam
- Countyline Detention Dam
- Kight Floodwater Dam
- Wasson Dam
- Garfield Arroyo Dam
- McLeod Dam
- Valverde Arroyo Dam
- North Salem Arroyo
- Reed Thurman Arroyo Dam
- South Salem Arroyo Dam
- Wardy Hedgecock Dam
- Hammet Dam
- Spring Canyon Dam
- Rodey Arroyo Dam
- Porter Whisenhunt Arroyo Dam
- Ralph Arroyo Dam

Segment 2

- Sandhill Arroyo Dam
- Alameda Dam
- North Fork Dam
- South Fork Dam
- Las Cruces Dam
- Tortugas Site #1
- Tortugas Site #2

Segment 3

- Fillmore Dam
- Salopek Dam
- Lower Fillmore Dam
- Apache Arroyo Dam
- Pena Blanca Dam
- Mossman Dam
- Bishop's Cap Dam

Segment 4

- Anthony Dam
- Mulberry Dam
- Thorn Dam
- Mesa Dam
- Keystone Dam
- Oxidation Pond Dam

During Initial calculations for the water budget, the river, drain, and diversion gage data were utilized to identify stormwater runoff and ungaged return data in the river. The gage data were initially evaluated and increases in downstream runoff was attributed to stormwater flow or ungaged return flow into the river. Because of uncertainties in the gaging, the stormwater and ungaged return flow were estimated based on increase in downstream runoff predicted by the calibrated HEC-RAS modeling as presented in **Appendix C, Table C-5**. The stormwater/ungaged return flow component was computed by taking the difference between the sum of the primary surface-water outflows (Q_{cds} and Q_{da}) and the sum of the primary surface-water inflows (Q_{cus} and Q_{irf} plus the effluent discharges) for periods when the primary outflow volume exceeds the primary inflow volume.

9.6 IRRIGATION RETURN FLOW, Q_{IRF}

Data from five EBID drain locations with irrigation return flow data were utilized in the water budget study. The locations are: Del Rio Drain, La Mesa Drain, East Drain, Nemexas Drain, and West Drain. Data for these locations are included in **Appendix B, Table B-1**. Irrigation return flow locations were identified at 84 locations (USACE and RTI, 1996) which are listed below. Thirty-eight of these locations are required to maintain gage data and are continuously operated by the USBR, the EBID, or the EPCWID No. 1 (USBR 2010). Based on a review of the available data at these return flow locations, the five drain inflows appear to be the most significant. If gaged or discharge information for additional drains is obtained in the future, the water budget study can be updated to include that new information. It should be noted that in some cases (e.g., the Electric Wasteway that returns flow from the Leasburg Canal to the Rio Grande), the wasteway is located upstream from the gage on the diversion and upstream from the river gage. These return flows were not incorporated into the analysis to insure that the water budget did not include any double counting.

Segment 1

- Trujillo Lateral
- Moore Lateral
- EBID Wasteway No. 3 (Rincon Valley)
- Palmer Lateral
- EBID Wasteway No. 6
- Silva Wasteway
- Garfield Drain – gaged (EBID)
- H–2 Lateral
- McCall Lateral
- Wasteway No. 5 at Hatch Siphon – gaged (EBID)
- Wasteway No. 16 at Rincon Siphon – gaged (EBID)
- USACE Wasteway 101
- Hatch Drain (USACE Wasteway 102) – gaged (EBID)
- Wasteway No. 18 from Rincon Lateral – gaged (EBID)
- Angostura Drain
- Angostura Lateral (EBID Wasteway No. 15/USACE Wasteway 103)
- Rincon Drain (Tonuco Interception Drain) – gaged (EBID). EBID maps indicated that Tonuco Drain discharges into the Rincon Drain.
- EBID Wasteway No. 1A

Segment 2

- EBID Wasteway No. 1
- Selden Drain (USACE Wasteway 2) – gaged (EBID)
- EBID Wasteway No. 2 (USACE Wasteway 2A)
- EBID Wasteway No. 8 (USACE Wasteway 6) – gaged (EBID)
- EBID Wasteway 39A
- EBID Wasteway No. 10 at Picacho Bridge

- EBID Wasteway No. 2A (Doña Ana Drain – EBID map indicates that the Doña Ana drain discharges to the Mesilla Drain which flows to the Del Rio Drain)
- Shalem Spur Drain (this goes to Del Rio Drain according to EBID maps)
- EBID Wasteway No. 3
- EBID Wasteway No. 5 (USACE Wasteway 4) – gaged (EBID). Doña Ana and North Doña Ana Dams flow to Wasteway No. 5.
- USACE Wasteway 5 – including Apache and Box Canyon consisting of North Picacho, Apache Canyon, South Picacho, and Box Canyon Dams (16.50 sm)
- EBID Wasteway No. 11 (USACE Wasteway 10)
- EBID Wasteway No. 12
- EBID Wasteway No. 40
- Picacho Drain – gaged (EBID)
- EBID Wasteway 13

Segment 3

- EBID Wasteway 14B
- EBID Wasteway No. 15 (USACE Wasteway 104) – gaged (EBID)
- Santo Tomas River Drain – gaged (EBID)
- Brazito River Lateral Wasteway– gaged (EBID)
- EBID Wasteway No. 25 – gaged (EBID)
- EBID Wasteway No. 26 – gaged (EBID)
- Del Rio Drain – gaged (EBID)
- EBID Wasteway No. 18 (USACE Wasteway 106) – gaged (EBID)
- USACE Wasteway 107
- EBID Wasteway No. 19 (USACE Wasteway 108) – gaged (EBID)
- EBID Wasteway No. 29
- EBID Wasteway No. 30 – gaged (EBID)
- La Mesa Drain – gaged (EBID)
- USACE Wasteway 109
- EBID Wasteway No. 31 (USACE Wasteway 110) – gaged (EBID)
- EBID Wasteway No. 20 (USACE Wasteway 111) – gaged (EBID)
- EBID Wasteway No. 31A at Old Anthony Bridge
- EBID Wasteway No. 21 (USACE Wasteway 112) – gaged (EBID)
- EBID Wasteway No. 31B (USACE 113) – gaged (EBID)

Segment 4

- Wasteway No. 32 (USACE 114) – gaged (EPCWID No. 1)
- East Drain – gaged. RGP operations manual indicates this gage is operated by EPCWID No. 1.
- Vinton River Drain
- USACE Wasteway 124 (Subarea 104 – 3.54 square miles)

- Wasteway No. 32A (USACE 115) – gaged (EPCWID No. 1)
- USACE Wasteway 116
- EBID Wasteway No. 23A (USACE Wasteway 117)
- USACE Wasteway 118 (Subarea 101 – 2.90 square miles)
- USACE Wasteway 119
- USACE Wasteway 119A (Subarea 102 – 6.53 square miles)
- USACE Wasteway 119B
- USACE Wasteway 120B
- USACE Wasteway 120A
- USACE Wasteway 120
- USACE Wasteway 121 (Subarea 103 – 5.35 square miles)
- Wasteway No. 32B – gaged (EPCWID No. 1)
- USACE Wasteway 122
- USACE Wasteway 123
- USACE Wasteway 125 (Subarea 105 – 0.98 square miles)
- USACE Wasteway 126 (Subarea 106A, 106B, 106C – 17.5 square miles)
- Wasteway No. 34 (USACE Wasteway 127)– gaged (EPCWID No. 1)
- USIBWC Wasteway No. 34A – gaged (EPCWID No. 1)
- EBID Wasteway No. 35 (USACE Wasteway 128) – gaged (EPCWID No. 1)
- EBID Wasteway No. 35C at County Club Bridge – gaged (EPCWID No. 1)
- EBID Wasteway No. 36 – gaged (EPCWID No. 1)
- EBID Wasteway No. 37A (Subarea 205 – 1.03 square miles)
- West Drain – gaged. Combines with Nemexas Drain and flows into Montoya Drain
- Nemexas Drain – gaged. Combines with West Drain and flows to Montoya Drain
- Montoya Drain – gaged (EPCWID No. 1)
- Wasteway No. 38 – gaged (EPCWID No. 1)
- USACE Wasteway 129.

9.7 GROUNDWATER RETURN FLOW, Q_{GWRF}, FLOODPLAIN RECHARGE, Q_{FPR} AND EVAPOTRANSPIRATION, ET

Groundwater flux information that is necessary for the RGCP-scale channel water budget analysis was extracted from the SSPA (2007) groundwater model for the Lower Rio Grande Basin. The model was developed using the USGS MODFLOW-2000 software (Harbaugh et al., 2000). The domain of this model spans the river valley from Caballo Dam to the El Paso Narrows and extends laterally to include the inter-montane region and includes parts of New Mexico, Texas and Mexico. The groundwater model simulates the movement of groundwater and changes in groundwater conditions associated with pumping of wells, irrigating land, and conditions in the river, canals and drains. For the RGCP-scale channel water budget analysis, the information from the model was limited to fluxes in the immediate vicinity of the floodplain. Five geographic zones were set up in this area, with four zones set along the channel and adjacent floodplain that correspond to the four water budget segments, and a fifth zone set along the perimeter of these zones to evaluate fluxes into and out of each zone (Figure 12). It should be noted that even though the zones generally cover the irrigated area along the RGCP, the fluxes that were extracted for the RGCP-scale channel water budget only include those fluxes into and out of the river and immediately adjacent floodplain (between the levees). The various fluxes into and out of each zone were extracted from the upper-most model layer for model stress periods 128 (November 2003 through February 2004) and 129 (March through October 2004), and represent cell-to-cell fluxes that were calculated using the MODFLOW "Zone Budget" tool. It should also be noted that because the MODFLOW model does not cover the drought period evaluated in this study and the amount of groundwater data along the RGCP is limited, the groundwater components of the RGCP-scale channel water budget should be considered approximate.

Several groundwater components were extracted from this model for use in the water budget study, including estimated riparian evapotranspiration, floodplain based recharge, and groundwater return flow to the river, as discussed in the following sections. The daily breakdown of groundwater interflow components is in **Appendix D**. The groundwater flux components are summarized in Table 13 and Table 14, respectively, for non-irrigation season (October to February) and the irrigation season (March to September), as defined by the MODFLOW model.

9.7.1 Groundwater Return Flow, Q_{gwrf}

Groundwater return flow information was obtained directly from the MODFLOW Stream-flow Routing (SFR) package. The representation of the river, canals and drains in the SFR Package provides a detailed simulation of surface-water/groundwater interactions important to understanding groundwater conditions and to understanding how changes to groundwater conditions, in turn, impact the flow of along the river and in the portions of canals and drains that are within the domain of the RGCP-scale channel water budget. Channel losses and gains are tracked as a function of the head in the surface-water bodies (which are affected by the flow in the river and the supply to the canals) and as a function of groundwater heads within the model cells traversed by the channels. For the RGCP-scale channel water budget analysis, the groundwater return flow that returns directly to the Rio Grande (excluding the groundwater return flow to canals and drains) was extracted from the MODFLOW model.

9.7.2 Floodplain Recharge, Q_{fpr}

Floodplain recharge in natural systems typically occurs during sustained periods of flood flows that are of sufficient magnitude to inundate the floodplain and of sufficient duration to result in percolation. However, along the RGCP, where the upstream releases are generally regulated to the capacity of the channel during periods of drought, "floodplain" recharge is driven by percolation of applied irrigation water and precipitation within the domain of the RGCP-scale channel water budget (i.e., the riparian zone between the levees). Because the surface area over which floodplain recharge can occur is relatively small as is the amount of applied irrigation water to the riparian zone, the floodplain recharge is a relatively small component of the RGCP-scale channel water budget. Nevertheless, the floodplain recharge was obtained from the model using the MODFLOW Recharge (RCH) package.

9.7.3 Evapotranspiration, ET

Riparian evapotranspiration makes up a portion of the overall evapotranspiration, which includes open-water evaporation. Riparian vegetation borders the RGCP and draws water directly from the water table. Although riparian vegetation has been reduced since construction of the RGCP, it remains as part of the water balance in the Lower Rio Grande region of New Mexico. Along many reaches stands of cottonwood and willow have been replaced with non-native species such as Russian olive and salt cedar.

These non-native riparian species may have higher evapotranspiration rates than the native vegetation they replace, thereby increasing the per-acre impact of what riparian vegetation remains. The Riparian Evapotranspiration (RIP-ET) Package, developed at the University of Arizona, is used to simulate evapotranspiration from riparian vegetation in the MODFLOW model. Evapotranspiration is calculated for that portion of a designated cell that has been mapped as containing riparian vegetation, with the percentage riparian coverage varying over the historical period. Evapotranspiration is calculated as a function of depth to groundwater from the land surface, time of year, plant classification, and areal coverage. The riparian evapotranspiration fluxes were obtained from the RIP-ET package. The total evapotranspiration was then computed by adding the riparian evapotranspiration to the open-water evaporation, as discussed in Section 8.0 (above) and in **Appendix I**.

9.8 DOWNSTREAM CHANNEL OUTFLOW, Q_{CDS}

Downstream channel outflows were initially provided by river gage data at the following locations:

- Segment 1 – Flows at the Leasburg metering station below Leasburg Diversion Dam
- Segment 2 – Flows at the Mesilla Dam
- Segment 3 – Anthony Bridge metering station
- Segment 4 – Below American Dam metering station

However, the hydrographs predicted by the hydraulic models at appropriate locations were ultimately used as the downstream channel outflow for each of the segments for similar reasons as those outlined under the upstream channel outflow (suspect gage data at Anthony and the need to use the predicted hydrographs for evaluating the hypothetical scenarios).

9.9 CHANNEL SEEPAGE, Q_{CS}

Channel seepage, delivery of water through canals and laterals and in addition, the irrigation of project acreage, recharges the unsaturated zone and the aquifer. Channel seepage is discussed in more detail in Section 7.0, above. Groundwater pumped from the aquifer is used to irrigate the crops and it is believed that only a small portion of the channel seepage should be considered a loss to the overall water budget through evaporation from the unsaturated zone. It is important to note that even though only a portion of the seepage may be entirely lost to the system, any seepage from the channel will likely not be used by the surface-water entity for which this volume of water is intended, so it is lost to that entity.

Channel seepage was estimated using the HEC-RAS and FLO-2D models. The seepage results from the FLO-2D models are discussed in **Appendix G1**. Because the HEC-RAS model results include erroneously high baseflows during periods of low flow, the associated seepage rates are also erroneously high. To account for this error, the seepage rates for each segment were limited to the adjusted upstream inflow during the baseflow periods for the 2010 through 2012 water budget period. The resulting daily channel seepage estimates are presented in **Appendix E**.

9.10 DIVERSIONS AUTHORIZED, Q_{DA}

Authorized diversions include irrigation water diverted at Percha, Leasburg, Mesilla, and American Diversion Dams. River diversions by segment are listed below.

Segment 1

- Bonita Private Irrigation Canal – This is a diversion just below Caballo Dam. Reclamation informs EBID, EPCWID No. 1, and USIBWC of diversions into this canal each month. No data were found for this diversion
- Percha Diversion Dam – Arrey Canal (Rincon Valley Main Canal) and Percha Private Lateral Canal—gaged
- Leasburg Diversion Dam—Leasburg Canal (Eastside)—gaged

Segment 2

- Mesilla Diversion Dam—Westside Canal—gaged
  - La Union Canal branches off Westside Canal
- Mesilla Diversion Dam—Eastside Canal—gaged below Del Rio Canal
  - Del Rio Canal and Three Saints East Canal branch off the Eastside Canal

Segment 3

- No diversions were identified in this segment.

Segment 4

- American Diversion Dam—American Canal—gaged (discharges into Franklin Canal)

Flow data for the Percha Diversion (Arrey Canal and Percha Private Lateral), Leasburg Diversion, and Mesilla Diversions (Westside, Eastside and Del Rio Canals) were obtained from the USBR. Diversion data for the American Canal were obtained from the USIBWC and contained data for the entire 2010-2012 study period.

9.11 DIVERSIONS UNAUTHORIZED, Q_{DU}

Unauthorized diversions were discussed during the project kickoff meeting and were estimated to be about 1 percent of the authorized diversions. The daily rate unauthorized diversions were therefore set equal to 1 percent of the total daily diversion rate for each segment.

10.0 WATER BUDGET CALCULATIONS – LOCAL-BASIN SCALE

The water-budget calculations at the local-basin scale estimate water inflows and outflows, and resulting change in storage for the period starting from January 1, 2010, and ending on November 30, 2012.

10.1 METHODOLOGY

The water budget analysis at the local-basin scale is similar to the analysis at the RGCP scale except the local-basin-scale analysis involves the hydrologic domain that includes the overall basin that receives and delivers flow along the RGCP. For purposes of the local-basin-scale water budget, the local-basin domain was set at the approximate extents of the area that is irrigated along the RGCP (Figure 12). A single local-basin-scale water budget analysis was performed over the local basin that interacts with the RGCP by evaluating the surface- and groundwater components. The surface-water components for the local-basin-scale water budget includes the upstream inflow, precipitation, surface water pumping, groundwater return flow, the downstream channel outflow, groundwater recharge, and evapotranspiration. The groundwater components include the upstream groundwater inflow, groundwater recharge, pumping from the aquifer, groundwater return flow, and the downstream groundwater outflow. Of the surface- and groundwater components, the magnitude of the groundwater recharge, groundwater return flow, and pumping components are the same in the surface- and groundwater budgets. However, for the surface-water budget, the pumping and groundwater return flow components are inflows and the groundwater recharge is an outflow, whereas the opposite is the case for the groundwater budget.

The water budget calculations were performed by first assembling the measured inflows and outflows on a mean daily-flow basis for the study period between January 1, 2010, and November 30, 2012. The measured data include the upstream inflow, precipitation, pumping data, and the downstream outflow, Consistent with the RGCP-scale channel water budget analysis; the data assembly was performed in a Microsoft Excel spreadsheet to facilitate organization of the large amounts of data.

For the local-basin-scale water budget, the groundwater components were extracted from an existing MODFLOW groundwater model (SSPA, 2007) that generally represents the area that is irrigated. This information includes the upstream groundwater inflow, groundwater return flow (including the groundwater return flow to the Rio Grande and irrigation/drainage return flow), groundwater recharge, riparian evapotranspiration, and the downstream groundwater outflow. The evapotranspiration component includes the riparian evapotranspiration predicted by the MODFLOW model, crop evapotranspiration that was based on consumptive use data (SSPA, 2007), and open-water evaporation. The water budget was then computed using the local-basin-scale water budget equations, as discussed below.

10.2 LOCAL-BASIN SCALE - GENERAL WATER BUDGET EQUATION

The local-basin-scale water budget provided in the Scope of Work (USIBWC, 2012a and 2012b) is shown in Figure 13. For a given time Δt, the local-basin-scale surface-water budget equation is:

$$\Delta S_{sw} = (Q_{us} + P + Q_{p} + Q_{gwrf}) - (Q_{ds} + Q_{gwr} + ET)$$

Components are listed below.

ΔS_{sw} = in-channel change in storage
Q_{us} = upstream dam release
P = precipitation
Q_{p} = pumping
Q_{gwrf} = groundwater return flow
Q_{ds} = downstream channel outflow
Q_{gwr} = groundwater recharge
ET = evapotranspiration

For a given time Δt, the groundwater budget is:

$\Delta S_{gw} = (Q_{gwus} + Q_{gwr}) - (Q_p + Q_{gwrf} + Q_{gwds})$ Components are listed below.

ΔS_{gw} = change in vadose zone and groundwater storage
Q_{gwus} = upstream groundwater inflow
Q_{gwr} = groundwater recharge
Q_p = pumping
Q_{gwrf} = groundwater return flow
Q_{gwds} = downstream groundwater outflow

10.3 UPSTREAM DAM RELEASE, Q_{US}

Outflow data from Caballo Reservoir (Rio Grande below Caballo Dam, USBR Gage No. 08362500) is utilized as the upstream dam release (Q_{us}).

10.4 PRECIPITATION DATA, P

Precipitation within the domain of the local-basin-scale analysis likely evaporates very quickly or is transpired through plants, and is not considered to be a significant component of the water budget. As such, precipitation inputs were assumed to only include the flows that result from precipitation on the Rio Grande, consistent with the RGCP-scale channel water budget analysis.

10.5 PUMPING DATA, Q_P

There are multiple irrigation pumps in the Rincon Valley:

- Greenwood
- Duran
- Roundtree
- Dulin
- Dorser
- Thurston

Pumping data for wells in the Lower Rio Grande Basin were downloaded in PDF format from the NMOSE website (http://nmwrrs.ose.state.nm.us/nmwrrs/meterReport.html). These data were converted from PDF to text and a FORTRAN program was developed to extract pumping data for the study period. The data were converted into Mean Daily Pumping Rates (cfs) that were summed and assigned to each segment based on well location. The pumping data are an inflow to the surface-water budget and an outflow from the groundwater budget.

10.6 DOWNSTREAM CHANNEL OUTFLOW, Q_{DS}

Downstream channel outflow is the discharge in the Rio Grande at the downstream limit of the study area, so the modeled mean daily discharges at American Dam were used for this component.

10.7 GROUNDWATER RETURN FLOW, Q_{GWRF} AND GROUNDWATER RECHARGE, Q_{GWR}

Groundwater flux information that is necessary for the local-basin-scale water budget analysis was extracted from the same SSPA (2007) groundwater model for the Lower Rio Grande Basin that was used to evaluate the groundwater components associated with the RGCP-scale channel water budget. Although the model-derived fluxes were obtained using the same five geographic zones that were set up to facilitate the RGCP-scale channel water budget analysis, these fluxes represent surface water/groundwater interactions along the irrigated area bounding the RGCP (Figure 12). The various fluxes into and out of each zone were extracted from the upper-most model layer for model stress periods 128 (November 2003 through February 2004) and 129 (March through October 2004), and represent cell-to-cell fluxes that were calculated using the MODFLOW "Zone Budget" tool. It should be noted that, in addition to the four zones shown in Figure 12, a fifth zone was set up as an external halo around the four primary zones to capture all fluxes entering or leaving the four primary zones. This halo zone was generally a three-cell (i.e., 0.75-mile-wide) ring around the outside to capture interaction with the aquifer outside of the considered domain. It should also be noted that because the MODFLOW model does not cover the drought period evaluated in this study and the amount of groundwater data along the RGCP is limited, the groundwater components of the local-basin scale water budget should be considered approximate.

Several groundwater components were extracted from this model for use in the local-basin-scale water budget, including groundwater/floodplain recharge, groundwater return flow, riparian evapotranspiration, the upstream groundwater inflow, and the downstream groundwater outflow. Many of these components were then added to estimated or measured surface water values to fully account for the groundwater fluxes between the surface- and groundwater budgets for the local-basin scale, as discussed in the following sections. The daily breakdown of groundwater interflow components is in **Appendix D**. The groundwater flux components are summarized for non-irrigation season (October to February) and the irrigation season (March to September) in Table 13 and Table 14, respectively.

10.7.1 Groundwater Return Flow, Q_{gwrf}

In the local-basin-scale water budget, groundwater return flows are considered for the hydrologic domain that includes the overall basin that receives and delivers flow along the RGCP. This includes groundwater that is returned to the Rio Grande as well as groundwater that is returned to the adjoining local basin on either side of the river. Since the groundwater that is returned to the adjoining basin would either be transpired through crops or vegetation (accounted for separately as evapotranspiration) or returned to the Rio Grande through the irrigation-drain network, the groundwater return flow was assumed to be the sum of the groundwater flow that is directly returned to the Rio Grande and the irrigation-drain return flow. Inputs for the groundwater return flow to the Rio Grande component for the non-irrigation and irrigation periods was extracted from the MODFLOW model (Table 13 and Table 14). Because the irrigation/drain return flows were extracted from the MODFLOW model were significantly less than the sum of the measured values at the drains (Q_{irf} in the RGCP-scale analysis), the measured values from the drains (**Appendix B, Table B-1**) were used for that portion of the overall groundwater return flow in the local-basin-scale analysis. In the local-basin-scale surface-water budget, groundwater return flow is an inflow; whereas it is an outflow in the groundwater budget.

10.7.2 Groundwater Recharge, Q_{gwr}

The groundwater recharge component is made up of all estimated flows recharging the groundwater within the domain of the local-basin budget. This component is made up of floodplain/irrigation-based recharge and the channel seepage (Q_{cs}) estimate from the RGCP-scale channel water budget. Floodplain/irrigation-based recharge is driven by percolation of applied irrigation water and precipitation within the domain of the local-basin-scale water budget. Recharge from applied irrigation water (sometimes referred to as deep percolation of applied irrigation water) is calculated in MODFLOW as the difference between water delivered to farms and the crop irrigation requirement, with an adjustment for soil moisture storage tracked with a monthly time step. Surface water delivered to farms is calculated based on historical records of diversions at canal headings as well as recorded information and assumptions regarding channel seepage. Mountain front recharge and slope front recharge were not considered to directly affect the local-basin budget, because these recharges occur outside of the model domain that was considered for the local-basin-scale water budget and are captured by the halo zone around the considered domain. The floodplain/irrigation-based recharge was obtained from the model using the MODFLOW Recharge (RCH) package that includes recharge due to precipitation and flood-irrigation (summarized for non-irrigation and irrigation seasons in Table 13 and Table 14, respectively). This component was then added to the channel seepage (Q_{cs}) estimate from the RGCP-scale channel water budget analysis to obtain the overall groundwater recharge, which is an outflow in the local-basin-scale surface-water budget and inflow in the groundwater budget.

10.8 EVAPOTRANSPIRATION, ET

The evapotranspiration component of the local-basin-scale water budget is a combination of open-water evaporation from the Rio Grande, evapotranspiration from the riparian corridor, and evapotranspiration from irrigated agriculture within the basin-scale domain.

10.8.1 Open Water Evaporation

For the open-water evaporation component, the estimated open-water evaporation from the Rio Grande that was used in the RGCP-scale channel water budget analysis (discussed in Section 8 and **Appendix I**) was prorated based on the ratio of the average surface area in the canal system to the surface area of the Rio Grande (a factor of 1.813).

10.8.2 Riparian Evapotranspiration

The riparian evapotranspiration fluxes were obtained from the MODFLOW RIP-ET package, and are identical to those fluxes used in the RGCP-scale analysis. Estimated riparian evapotranspiration rates for non-irrigation and irrigation seasons are summarized in Table 13 and Table 14.

10.8.3 Crop Evapotranspiration

The irrigated area along the RGCP includes about 17,000 acres in the Rincon Valley and about 80,000 acres in the Mesilla Valley. Crop evapotranspiration was estimated using reported values of Actual Consumptive Use for 2004 (Table F-8 in SSPA, 2007). To disaggregate the annual value for 2004 (160,329 acre-feet), it was assumed that the crop evapotranspiration would be distributed between the

MODFLOW-defined non-irrigation season (November 2003 through February 2004) and the MODFLOW-defined irrigation season (March to October 2004) in a manner similar to the volume of applied water during the two seasons. Based on historical diversion data, the volume of applied water during the non-irrigation season ranges from between 15 percent and 43 percent; a value of 30 percent was used to estimate the portion of the annual crop evapotranspiration that occurs during the non-irrigation season. The seasonal values were then distributed uniformly on a daily basis.

10.9 UPSTREAM GROUNDWATER INFLOW, Q_{GWUS} AND DOWNSTREAM GROUNDWATER OUTFLOW, Q_{GWDS}

Upstream groundwater inflows were extracted from the MODFLOW model along the portion of the model domain that is considered for the local-basin-scale water budget. This location generally aligns with the latitude of the below Caballo gage. Similarly, the downstream groundwater outflow rates were extracted from the MODFLOW model as the groundwater outflow at a location near the Below American Dam metering station. Estimated rates for non-irrigation and irrigation seasons are shown in Table 13 and Table 14.

11.0 RESULTS

11.1 RGCP-SCALE CHANNEL WATER BUDGET ANALYSIS – RESULTS

11.1.1 Entire Study Period - 2010 through 2012

Results from the RGCP-scale channel water budget analysis were evaluated to assess the effects of the individual components on the water budget, and to assess the change in-channel storage along each reach. It should be noted that, due to limitations in inflow/outflow information (missing or inaccurate gage data and potential error in estimated or modeled values), a significant portion of the predicted change in storage is likely associated with unknown fluxes into or out of the system. For purposes of this discussion, segments that have a negative change in-channel storage will be referred to as losing segments, while segments that have a positive change in-channel storage will be referred to as gaining segments. The RGCP-scale channel water budget spreadsheet is included in **Appendix F1**.

As expected, the most significant components of the RGCP-scale channel water budget, in terms of magnitude, are the upstream inflow and downstream outflow (Table 15 and Table 16). Diversions, channel seepage and irrigation return flows are the next significant components, followed by effluent return flows, evapotranspiration and in-channel stormwater/ungaged inflow (at least in Segments 1 and 3). The remaining components are much less significant. The total annual volumes indicate that Segments 1 and 2 are moderately gaining segments, Segment 3 is a moderately losing segment, and Segment 4 is a slightly gaining segment with the largest gains indicated in 2012 (Table 15). Although the predicted change in volume of channel storage is relatively high in each of the segments, the total change in volume is less than 5 percent of the upstream inflow in each of the segments at the end of the 3-year study period (Table 16). Hydrographs of the total inflow, total outflow, and change in storage for each of the segments are included in **Appendix F1**.

Inflows to Segment 1 are less than the modeled and measured outflows from this segment during the majority of the study period (Figure 14), resulting in a net gain of about 51,300 acre-feet. Most of the gains occur during the non-irrigation season between 2010 and 2011 and at the beginning of the 2011 release, with very little change during the remaining irrigation seasons. The primary gains along this reach are stormwater/ungaged return flow and groundwater return flow (Table 15 and Table 16). The total downstream outflow increases from about 74 percent of the upstream inflow in 2010 to about 85 percent and 82 percent in 2011 and 2012, and makes up about 79 percent of the upstream inflow at the end of the 3-year period (Table 15 and Table 16). In addition to the downstream outflow, authorized diversions, channel seepage and evapotranspiration account for the majority of the outflows (Figure 15).

Segment 2 is a slightly gaining segment. The total increase to channel storage at the end of the 3-year study period is about 29,300 acre-feet, or about 3 percent of the upstream inflow (Table 15 and Table 16). The most significant gains occur during the non-irrigation season, and appear to result from irrigation and effluent return flows along the segment (Figure 16). Downstream outflows are about 61 percent of the upstream inflow, while diversions and seepage make up another 32 and 10 percent, respectively, of the upstream inflow (Table 16 and Figure 17).

Segment 3 is consistently a losing segment in each of the three years, with a total decrease to channel storage of about 25,800 acre-feet at the end of the 3-year period. Although irrigation return flows are relatively high along this segment, this component is more than offset by the high downstream outflows and significant seepage (Figure 18). Irrigation return flows are more significant than in upstream segments, especially 2010, but diminish with time. Downstream outflows exceed the upstream inflow from Mesilla Dam in 2010, but also diminish with time to about 95 percent of the upstream inflow in 2012 (Table 16 and Figure 19).

In Segment 4, the modeled inflows exceed the modeled outflows by about 9,700 acre-feet by the end of 2012, or by 1 percent of the modeled inflow delivered at the Anthony metering station. Similar to Segment 3, the majority of the gains occur as a result of the large volumes delivered to the channel by irrigation return flows that occur in 2010 and the relatively large effluent inflows in 2011 and 2012 (Figure 20). The contribution of irrigation return flows are also consistent with Segment 3, with the largest impact in early 2010, and diminishing effects later in the study period. Downstream outflows exceed the upstream (modeled) inflow at Anthony in 2010, but decrease to between 93 and 95 percent for the remainder of the study period (Table 16 and Figure 21).

Along the overall RGCP, the most significant inflows are obviously the upstream inflow from Caballo Reservoir, followed by irrigation return flows and treated effluent inflows, with somewhat less significant effects from groundwater return flows and stormwater/ungaged return flows (Figure 22 and Figure 23). The most significant outflows along the overall RGCP are the downstream channel outflow at American Dam and authorized diversions, followed by channel seepage, evapotranspiration and floodplain recharge, in that order (Figure 22 and Figure 23).

11.1.2 Delayed Single Pulse (S1) and Normal Single Pulse (S2)

Channel water budget analyses at the RGCP scale of the delayed single pulse scenario (Scenario S1) and the normal single pulse scenario (Scenario S2) are presented in **Appendix F3** and **Appendix F4**, respectively, and were carried out for the 2012 condition and compared to the results from the baseline channel water budget for actual 2012 conditions (**Appendix F2**). As discussed in more detail in **Appendix H** (HEC-RAS Modeling), the diversions flows under Scenario 1 were adjusted to eliminate the portions of the diversions that occurred prior to the delayed release. This adjustment involved shifting the timing and adjusting the magnitude of the diversions at Percha and Mesilla Diversion Dams to preserve the overall volume of the actual diversions that occurred at these locations in 2012. Likewise, the diversions under Scenario 2 were adjusted to prevent diversion flows from exceeding the inflow hydrograph. This adjustment involved shifting the timing and adjusting the magnitude of the diversion the Mesilla Diversion Dam to match 2012 diversion record.

Although the water budget analysis includes an evaluation of the individual water budget components, it is worth noting that, as indicated in the discussion of seepage presented above, the total RGCP seepage volume during the 2012 release would decrease from about 76,084 acre-feet under baseline conditions to about 66,786 acre-feet under Scenario S1 and about 74,087 acre-feet under Scenario S2.

Results from the analysis are summarized in Table 17 and Table 18 and were used to evaluate the change in-channel storage over the course of 2012 that would result under the hypothetical single-pulse releases (Scenarios S1 and S2) compared to the actual (baseline) double pulse release that occurred in 2012. This comparison indicates that, by the end of the release, Scenario S1 would result in a moderate reduction to the in-channel storage in Segment 1, while Scenario S2 would result in a slight decrease in storage (Figure 24). Compared to baseline conditions, the total volume of seepage in Segment 1 is lower under Scenario S1 and higher under Scenario S2. However, the change in-channel seepage is more than offset by reduced in-channel stormwater flows and reduced downstream outflows (Table 17 and Table 18).

In Segment 2, both of the hypothetical release scenarios would result in decreased channel storage at the end of the release (Figure 25). The results in Segment 2 indicate that both Scenarios S1 and S2 have lower cumulative seepage volumes compared to baseline conditions. Compared to baseline conditions, both of the hypothetical scenarios show reduced in-channel stormwater flows in Segment 2, and Scenario S1 has a higher downstream outflow while Scenario S2 has a lower downstream outflow (Table 17 and Table 18).

The baseline condition indicates that a decrease to channel storage occurs in Segment 3, while both Scenarios S1 and S2 would result in some increase to channel storage (Figure 26) that is primarily due to reduced downstream channel outflows and reduced seepage (Table 17 and Table 18). Under Scenario S1, the reduced outflow is not as significant as the higher upstream inflow at Mesilla. Compared to baseline conditions, Scenario S2 has a moderately lower upstream inflow, but the downstream outflow is significantly reduced.

Increases to channel storage are indicated for all cases in Segment 4, but the increases to channel storage are about 55 to 60 percent higher under both of the hypothetical scenarios (Figure 27). The hypothetical release scenarios result in reduced seepage and downstream channel outflow components in this segment that are more significant than the reductions to the upstream inflow. In general, it appears that the differences in in-channel storage among the 2012 release scenarios for each of the segments are primarily caused by differences in the upstream inflow (except in Segment 1), in-channel stormwater inflows, channel seepage, and the downstream outflow.

The stormwater/ungaged return flow component (Q_{cin}) was estimated by the predicted increase in downstream runoff, and is one of the least substantiated components due to the lack of gage data in the tributary channels and return flow locations. Although the methods used to estimate this component are reasonable, this component may be overestimated during times of hydrograph translation (i.e., on the rising limb of the hydrograph) and could be lumped into the overall change in-channel storage component since it is a significant unknown. A sensitivity analysis was therefore conducted by carrying out a separate water budget analysis that removed the Q_{cin} component from the calculations, which obviously results in a reduction to the predicted change in-channel storage. A comparison of the results with and without the Q_{cin} component indicates that the effects of this component are most significant in Segment 1, moderately significant in Segment 2, and relatively insignificant in Segments 3 and 4 (Figure 28). Although the Q_{cin} component makes up less than 10 percent of the release volume under each model scenario, the effects of this component are significant on the overall change in-channel storage volumes along the overall RGCP. Under the baseline condition, the change in RGCP channel storage decreases from a net gain of about 12,800 acre-feet to a net loss of 16,100 acre-feet without this component. The overall RGCP net gain of about 8,780 acre-feet indicated by Scenario S1 reduces to a net loss of about 1,060 acre-feet without the Q_{cin} component. For Scenario S2, the net gain would reduce from about 17,100 to 1,540 acre-feet if this component were removed.

11.2 LOCAL-BASIN WATER BUDGET ANALYSIS – RESULTS

11.2.1 Entire Study Period - 2010 through 2012

The local-basin-scale water budget analysis is presented in **Appendix F1**, along with inflow-outflow hydrographs for the surface- and groundwater budgets. The annual volumes associated with each component, along with the resulting annual change in surface-water/groundwater storage, are presented in Table 19, Figure 29 and Figure 30. Table 19 also shows the percentage of each component and change in storage relative to the total upstream inflow (surface-water plus groundwater). Results from the local-basin-scale water budget analysis for the 2010 to 2012 period indicate that, similar to the RGCP-scale channel water budget, the upstream channel inflow and the downstream channel outflow are significant components. However, except for precipitation, upstream groundwater inflow, and downstream groundwater outflow, most of the other components are also very significant. The 2007 groundwater model predicts a zero downstream groundwater outflow because the total depth of alluvium through El Paso Gap is less than 100 feet (SSPA, 2007). Except for the pumping component, the volume of the other components decreases from year to year. The increased pumping in 2011 results in a net decrease to the groundwater storage of 100,000 acre-feet over the course of that year. The surface-water budget indicates a net increase in surface-water storage of about 608,100 acre feet over the 3-year study period, or about 41 percent of the overall upstream inflow, but the magnitude of the increases reduces from year to year. The groundwater budget indicates a net decrease in groundwater storage of about 149,800 acre-feet (about 10 percent of the overall upstream inflow) by the end of the study period. The resulting total increase to the local-basin scale net storage is about 458,300 acre–feet

(608,100 acre-feet minus 149,800 acre-feet), or about 31 percent of the total inflow. Because it is highly unlikely that the net storage at the local-basin scale would increase during periods of drought, there appears to be significant outflows that are not being accounted for in this analysis. Nevertheless, the baseline analysis does provide insight into the relative effects of the hypothetical release patterns through a comparison with the results from the water budget analyses of these releases, as discussed in the following section.

11.2.2 Release Scenario S1 (Delayed Single Pulse) and Scenario S2 (Normal Single Pulse)

Local-basin-scale water budget analyses of the delayed single-pulse release scenario (Scenario S1) and the normal single-pulse release scenario (Scenario S2) are presented in **Appendix F3** and **Appendix F4**, respectively, and were carried out for the 2012 condition and compared to the results from the baseline water budget for actual 2012 conditions (**Appendix F2**). Results from this analysis are generally intuitive in that, by the end of the release, many of the components do not change from baseline conditions (Figure 31 and Figure 32). This can be said of the upstream discharge, pumping, upstream groundwater inflow, downstream groundwater outflow and groundwater return flow. Surface-water flow due to precipitation is slightly lower under Scenario S1 due to the shortened period of release, since this component was assumed to only occur as an addition to the flow in the Rio Grande. Scenario S1 results in a lower absolute downstream surface-water discharge, lower absolute groundwater recharge (due to reduced seepage), and lower absolute evapotranspiration (due to a reduced open-water evaporation duration). Scenario S2 results in absolute decreases to the downstream surface-water outflow and groundwater return flow. Compared to baseline conditions, the net surface-water storage increases under Scenarios 1 and 2 by about 10 and 11 percent, respectively; whereas, the net groundwater storage decreases significantly under Scenario 1 and decreases by about 25 percent under Scenario 2. It appears that the shorter release duration under Scenario 1 results in a net increase to the combined surface-water/groundwater storage of about 5 percent and that this increase is primarily associated with the reduced seepage. Scenario S2 has a slightly longer duration of release than under baseline conditions, but the absolute volume of surface water outflow is lower than baseline conditions, resulting in a net increase to the combined surface-water/groundwater storage of about 10 percent.

12.0 RECOMMENDATIONS AND LIMITATIONS

12.1 AGRICULTURAL TRENDS AFFECTING THE AQUIFER

A review of agricultural trends along the RGCP was conducted and presented herein to provide context for the recommendations identified in the following sections. During the 3-year period that is covered in this study, the annual volume released from Caballo Reservoir decreased by 38 percent between 2010 and 2011, and 43 percent between 2010 and 2012. However, the volume of authorized diversions decreased from about 337,000 acre-feet in 2010 to only 81,800 acre-feet in 2011 (a 76-percent decrease). The reduction to the authorized diversion volume in 2012 (164,000 acre-feet) was not as significant and represented a 52-percent decrease from 2010.

In 2011, pumping from the aquifer nearly doubled from 140,100 acre-feet in 2010 to 272,900 acre-feet in 2011, presumably to offset the low authorized diversions. For comparison, the pumping in 2012 was

199,600 acre-feet, a 42-percent increase over 2010. The significant pumping that occurred in 2011 appears to have resulted in lower groundwater levels in 2012 that likely played a significant role in the high seepage rates that occurred during the initial portions of the 2012 release. Considering the effects of the 2011 pumping on the aquifer and the recent reductions to irrigation releases, there appears clearly a need for improved water management practices and investments, as outlined below.

12.2 BEST WATER MANAGEMENT PRACTICES FOR FUTURE YEARS

Based on the results from this study, the channel seepage component of the water budget study appears to be a significant variable in the water budget. In 2012, this component accounted for about 21 percent (HEC-RAS-based results) to 28 percent (FLO-2D-based results) of the release volume. Both model platforms indicate that the delayed single-pulse release would reduce channel seepage by relatively significant amounts due to the shortened duration over which the seepage occurs. The results also indicate that the normal single-pulse release would result in a negligible change in-channel seepage (FLO-2D-based results) or a very small reduction (HEC-RAS-based results) to channel seepage. The delayed single pulse release also results in some reduction to evaporation, where this component is unaffected by the normal-pulse release. It is therefore recommended that a delayed single-pulse release be considered during future years of drought.

Considering the effects that the 2011 pumping had on the aquifer in 2012 and the associated high degree of seepage that occurred during the beginning of the 2012 release, significant pumping from the aquifer similar to that which occurred in 2011 is not recommended. Instead, a more detailed investigation of the linkage between the 2011 pumping and groundwater levels and channel seepage in 2012 should be undertaken. The results from this investigation could then be used to determine upper limits of the pumping that would prevent overdraft of the aquifer.

Water management improvements may also come in the form of methods to improve on-farm efficiency. These methods may include scientifically based scheduling of irrigation, increased use of tailwater return systems, and improvements to the irrigation systems. Examples of improved irrigation systems include improved furrows or changing from surface irrigation to pressurized systems.

12.3 SUGGESTED WATER MANAGEMENT INVESTMENTS

A number of recommendations for water management investments were developed as part of this study, as follows:

- The single-most significant limitation to this study is the availability of accurate measured data that could be used to calibrate or validate the hydraulic models and provide valuable input to the water budget calculations. It is therefore recommended that the shareholders improve the quality of the existing surface-water gages along the river, at diversions, and at the return locations. Improvements to the accuracy of the gages could be achieved by increasing the frequency of gage measurements for calibration purposes. Of particular interest would be the river gages at Haynor, Picacho and Anthony.
- Information regarding stormwater inflow and ungaged return flows is limited along the RGCP. Additional stream gages along the arroyos and drains would provide valuable information to assess

the water budget balance. Models for quantifying arroyo flows could also be developed. A few major arroyos could be instrumented to study the rainfall-runoff relationships and calibrated models could be developed for these arroyos. Models with similar parameters could then be used to calculate stormwater inflows from ungaged arroyos for the measured precipitation amounts. Models that will be developed by counties and cities adjoining the RGCP as part of the interior drainage analysis for the levee system can be used when they become available.

- Groundwater flux information extracted from the SSPA (2007) MODFLOW groundwater model does not include a simulation period that covers the 2010 through 2012 drought period evaluated in this study. The predicted groundwater fluxes in 2004 that were adopted for use in this study could be significantly different than the actual fluxes that occurred during the drought period of interest. It would therefore be worthwhile to update the existing groundwater model to reflect the current drought conditions.
- The accuracy of the majority of the available gage data that were used for this study is not known. Previously collected data should be reviewed and a level of accuracy assigned to each dataset.
- As stated below, the degree to which groundwater pumping affects the groundwater table prior to irrigation releases, and hence seepage rates during the initial portion of the release, is not known. The accuracy and completeness of the available pumping data is also not known. As such, groundwater pumping should be rigorously monitored to insure that the data reflects actual pumping rates. This action will likely require resources in the form of improved monitoring devices at the existing monitoring locations, additional monitoring devices at pumps that are currently not monitored, and inspections to insure the monitoring devices are operating correctly.

12.4 CHANNEL CONVEYANCE IMPROVEMENTS

A number of improvements could be made along the RGCP to enhance the channel conveyance. These improvements include:

- Removal of vegetation along the channel banks that increases the hydraulic roughness and reduces the conveyance efficiency, provided this is accomplished within the framework of the USIBWC Record of Decision for River Management Alternatives for the Rio Grande Canalization Project (USIBWC, 2009). Areas that have dense salt cedar or other non-native woody vegetation should be considered high priority sites for vegetation removal, while areas where this vegetation does not significantly affect the hydraulic roughness should be considered low priority sites. Considering the need for improved riparian habitat (USIBWC et al., 2004), removal of native vegetation along overbanks and within the floodway should not be considered. It should be noted that at some locations (i.e., at confluences with arroyos), vegetation also grows along the channel bed margins, but this vegetation is typically grass and reeds so it does not appear to significantly affect the hydraulic roughness.
- Localized accumulations of sediment along the RGCP also appear to affect channel conveyance, and removal of these sediments would improve efficiency. The most significant deposits tend to occur upstream from the diversion dams and at the confluences of the tributary arroyos. Reducing the amount of sedimentation at the arroyo confluences could be achieved by reducing the amount of

sediment that is delivered by the arroyos (i.e., using sedimentation basins in the arroyo watershed) or by mechanically removing the material from the RGCP channel.

- Similarly localized accumulations of sediment also appear to affect conveyance through the canal and drain system, especially in the downstream portion of the wasteways where water is returned to the Rio Grande. Mechanical removal of this material would improve the delivery of return flows, thereby increasing the overall efficiency of the RGCP system.
- Sedimentation could also be reduced by implementing the modified leases for grazing that would result in reduced erosion as identified in the EIS (USIBWC et al., 2004).
- Lining the RGCP with concrete would greatly improve the conveyance efficiency by reducing seepage and increasing flow velocities, but this option is probably not feasible due to cost constraints and ecological concerns. However, use of a synthetic impermeable membrane would limit seepage and may be more cost effective and more environmentally sensitive than the concrete lining.
- It may also be possible to identify reaches where irregularities in the banks could be smoothed to reduce energy losses and improve conveyance.

12.5 FUTURE STUDIES

The water budget analysis could be further refined with additional data or analysis as summarized below.

12.5.1 Depth to Groundwater

Hydrographs of groundwater fluctuations in 2010, 2011, and 2012 were obtained from 28 representative groundwater wells located along the length of the project. The wells were generally located in the floodplain, between 150 and 6,400 feet from the channel. Preliminary studies attempted to calibrate the HEC-RAS models using the wells as they are located and the distance from the riverbed to the well. It became clear that wells were too far away to represent actual groundwater conditions at the river so the decision was made to treat the well hydrographs as pattern hydrographs that could be transposed to represent groundwater fluctuations under the riverbed.

The distance to groundwater at the riverbed was estimated using USIBWC Rio Grande Canalization Project River Restoration Depths to Groundwater at Restoration Sites (USIBWC, 2010). The data were collected in June and July 2010, and represent a single data point that can be used to transpose groundwater hydrographs from wells in the floodplain to the river channel. Estimates could be improved with groundwater depth measurements over the entire irrigation season for the period of analysis (2010-2012).

The HEC-RAS groundwater interflow routine allows the user to assign a consistent groundwater depth or time series of groundwater depths. In the RGCP, the groundwater hydrographs for each of the 28 wells are assigned to a range of cross sections along the river. The groundwater depths are assigned to the downstream most cross section in each group and cannot be varied across that range of cross sections. As a result, the groundwater fluctuations at the upstream cross section are off by a vertical distance equal to the change in elevation over the range of cross sections. For example, if the upstream cross section in a group is 30 feet higher than the downstream cross section, the groundwater elevations at the upstream section will effectively be 30 feet lower. The problem can be remedied by adding more wells so that there are fewer cross sections assigned to each well, or by interpolating groundwater elevations between the up- and downstream cross sections. When the groundwater elevation inputs are a time step, the data requirements can be voluminous and may exceed the limitations for boundary condition inputs in HEC-RAS. The water budget analysis could be refined with additional well data to better define the groundwater profile along the RGCP.

12.5.2 Updated Groundwater Modeling

As discussed below, groundwater flux information was extracted from the SSPA (2007) MODFLOW groundwater model, which does not include a simulation period that covers the 2010 through 2012 drought period that is being evaluated in this study. Updated groundwater modeling that includes the 2010 through 2012 drought period would provide better estimates of the groundwater components and would improve the accuracy of the study.

12.5.3 Evaluation of Baseflow Release

It is also recommended that an analysis be carried out to determine the baseflow release rate prior to the irrigation release that would be necessary to reduce the very high seepage rates that are indicated by the FLO-2D model at the beginning of each pulse release. This analysis would likely involve modeling of the proposed baseflow to determine the volume that would be required to maintain a nominal flow in the channel over a given duration. This volume could then be compared to the estimated initial seepage volume that would occur without the baseflow to determine if the baseflow option is viable.

12.5.4 Water Budget Study Extension

The project reach of the RGCP water budget study could be extended farther downstream to include reaches of the Lower Rio Grande to better assess the effects of the various features along the extended reach. Some of the features that may be of importance to the water budget include American Dam, the American Canal, the City of El Paso and Ciudad Juarez, Riverside and International Dams, and the various control structures, drains and diversions in the extended reach. To assess these features, it is recommended that the water budget study reach be extended to the Fort Quitman gaging station.

12.5.5 Evaluation of Effects of Delayed Release on Groundwater Pumping

Although this analysis indicates that the reduced duration of a delayed single pulse release would result in reduced seepage volumes, the degree to which the delayed release would affect groundwater pumping prior to the release is not known. If groundwater pumping were to increase during the period prior to the release, the resulting reduction to groundwater levels could increase seepage rates during the release, thereby reducing the benefits of the delayed release that are indicated by this study. As such, it is recommended that a study be carried out to determine the degree to which the delayed release would affect groundwater pumping prior to the release, and assess how this change in pumping would affect seepage during the release.

12.6 STUDY LIMITATIONS AND RECOMMENDATIONS

A number of potential limitations and recommended improvements to the study were identified during the course of the analysis:

12.6.1 Records for Diversion and Irrigation Returns

Records for authorized diversions were available at three locations and records for irrigation return flows were available at five locations along the study area. However, it is understood that there are numerous unauthorized diversions and many more irrigation return locations that were not included in this modeling effort. A recommendation would be to increase the number of data collection facilities and add to a central database for the river system where the irrigation return flow data for all locations could be represented to improve the modeling effort.

12.6.2 Groundwater Flux Estimates

Groundwater flux information was extracted from the SSPA (2007) MODFLOW groundwater model, which does not include a simulation period that covers the 2010 through 2012 drought period that is being evaluated in this study. Differences between the predicted groundwater fluxes in 2004 that were adopted for use in this study could be significantly different than the actual fluxes that occurred during the drought period of interest.

12.6.3 Groundwater Data

Measured groundwater data along the RGCP and adjoining groundwater basin are limited, especially along the Rio Grande and the primary canals and drains, where complex processes govern stream-groundwater interactions. After an evaluation of existing gages and measurements of groundwater elevations, transects of additional groundwater measurement points could be established to improve the characterization of groundwater level variations along the RGCP. This will help in the understanding of river-groundwater linkages over the year and under a range of flow conditions.

12.6.4 Open Channel Evaporation

Evaporation along the RGCP is currently estimated by transposing the estimated evaporation rates from the USBR URGWOM (RiverWare) model of the Rio Grande upstream from Elephant Butte Reservoir. The existing RiverWare model along the RGCP (USACE, 2012) was not available for this study, and it is not known whether or not this model includes estimates for evaporation. If this model does include estimates of evaporation, these estimates should be used for the water budget analyses.

12.6.5 Daily Water-budget Computations

Considering the relatively long reach over which this study is being performed, comparing the various inflows and outflows on a daily basis can lead to misleading results under both the RGCP-scale channel water budget and the local-basin scale water budget. Even though the HEC-RAS and FLO-2D modeling account for routing effects and hydrograph translation, the water budget computations assume that the mean daily inflows and outflows are representative of an instantaneous point in time. While this may be appropriate under relatively steady flow conditions and reflect the overall interaction of the groundwater components over longer periods, daily comparisons during periods with rapidly changing releases from Caballo Dam (i.e., at the start or end of a release) may not reflect actual instantaneous changes to the water budget. For example, at the end of May during the actual 2012 release, the outflow from Caballo Dam increased from about 420 acre-feet on May 28 to about 2070 acre-feet on May 29, but the flow at Leasburg was about was about 490 acre-feet on both of these days. Under the RGCP-scale channel water budget, the other inflows and outflows did not change significantly during this period, so the change in-channel storage shows a spike of about 1,080 acre-feet on May 29, 2012 (**Appendix F2, F2-1 2012 Chart**). This spike in-channel storage is probably not accurate, since the frontal wave of the increased release would take some time to reach Leasburg. Similar spikes can be observed under the local-basin scale water (surface-water) budget computations, especially during the initial release period, although the routing effects are somewhat masked by the other components during the majority of the 2012 release (**Appendix F2, Table F2-5**).

12.6.6 Crop Evapotranspiration

Crop evapotranspiration was estimated using the 2004 consumptive use values presented in SSPA (2007). If consumptive use values become available for the 2010 through 2012 period, these values should be used to estimate crop evapotranspiration for this study.

12.6.7 HEC-RAS and FLO-2D Groundwater Interflow

Hydraulic Conductivity

The groundwater interflow component within HEC-RAS is a simplified approach with significant limitations. The input for saturated hydraulic conductivity (K_{sat}) does not allow for temporal variation and cannot account for differences in K_{sat} at the beginning of the release, when dry antecedent moisture conditions control seepage rates, and the remainder of the release, when seepage is based on saturated conditions.

Storage

The HEC-RAS groundwater interflow does not recognize limited or variable storage within a shallow aquifer beneath the river. It will continue to calculate seepage based on the gradient and the saturated hydraulic conductivity regardless of how much water has seeped into or out of the channel.

Groundwater Elevations

The HEC-RAS model assigns the same groundwater stage hydrograph to all of the cross sections identified within a groundwater interflow boundary condition, and does not adjust the hydrograph to account for the longitudinal slope of a shallow riverine aquifer. The longitudinal slope can be approximated by specifying the groundwater boundary conditions at more frequent intervals, but the computation time will likely be extended and the data inputs can be onerous. A sensitivity analysis that evaluates how changes in well hydrographs affect the seepage calculation should be conducted to see if additional data inputs are justified.

Riverbed Thickness

Both the HEC-RAS model and the FLO-2D model require a river sediment thickness (termed the limiting storage depth in FLO-2D) to perform the groundwater infiltration calculations. Any available information such as sediment boring logs should be obtained and reviewed to better assess the spatial variability of this parameter. Additional sediment borings may be necessary to quantify this parameter in areas where the available information is insufficient. The measured thickness of alluvial sediments could then be used to update the HEC-RAS and FLO-2D models to better assess seepage conditions along the study reach.

Model Selection

Both the HEC-RAS model and FLO-2D model appear to reasonably replicate the measured hydrographs, and thus reasonably predict channel seepage rates. However, considering the above listed limitations of the HEC-RAS model for use in estimating channel seepage, along with the improvements to the FLO-2D model that were made specifically for this study, it is recommended that the FLO-2D model be used in future water budget studies along the RGCP.

13.0 REFERENCES

Baker, W.W., 1943. Final Report on the Construction of the Canalization Feature of the Rio Grande Canalization Project, January.

Fullerton, W.T. and Batts, D., 2003. *Hope for a Living River: A Framework for a Restoration Vision for the Rio Grande.* Prepared for The Alliance for Rio Grande Heritage, and World Wildlife Fund, 131 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model – User guide to modularization concepts and the Ground-Water Flow Process. USGS Open-File Report 00-92. Reston, Virginia: U.S. Geological Survey.

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, 2012. *Draft Analysis of River Conveyance Efficiency for Initial Release of Project Water for Delivery to Acequia Madre Canal in 2012,* March 29.

Rio Grande Project Allocation Committee, 2012. *Draft Analysis of Multi-Year Drought and D2 Linear Regression Equation,* May 22.

S.S. Papadopulos and Associates, Inc. 2007. Groundwater Flow Model for Administration and Management in the Lower Rio Grande Basin – Draft, November.

TRC, 2010. Soil Survey Resource Report for Rio Grande Canalization Project River Restoration Implementation Plan. Prepared for the U.S. International Boundary and Water Commission, El Paso, Texas, August, 137 p.

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.

USACE and Resource Technology Inc., 1996. Sedimentation Analysis from the Rio Grande Tributary Basins. Rio Grande Canalization Improvement District, Percha Diversion Dam, New Mexico to American Diversion Dam, Texas. Prepared for International Boundary and Water Commission, United States and Mexico, United States Section, July.

U.S. Bureau of Reclamation (USBR), 2010. Rio Grande Project – Operations Manual, January 2010.

U.S. Geological Survey (USGS), 1984-2011. Monitoring Well Data, email correspondence with USGS, 1984-2011.

USGS, 1988-2007. Rio Grande Basin – Rio Grande Seepage Investigations, email correspondence with USGS, 1988-2007.

USGS, 2012. Data provided via email by Sarah E. Falk, USGS, on September 10.

U.S. International Boundary and Water Commission (USIBWC), 1993. Letter to Mr. Dan Page, Bureau of Reclamation from Mr. Conrad G. Keyes, Jr., Principal Engineer, Planning regarding summary tables showing the gains and losses in the Rio Grande between Picacho Bridge near Las Cruces and Courchesne Bridge in El Paso, Texas, September 1, 22 p.

USIBWC, 2001. Alternatives formulation report, Rio Grande Canalization Project.

USIBWC, 2009. Record of Decision: River Management Alternatives for the Rio Grande Canalization Project, June 4.

USIBWC, 2010. USIBWC Rio Grande Canalization Project River Restoration Depths to Groundwater at Restoration Sites. Prepared by TRC, Austin, Texas, October. USIBWC. 2010. USIBWC Rio Grande Canalization Project River Restoration Depths to Groundwater at Restoration Sites. Prepared by TRC, Austin, Texas, October.

USIBWC, 2012a. Scope of Work for the Rio Grande Canalization Project (RGCP) Water Budget Study.

USIBWC, 2012b. Scope of Work for the Rio Grande Canalization Project (RGCP) Water Budget Study - Modification 1.

USIBWC, U.S. Dept. of the Interior and USBR, 2004. River Management Alternatives for the Rio Grande Canalization Project: Final Environment Impact Statement. El Paso, Texas (IBWC), Albuquerque, New Mexico (USDI and USBR), and technical support by Parsons, Austin, Texas, June.

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/

14.0 TABLES

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Table 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**

Table 2. EBID River Gage River Station Table

Source	HEC-RAS River Stations	Gage Name
USBR/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
IBWC/USGS	**9006.36**	**El Paso**
IBWC/USGS	NA	American Canal
IBWC/USGS	NA	Below American Dam

Vales in **bold** were used in calibration

Table 3. Groundwater and River Bed Elevation Comparison

Well ID	2010 Groundwater Elev.			2011 Groundwater Elev.			2012 Groundwater Elev.			GW Difference 2010 – 2012 (feet)	HEC-RAS Channel Invert (feet)	GW Depth Compared to HEC-RAS Channel Invert June 2012
	Beg. Jan 2010 (feet)	Ending Dec 2010 (feet)	Delta (feet)	Beg. Jan 2011 (feet)	Ending Dec 2011 (feet)	Delta (feet)	Beg. Jan 2012 (feet)	Ending Dec 2012 (feet)	Delta (feet)			
RIN_10R	4117.37	4117.43	0.06	4117.26	4114.79	-2.47	4114.79	4117.22	2.43	-0.15	4113.6	+3.62
RIN_1R	4097.94	4097.57	-0.37	4097.97	4094.86	-3.11	4094.87	4094.44	-0.43	-3.5	4094.1	+0.34
RIN_9R	4088.39	4088.10	-0.29	4088.07	4081.42	-6.65	4081.43	4079.68	-1.75	-8.71	4082.5	-2.82
RIN_2R	4070.34	4069.79	-0.55	4069.67	4065.01	-4.66	4065.01	4064.06	-0.95	-6.28	4061.3	+2.76
RIN_8R	4054.68	4051.08	-3.6	4053.60	4052.13	-1.47	4052.15	4049.99	-2.16	-4.69	4052.2	-2.21
RIN_7R	4029.55	4027.85	-1.7	4028.73	4026.45	-2.28	4026.49	4018.22	-8.27	-11.33	4025.5	-7.28
RIN_5R	4012.78	4013.52	0.74	4013.36	4011.71	-1.65	4011.73	4013.55	1.82	0.77	4010.6	+2.95
RIN_12R	4003.35	4002.41	-0.94	4002.59	3999.76	-2.83	3999.78	3998.00	-1.78	-5.35	4001.8	-3.8
MES_41R	3946.81	3946.89	0.08	3946.87	3946.52	-0.35	3946.52	3948.91	2.39	2.1	3944.4	+4.51
MES_43R	3930.02	3929.86	-0.16	3929.83	3928.03	-1.8	3928.54	3929.51	0.97	-0.51	3927.6	+1.91
MES_20R	3917.07	3916.93	-0.14	3916.92	3911.82	-5.1	3911.83	3908.90	-2.93	-8.17	3916.6	-7.7
MES_15R	3900.35	3900.43	0.08	3900.42	3897.94	-2.48	3897.93	3899.45	1.52	-0.9	3896.32	+3.13
MES_12R	3883.39	3883.13	-0.26	3883.13	3880.46	-2.67	3880.45	3880.18	-0.27	-3.21	3884.7	-4.52
MES_48R	3871.92	3871.2	-0.72	3871.18	3869.72	-1.46	3869.69	3870.96	1.27	-0.96	3868.41	+2.55
MES_13R	3846.59	3846.82	0.23	3846.83	3843.55	-3.28	3843.22	3845.12	1.9	-1.47	3846.7	-1.58
ME_S8R	3838.37	3838.35	-0.02	3838.32	3838.29	-0.03	3837.93	3838.34	0.41	-0.03	3837.6	+0.74
ME_S6R	3818.24	3817.95	-0.29	3817.94	3815.07	-2.87	3815.07	3813.68	-1.39	-4.56	3819.6	-5.92
MES_23R	3799.00	3799.08	0.08	3798.86	3795.53	-3.33	3795.94	3794.19	-1.75	-4.81	3796.4	-2.21
MES_32R	3788.28	3788.39	0.11	3788.36	3783.79	-4.57	3783.80	3782.69	-1.11	-5.59	3784.1	-1.41
MES_39R	3782.41	3782.25	-0.16	3782.07	3778.71	-3.36	3778.77	3777.10	-1.67	-5.31	3779.7	-2.6
ISC_7	3748.22	3748.31	0.09	3748.31	3748.47	0.16	3748.49	3748.69	0.2	0.47	3748.2	+0.49
ISC_5	3741.01	3741.27	0.26	3741.23	3739.28	-1.95	3739.28	3740.18	0.9	-0.83	3739.6	+0.58

Table 4. Groundwater Monitoring Wells Utilized in HEC-RAS Model

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

Table 5. Average Groundwater Depth at Groundwater Monitoring Wells Utilized in HEC-RAS Model

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

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

Table 6. Channel Seepage Results, Unsteady HEC-RAS Modeling with Diversions, Returns, and Groundwater Interflow, March 31, 2012, 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 would indicate groundwater flow into the channel

Table 7. Comparison of Flow Volumes, HEC-RAS Model Hydrographs without and with Returns, March 31, 2012 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 8. 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 would indicate groundwater flow into the channel
Average and total values for Scenario S1 based on the pulse duration of 110 days

Table 9. 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 would indicate groundwater flow into the channel
Average and total values for Scenario S2 based on the pulse duration of 168 days

Table 10. **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 11. Comparison of HEC-RAS-based Seepage Estimates with the Gains and Losses Reported in USIBWC (1993)

Segment	HEC-RAS Seepage[1] (ac-ft/day/mile)			USIBWC (1993) Gains/Losses[1] (ac-ft/day/mi)			
	Minimum	Maximum	Average	Period	Maximum Gain	Maximum Loss	Average
Segment 1	-0.3	-2.8	-1.8	NA	NA	NA	NA
Segment 2[2]	-0.5	-12.2	-7.7	1991-1992	58.1	-164.6	-8.3
Segment 3[3]	-0.6	-10.1	-5.6	1986-1992	83.0	-44.3	-0.7
Segment 3[4]				1986-1992	31.0	-64.0	-3.9
Segment 4[5]	-0.5	-9.4	-5.1	1986-1992	23.4	-47.8	-8.4
Total[6]	-0.4	-6.6	-4.3	1991-1992	7.2	-24.4	-1.3

[1]Seepage and Gains/Losses are defined differently in the two studies.
[2]USIBWC (1993) includes only the reach from Picacho Bridge to Mesilla Dam.
[3]USIBWC (1993) reach from Mesilla Dam to Vado Bridge.
[4]USIBWC (1993) reach from Vado Bridge to Canutillo Bridge.
[5]USIBWC (1993) reach from Canutillo Bridge to Courchesne Bridge.
[6]USIBWC (1993) reach from Picacho Bridge to Courchesne Bridge (1991 and 1992).

Table 12. 2012 Actual (calculated) v. Predicted Lake Evaporation at Elephant Butte and Caballo Reservoirs using S1 (Delayed Single Pulse) and S2 (Normal Single Pulse) Release Scenarios

Month	Storage (ac-ft)	Actual (Calculated) Evaporation (acre-feet)	Estimated Evaporation S1 Release (acre-feet)	Estimated Evaporation S2 Release (acre-feet)
Elephant Butte Reservoir				
January	10,087	2,537	2,534	2,534
February	10,817	3,702	3,711	3,710
March	11,200	7,502	7,583	7,548
April	10,924	8,767	9,351	8,770
May	10,797	11,236	12,905	10,942
June	8,668	14,142	16,080	13,579
July	6,557	6,955	7,749	6,980
August	4,817	4,843	5,271	5,114
September	4,851	3,788	3,903	4,117
October	4,883	3,236	3,186	3,365
November	5,127	1,903	1,882	1,979
December	6,142	1,457	1,429	1,478
Total:	--	**70,068**	**75,584**	**70,116**
Caballo Reservoir				
January	1,851	446	437	444
February	1,955	566	520	546
March	2,591	1,122	976	1,124
April	2,401	1,600	1,470	1,507
May	2,462	2,707	2,229	1,959
June	2,250	2,641	2,778	2,450
July	2,246	2,352	1,700	1,716
August	1,703	1,394	1,890	1,685
September	1,148	922	1,688	1,510
October	1,193	652	1,237	1,114
November	1,249	406	725	661
December	1,320	296	448	435
Total:	--	**14,658**	**16,098**	**15,151**

See Section 7.3.2 for description of S1 (Delayed Single-pulse) and S2 (Normal Single-pulse) release scenarios provided by the RGPAC

Table 13. **Groundwater Budget Components from MODFLOW for Non-Irrigation Season (October – February)**

Water Budget Component	Unit	Segment 1	Segment 2	Segment 3	Segment 4
Project-Scale and Local-Basin-Scale Components					
Riparian Evapotranspiration	acre-feet/day	11.54	1.39	2.93	2.51
Groundwater return flow to Rio Grande	acre-feet/day	51.75	6.48	0.14	0.76
Project-Scale Components					
Floodplain Recharge	acre-feet per day	0.07	0.07	0.13	0.06
Local-Basin-Scale Components					
Floodplain/Irrigation-based Recharge	acre-feet/day	0.78	0.77	1.44	0.74

Table 14. **Groundwater Budget Inflow Components from MODFLOW for Irrigation Season (March – September)**

Water Budget Component	Unit	Segment 1	Segment 2	Segment 3	Segment 4
Project-Scale and Local-Basin-Scale Components					
Riparian Evapotranspiration	acre-feet/day	33.72	8.86	8.36	7.18
Groundwater return flow to Rio Grande	acre-feet/day	28.83	2.99	0.00	0.00
Project-Scale Components					
Floodplain Recharge	acre-feet per day	6.33	6.29	11.76	6.42
Local-Basin-Scale Components					
Floodplain/Irrigation-based Recharge	acre-feet/day	72.72	72.26	135.20	73.85

Table 15. Annual and Total Water Volumes (acre-feet) for the Various Components of the RGCP-scale Channel Water Budget Study

Segment	Year	Q_{cus}[1]	P_c[2]	Q_{cin}[3]	Q_{irf}[4]	Q_{eff}[5]	Q_{gwrf}[6]	Q_{cds}[7]	Q_{cs}[8]	Q_{fpr}[9]	ET[10]	Q_{da}[11]	Q_{du}[12]	ΔS_{ic}[13]
1	2010	652,000	1,100	8,200	0	400	13,300	-481,000	-23,600	-1,600	-12,900	-133,600	-1,300	21,000
	2011	402,500	1,100	7,400	0	400	13,300	-342,200	-16,600	-1,600	-12,900	-26,700	-300	24,600
	2012	372,000	1,000	19,300	0	300	11,700	-306,400	-13,900	-1,600	-12,600	-63,700	-600	5,600
	Total	1,426,500	3,200	34,900	0	1,100	38,300	-1,129,600	-54,100	-4,700	-38,500	-224,000	-2,200	51,300
2	2010	481,000	600	100	17,000	16,200	1,500	-253,700	-45,500	-1,500	-3,800	-203,400	-2,000	7,600
	2011	342,200	600	1,200	4,100	16,200	1,500	-257,700	-35,000	-1,500	-3,800	-55,100	-600	12,400
	2012	306,400	600	300	2,000	14,900	1,300	-179,400	-30,600	-1,500	-3,800	-100,500	-1,000	9,300
	Total	1,129,600	1,800	1,600	23,100	47,400	4,300	-690,900	-111,100	-4,600	-11,400	-358,900	-3,600	29,300
3	2010	253,700	400	1,000	35,200	1,100	0	-268,100	-25,900	-2,900	-3,800	0	0	-9,200
	2011	257,700	400	1,300	15,500	1,100	0	-254,100	-24,900	-2,900	-3,800	0	0	-9,800
	2012	179,400	400	900	5,300	1,000	0	-169,700	-17,500	-2,900	-3,700	0	0	-6,900
	Total	690,900	1,200	3,300	56,000	3,100	0	-691,900	-68,300	-8,700	-11,400	0	0	-25,800
4	2010	268,100	500	500	35,000	12,000	100	-277,800	-31,500	-1,600	-3,400	0	0	1,900
	2011	254,100	500	1,000	4,200	12,000	100	-236,400	-27,300	-1,600	-3,400	0	0	3,100
	2012	169,700	400	600	6,400	11,100	100	-160,900	-17,700	-1,600	-3,300	0	0	4,700
	Total	691,900	1,400	2,100	45,600	35,100	300	-675,200	-76,600	-4,700	-10,200	0	0	9,700
Total RGCP	2010	652,000	2,600	9,800	87,200	29,700	14,900	-277,800	-126,500	-7,600	-23,900	-337,000	-3,300	20,100
	2011	402,500	2,600	10,900	23,800	29,700	14,900	-236,400	-103,800	-7,600	-23,900	-81,800	-900	30,000
	2012	372,000	2,400	21,100	13,700	27,300	13,100	-160,900	-79,700	-7,600	-23,400	-164,200	-1,600	12,300
	Total	1,426,500	7,600	41,900	124,700	86,700	42,900	-675,200	-310,100	-22,700	-71,500	-582,900	-5,800	62,200

[1] Q_{cus} Upstream Channel Inflow
[2] P_c Precipitation Flows in River Channel
[3] Q_{cin} In-channel Stormwater/Ungaged Return Inflow
[4] Q_{irf} Irrigation Return Flow
[5] Q_{eff} Treated Effluent Return Flow
[6] Q_{gwrf} Groundwater Return Flow
[7] Q_{cds} Downstream Channel Outflow
[8] Q_{cs} Channel Seepage
[9] Q_{fpr} Floodplain Recharge
[10] ET Evapotranspiration
[11] Q_{da} Diversions Authorized
[12] Q_{du} Diversions Unauthorized (1% of Authorized)
[13] Δs_{ic} In-channel Change in Storage

Table 16. Annual and Total Water Volumes for the Various Components of the RGCP-scale Channel Water Budget Study as Percentage of Upstream Inflow

Segment	Year	Q_{cus}[1]	P_c[2]	Q_{cin}[3]	Q_{irf}[4]	Q_{eff}[5]	Q_{gwrf}[6]	Q_{cds}[7]	Q_{cs}[8]	Q_{fpr}[9]	ET[10]	Q_{da}[11]	Q_{du}[12]	ΔS_{ic}[13]
1	2010	100%	0%	1%	0%	0%	2%	-74%	-4%	0%	-2%	-20%	0%	3%
	2011	100%	0%	2%	0%	0%	3%	-85%	-4%	0%	-3%	-7%	0%	6%
	2012	100%	0%	5%	0%	0%	3%	-82%	-4%	0%	-3%	-17%	0%	2%
	Total	100%	0%	2%	0%	0%	3%	-79%	-4%	0%	-3%	-16%	0%	4%
2	2010	100%	0%	0%	4%	3%	0%	-53%	-9%	0%	-1%	-42%	0%	2%
	2011	100%	0%	0%	1%	5%	0%	-75%	-10%	0%	-1%	-16%	0%	4%
	2012	100%	0%	0%	1%	5%	0%	-59%	-10%	-1%	-1%	-33%	0%	3%
	Total	100%	0%	0%	2%	4%	0%	-61%	-10%	0%	-1%	-32%	0%	3%
3	2010	100%	0%	0%	14%	0%	0%	-106%	-10%	-1%	-2%	0%	0%	-4%
	2011	100%	0%	1%	6%	0%	0%	-99%	-10%	-1%	-1%	0%	0%	-4%
	2012	100%	0%	1%	3%	1%	0%	-95%	-10%	-2%	-2%	0%	0%	-4%
	Total	100%	0%	0%	8%	0%	0%	-100%	-10%	-1%	-2%	0%	0%	-4%
4	2010	100%	0%	0%	13%	4%	0%	-104%	-12%	-1%	-1%	0%	0%	1%
	2011	100%	0%	0%	2%	5%	0%	-93%	-11%	-1%	-1%	0%	0%	1%
	2012	100%	0%	0%	4%	7%	0%	-95%	-10%	-1%	-2%	0%	0%	3%
	Total	100%	0%	0%	7%	5%	0%	-98%	-11%	-1%	-1%	0%	0%	1%
Total RGCP	2010	100%	0%	2%	13%	5%	2%	-43%	-19%	-1%	-4%	-52%	-1%	3%
	2011	100%	1%	3%	6%	7%	4%	-59%	-26%	-2%	-6%	-20%	0%	7%
	2012	100%	1%	6%	4%	7%	4%	-43%	-21%	-2%	-6%	-44%	0%	3%
	Total	100%	1%	3%	9%	6%	3%	-47%	-22%	-2%	-5%	-41%	0%	4%

[1]Q_{cus} Upstream Channel Inflow
[2]P_c Precipitation Flows in River Channel
[3]Q_{cin} In-channel Stormwater/Ungaged Return Inflow
[4]Q_{irf} Irrigation Return Flow
[5]Q_{eff} Treated Effluent Return Flow
[6]Q_{gwrf} Groundwater Return Flow
[7]Q_{cds} Downstream Channel Outflow
[8]Q_{cs} Channel Seepage
[9]Q_{fpr} Floodplain Recharge
[10]ET Evapotranspiration
[11]Q_{da} Diversions Authorized
[12]Q_{du} Diversions Unauthorized (1% of Authorized)
[13]ΔS_{ic} In-channel Change in Storage

Table 17. Comparison of Cumulative Volume (acre-feet) of the RGCP-scale Channel Water Budget Components under Baseline 2012, Scenario S1 and Scenario S2

Segment	Scenario	Qcus	Pc	Qcin	Qirf	Qeff	Qgwrf	Total Inflow	Qcds	Qcs	Qfpr	ET	Qda	Qdu	Total Outflow	ΔSic[4]
1	Baseline[1]	372,028	642	20,206	0	173	4,844	**397,893**	-305,912	-13,901	-1,063	-8,575	-63,721	-637	**-393,679**	**4,214**
	Scenario S1[2]	372,028	670	6,396	0	173	4,844	**384,111**	-302,208	-12,290	-1,063	-7,556	-63,722	-637	**-387,390**	**-3,279**
	Scenario S2[3]	372,028	606	8,123	0	173	4,844	**385,774**	-295,348	-14,309	-1,063	-8,575	-63,721	-637	**-383,523**	**2,251**
2	Baseline[1]	305,912	373	7,072	1,894	7,476	502	**323,230**	-177,957	-29,505	-1,056	-2,786	-100,475	-1,005	**-312,909**	**10,321**
	Scenario S1[2]	302,208	373	3,071	1,894	7,476	502	**315,524**	-180,808	-25,418	-1,056	-2,322	-100,267	-1,003	**-310,954**	**4,570**
	Scenario S2[3]	295,348	373	5,561	1,894	7,476	502	**311,154**	-169,925	-29,207	-1,056	-2,786	-100,269	-1,003	**-304,370**	**6,784**
3	Baseline[1]	177,957	238	945	5,147	485	0	**184,772**	-168,933	-16,876	-1,976	-2,657	0	0	**-190,448**	**-5,676**
	Scenario S1[2]	180,808	238	147	5,147	485	0	**186,826**	-166,392	-14,838	-1,976	-2,209	0	0	**-185,418**	**1,408**
	Scenario S2[3]	169,925	238	985	5,147	485	0	**176,779**	-154,675	-15,792	-1,976	-2,657	0	0	**-175,105**	**1,674**
4	Baseline[1]	168,933	281	631	3,072	5,542	0	**178,458**	-155,238	-15,802	-1,079	-2,404	0	0	**-174,523**	**3,935**
	Scenario S1[2]	166,392	281	227	3,072	5,542	0	**175,513**	-152,284	-14,093	-1,079	-1,971	0	0	**-169,428**	**6,085**
	Scenario S2[3]	154,675	281	862	3,072	5,542	0	**164,430**	-139,810	-14,780	-1,079	-2,404	0	0	**-158,073**	**6,357**
Total	**Baseline[1]**	**372,028**	**1,534**	**28,855**	**10,113**	**13,675**	**5,347**	431,551	**-155,238**	**-76,084**	**-5,174**	**-16,421**	**-164,196**	**-1,642**	-418,756	12,794
	Scenario S1[2]	**372,028**	**1,562**	**9,842**	**10,113**	**13,675**	**5,347**	412,566	**-152,284**	**-66,638**	**-5,174**	**-14,058**	**-163,989**	**-1,640**	-403,782	8,783
	Scenario S2[3]	**372,028**	**1,498**	**15,530**	**10,113**	**13,675**	**5,347**	418,190	**-139,810**	**-74,087**	**-5,174**	**-16,421**	**-163,991**	**-1,640**	-401,123	17,067

[1]Appendix F2 - 2012 Baseline
[2]Appendix F3 - Scenario S1
[3]Appendix F4 - Scenario S2
[4]ΔSic = Total Inflow + Total Outflow

Table 18. Comparison of Cumulative Volume (as Percent of Inflow) of the RGCP-scale Channel Water Budget Components under Baseline 2012, Scenario S1 and Scenario S2

Segment	Scenario	Qcus	Pc	Qcin	Qirf	Qeff	Qgwrf	Total Inflow	Qcds	Qcs	Qfpr	ET	Qda	Qdu	Total Outflow	ΔSic[4]
1	Baseline[1]	100.0%	0.2%	5.4%	0.0%	0.0%	1.3%	107.0%	-82.2%	-3.7%	-0.3%	-2.3%	-17.1%	-0.2%	-105.8%	1.1%
	Scenario S1[2]	100.0%	0.2%	1.7%	0.0%	0.0%	1.3%	103.2%	-81.2%	-3.3%	-0.3%	-2.0%	-17.1%	-0.2%	-104.1%	-0.9%
	Scenario S2[3]	100.0%	0.2%	2.2%	0.0%	0.0%	1.3%	103.7%	-79.4%	-3.8%	-0.3%	-2.3%	-17.1%	-0.2%	-103.1%	0.6%
2	Baseline[1]	100.0%	0.1%	2.3%	0.6%	2.4%	0.2%	105.7%	-58.2%	-9.6%	-0.3%	-0.9%	-32.8%	-0.3%	-102.3%	3.4%
	Scenario S1[2]	100.0%	0.1%	1.0%	0.6%	2.5%	0.2%	104.4%	-59.8%	-8.4%	-0.3%	-0.8%	-33.2%	-0.3%	-102.9%	1.5%
	Scenario S2[3]	100.0%	0.1%	1.9%	0.6%	2.5%	0.2%	105.4%	-57.5%	-9.9%	-0.4%	-0.9%	-33.9%	-0.3%	-103.1%	2.3%
3	Baseline[1]	100.0%	0.1%	0.5%	2.9%	0.3%	0.0%	103.8%	-94.9%	-9.5%	-1.1%	-1.5%	0.0%	0.0%	-107.0%	-3.2%
	Scenario S1[2]	100.0%	0.1%	0.1%	2.8%	0.3%	0.0%	103.3%	-92.0%	-8.2%	-1.1%	-1.2%	0.0%	0.0%	-102.5%	0.8%
	Scenario S2[3]	100.0%	0.1%	0.6%	3.0%	0.3%	0.0%	104.0%	-91.0%	-9.3%	-1.2%	-1.6%	0.0%	0.0%	-103.0%	1.0%
4	Baseline[1]	100.0%	0.2%	0.4%	1.8%	3.3%	0.0%	105.6%	-91.9%	-9.4%	-0.6%	-1.4%	0.0%	0.0%	-103.3%	2.3%
	Scenario S1[2]	100.0%	0.2%	0.1%	1.8%	3.3%	0.0%	105.5%	-91.5%	-8.5%	-0.6%	-1.2%	0.0%	0.0%	-101.8%	3.7%
	Scenario S2[3]	100.0%	0.2%	0.6%	2.0%	3.6%	0.0%	106.3%	-90.4%	-9.6%	-0.7%	-1.6%	0.0%	0.0%	-102.2%	4.1%
Total	Baseline[1]	100.0%	0.4%	7.8%	2.7%	3.7%	1.4%	116.0%	-41.7%	-20.5%	-1.4%	-4.4%	-44.1%	-0.4%	-112.6%	3.4%
	Scenario S1[2]	100.0%	0.4%	2.6%	2.7%	3.7%	1.4%	110.9%	-40.9%	-17.9%	-1.4%	-3.8%	-44.1%	-0.4%	-108.5%	2.4%
	Scenario S2[3]	100.0%	0.4%	4.2%	2.7%	3.7%	1.4%	112.4%	-37.6%	-19.9%	-1.4%	-4.4%	-44.1%	-0.4%	-107.8%	4.6%

[1]Appendix F2 - 2012 Baseline
[2]Appendix F3 - Scenario S1
[3]Appendix F4 - Scenario S2
[4]ΔSic = Total Inflow + Total Outflow

Table 19. Annual and Total Water Volumes (Acre-feet or as Percentage of Total Inflow) for the Various Components of the Local-basin-scale Water Budget Study

Budget	Component	Volumes (acre-feet)				As Percent of Total Upstream Inflow			
		2010	2011	2012	Total	2010	2011	2012	Total
Surface-water	Upstream Channel Inflow	652,000	402,500	372,000	1,426,500	97%	95%	95%	96%
	Precipitation Flows in River Channel	2,600	2,600	2,400	7,600	0%	1%	1%	1%
	Pumping	140,100	272,900	199,600	612,600	21%	65%	51%	41%
	Groundwater Return Flow	102,100	38,700	26,900	167,700	15%	9%	7%	11%
	Downstream Channel Outflow	-277,800	-236,400	-160,900	-675,100	-41%	-56%	-41%	-45%
	Groundwater Recharge	-213,600	-191,100	-166,900	-571,600	-32%	-45%	-43%	-38%
	Total ET	-121,300	-121,300	-116,900	-359,500	-18%	-29%	-30%	-24%
	Changes in Surface-water Storage	284,000	167,900	156,200	608,100	42%	40%	40%	41%
Ground-water	Upstream Groundwater Inflow	20,500	20,500	17,900	58,900	3%	5%	5%	4%
	Groundwater Recharge	213,600	191,100	166,900	571,600	32%	45%	43%	38%
	Pumping	-140,100	-272,900	-199,600	-612,600	-21%	-65%	-51%	-41%
	Groundwater Return Flow	-102,100	-38,700	-26,900	-167,700	-15%	-9%	-7%	-11%
	Downstream Groundwater Outflow	0	0	0	0	0%	0%	0%	0%
	Change in Vadose Zone and Groundwater Storage	-8,100	-100,000	-41,700	-149,800	-1%	-24%	-11%	-10%
Net	Net Change in Storage	275,900	67,900	114,500	458,300	41%	16%	29%	31%

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15.0 FIGURES

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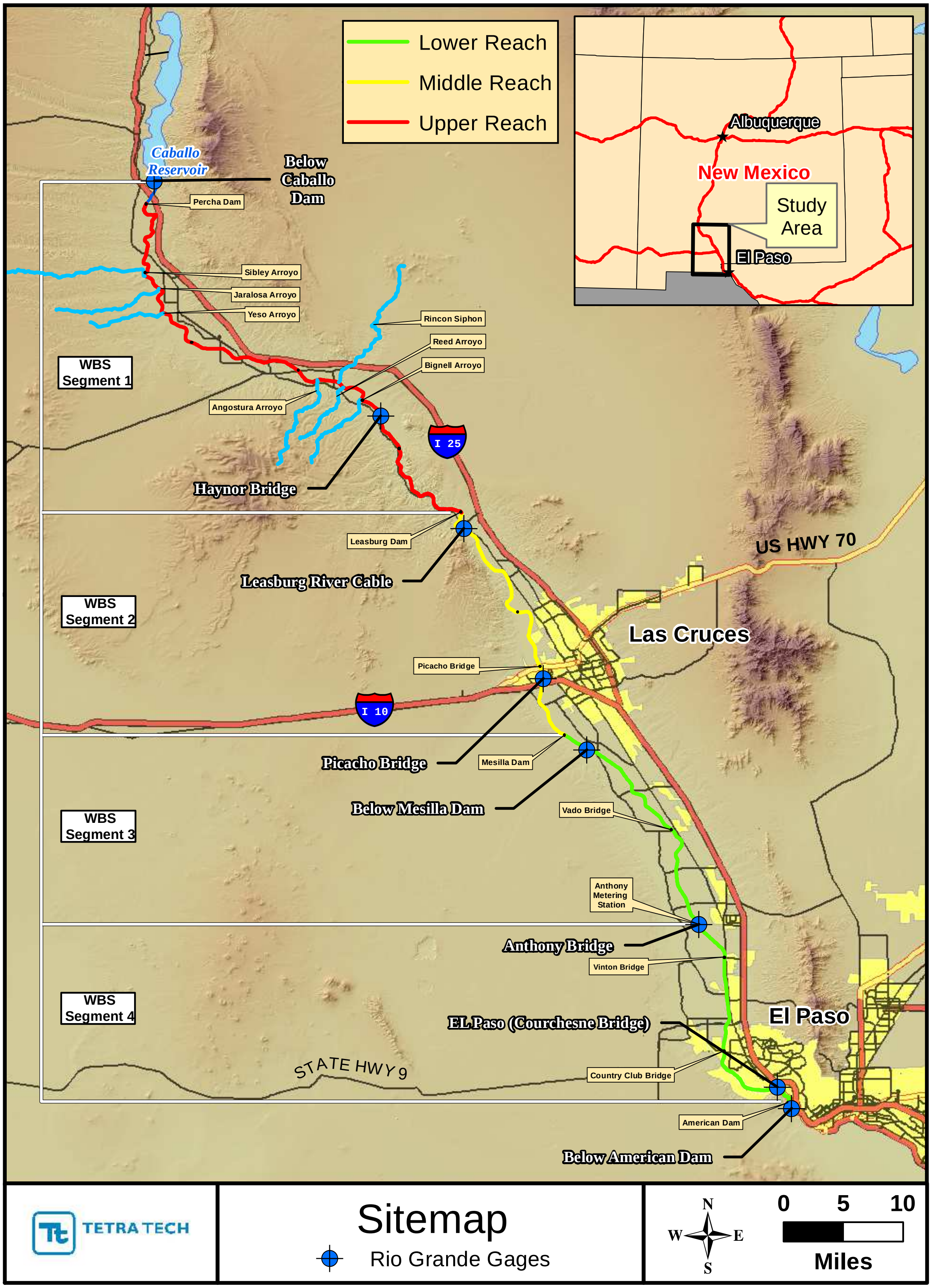


Figure 1. Location of the Rio Grande Canalization Project (adapted from USACE, 2007)

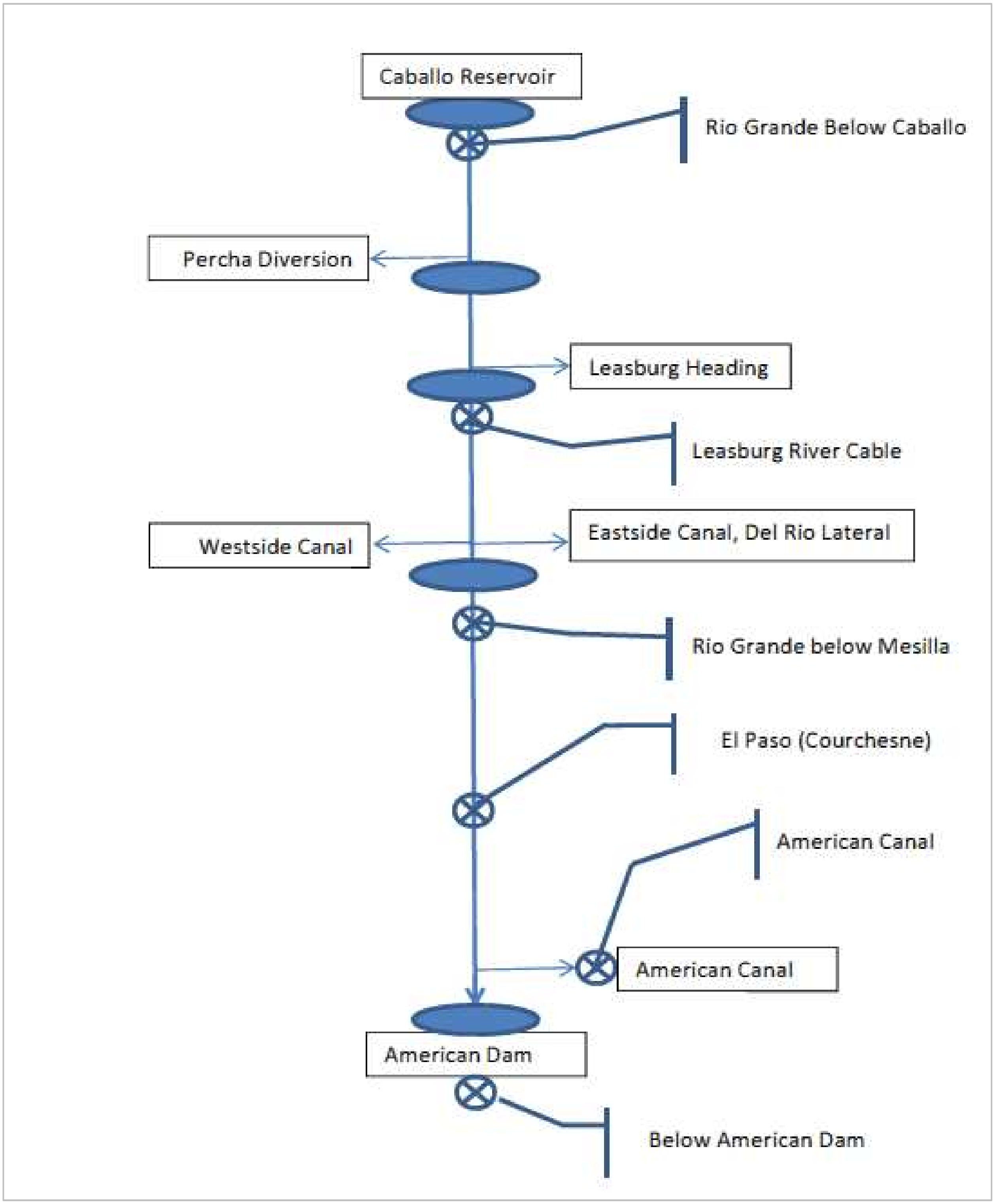


Figure 2. HEC-RAS Model Coverage and Key Locations

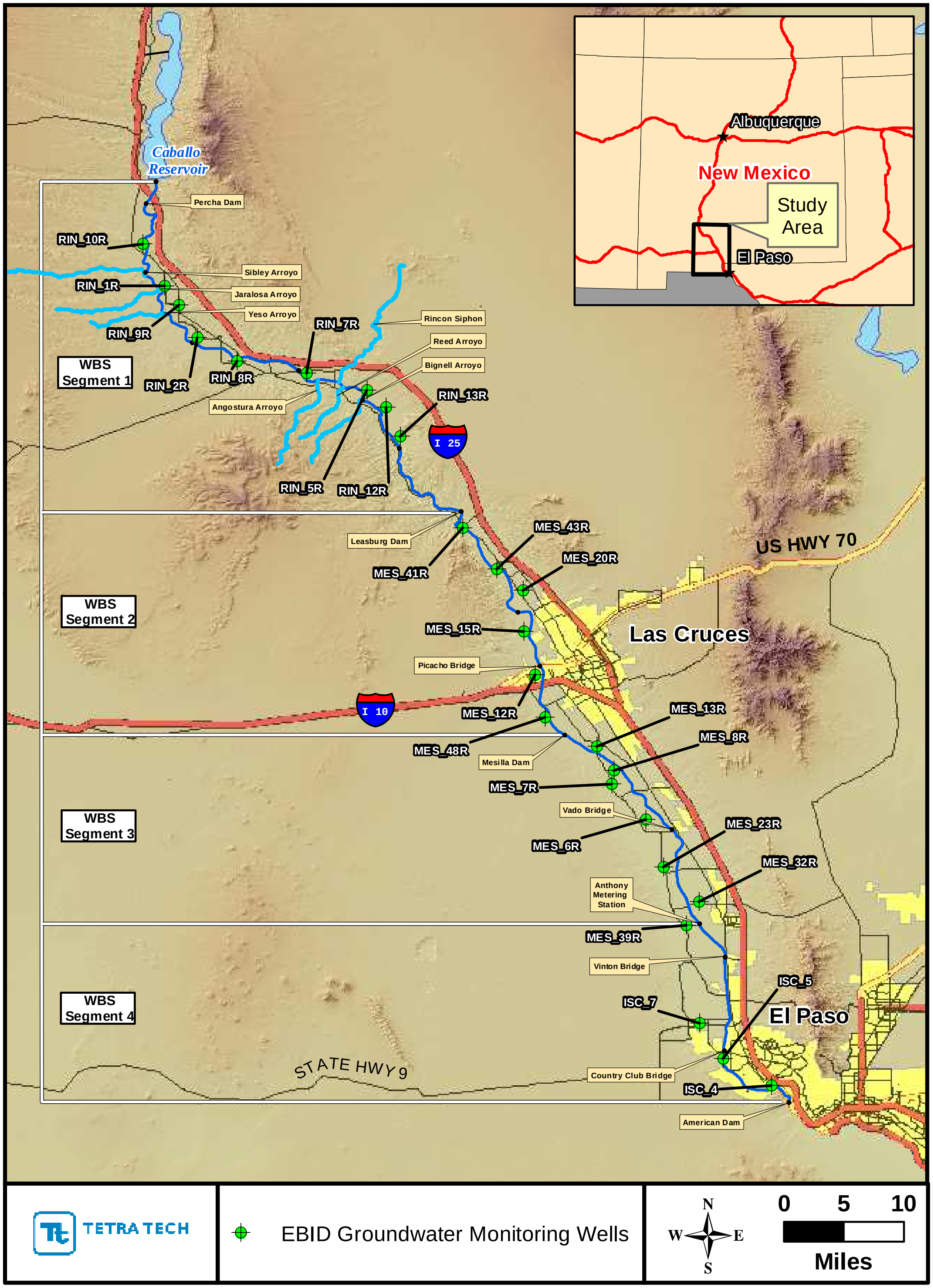


Figure 3. Groundwater Monitoring Well Locations

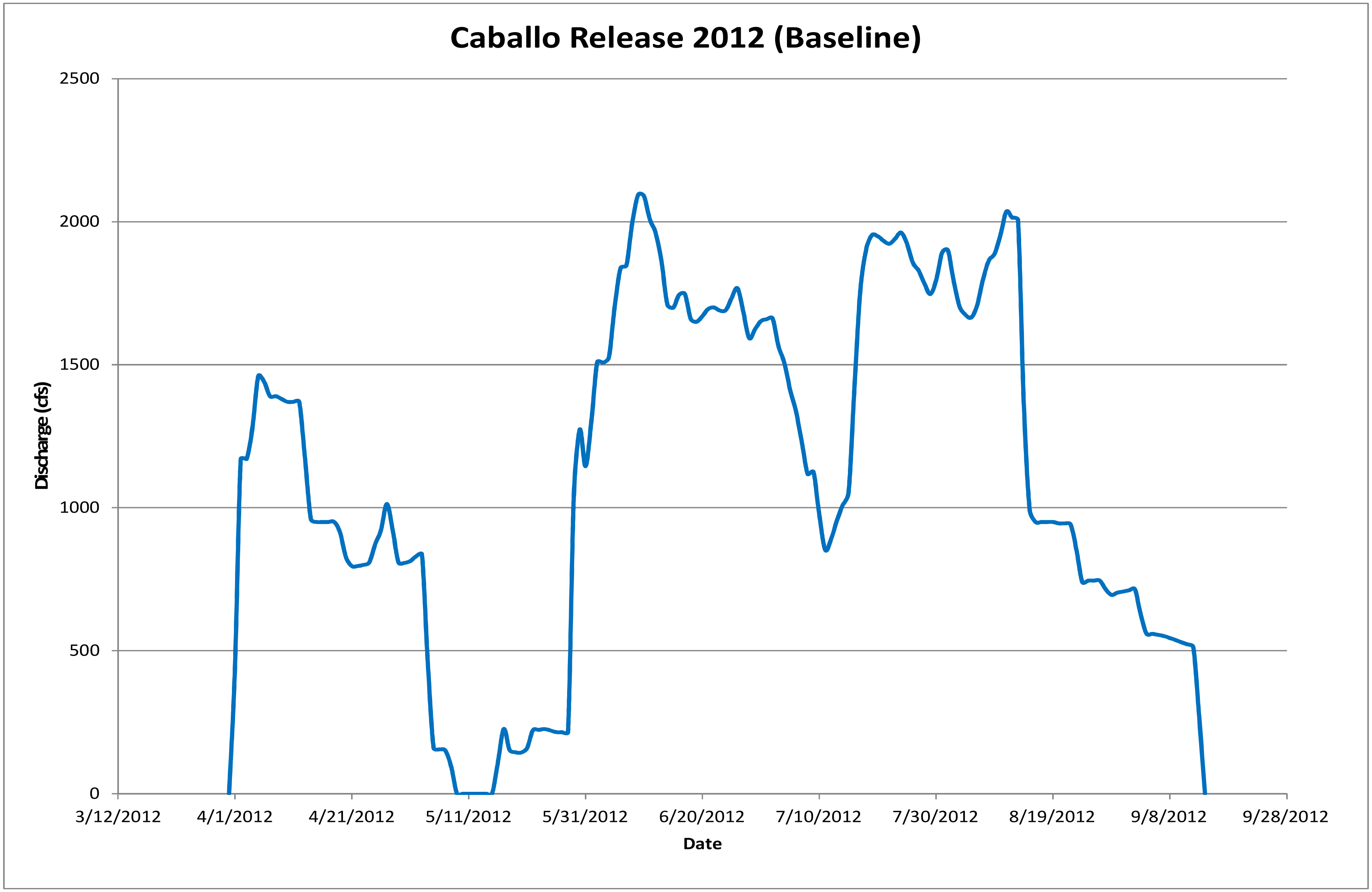
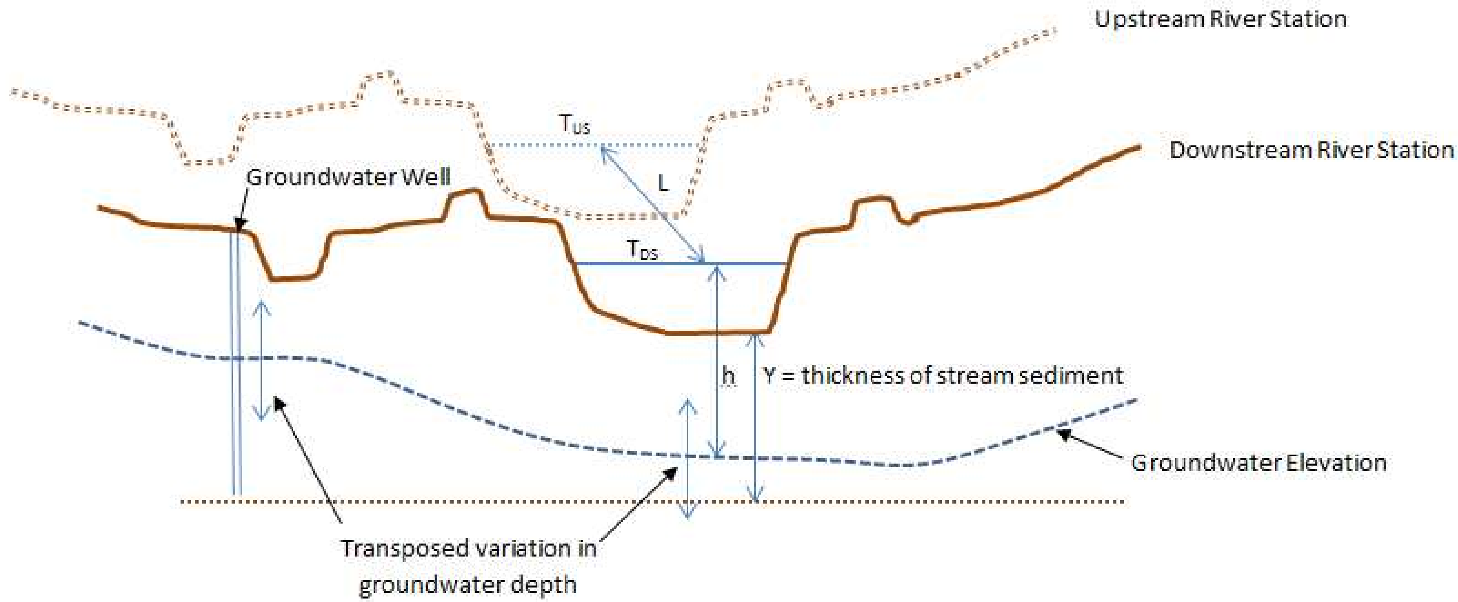


Figure 4. Caballo Release 2012 (Baseline) hydrograph, provided by Rio Grande Project Allocation Committee



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 5. HEC-RAS Groundwater Interflow Schematic

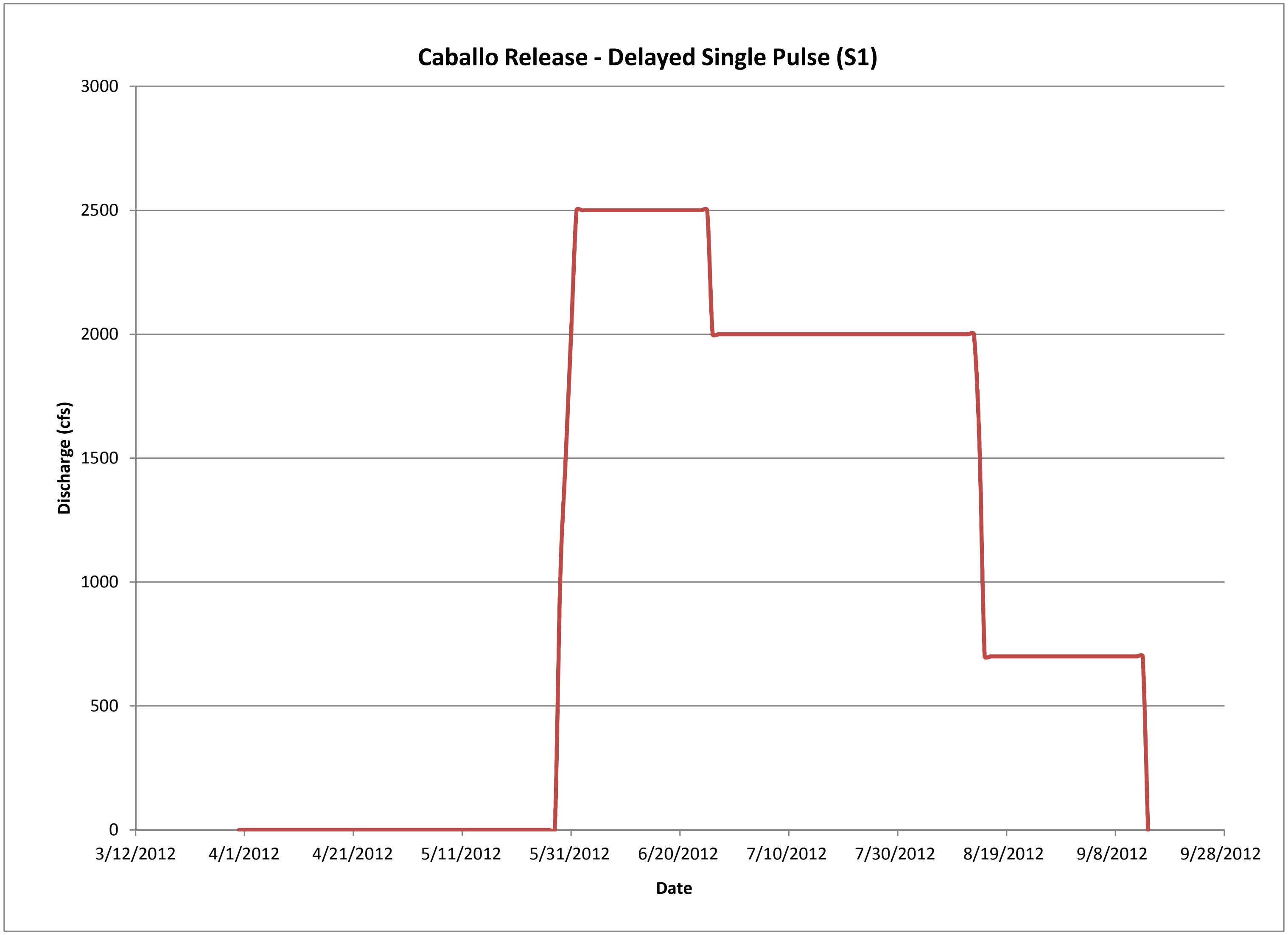


Figure 6. S1 (Delayed Single-pulse) hydrograph, Provided by Rio Grande Project Allocation Committee

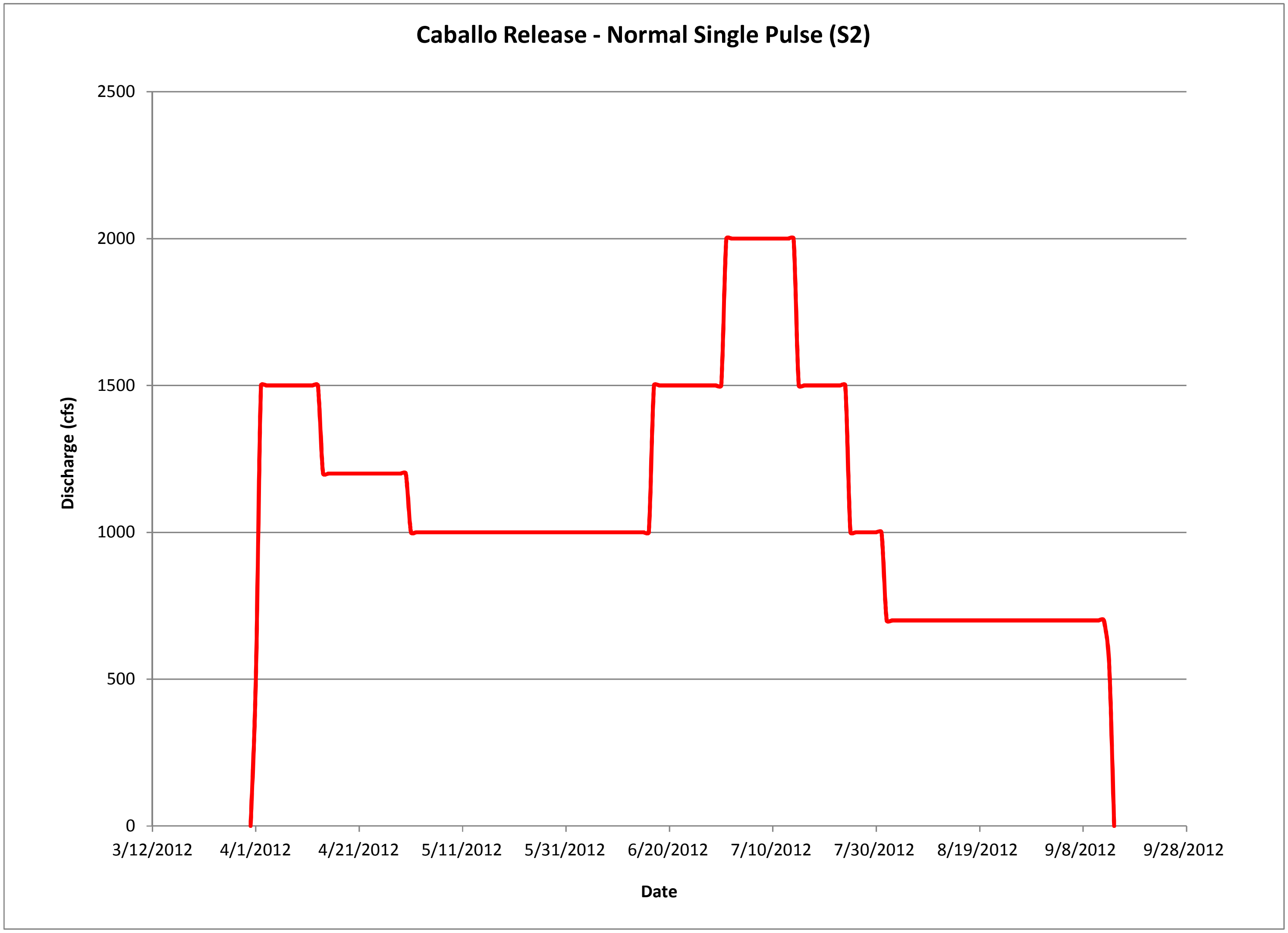


Figure 7. S2 (Normal Single-pulse) Hydrograph, provided by Rio Grande Project Allocation Committee

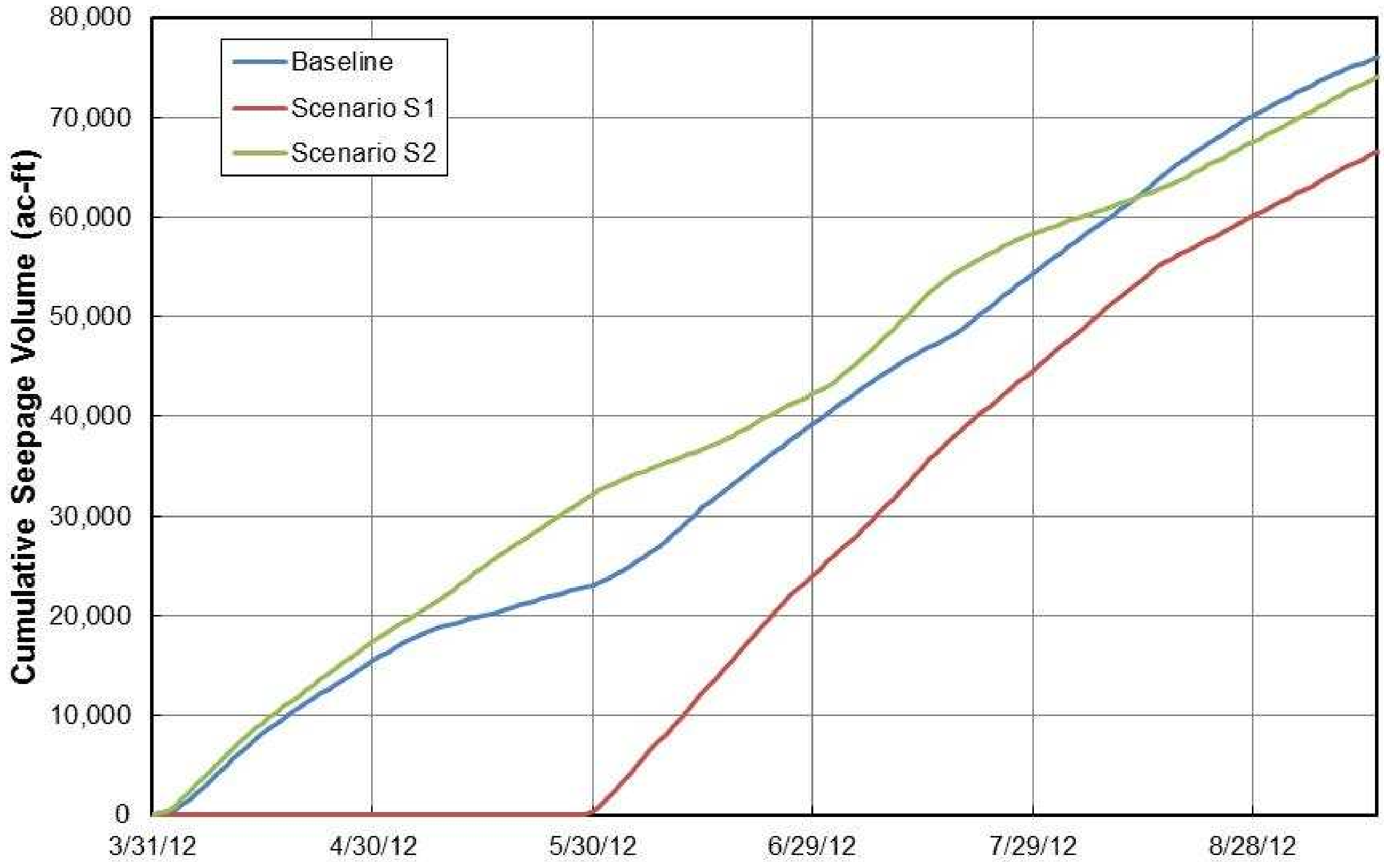
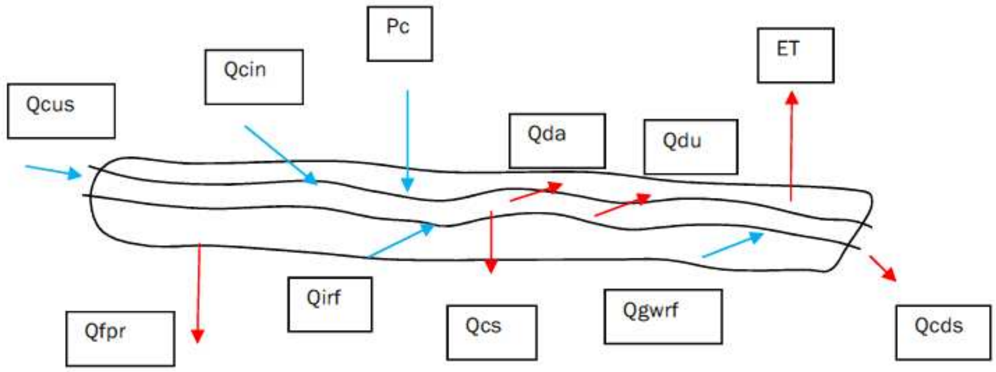


Figure 8. Cumulative seepage volumes predicted by the HEC-RAS models for baseline 2012 conditions, and under the Scenario S1 (delayed single pulse) and Scenario S2 (normal single pulse) releases



For a given time Δt, the channel water budget equation is:

$$\Delta S_{ic} = \left(Q_{cus} + P_c + Q_{cin} + Q_{irf} + Q_{gwrf}\right) - \left(Q_{cds} + Q_{cs} + Q_{fpr} + ET + Q_{da} + Q_{du}\right)$$

where ΔS_{ic} = in-channel change in storage, Q_{cus} = upstream dam release or inflow, P_c = precipitation, Q_{cin} = in-channel stormwater inflow, Q_{irf} = irrigation return flow, Q_{gwrf} = groundwater return flow, Q_{cds} = downstream channel outflow, Q_{cs} = channel seepage, Q_{fpr} = floodplain recharge, ET = evapotranspiration, Q_{da} = diversions authorized, and Q_{du} = diversions unauthorized.

Figure 9. RGCP-scale Channel Water Budget Equation and Schematic Diagram (as provided in the Scope of Work) (USIBWC, 2012a)

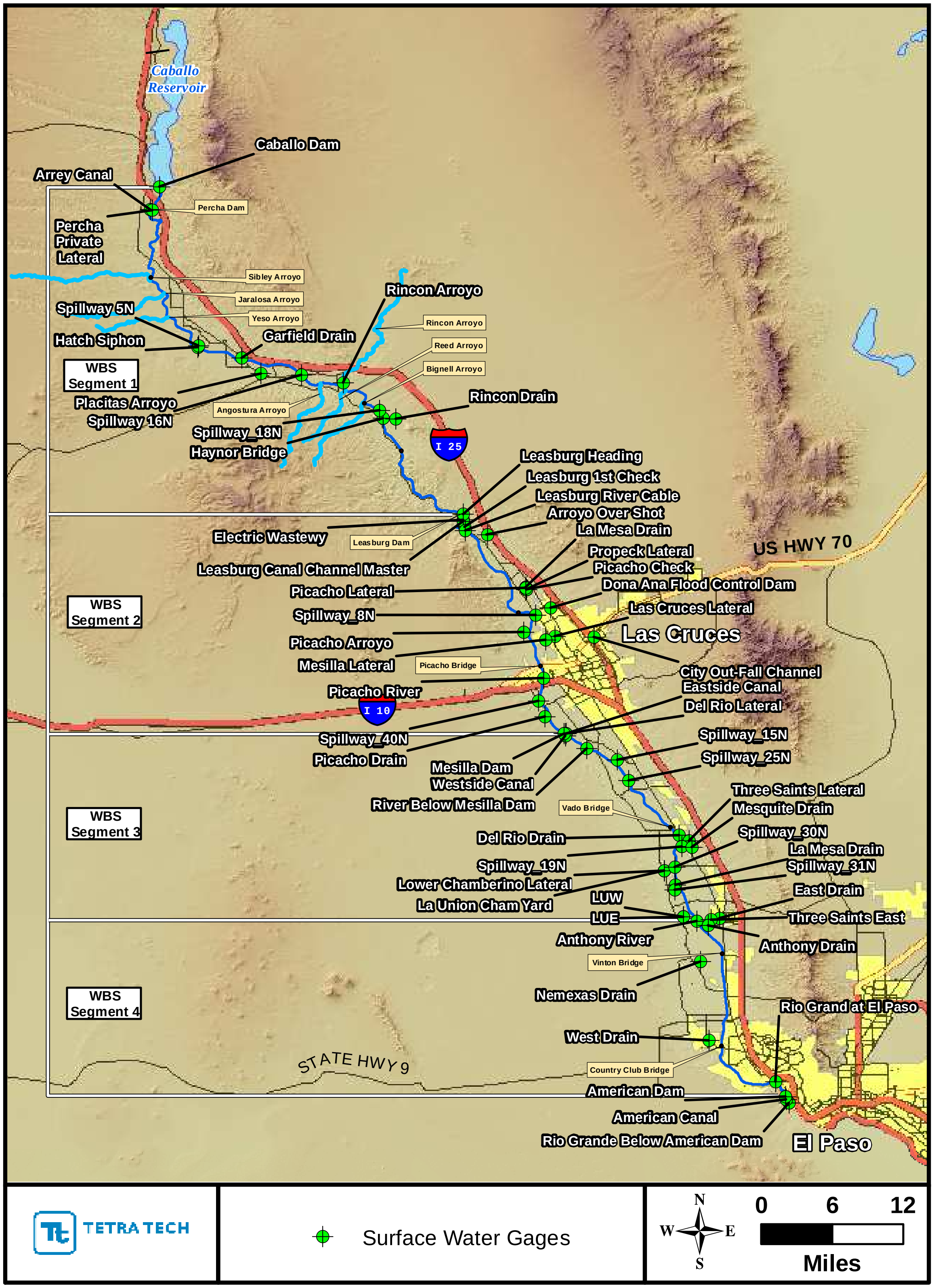


Figure 10. Surface-water Gage Locations

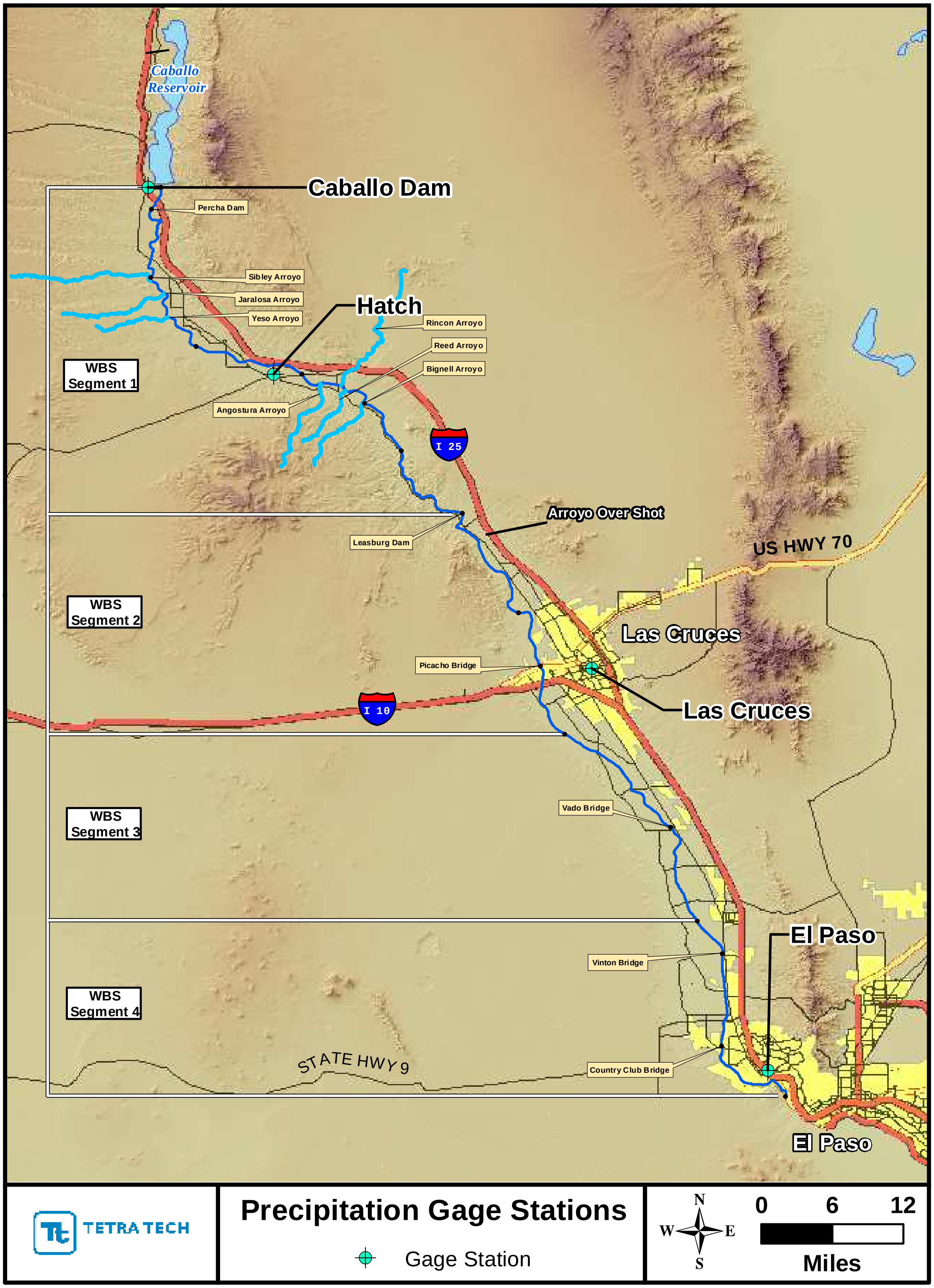


Figure 11. Precipitation Gage Locations

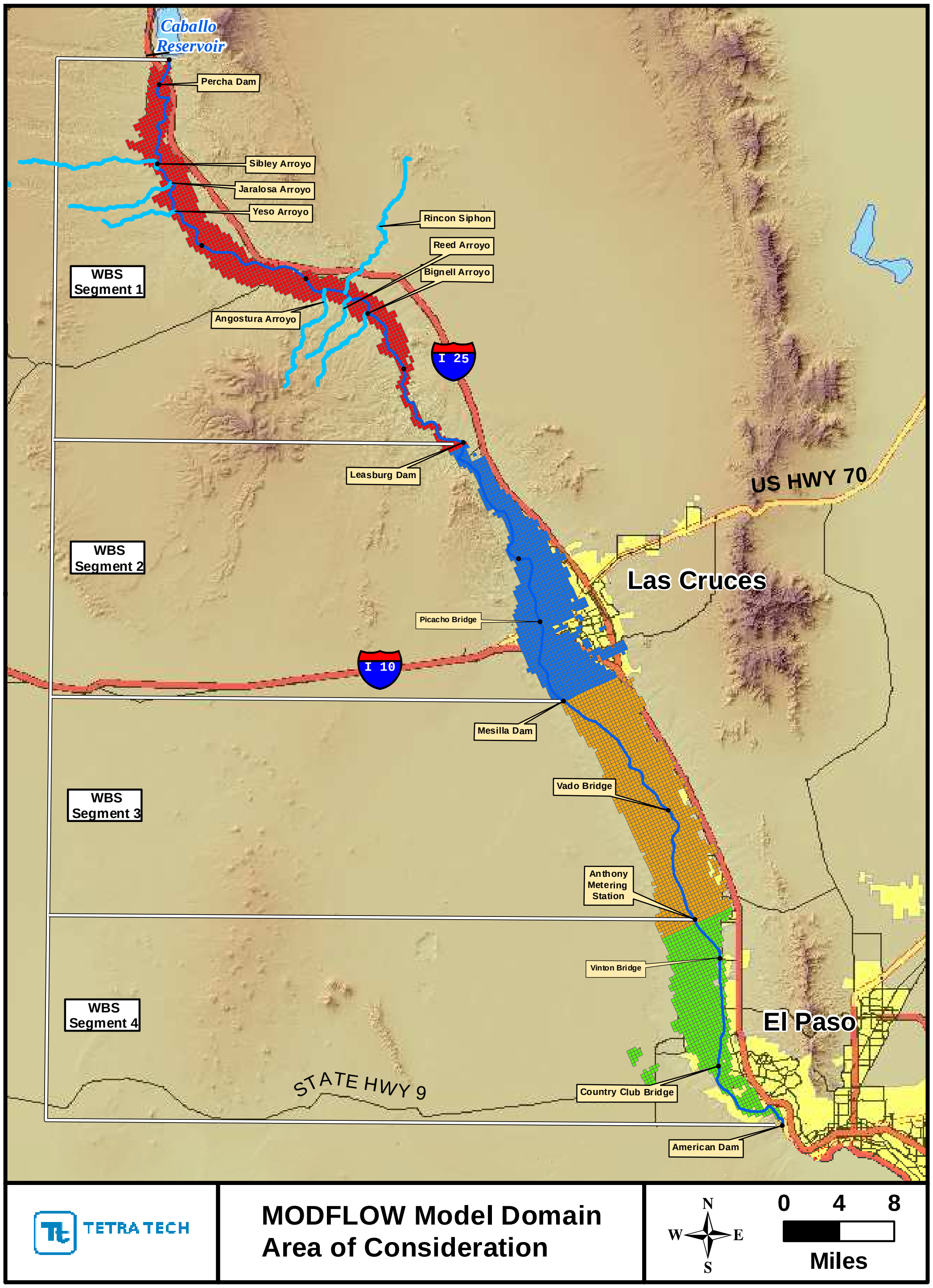
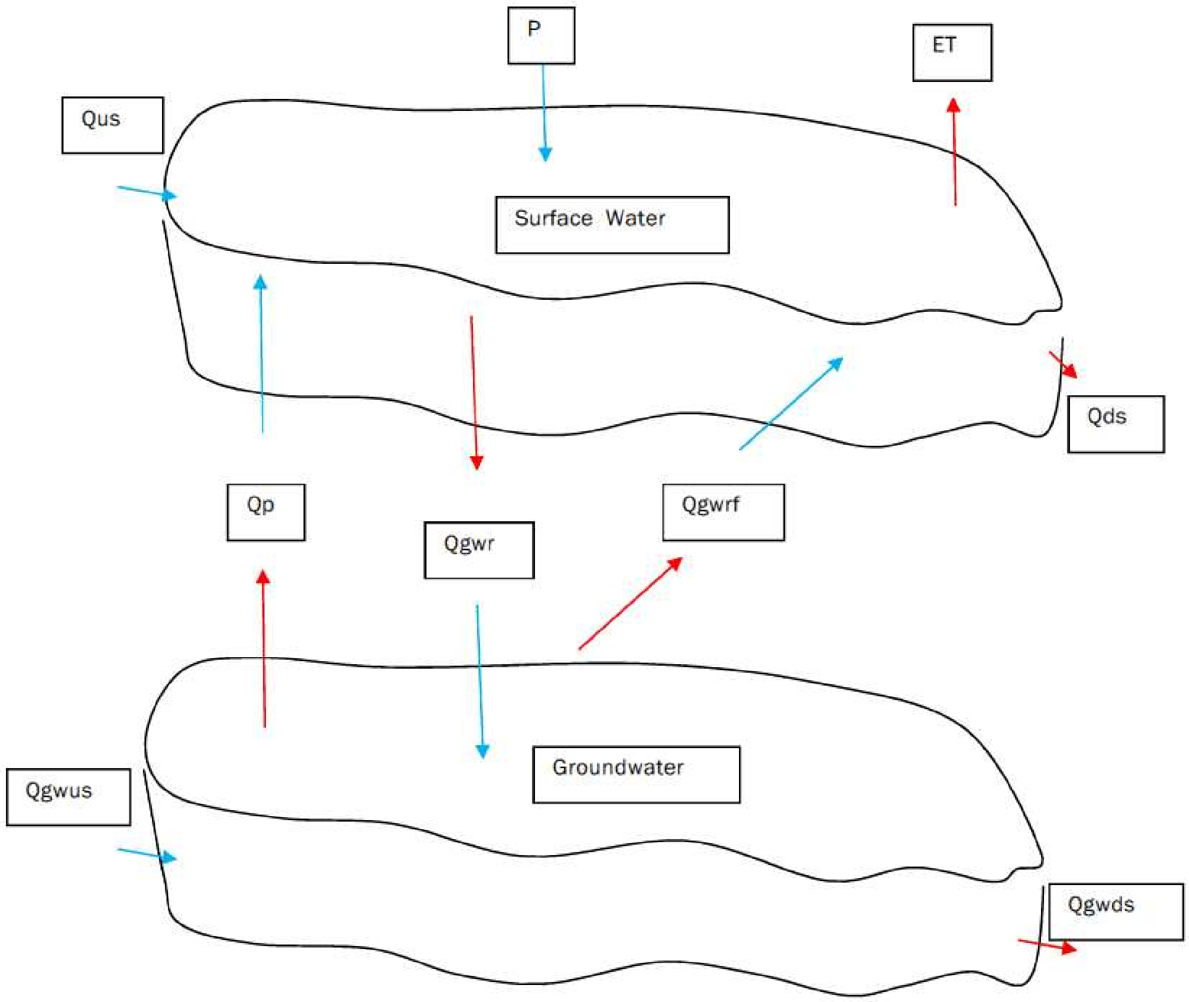


Figure 12. Geographic zones representing the portion of the MODFLOW model domain that were used to extract groundwater fluxes from the model

For the RGCP-scale channel water budget, the fluxes were limited to the RGCP channel and adjacent floodplain (between the levees). For the local-basin scale water budget, the fluxes were extracted from the entire domain shown on the figure.



For a given time Δt, the equation for the surface water budget is:

$$\Delta S_{sw} = \left(Q_{us} + P + Q_p + Q_{gwrf}\right) - \left(Q_{ds} + Q_{gwr} + ET\right)$$

where ΔS_{sw} = change in surface water storage, Q_{us} = upstream dam release, P = precipitation, Q_p = pumping, Q_{gwrf} = groundwater return flow, Q_{ds} = downstream channel outflow, Q_{gwr} = groundwater recharge and ET = evapotranspiration.

For a given time Δt, the equation for the groundwater budget is:

$$\Delta S_{gw} = \left(Q_{gwus} + Q_{gwr}\right) - \left(Q_p + Q_{gwrf} + Q_{gwds}\right)$$

where ΔS_{gw} = change in vadose zone and groundwater storage, Q_{gwus} = upstream groundwater inflow, Q_{gwr} = groundwater recharge, Q_p = pumping, Q_{gwrf} = groundwater return flow and Q_{gwds} = downstream groundwater outflow.

Figure 13. Local-basin-scale Water Budget Equation and Schematic Diagram (as provided in the Scope of Work) (USIBWC, 2012a)

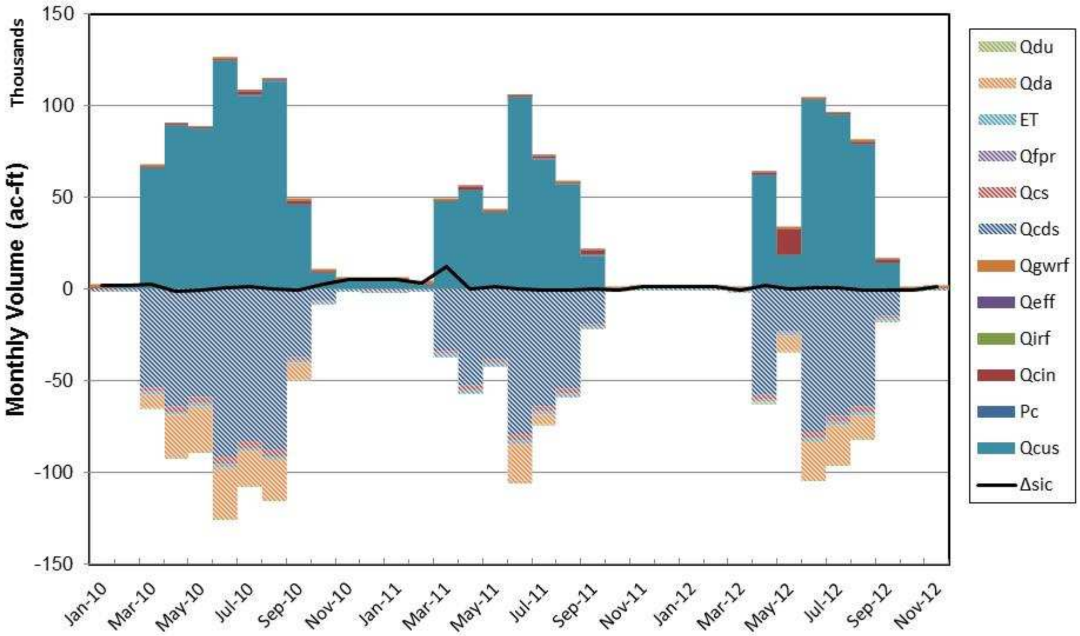


Figure 14. **Stacked bar chart showing monthly volumes of the RGCP-scale channel water budget analysis and the resulting monthly change in-channel storage in Segment 1**

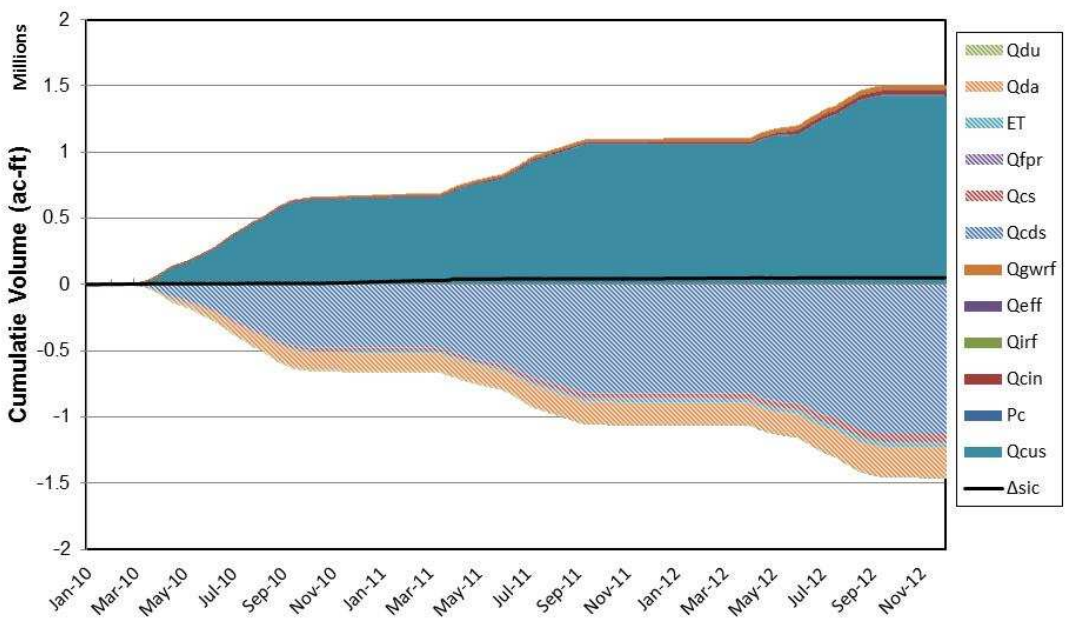


Figure 15. **Stacked bar chart showing cumulative volumes of the RGCP-scale channel water budget analysis and the resulting cumulative change in-channel storage in Segment 1**

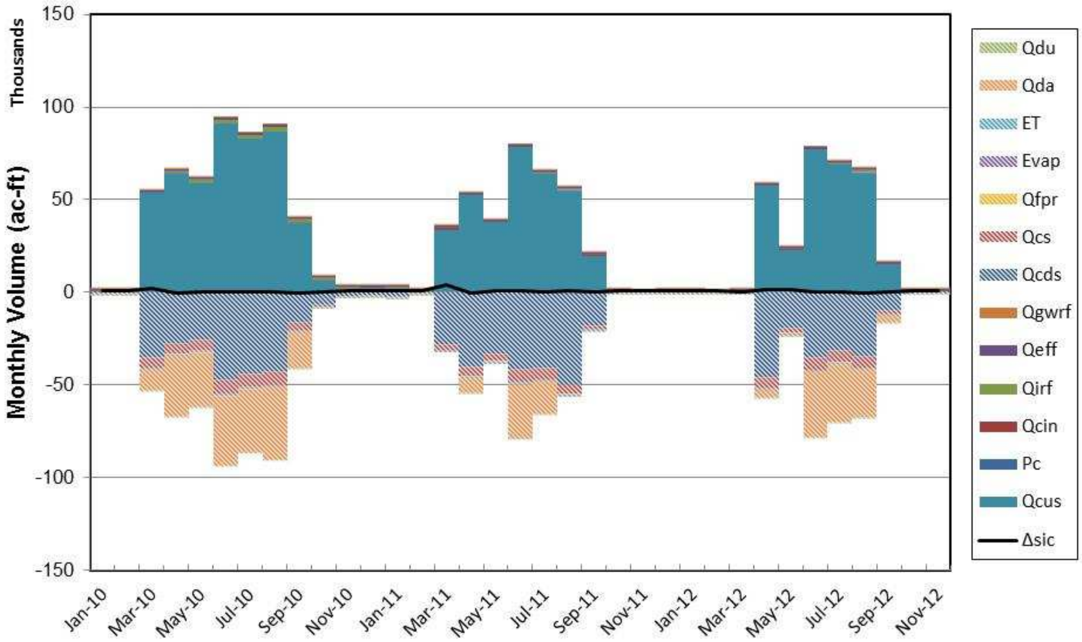


Figure 16. **Stacked bar chart showing monthly volumes of the RGCP-scale channel water budget analysis and the resulting monthly change in-channel storage in Segment 2**

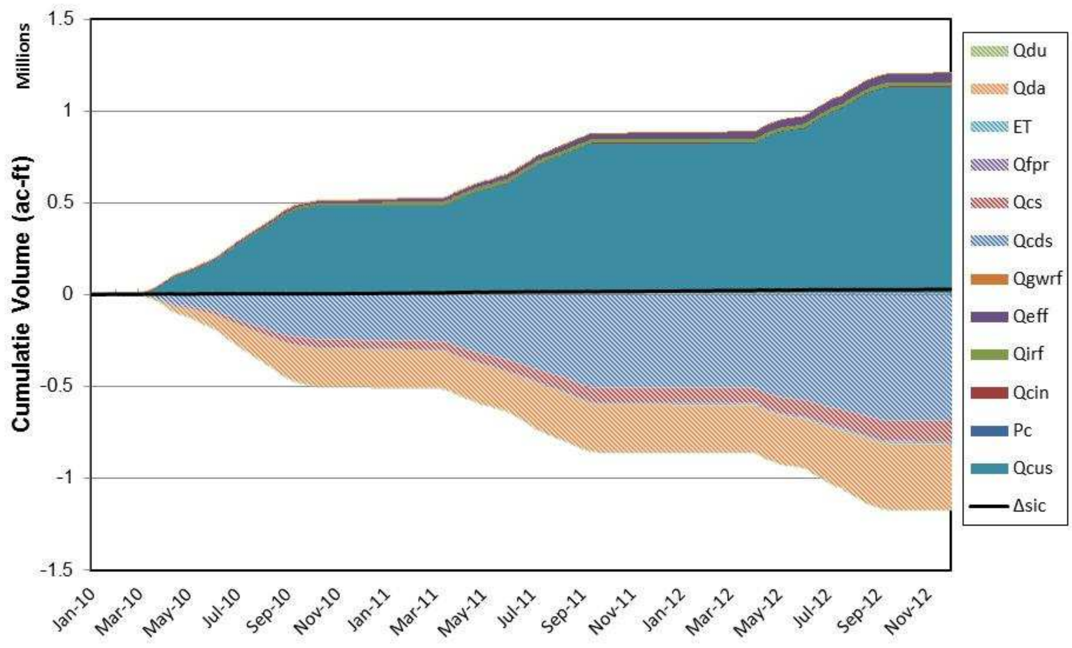


Figure 17. **Stacked bar chart showing cumulative volumes of the RGCP-scale channel water budget analysis and the resulting cumulative change in-channel storage in Segment 2**

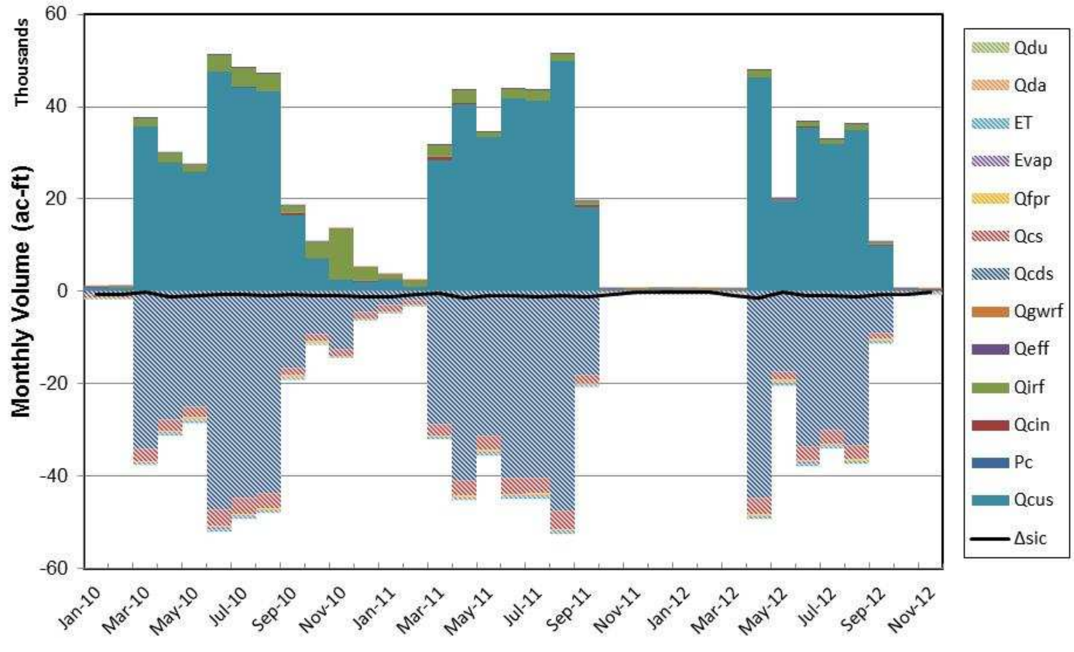


Figure 18. **Stacked bar chart showing monthly volumes of the RGCP-scale channel water budget analysis and the resulting monthly change in-channel storage in Segment 3**

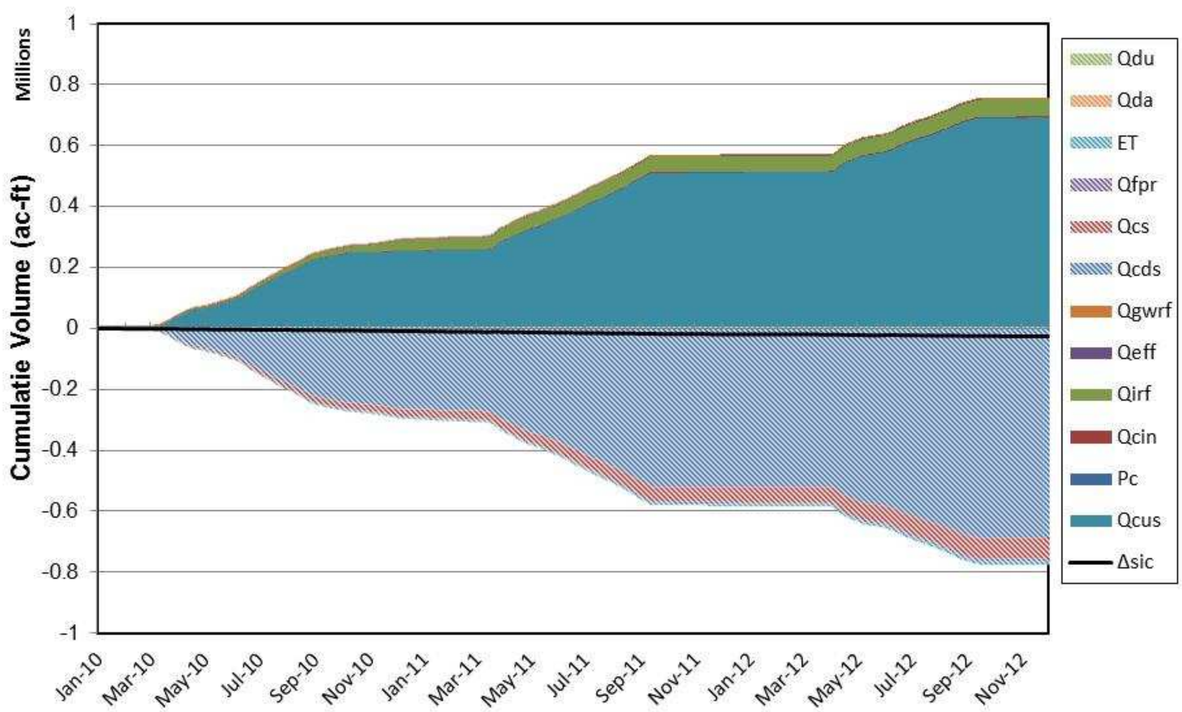


Figure 19. **Stacked bar chart showing cumulative volumes of the RGCP-scale channel water budget analysis and the resulting cumulative change in-channel storage in Segment 3**

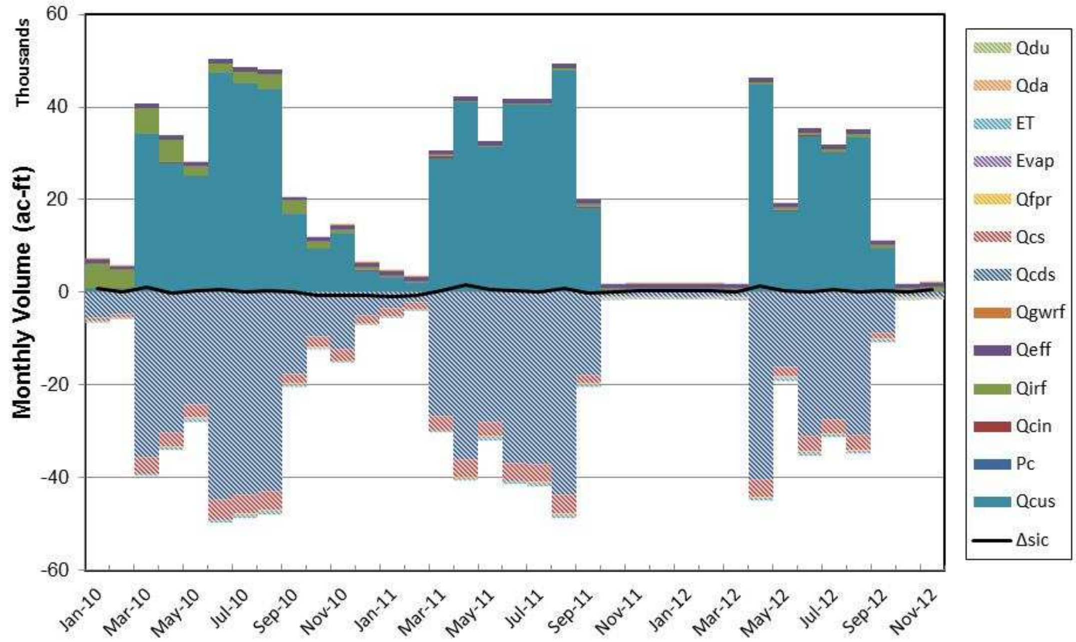


Figure 20. **Stacked bar chart showing monthly volumes of the RGCP-scale channel water budget analysis and the resulting monthly change in-channel storage in Segment 4**

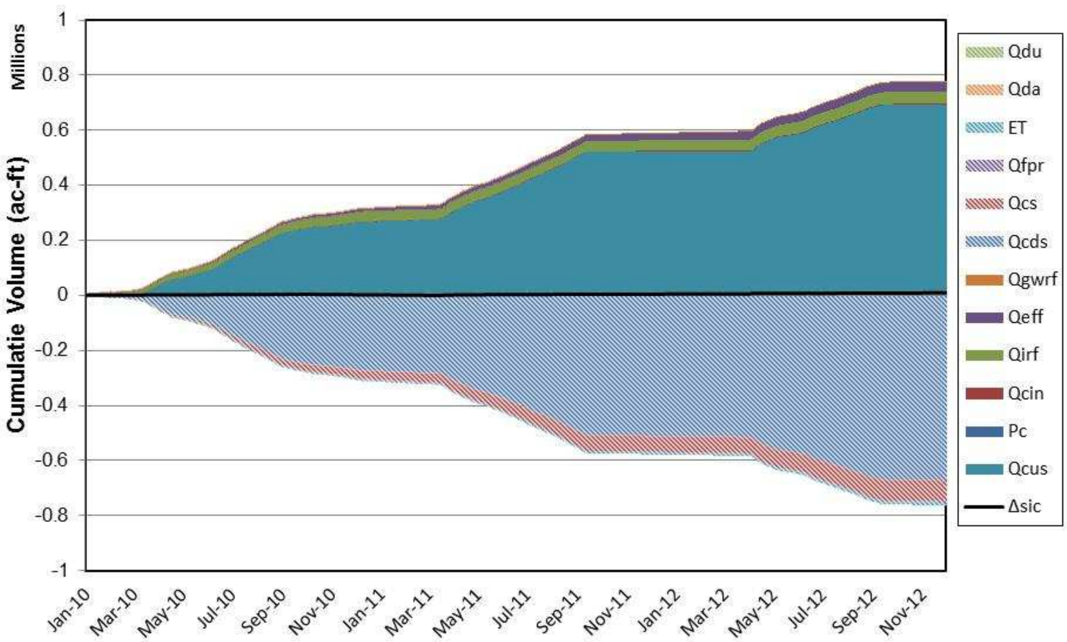


Figure 21. **Stacked bar chart showing cumulative volumes of the RGCP-scale channel water budget analysis and the resulting cumulative change in-channel storage in Segment 4**

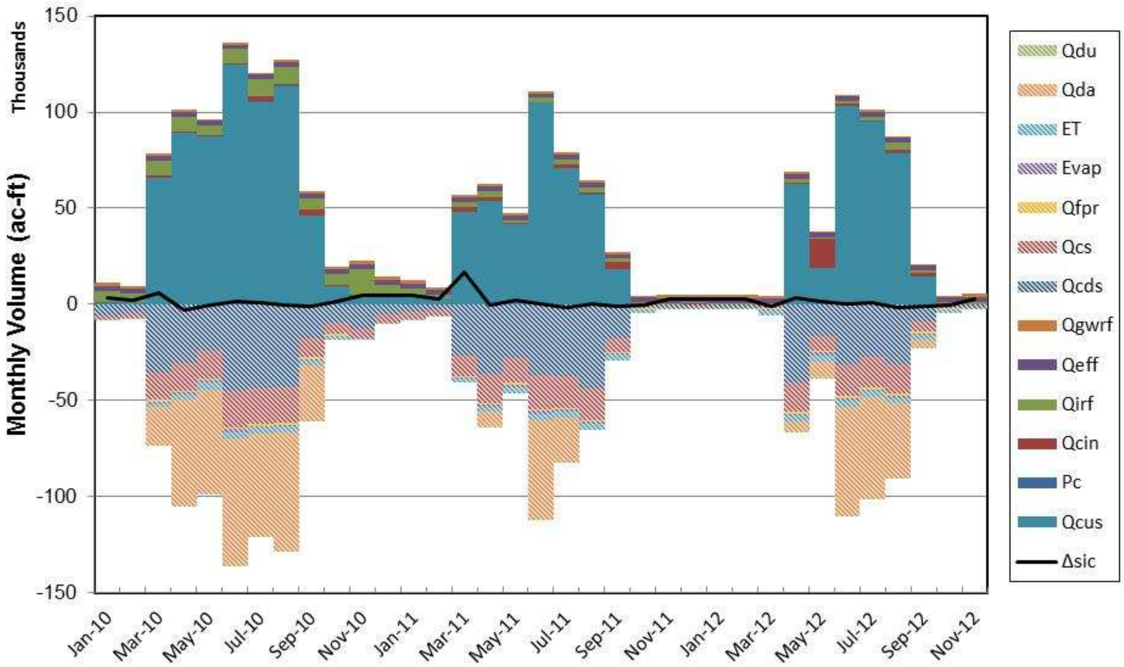


Figure 22. **Stacked bar chart showing monthly volumes of the RGCP-scale channel water budget analysis and the resulting monthly change in-channel storage in the overall RGCP**

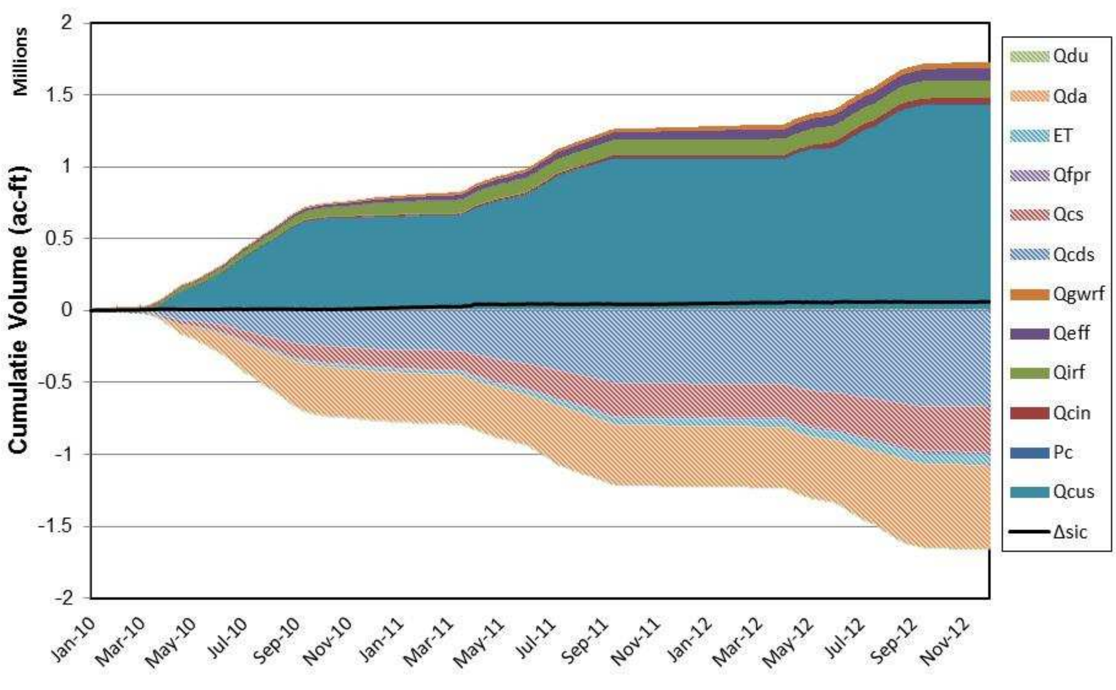


Figure 23. **Stacked bar chart showing cumulative volumes of the RGCP-scale channel water budget analysis and the resulting cumulative change in-channel storage in the overall RGCP**

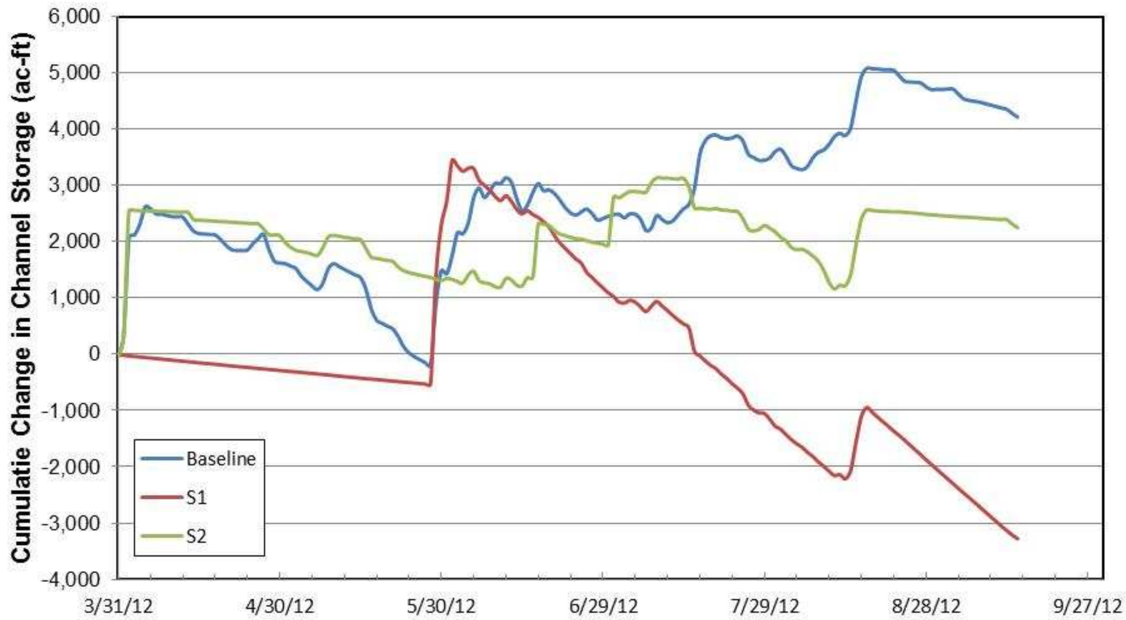


Figure 24. **Cumulative change in-channel storage during 2012 under baseline (actual) conditions and under the hypothetical release scenarios (Scenarios S1 and S2) – Segment 1**

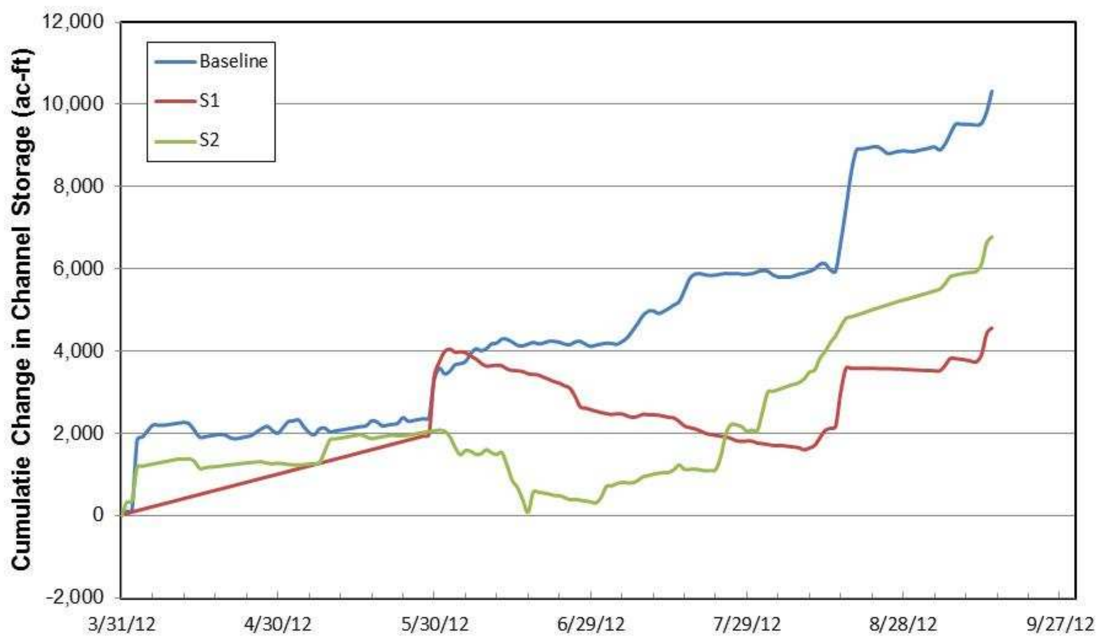


Figure 25. **Cumulative change in-channel storage during 2012 under baseline (actual) conditions and under the hypothetical release scenarios (Scenarios S1 and S2) – Segment 2**

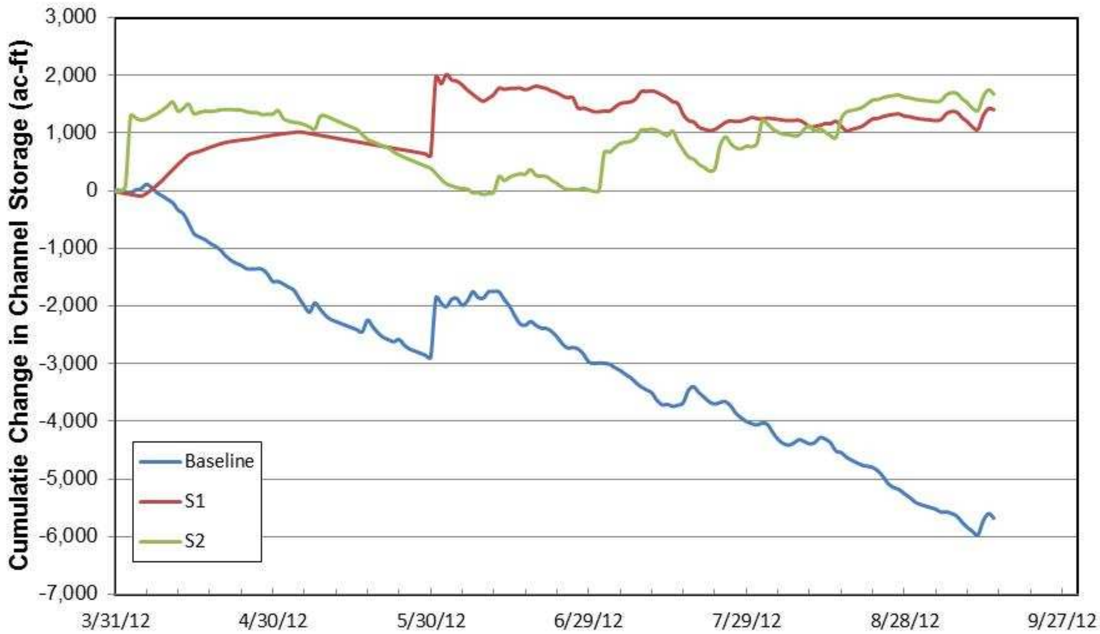


Figure 26. **Cumulative change in-channel storage during 2012 under baseline (actual) conditions and under the hypothetical release scenarios (Scenarios S1 and S2) – Segment 3**

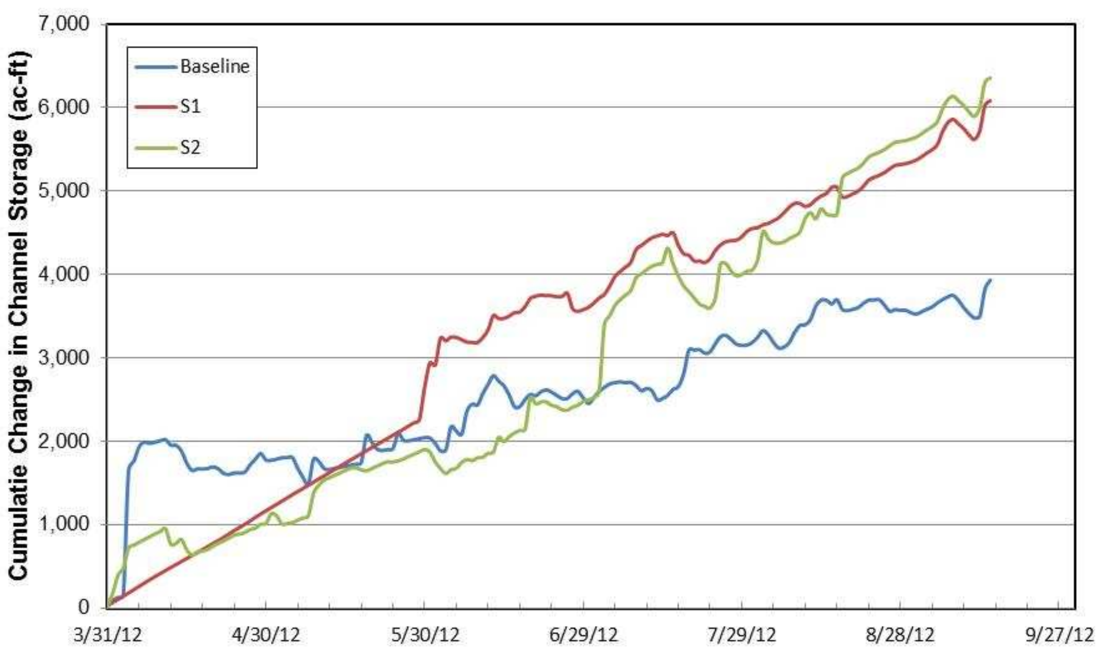


Figure 27. **Cumulative change in-channel storage during 2012 under baseline (actual) conditions and under the hypothetical release scenarios (Scenarios S1 and S2) – Segment 4**

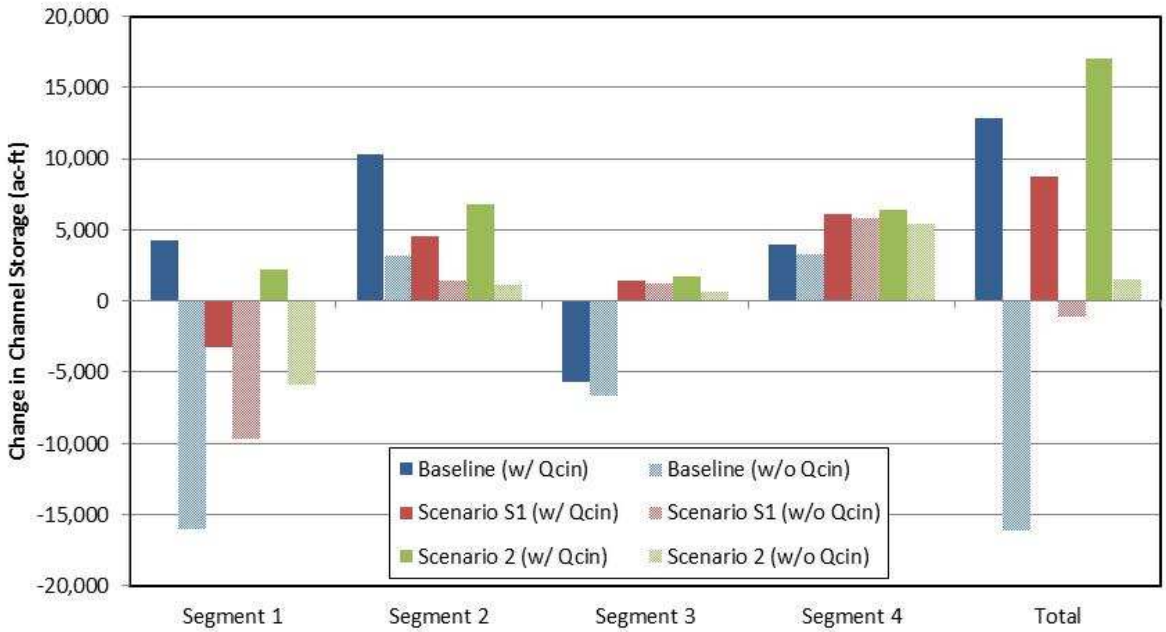


Figure 28. **Total change in-channel storage with and without the Q_{cin} component at the end of the 2012 release under baseline (actual) conditions and under the hypothetical release scenarios (Scenarios S1 and S2)**

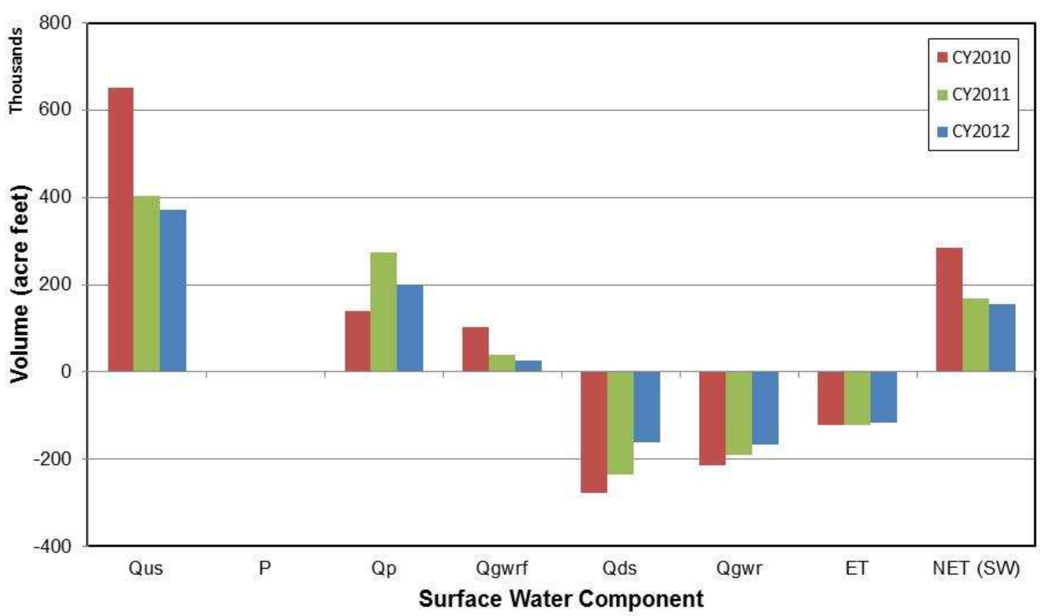


Figure 29. **Annual and total volume for each component of the local-basin-scale surface-water budget**

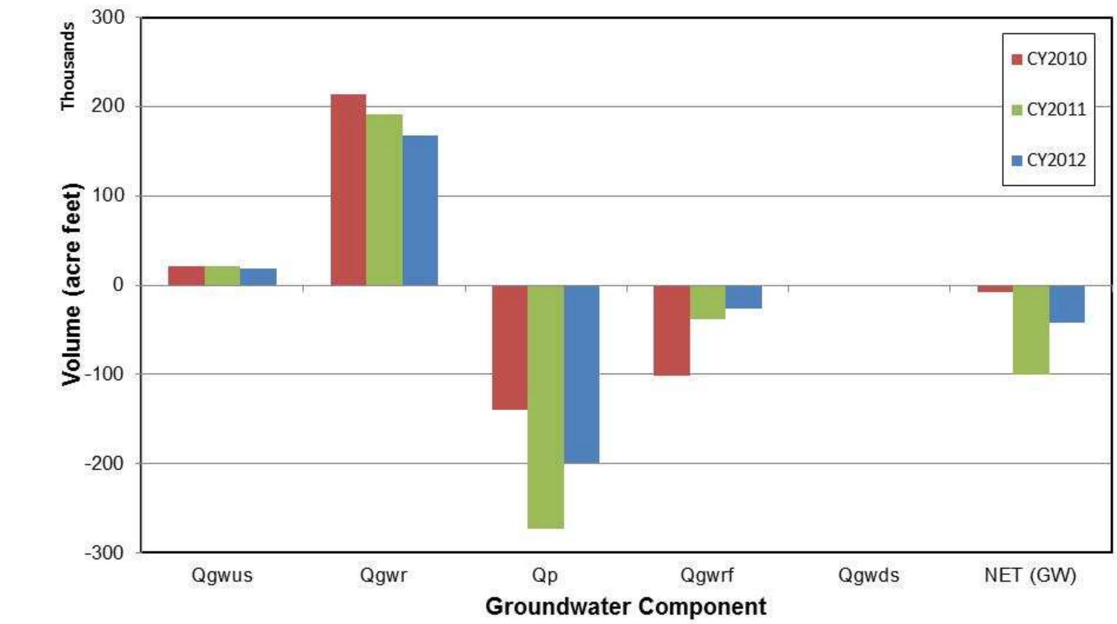


Figure 30. **Annual and total volume for each component of the local-basin-scale groundwater budget**

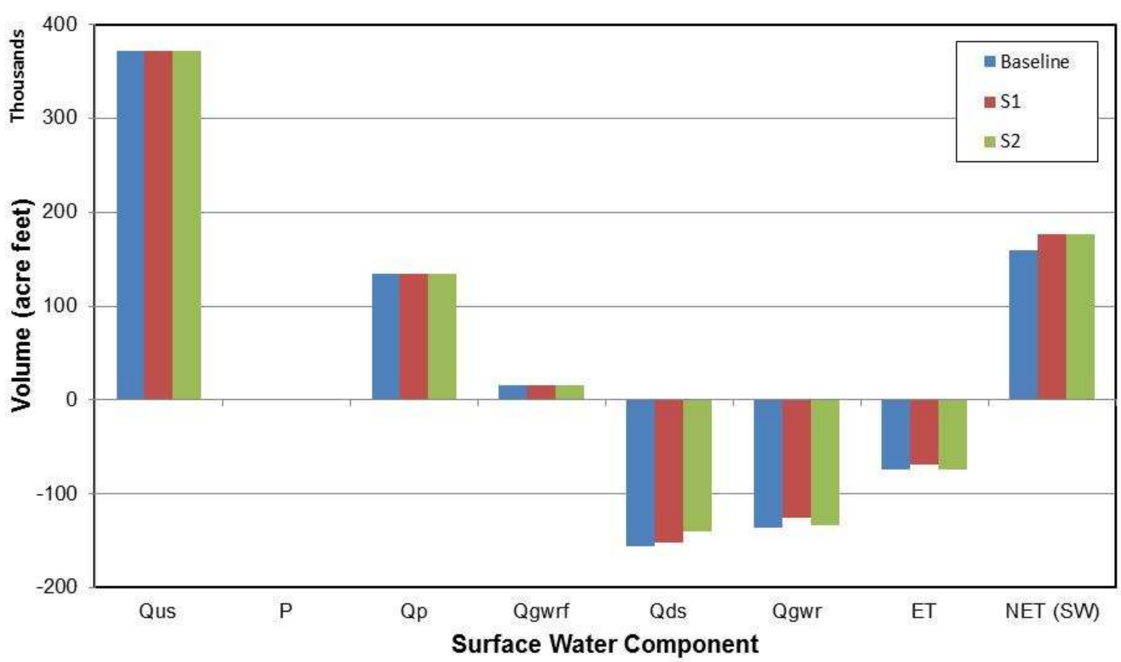


Figure 31. **Comparison of the local-basin-scale surface-water components under baseline (actual) conditions and under Scenarios S1 and S2**

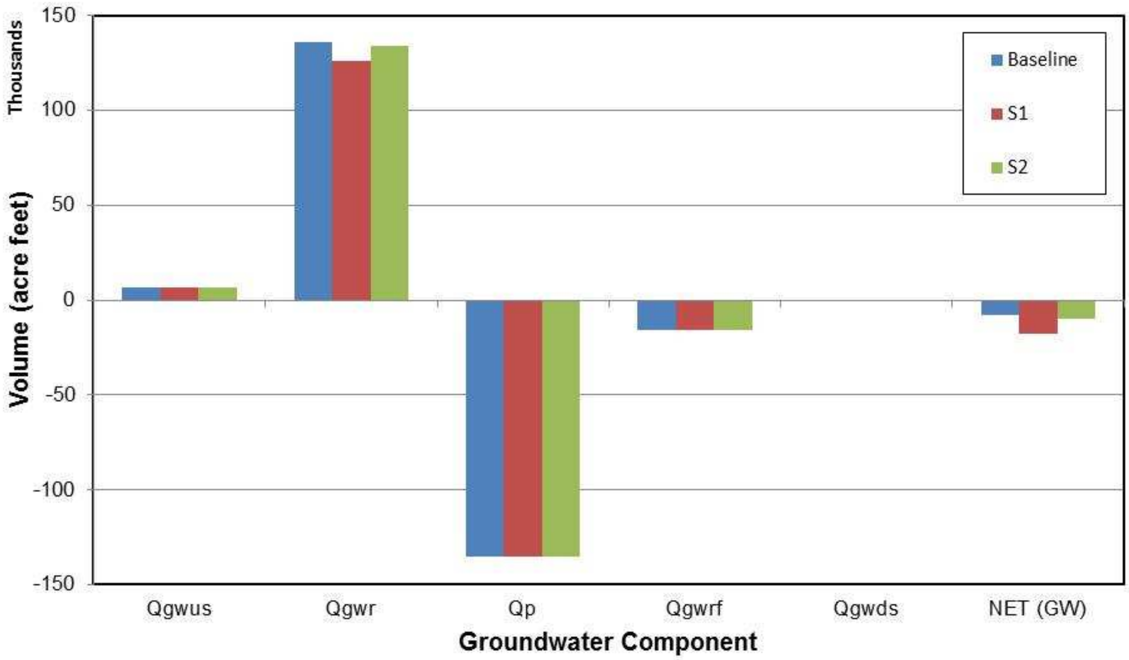


Figure 32. **Comparison of the local-basin-scale groundwater components under baseline (actual) conditions and under Scenarios S1 and S2**