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

Appendix I
Lake, Channel, and Vadose Zone Evaporation

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1.0 LAKE, CHANNEL, AND VADOSE-ZONE EVAPORATION ASSESSMENTS

An assessment of lake, channel, and vadose (unsaturated) zone evaporation, relative to their impact on the Rio Grande Water Budget, was conducted for the study reach. The trend in lake evaporation was, in large part, based upon data for the Elephant Butte Reservoir and the Caballo Reservoir. Open-water channel evaporation along the RGCP was based on estimates provided in previous studies. 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 conducting a detailed Internet literature search of vadose-zone processes.

1.1 LITERATURE SEARCH

The following documents represent the principal sources that were acquired from the technical literature that were consulted during the assessment of lake, channel, and vadose-zone evaporation along the RGCP:

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- Middle Rio Grande Endangered Species Collaborative Program, Water Acquisition and Management Subcommittee, 2004, "Position Paper: Reservoir Evaporation Water"
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- R. L. Snyder, K. Bali, F. Ventura, and H. Gomez-MacPherson, Journal of Irrigation and Drainage Engineering, November/December 2000, "Estimating Evaporation from Bare or Nearly Bare Soil"
- R. T. RAJU and K. JEMNO, IAHS Publication No. 212, 1993, "Unsaturated Flow in an Evaporative Regime and Cation Exchange in Soils"
- Rio Grande Project (RGP) Allocation Committee, 2012, "Analysis of River Conveyance Efficiency for Initial Release of Project Water for Delivery to Acequia Madre Canal in 2012"
- Steve Deverel, et al., Desert Research Institute, Nevada System of Higher Education, 2005, "Groundwater Evaporation Estimates Using Stable Isotope and Chloride Data, Yelland Playa, Spring Valley, Nevada"
- Terry A. Howell, Ph.D., P.E. and Steven R. Evett, Ph.D., United States Department of Agriculture, Agricultural Research Service, 2004, "the Penman-Monteith Method"
- Thomas Harter and Jan W. Hopmans, 2004, "Role of Vadose-Zone Flow Processes in Regional-Scale Hydrology: Review, Opportunities and Challenges"
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- U.S. Environmental Protection Agency, 1998, "Estimation of Infiltration Rate in the Vadose Zone: Compilation of Simple Mathematical Models, Volumes 1 and 2"
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- United States Bureau of Reclamation, 2008, "Evapotranspiration Toolbox for the Middle Rio Grande"
- United States Bureau of Reclamation, 2009, "Elephant Butte Reservoir Five-year Operational Plan, Biological Assessment"

- United States Department of Agriculture, Agricultural Research Service, Vadose Zone Journal, August 2011, "Cumulative Soil Water Evaporation as a Function of Depth and Time"
- USGS Circular 1222, 2002, "Chapter 4: The hydrologic system of the Middle Rio Grande Basin"
- Waleed Abdalati, 2011, "Water in Soils: Infiltration and redistribution, online at *http://www.colorado.edu/geography/class_homepages/geog_3511_s11/notes/Notes_8.pdf*

1.2 LAKE EVAPORATION AT ELEPHANT BUTTE AND CABALLO RESERVOIR

Pan evaporation data for 2010, 2011, and 2012 were collected from USBR Monthly Weather Report Summary Spreadsheets (EXCEL) for a single pan at Elephant Butte Reservoir and for a single pan at Caballo Reservoir. The data was located by navigating through the following web page:

http://www.usbr.gov/uc/crsp/GetSiteInfo

The pan for Elephant Butte Reservoir is located at USBR Station Number 29-2848-05, at the Elephant Butte Dam, and the pan for Caballo Reservoir is located at USBR Station Number 29-1286-08, at Caballo Dam. Using a Bureau-provided factor of 0.7, the pan-evaporation rates, in inches, were converted to lake-evaporation rates, in inches.

Average monthly evaporation rates for the two reservoirs (Figure I1) were compiled to develop a relationship between evaporation rates in the two reservoirs (Figure I2). A regression of the monthly evaporation rates between the two reservoirs (Figure I2) indicates a reasonable power relationship between the two data sets ($R^2 = 0.91$), and is defined as follows:

$$CRE = 0.0425(EBRE)^{1.187}$$

where CRE is the monthly Caballo Reservoir Evaporation (acre-feet) and EBRE is the monthly Elephant Butte Reservoir Evaporation (acre-feet). When the monthly evaporation from Elephant Butte Reservoir has been determined for a particular time period, this relationship may be used to roughly estimate the corresponding evaporation from Caballo Reservoir. It may also be used to roughly estimate and compare future evaporation rates for the two reservoirs during identical monthly time periods.

Surveys of both Elephant Butte Reservoir and Caballo Reservoir were conducted by the USBR in 2007. Relationships between pool elevations, storage volumes, and water surface areas obtained from these surveys were formulated via regression equations. Knowing the monthly average pool elevations, storage volumes, and lake surface acres for 2010, 2011, and 2012, and knowing the lake-evaporation rates, in inches, for each corresponding month of the respective year, total monthly evaporation rates, in acre-feet, were calculated. Results are summarized in Table I1.

For the year 2012, the IBWC also provided Tetra Tech with synthetic hydrographs specifying the Delayed Single Pulse Scenario (S1) and the Normal Single Pulse Scenario (S2) release rates from Caballo reservoir. Using the same procedure as described in the preceding text, drawdowns due to releases from these two synthetic hydrographs were analyzed to determine their impact on evaporation rates in both reservoirs during 2012.

Table I2 summarizes actual and predicted values of evaporation loss on a monthly basis in 2012. The values of reported storage loss due to lake evaporation at the Elephant Butte Reservoir and the Caballo

Reservoir during the referenced time periods during 2012 are in reasonable agreement with one another. It is interesting to note the table 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).

1.3 OPEN-WATER CHANNEL EVAPORATION

Open-water evaporation from channels is typically different from lake evaporation due to the difference in factors such as energy input, wind profiles, topography, and surrounding vegetation. Accordingly, since there was interest in estimating changes in evaporation losses due to delaying March 2012 releases from the reservoirs until May 2012, open-water evaporation estimates were specifically determined for March, April, and May of 2012.

On March 29, 2012, the Rio Grande Project Allocation Committee (RGPAC) prepared a Draft Report titled, "*Analysis of River Conveyance Efficiency for Initial Release of Project Water for Delivery to Acequia Madre Canal in 2012*." The report summarized anticipated conveyance efficiency for a release of Project Water from Caballo Reservoir for delivery to the Acequia Madre Canal, located approximately 2.1 miles downstream of the American Diversion Dam.

There are no measured values of open-water evaporation along the RGCP. However, as noted in the RGPAC Draft Report (2012), an estimate of open-water evaporation along the calculated 106.9-mile-long reach of the RGCP was included, as follows:

> *During March and April high winds can lead to significant water evaporation. The volume of daily evaporation is 26 acre-feet for every 0.10 inches per day of water-surface evaporation (106.9 miles x 5280 ft per mile x 240 ft x 0.10 inch/12 inches per ft /43,560 acres per sq. ft.).*

The preceding calculation, which assumes an average channel width of 240 feet, equates to 260 acre-feet of evaporation per day per inch of open-water evaporation along the channel within the project reach. Calculations indicate that during the months of March, April, and May of 2012, monthly lake evaporation losses from Elephant Butte Reservoir were 7,502 acre-feet, 8,767 acre-feet, and 11,236 acre-feet, respectively—an average of 9,168 acre-feet per month over this three-month time period. During this same three-month time period, the wetted surface area of the reservoir was approximately 10,974 acres. This equates to an average lake evaporation loss of approximately 10.0 inches per month at Elephant Butte Reservoir during the subject time period, or 0.326 inches per day. Since, as noted above, there are no measured values of open-water evaporation along the RGCP, similar data from The Upper Rio Grande Water Operations Model (URGWOM), developed by the USBR, was transposed to the study reach, resulting in an estimate that 0.055 inches, 0.121 inches, and 0.187 inches of open-water evaporation likely occurred on a daily basis along the RGCP channel during the months of March, April, and May of 2012, respectively.

Accordingly, on this basis open-water evaporation along the RGCP channel is estimated to have been about 443 acre-feet in March, about 944 acre-feet in April, and about 1,507 acre-feet in May, for an estimated total of 2,894 acre-feet of open-water evaporation from March through May 2012. This predicted amount of open-water evaporation along the RGCP channel amounts to a little more than 10.5 percent of the lake evaporation (27,505 acre-feet) that occurred per month at Elephant Butte Reservoir, but more than 53.3 percent of the lake evaporation (5,429 acre-feet) that occurred at Caballo Reservoir during this same three-month time period (see Table I1).

1.4 VADOSE (UNSATURATED) ZONE EVAPORATION

The prediction of vadose-zone evaporation along the RGCP is a complex undertaking. Without extensive field data collected over an extended time period quantifying soils types and characteristics, depth to groundwater, vegetative cover species, etc., along the RGCP, a precise quantitative prediction of vadose-zone evaporation cannot be provided other than in the form of a broad range of upper and lower limits. To this end, an important characteristic of soils types is the porosity of the in-situ soils, which affects the quantitative value of vadose-zone evaporation on a per-unit-area basis. In addition, the depth of the vadose zone is also a critical factor. Most vadose-zone evaporation typically occurs from the subsurface that extends only a short distance below the ground surface, typically only a few inches to a few feet in depth.

Research of the technical literature on vadose-zone evaporation indicates that bare-soil vadose-zone evaporation in arid and semi-arid regions, similar to the RGCP study reach, can range from as little as 0.0394 inches (1 mm) to as much as 0.3150 inches (8 mm) per day, or 1.22 inches to 9.77 inches per continuous 31-day time period, with a number of observations indicating that 0.1575 inches (4 mm) per day (i.e., 4.88 inches per continuous 31-day time period) is a typical "mean value" of vadose-zone evaporation during warmer months of the year. As expected, lower rates of vadose-zone evaporation generally occur during the coolest months of the year, while the higher rates of vadose-zone evaporation generally occur during the warmest months of the year. Rates are also dependent upon water content in the vadose zone; which, in turn, is highly dependent upon the annual source of supply. Thus, extremely arid regions, which receive little to no rainfall or surface water, will have the smallest rates of vadose-zone evaporation, regardless of the time of the year, because of the scarcity of water content in arid-region vadose zones.

For purposes of this study effort, it was assumed that (1) the near-surface soils along the RGCP study reach have average porosities, and that, (2) quantitatively, a reasonable value for an average vadose-zone evaporation rate, on a per-unit-acre basis, is the above-referenced 0.1575 inches (4 mm) per day, or 0.4067 acre-feet per acre of ground surface when extended over a continuous 31-day time period. Given the preceding assumptions, at the end of May 2012, the surface area at Elephant Butte Reservoir was about 10,797 acres; and during the month of May 2012, 11,236 acre-feet of water was lost from the reservoir due to lake evaporation. This equates to a lake evaporation rate of about 1.04 acre-feet per acre of surface area at the reservoir for this continuous 31-day time period. Correspondingly, at Caballo Reservoir the lake evaporation for this same time period was about 1.10 acre-feet per acre. Based upon these data, on a per-unit basis of surface acre the maximum expected vadose-zone evaporation is predicted to be about 39.1 percent compared to the lake evaporation that occurred at Elephant Butte

Reservoir in May 2012; and is predicted to be about 37.9 percent compared to the lake evaporation that occurred at Caballo Reservoir in May 2012. It should be kept in mind that the month of May is one of the warmer months of the year, with one of the highest open-water evaporation rates along the RGCP. However, given the range of vadose-zone evaporation rates noted in the technical literature, vadose-zone evaporation along the study reach of the Rio Grande could range from as little as 0.102 acre-feet per acre to as much as 0.814 acre-feet per acre over a continuous 31-day time period.

As stated previously, the actual volume of vadose-zone evaporation, when compared to open-water and to lake evaporation would depend greatly upon the maximum depth from which water can evaporate from the vadose zone; however, the preceding assessment does provide a *qualitative range* of what the potential vadose-zone evaporation rates might be along the RGCP study reach.

1.5 EVAPORATION SUMMARY

As shown in Table I2, 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.

Assuming average vadose-zone conditions, on a per-unit basis of surface acres vadose-zone evaporation over the continuous 31-day time period of May 2012 along the study reach of the Rio Grande is predicted to have been about 39.1 percent of the lake evaporation at Elephant Butte Reservoir, and about 37.9 percent of the lake evaporation at Caballo Reservoir.

2.0 TABLES

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Table I1. 2012 Actual (Calculated) Evaporation Losses at Elephant Butte and Caballo Reservoirs

		Elephant Butte Reservoir – Monthly Evaporation with End-of-Month Values Listed for Other Parameters (Storage Excludes "Other" Gains/Losses)					Caballo Reservoir – Monthly Evaporation with End-of-Month Values Listed for Other Parameters (Storage Excludes "Other" Gains/Losses)				
Year	Month	Surface Area (acres)	Evap (ac-ft)	Inflow (ac-ft)	Release (ac-ft)	Storage (ac-ft)	Surface Area (acres)	Evap (ac-ft)	Inflow (ac-ft)	Release (ac-ft)	Storage (ac-ft)
2010	1	14,787	-2,651	42,526	-738	561,478	2,929	-776	2,659	-98	31,736
2010	2	14,907	-3,992	49,717	-39,320	567,087	4,446	-934	34,267	-101	61,821
2010	3	14,347	-7,773	49,209	-75,691	540,576	4,248	-1,962	68,432	-71,238	57,377
2010	4	14,387	-10,596	122,274	-116,390	542,496	4,852	-2,910	109,187	-92,165	71,545
2010	5	15,623	-15,104	150,489	-92,908	600,079	4,288	-3,840	80,154	-89,489	58,257
2010	6	14,134	-17,462	67,629	-134,896	530,355	4,042	-3,785	128,752	-130,430	52,916
2010	7	12,384	-10,757	37,192	-122,852	444,331	4,402	-3,251	116,087	-106,945	60,814
2010	8	11,146	-8,700	43,373	-104,590	383,108	3,358	-2,763	95,713	-115,327	39,378
2010	9	10,793	-7,390	16,352	-32,370	365,862	2,291	-1,567	26,920	-42,447	21,370
2010	10	10,928	-5,913	7,869	-1,045	372,462	2,094	-948	2,568	-2,527	18,381
2010	11	11,346	-6,043	21,897	-714	392,939	2,203	-992	1,884	-123	20,026
2010	12	12,240	-4,017	44,863	-615	437,170	2,335	-587	2,210	-123	22,049
	Totals:		**-100,398**	**653,391**	**-722,129**			**-24,316**	**668,833**	**-651,012**	
2011	1	12,987	-4,257	37,622	-553	474,227	2,431	-804	1,701	-123	23,563
2011	2	13,598	-5,042	34,311	-444	504,283	2,509	-734	1,539	-123	24,790
2011	3	12,829	-9,957	27,842	-65,484	466,386	3,068	-1,990	58,637	-48,023	34,143
2011	4	11,157	-11,492	12,002	-93,957	383,662	4,504	-3,203	86,116	-57,727	63,167
2011	5	10,658	-12,029	14,814	-38,430	359,320	4,048	-3,961	33,006	-43,133	53,040
2011	6	9,039	-12,658	20,275	-95,445	283,123	3,254	-3,706	91,121	-107,202	37,478
2011	7	7,669	-8,708	7,379	-66,284	222,986	3,339	-3,075	70,024	-75,336	39,026
2011	8	7,172	-6,427	10,851	-30,252	202,229	1,305	-1,445	30,089	-54,998	7,256
2011	9	7,141	-4,742	16,457	-16,542	200,960	1,395	-857	23,217	-21,973	8,460
2011	10	7,313	-4,114	7,706	-553	208,055	1,518	-711	4,682	-2,970	10,141
2011	11	8,090	-4,900	34,173	-119	241,003	1,620	-760	664	-29	11,554
2011	12	9,288	-1,011	53,567	-61	294,518	1,766	-125	0	0	13,604
	Totals:		**-85,335**	**276,999**	**-408,124**			**-21,371**	**400,795**	**-411,636**	
2012	1	10,087	-2,537	37,634	-246	331,891	1,851	-446	1,817	-61	14,822
2012	2	10,817	-3,702	38,612	-978	367,048	1,955	-566	2,449	-62	16,329
2012	3	11,200	-7,502	28,711	-12,543	385,773	2,591	-1,122	10,959	-62	26,103
2012	4	10,924	-8,767	50,214	-62,122	372,245	2,401	-1,600	62,947	-64,443	23,091
2012	5	10,797	-11,236	16,849	-22,566	366,077	2,462	-2,707	22,411	-18,718	24,040
2012	6	8,668	-14,142	2,155	-99,788	266,412	2,250	-2,641	103,082	-106,484	20,747
2012	7	6,557	-6,955	4,488	-92,108	177,385	2,246	-2,352	94,956	-95,022	20,681
2012	8	4,817	-4,843	5,458	-70,034	111,813	1,703	-1,394	70,638	-78,613	12,706
2012	9	4,851	-3,788	6,528	-4,820	113,063	1,148	-922	7,063	-14,737	5,184
2012	10	4,883	-3,236	1,430	0	114,212	1,193	-652	693	0	5,775
2012	11	5,127	-1,903	9,145	-60	123,019	1,249	-406	895	-61	6,504
2012	12	6,142	-1,457	38,274	-184	161,138	1,320	-296	8,724	-61	7,461
	Totals:		**-70,068**	**239,499**	**-365,449**			**-15,104**	**386,633**	**-378,326**	

Table I2. 2012 Actual (Calculated) v. Predicted Lake Evaporation at Elephant Butte and Caballo Reservoirs Using IBWC S1 (Delayed Single Pulse) and S2 (Normal Single Pulse) Release Scenarios

		Actual (from Measured)					S1 Release Scenario						S2 Release Scenario					
Elephant Butte Reservoir																		
Year	Month	Surface Area (acres)	Evap (ac-ft)	Inflow (ac-ft)	Release (ac-ft)	Storage (ac-ft)	Surface Area (acres)	Evap (ac-ft)	Inflow (ac-ft)	Release (ac-ft)	"Other" Gains/ Losses	Storage (ac-ft)	Surface Area (acres)	Evap (ac-ft)	Inflow (ac-ft)	Release (ac-ft)	"Other" Gains/ Losses	Storage (ac-ft)
2012	1	10,087	-2,537	37,634	-246	331,891	10,086	-2,534	37,634	-284	2,522	331,856	10,087	-2,534	37,634	-233	2,522	331,907
2012	2	10,817	-3,702	38,612	-978	367,048	10,828	-3,711	38,612	-404	1,225	367,578	10,819	-3,710	38,612	-925	1,225	367,109
2012	3	11,200	-7,502	28,711	-12,543	385,773	11,430	-7,583	28,711	-1,706	10,059	397,059	11,335	-7,548	28,711	-5,926	10,059	392,405
2012	4	10,924	-8,767	50,214	-62,122	372,245	12,201	-9,351	50,214	-9,830	7,147	435,239	10,823	-8,770	50,214	-73,655	7,147	367,341
2012	5	10,797	-11,236	16,849	-22,566	366,077	12,328	-12,905	16,849	-8,440	10,785	441,528	9,961	-10,942	16,849	-58,126	10,785	325,907
2012	6	8,668	-14,142	2,155	-99,788	266,412	9,489	-16,080	2,155	-135,910	12,110	303,803	8,461	-13,579	2,155	-69,376	12,110	257,217
2012	7	6,557	-6,955	4,488	-92,108	177,385	6,868	-7,749	4,488	-116,230	5,548	189,860	6,281	-6,980	4,488	-93,752	5,548	166,521
2012	8	4,817	-4,843	5,458	-70,034	111,813	5,040	-5,271	5,458	-73,997	3,847	119,867	5,308	-5,114	5,458	-41,075	3,847	129,637
2012	9	4,851	-3,788	6,528	-4,820	113,063	4,731	-3,903	6,528	-17,045	3,330	108,777	5,004	-4,117	6,528	-16,808	3,330	118,570
2012	10	4,883	-3,236	1,430	0	114,212	4,762	-3,186	1,430	-108	2,955	109,868	5,022	-3,365	1,430	-373	2,955	119,217
2012	11	5,127	-1,903	9,145	-60	123,019	5,006	-1,882	9,145	-138	1,625	118,618	5,250	-1,979	9,145	-483	1,625	127,525
2012	12	6,142	-1,457	38,274	-184	161,138	5,998	-1,429	38,274	-1,357	1,486	155,592	6,141	-1,478	38,274	-4,717	1,486	161,090
	Totals:		**-70,068**	**239,499**	**-365,449**			**-75,583**	**239,499**	**-365,449**	**62,638**			**-70,117**	**239,499**	**-365,449**	**62,638**	
Caballo Reservoir																		
Year	Month	Surface Area (acres)	Evap (ac-ft)	Inflow (ac-ft)	Release (ac-ft)	Storage (ac-ft)	Surface Area (acres)	Evap (ac-ft)	Inflow (ac-ft)	Release (ac-ft)	"Other" Gains/ Losses	Storage (ac-ft)	Surface Area (acres)	Evap (ac-ft)	Inflow (ac-ft)	Release (ac-ft)	"Other" Gains/ Losses	Storage (ac-ft)
2012	1	1,851	-446	1,817	-61	14,822	1,750	-437	300	0	-91	13,376	1,801	-444	1,039	0	-91	14,108
2012	2	1,955	-566	2,449	-62	16,329	1,720	-520	403	0	-313	12,946	1,839	-546	1,401	0	-313	14,650
2012	3	2,591	-1,122	10,959	-62	26,103	1,778	-976	1,805	0	-1	13,774	2,188	-1,124	6,269	0	-1	19,794
2012	4	2,401	-1,600	62,947	-64,443	23,091	2,382	-1,470	10,400	0	85	22,789	2,093	-1,507	77,157	-77,157	85	18,372
2012	5	2,462	-2,707	22,411	-18,718	24,040	2,235	-2,229	8,926	-8,926	-37	20,523	1,958	-1,959	61,488	-61,488	-37	16,376
2012	6	2,250	-2,641	103,082	-106,484	20,747	2,234	-2,778	143,802	-143,802	2,751	20,496	1,979	-2,450	73,388	-73,388	2,751	16,677
2012	7	2,246	-2,352	94,956	-95,022	20,681	2,276	-1,700	122,975	-122,975	2,351	21,147	2,022	-1,716	99,174	-99,174	2,351	17,312
2012	8	1,703	-1,394	70,638	-78,613	12,706	2,244	-1,890	78,276	-78,276	1,394	20,651	2,002	-1,685	43,041	-43,041	1,394	17,021
2012	9	1,148	-922	7,063	-14,737	5,184	2,203	-1,688	18,050	-18,050	1,073	20,036	1,972	-1,510	17,780	-17,780	1,073	16,584
2012	10	1,193	-652	693	0	5,775	2,166	-1,237	114	0	550	19,463	1,961	-1,114	395	0	550	16,415
2012	11	1,249	-406	895	-61	6,504	2,147	-725	146	0	301	19,185	1,971	-661	511	0	301	16,566
2012	12	1,320	-296	8,724	-61	7,461	1,707	-448	1,436	0	-7,409	12,764	1,774	-435	4,990	0	-7,409	13,712
	Totals:		**-15,104**	**386,633**	**-378,326**		**741**	**-16,099**	**386,633**	**-372,029**	**653**			**-15,150**	**386,633**	**-372,028**	**653**	

3.0 FIGURES

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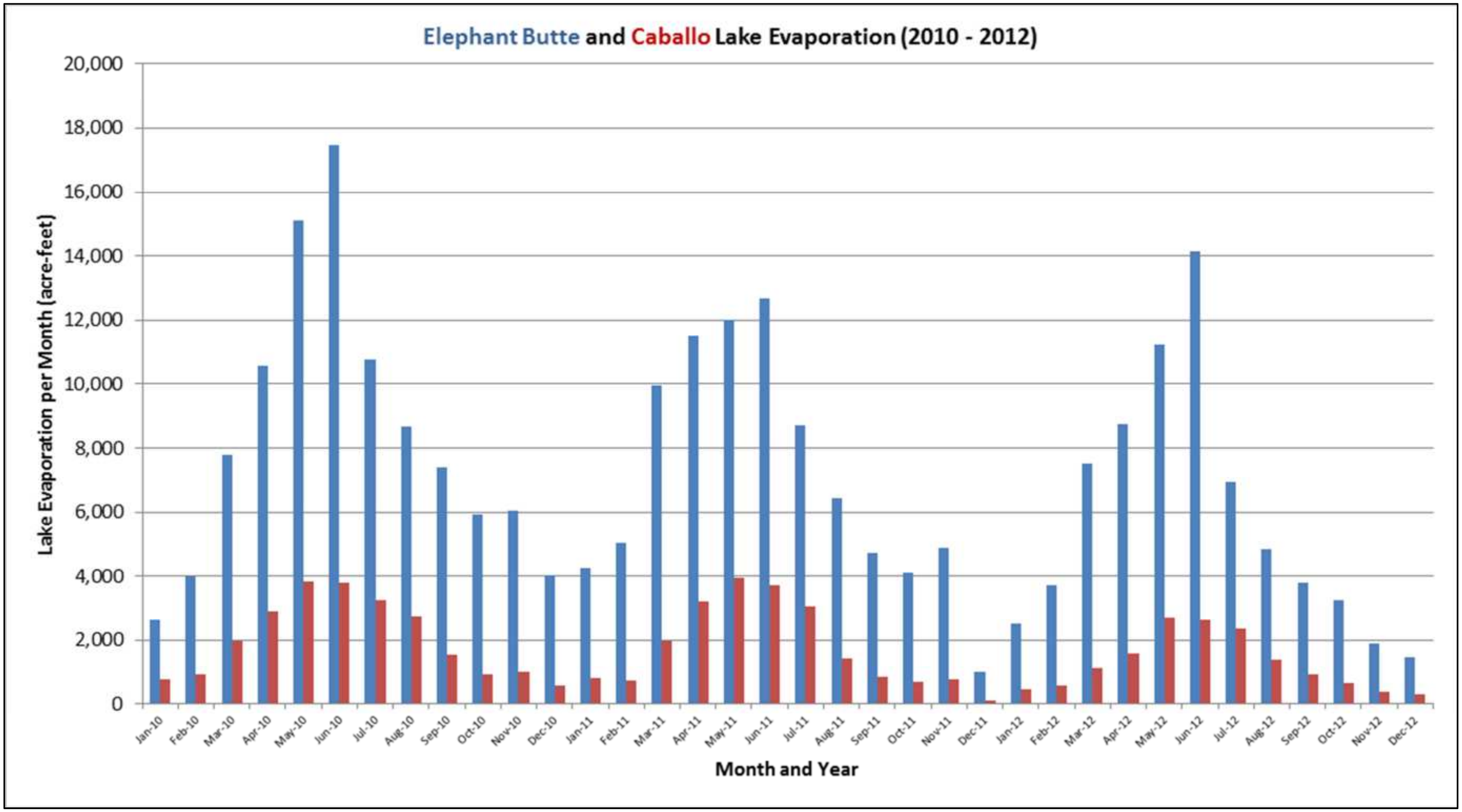

Figure I1. Measured Monthly Lake Evaporation Rates in Elephant Butte and Caballo Reservoirs for the Period Between January, 2010 and December, 2012.

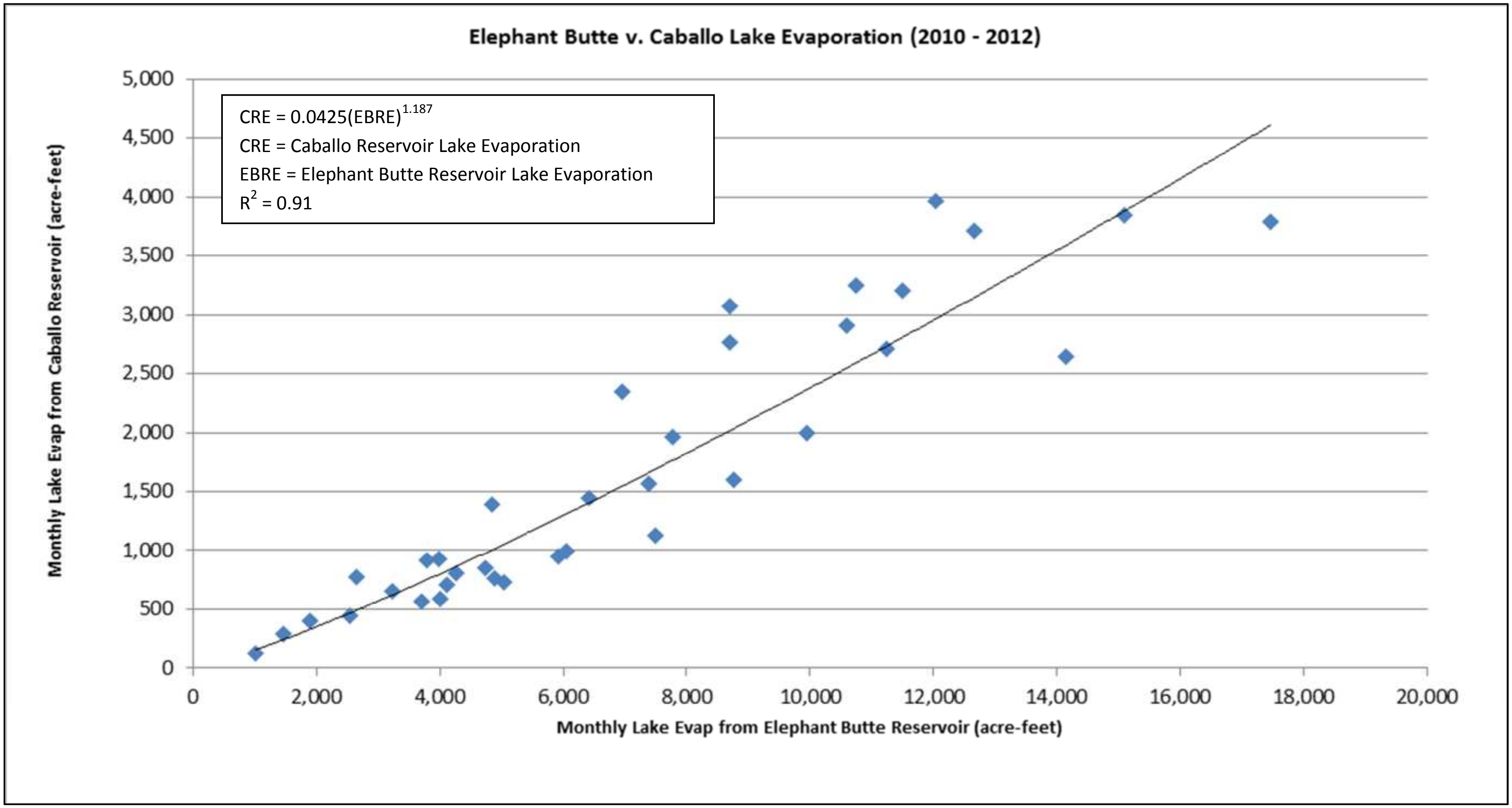

Figure I2. Relationship Between Monthly Lake Evaporation Rates in Elephant Butte and Caballo Reservoirs Based on Measured Values Collected During the Period Between January, 2010 and December, 2012.