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Technical Memorandum

Prepared for: Monterey County Water Resources Agency

Project Title: Salinas River Groundwater Basin Investigation

Project No.: 146430.104

Technical Memorandum No. 2

Subject: Storage Change Analysis

Date: October 21, 2014

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Section 1: Introduction

As part of the Salinas River Groundwater Basin Investigation, Brown and Caldwell (BC) was tasked with analyzing how groundwater storage (storage) has changed over time within the Salinas River Groundwater Basin (Basin). This Technical Memorandum (TM) presents the results of this analysis. This analysis is part of a larger investigation into the groundwater and surface water resources of the Basin that will be discussed in subsequent reports. As such, this TM will not provide an exhaustive description of the hydrogeologic background of the study area.

1.1 Scope and Purpose

The Scope of Work presented to the Monterey County Water Resources Agency (MCWRA or Agency) and the County of Monterey Resource Management Agency (RMA) by BC included a task (Task 4) on storage change within Zone 2C. This task examines how groundwater storage has changed over time throughout Zone 2C and within the individual subareas that compose it. The primary purpose of this evaluation is to provide (1) a preliminary quantification of how storage has changed over time in the groundwater aquifers, (2) the apparent causes of these storage changes, and (3) potential future storage changes under continued drought conditions.

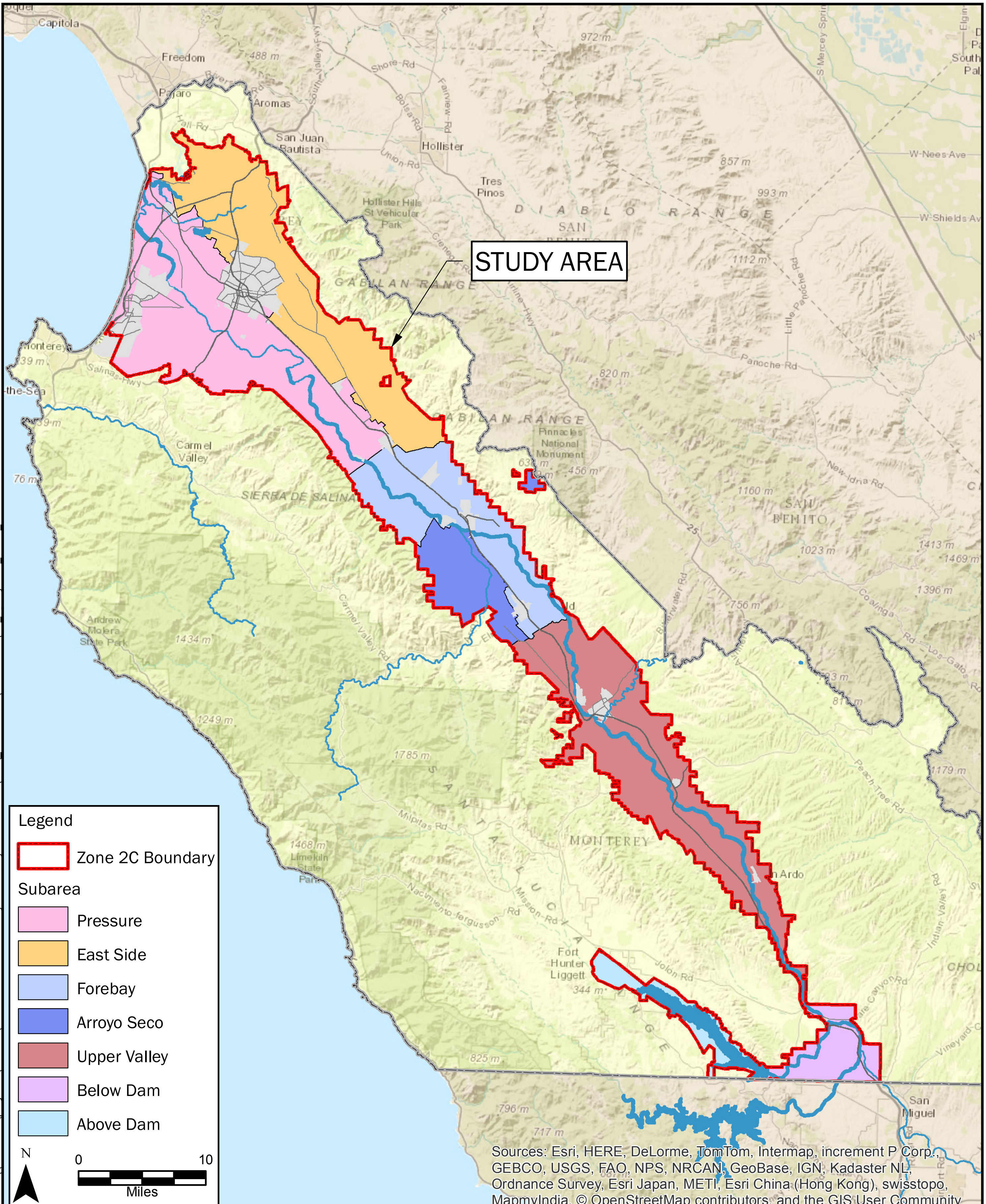
1.2 Study Area

The study area for the groundwater storage change analysis of the Basin Investigation is defined by Zone 2C of the Salinas River Valley, shown on Figure 1. This study area consists of an alluvial basin straddling the Salinas River, which runs northwest from near Santa Margarita in San Luis Obispo County to where it drains into Monterey Bay. Zone 2C extends from the Monterey-San Luis Obispo County Line to Monterey Bay, and lies entirely within Monterey County. Zone 2C consists of 7 subareas, as shown on Figure 1; the analysis presented in this TM evaluates conditions in the four largest subareas (Pressure, East Side, Forebay, and Upper Valley), with the Forebay subarea including the area designated on Figure 1 as the Arroyo Seco subarea. These four subareas provide the bulk of groundwater storage and have been the heaviest utilized for groundwater production. Subareas were defined by the California Department of Water Resources (DWR), based on the sources of recharge to groundwater within each subarea (DWR, 1946).

The Basin consists of alluvium eroded from the surrounding highlands by the Salinas River and its tributaries. The alluvium contains extensive, relatively homogenous, coarse-grained deposits forming aquifers, which bear and yield useful quantities of water and also extensive deposits of relatively fine-grained sediments forming aquitards, which act to slow groundwater flow. The depositional environment in which the sediments were laid down determines the distribution of course- and fine-grained sediments and the continuity and interconnectedness of the aquifers.

The depositional history of the study area has been detailed in previous reports, particularly Tinsley (1975) and Kennedy/Jenks (2004). The sediments that make up the aquifers and aquitards were laid down in a mixture of fluvial (river generated) and alluvial fan settings. The sediments in the Pressure subarea are typically fluvial in origin, and made up of coarse- and fine-grained layers that are somewhat extensive and continuous. The sediments in the East Side subarea, on the other hand, are thinner-bedded and more discontinuous (Kennedy/Jenks, 2004).

Despite the generally discontinuous nature of the sedimentary layers in the alluvial deposits, sediments have been classified into multiple aquifers in the Pressure and East Side subareas (Figure 2). In the Pressure subarea, aquifer designations are based largely on the locations of extensive, mostly continuous



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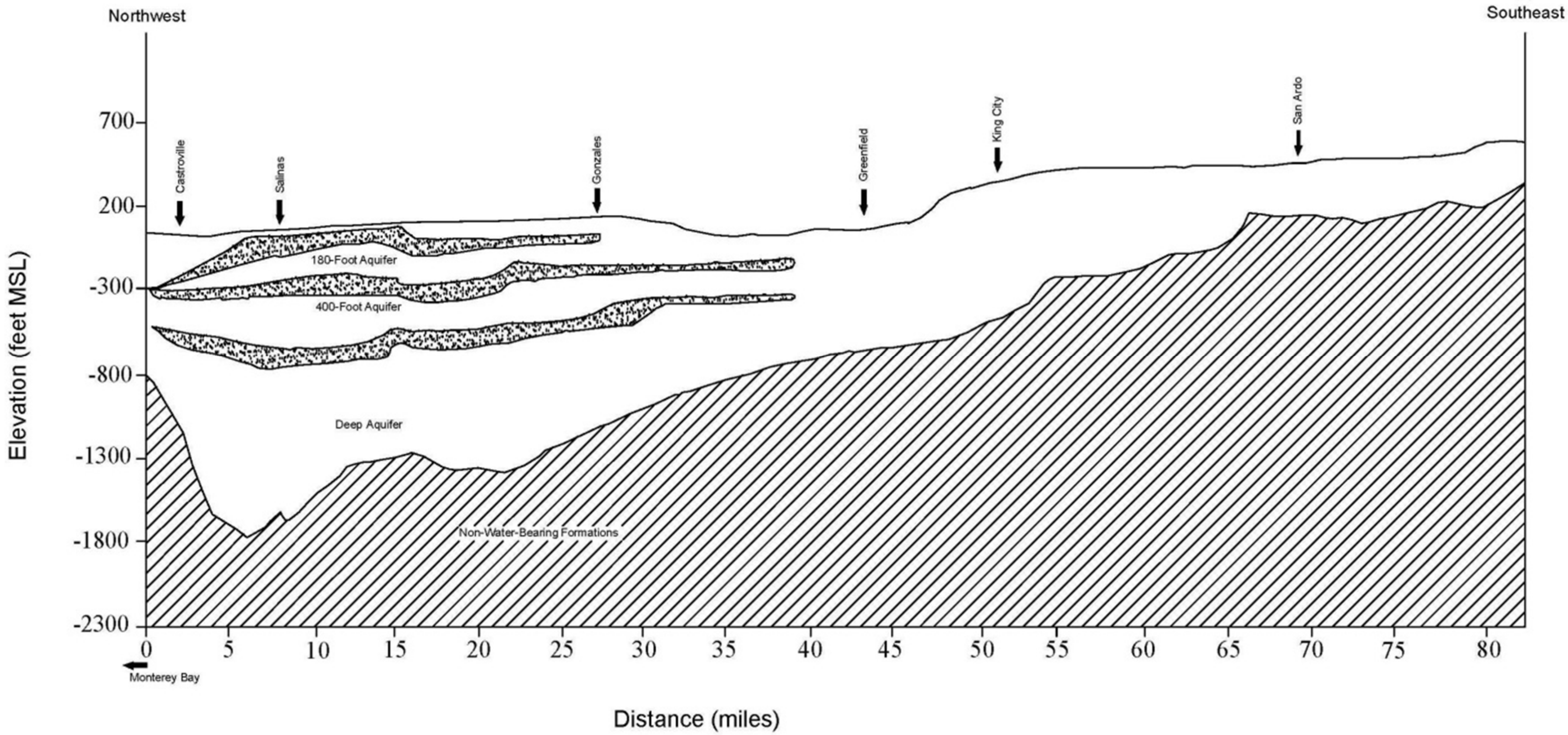
10/21/14	146430	**Salinas River Groundwater Basin Investigation**	**Figure 1**
Brown AND Caldwell		TITLE **Study Area Map**	



Modified from MCWRA, 2006

Brown AND Caldwell	DATE 10/21/14	SITE Salinas River Groundwater Basin Investigation	Figure 2
	PROJECT 146430	TITLE Schematic Depiction of the Pressure Subarea Aquifers	

aquitards; there are up to four aquifers present in the subsurface (the Shallow Aquifer, the 180-Foot Aquifer, the 400-Foot Aquifer, and the Deep Aquifer), separated by three aquitards (the Salinas Valley Aquitard, the 180-Foot/400-Foot Aquitard, and the 400-Foot/Deep Aquitard) made up of blue clay layers deposited during marine transgressions (Tinsley, 1975). In the East Side subarea, there is no extensive, continuous aquitard layer, and the blue clays typical of the Pressure subarea aquitards are largely absent. Still, some authors have divided the sediments of the East Side subarea into a Shallow Aquifer and a Deep Aquifer (note that the Shallow and Deep Aquifers in the East Side subarea do not correlate to the Shallow and Deep Aquifers in the Pressure subarea). The Pressure Deep Aquifer is also present within the East Side subarea. Sediments in the Forebay and Upper Valley subareas are not divided into separate aquifers.

The existence or lack of continuous aquitards largely determines the confinement of the aquifers present in the study area. In the Pressure subarea, all of the aquifers except for the Shallow Aquifer are overlain by extensive, continuous blue clay aquitards, and are therefore confined (except in the 180-Foot Aquifer, where a few gaps in the Salinas Valley Aquitard may create unconfined to semi-confined conditions; MCWRA, 2006). In the East Side subarea, the deposits are generally unconfined to locally confined (MCWRA, 2006), with confinement increasing with depth due to the combined effect of numerous fine-grained interbeds (Kennedy/Jenks, 2004). The Forebay and Upper Valley subarea aquifers are unconfined.

1.3 Previous Investigations

Numerous investigators have studied the water resources of Zone 2C in the past. The most important reports resulting from these previous studies are listed below. More detailed citations are available in the References section included after the text of this TM.

- Hamlin, 1904, Water Resources of the Salinas Valley, California
- DWR, 1946, Salinas Basin Investigation
- MWH, 1997, Salinas Valley Integrated Ground Water and Surface [sic] Model Update
- DWR, 2003, California's Groundwater (Bulletin 118)
- Kennedy/Jenks, 2004, Hydrostratigraphic Analysis of the Northern Salinas Valley
- MCWRA, 2006, Monterey County Groundwater Management Plan

1.4 Data

The various data sets utilized in the preparation of this TM are noted below.

- Annual Groundwater Pumping Data: provided by MCWRA on a subarea basis from 1949 to 2012; prior to the availability of monthly well pumping data in 1994, these quantities were derived from the existing Salinas Valley Integrated Ground and Surface Water Model (SVIGSM)
- Monthly Precipitation Data: provided by MCWRA for the Salinas Municipal Airport gauge from July 1872 to September 2014
- Subarea-Averaged Annual Groundwater Head Elevation Changes: provided by MCWRA from 1944 to 2013
- Reservoir Releases: daily release data provided by MCWRA starting in October 1958
- Streamflow: available publicly from the U.S. Geological Survey (USGS)
- Storage Coefficients: subarea-averaged values estimated by various authors, summarized in DWR (2003); additional values for the Pressure subarea discussed in Section 2.1

- Area: derived from the SVIGSM, provided by MCWRA

The data listed above were used to perform the groundwater storage analysis, as described in the following sections.

Section 2: Storage Calculation Method

The aquifers underlying the Salinas River Groundwater Basin represent a critical reservoir for storage of water. How the quantity of water in storage changes over time depends on many different factors, including properties of the aquifer itself as well as external hydrological variables. Understanding how storage has changed during past drought periods is crucial to predicting how it is likely to change should drought conditions persist.

The estimation of total storage in a groundwater basin is subject to significant uncertainties in both the physiography of the basin and the various physical aquifer parameters that are incorporated into a storage estimate. Basins are frequently ill-defined due to an incomplete knowledge of the full three-dimensional extent of the basin and the lithologic units that compose it as well as the nature of the basin boundaries. The natural materials that make up groundwater basins tend to be highly heterogeneous over various spatial scales, and this heterogeneity is typically not well characterized, meaning that spatially varying aquifer properties are usually represented by gross average values considered representative of the aquifer as a whole. The determination of the full three-dimensional extent of each aquifer is beyond the scope of this TM; therefore, this analysis does not seek to define an absolute amount of storage in the SRGB. Instead, a relative change in storage that is independent of knowledge of total storage capacity can be estimated based on aquifer parameters; here we present such an estimate. It is noted that DWR has estimated total storage and storage capacity for each of the subareas (DWR, 2003), as shown in Table 1 below.

This section describes the method used to calculate storage change over time. First, the variables required for the calculation are described: the aquifer storage coefficients, the land area of the aquifers, and the groundwater head elevation change.

2.1 Storage Coefficient

The storage coefficient is an aquifer parameter that quantifies the volume of groundwater released from storage per foot of decline in groundwater head. Storage coefficient is a vertically integrated parameter, meaning that it is meant to be representative of the entire thickness of the aquifer at a given location.

Table 1. Storage Coefficient and Land Area by Subarea

Subarea	Pressure	East Side	Forebay	Upper Valley
Storage Coefficient [ft^3/ft^3]	0.036/0.004	0.08	0.12	0.10
Land Area [acres]	126,000	75,000	87,000	92,000
Total Storage [af]	6,860,000	2,560,000	4,530,000	2,460,000
Total Storage Capacity [af]	7,240,000	3,690,000	5,720,000	3,100,000

Note: Areas rounded to nearest 1,000 acres. Total storage and total storage capacity from DWR (2003); total storage estimates were for 1994 except in the Pressure subarea, where the estimate was for 1998. af = acre-feet. Pressure subarea storage change was calculated using both storage coefficients presented here; see the text for explanation.

Storage coefficient values reported by DWR in Bulletin 118 (DWR, 2003) were used in this study; the storage coefficient value used for each subarea is an average value for the entire subarea, based on existing studies (G. Criollo, MCWRA, personal communication, 26 August 2014). The value in the Pressure subarea (0.036) represents the simple average of the (model-calibrated) storage coefficient values for three parts of the subarea as reported by Yates (1988); that study did not document any difference in storage coefficient between the Shallow, 180-Foot, 400-Foot, and Deep Aquifers, because it treated the entire thickness of sediments as a single layer. The values in the East Side (0.08) and Forebay (0.12) subareas were reported in SWRB (1955). The value in the Upper Valley subarea (0.10) was provided to DWR by MCWRA. Table 1 includes the values of storage coefficient used in the analysis.

The values of storage coefficient presented above were not modified from the values presented by DWR (2003). However, it must be noted that these values do not necessarily fit the hydrogeologic conceptual model of the study area. As noted in Section 1.2, the confinement of aquifers in the study area varies by subarea, with the aquifers of the Pressure subarea being mostly confined with locally unconfined conditions, the aquifers of the East Side subarea being unconfined with increasing confinement with depth, and the aquifers of the Forebay and Upper Valley subareas being unconfined (MCWRA, 2006). However, the storage coefficient for the Pressure subarea is much higher than is typical of confined aquifer, which generally have storage coefficients in the range of 0.00005 to 0.005 (Freeze and Cherry, 1979). This indicates that the storage coefficient value ascribed to the Pressure subarea in DWR (2003) may be too high, possibly by two orders of magnitude. A smaller value of storage coefficient would result in a proportionately smaller storage change for the same change in groundwater head. Other studies have published storage coefficient values for the Pressure subarea ranging from 0.00001 to 0.004 (Yates, 1988; MWH, 1997; Geoscience, 2013), with storage coefficients typically much lower in the 400-Foot Aquifer than in the 180-Foot Aquifer.

2.2 Area

The land surface area was retrieved from the horizontal extent of the subareas in the existing SVIGSM. Table 1 includes the values used in this analysis.

2.3 Groundwater Head Change

The annual average groundwater head change is calculated by MCWRA as a single value averaged across each subarea (G. Criollo, MCWRA, personal communication, 21 August 2014). Head measurements are collected by MCWRA staff from about 400 wells each Fall, from mid-November to mid-December. This is the time of year following the peak growing (and groundwater pumping) season, before rainfall has begun to recharge basin aquifers. Groundwater conditions at this time of year are most likely to reflect overall changes in storage from year to year. After confirming the quality of the head measurements, a head change from the previous year's measurement is calculated for each well where possible. Wells are then grouped into blocks based on the Public Land Survey System (i.e. township and range blocks, each block covering about 36 square miles), and an average head change is calculated for each block. These average values are then used to calculate a subarea average head change using a weighted average (weighted by the number of measurements in each block). Individual aquifers are only considered in the Pressure subarea; the subarea average head changes for the 180-Foot and 400-Foot Aquifers are then transformed into a single value for the Pressure subarea using a weighted average (weighted by number of measurements in each aquifer). Head measurements in the Deep Aquifer are not used in the subarea head change calculation.

2.4 Storage Change Calculation

Storage change was calculated in the four main subareas of the Basin by considering the total area of each, its storage coefficient, and the change in piezometric head:

$$\Delta S = SA\Delta h \qquad (1)$$

where ΔS is the change in storage [L^3T^{-1}], S is the storage coefficient [L^3L^{-3}], A is the basin area [L^2], and Δh is the change in piezometric head [LT^{-1}]. MCWRA has calculated the annual groundwater head change by Basin subarea (Pressure, East Side, Forebay, and Upper Valley) over the period from 1945 (representing the change from the fall 1944 measurements to the fall 1945 measurements) to 2013. Therefore, this is the period for which the annual storage changes were calculated.

In the Pressure subarea, the storage change calculation was performed both for the storage coefficient value provided by MCWRA (0.036) and a value of 0.004, more appropriate for the confined conditions known to exist in this subarea (see Section 2.1). The smaller value represents the storage coefficient for the 180-Foot Aquifer in the Pressure subarea determined by MWH (1997); because the storage coefficient is a vertically integrated property, the total storage coefficient for a unit area of the Pressure subarea is equal to the sum of the storage coefficients of all of the aquifers at that location. Since the storage coefficient for the 180-Foot Aquifer is so much larger than the storage coefficients for the 400-Foot Aquifer (0.00009; Geoscience, 2013) and the Deep Aquifer (0.00001 to 0.0003; MWH, 1997), using the 180-Foot Aquifer storage coefficient as the storage coefficient for the entire Pressure subarea is a reasonable and conservative approach.

It must be noted, however, that the change in groundwater head provided by MCWRA represents a weighted average of the head changes throughout both the 180-Foot and 400-Foot Aquifers in the Pressure subarea. As shown by Geoscience (2013), the average historical decline in groundwater head elevation has been greater in the 400-Foot Aquifer (51 feet) than in the 180-Foot Aquifer (33 Feet). However, because the storage coefficient in the 400-Foot Aquifer (0.00009) is much smaller than in the 180-Foot Aquifer (0.004), the actual storage depletion calculated by Geoscience (2013) is also much smaller in the 400-Foot Aquifer (400 acre-feet, af, compared to 11,100 af in the 180-Foot Aquifer). Using the average head change (42 feet) combined with the storage coefficient representative of the 180-Foot Aquifer (0.004) would result in a calculated total storage loss on the order of about 14,100 af for the combined aquifer system, versus 11,500 af calculated when considering each of the two aquifers separately (with their own appropriate storage coefficients). Because this approach overestimates storage change, it is considered a conservative assumption for the purposes of this analysis.

2.5 Forcings

There are several potential hydrologic inputs, or “forcings” that can affect groundwater head (and therefore storage) within an aquifer. These forcings are assumed to be largely independent of the annual storage change, a necessary constraint for this analysis; any dependence of the forcings on storage change would artificially increase the correlation between the two. This analysis investigated which of these independent forcings had the greatest impact on annual storage change.

2.5.1 Groundwater Pumping

Over the period from 1949 to 1994, groundwater pumping data are available on a subarea basis, as estimated for the existing SVIGSM (MWH, 1997). These data represent model inputs that were estimated outside of the model, and modified during the model calibration process. Since November 1995, MCWRA has compiled groundwater extraction data reported by individual well owners in accordance with a County of Monterey ordinance. Under this ordinance, well owners are required to report monthly pumping volumes for every well with a discharge pipe of diameter 3 inches or greater. Groundwater pumping volumes are generally reported in November.

2.5.2 Precipitation

Precipitation data are available from a variety of gauges throughout Monterey County. While an exhaustive study could be made of the spatial variability of precipitation demonstrated by these data, it is beyond the scope of this study to do so. Instead, precipitation data were provided by MCWRA for the Salinas Municipal Airport station. This dataset (monthly totals) spans over 140 years, from July 1872 to present. The time series of annual precipitation is shown in Figure 3; this chart presents Water Year (WY) precipitation, which is totaled over the period October to September (i.e. WY 2011 ran from October 2010 to September 2011). The average annual (Water Year) precipitation is about 13.4 inches, with a standard deviation of about 4.8 inches.

To more easily recognize years that are wetter or drier than normal and extended periods of wet or dry years, annual precipitation totals were categorized into wetness levels based on the statistical distribution of annual precipitation over the period of record. Wetness levels were defined based on the number of standard deviations away from the mean the precipitation for a given year lies. Table 2 summarizes the range of precipitation values contained within each wetness level as well as the number of standard deviations defining each wetness level and the number of years that fall within each level. Years with precipitation at least 2 standard deviations away from the mean are considered Extremely Dry (ED) and Extremely Wet (EW). Very Dry (VD) and Very Wet (VW) years are between 1 and 2 standard deviations away from the mean. Dry (D) and Wet (W) years are between 0.5 and 1 standard deviations away from the mean. Normal (N) years are within 0.5 standard deviations of the mean. The precipitation time series shown on Figure 3 is color-coded by wetness level, using the colors indicated on Table 2.

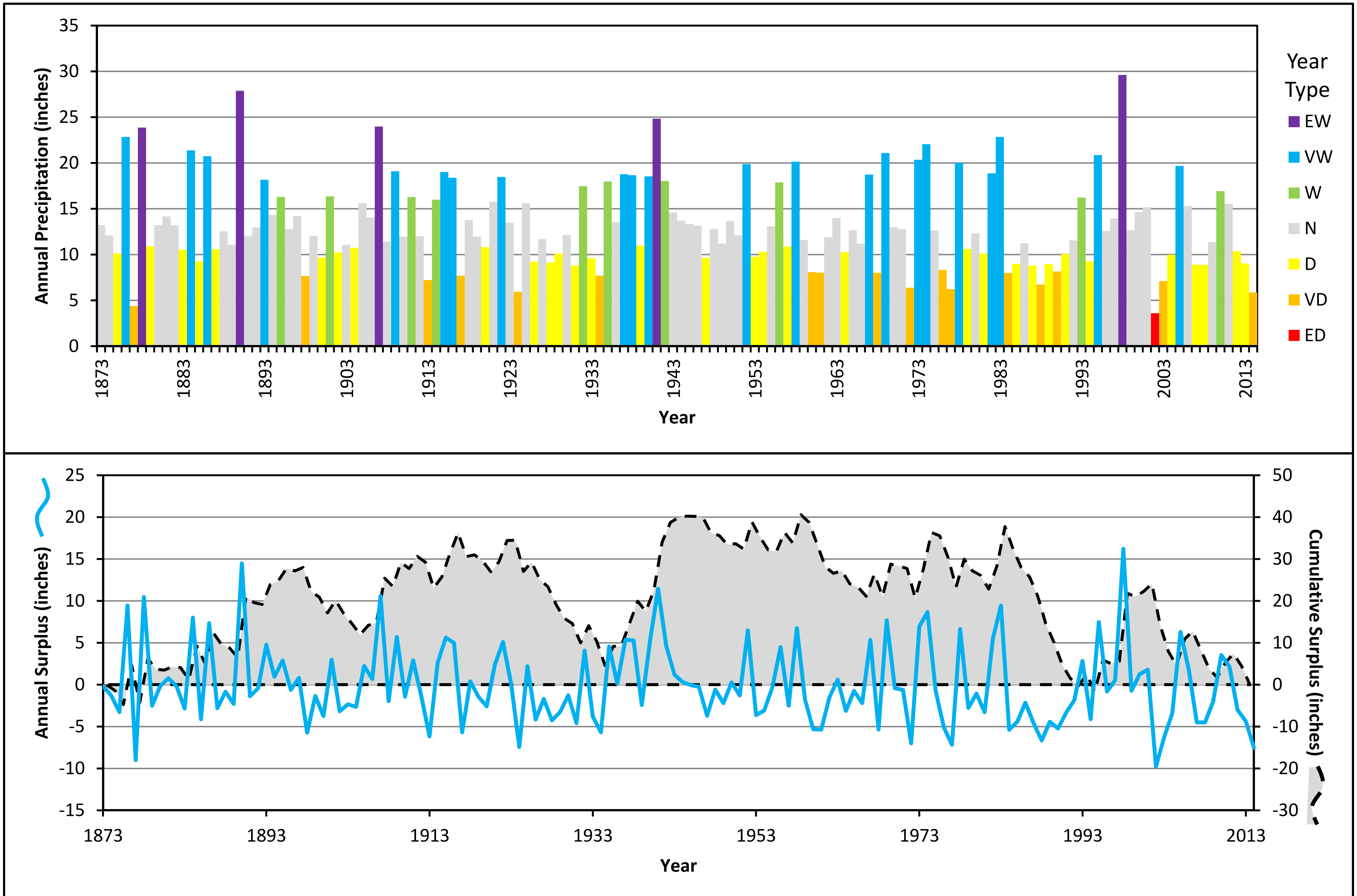
Table 2. Annual Precipitation Totals Defining Wetness Levels

Wetness Level	Extremely Dry	Very Dry	Dry	Normal	Wet	Very Wet	Extremely Wet
Abbreviation	ED	VD	D	N	W	VW	EW
Range (inches)	<3.8	3.8 – 8.6	8.6 – 11.0	11.0 – 15.7	15.7 – 18.1	18.1 – 22.9	>22.9
SDs from Mean	>2.5	1.0 to 2.5	0.5 to 1.0	<0.5	0.5 to 1.0	1.0 to 2.5	>2.5
# of Years	1	17	31	55	11	22	5
Color on Figure 3	Red	Orange	Yellow	Gray	Green	Blue	Purple

A simple statistic calculated using the precipitation time series is precipitation surplus. The annual precipitation surplus is calculated as the annual precipitation minus the mean precipitation. The annual surplus can be summed over a given period to calculate the cumulative precipitation surplus. Figure 3 includes the annual precipitation surplus over the entire period of record, covering WY 1873 to 2014, and the cumulative precipitation surplus from WY 1873 to 2013, the period used to calculate mean annual precipitation (to avoid preliminary data from 2014; see below). By definition, the cumulative surplus must begin and end at zero if the period of record used is the same as that used to calculate the mean, as in this case. The maximum cumulative surplus occurred in 1958, when the surplus was 40.6 inches, with similarly high surplus values of about 40 inches from WY 1943 to 1946. This indicates that the early part of the precipitation record, prior to the 1940s, was substantially wetter compared to the fifty years since then.

Of special interest for considering storage changes under future dry years is what has happened during past dry periods. One important period to consider is water years 1984 to 1991, which included 3 VD years, 4 D years, and 1 N year. During this period, the cumulative precipitation surplus declined by about 36 inches, an average of about 4.5 inches per year.

Precipitation data were available through June 2014 at the time of the writing of this TM, so, while the final WY 2014 total is currently unavailable, provisional data for July to September 2014 suggest a WY 2014 precipitation total of about 5.9 inches. This would be the third-driest year on record, surpassing only the 3.6 inches of 2002 and the 4.4 inches of 1877.



DATE	SITE
10/21/14	Salinas River Groundwater Basin Investigation
PROJECT	TITLE
146430	Precipitation and Precipitation Surplus Time Series

Brown AND Caldwell

Figure 3

2.5.3 Reservoir Releases

MCWRA owns and operates two surface water storage reservoirs along tributaries to the Salinas River: Nacimiento Reservoir and San Antonio Reservoir. Nacimiento Reservoir began releasing water in October 1958, while San Antonio Reservoir began releasing water in November 1966. MCWRA provided a time series of daily releases, storage, and lake stage. Reservoir releases were summed into annual totals over the course of the water year.

2.5.4 Streamflow

As with precipitation, streamflow is available from numerous gauges in Monterey County, but a study of the streamflow at all of these gauges is beyond the scope of this study. Instead, streamflow was considered at the Salinas River gauge near Bradley, which has a period of record (daily streamflow) of October 1948 to present. Streamflow was summed into annual mean streamflow volume over the course of the water year.

Section 3: Storage Change Results

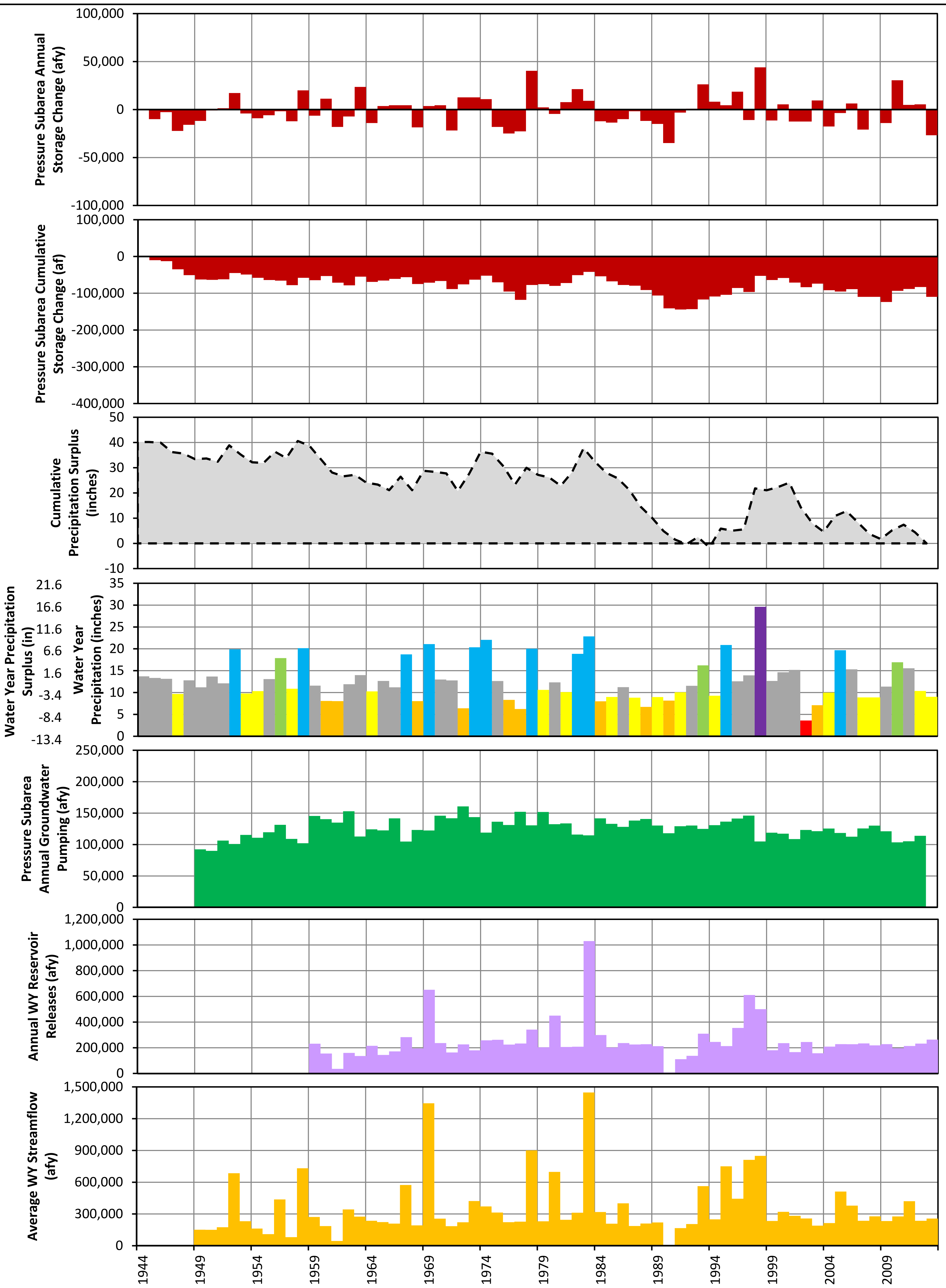
Storage change (Equation 1) was calculated on an annual basis, based on estimated annual subarea-average groundwater head elevation change, as detailed in Section 2. The storage change was calculated for each subarea separately, and a total storage change for Zone 2C was calculated as the sum of the subarea storage changes. Figures 4 through 8 show the storage change time series for the four subareas and for Zone 2C as a whole, along with the various forcings that may be affecting storage change.

3.1 Pressure Subarea

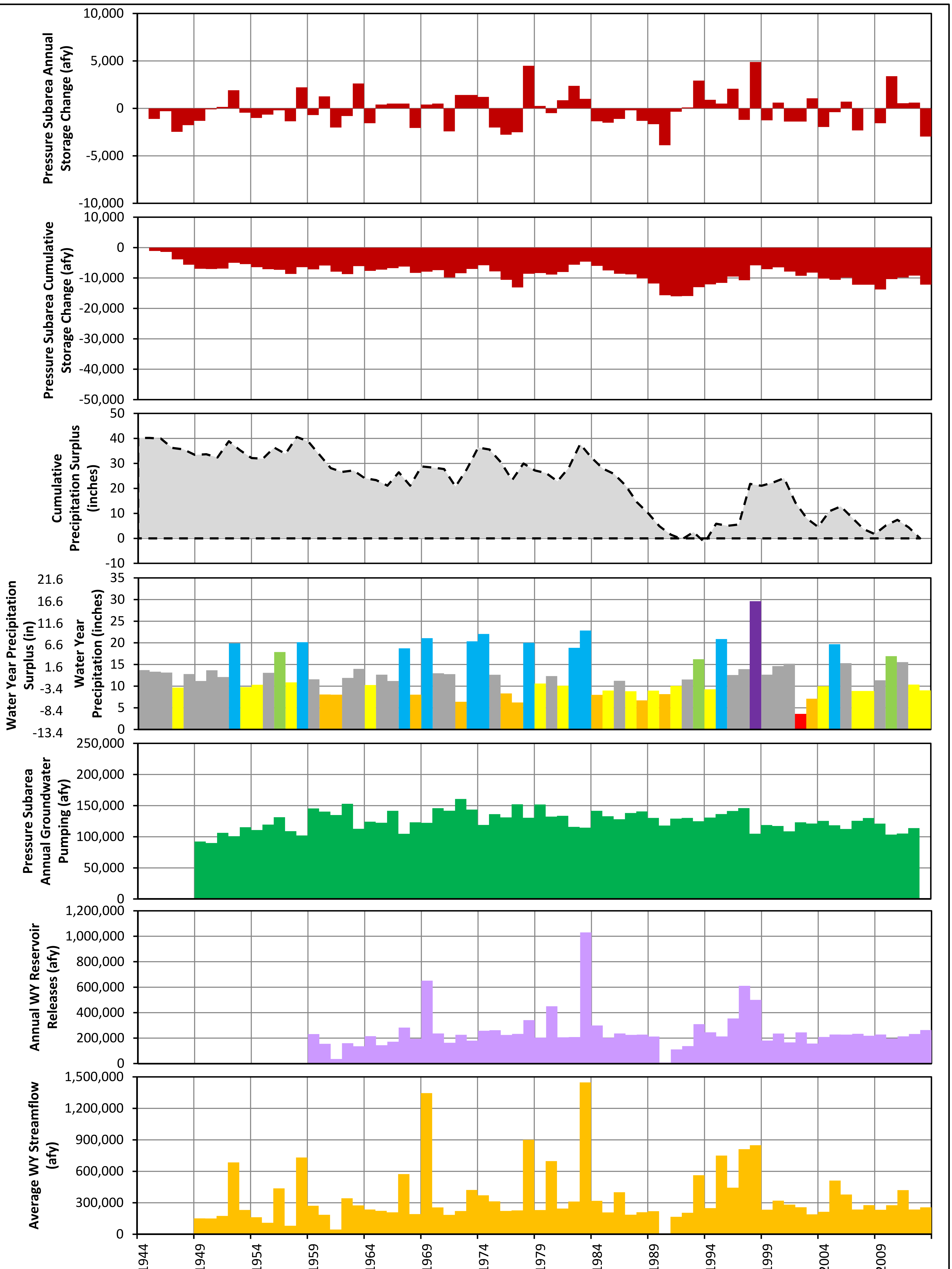
The Pressure subarea experienced annual storage changes estimated at between about -34,900 and +44,000 acre-feet per year (afy) over the period from 1944 to 2013 (calculated using a storage coefficient value of 0.036; Figure 4a). The cumulative storage change was negative over the entire period, reaching about -144,300 af in 1991 and ending at about -109,700 af in 2013. The average change in storage over the period of record was about -1,600 afy. Of the 70 years included in the analysis, 38 had negative storage change, 2 had no change, and 30 had positive change.

The general pattern of storage changes in the Pressure subarea follows annual precipitation, with most years of significant storage loss occurring during relatively dry years and most years of significant storage gain occurring during relatively wet years. Examples of this are 1998, which was one of the wettest years on record, and 1968, which was Very Dry (VD). However, this relationship does not hold for all years; 2002, the driest year on record, saw approximately no change in storage, while large declines in storage occurred during Normal (N) years 1975 and 2011, following Very Wet (VW) and Wet (W) years, respectively. Over the 70 years of the period of record, a linear regression between the annual storage change and annual precipitation has a p-value of 9.2×10^{-9} and an r^2 coefficient of only 0.39, indicating a significant relationship between the two variables but one that cannot be used for accurate prediction.

As shown in Figure 4a, extraction has remained fairly steady over the entire period of record, with an average extraction of about 125,500 afy in this subarea. Because of the relatively steady extraction rate, there is not an obvious relationship between pumping and storage change. This is reflected in the linear correlation between the two, which has a p-value of 0.11 and an r^2 coefficient of 0.04; the p-value is too large to definitively state that there is a statistically significant relationship between the two variables at the 95% confidence level. The slope of the linear regression is negative, indicating that higher extraction rates correspond to more negative storage change.



Brown AND Caldwell	DATE 10/21/14	SITE Salinas River Groundwater Basin Investigation	Figure 4a
	PROJECT 146430	TITLE Storage Change in the Pressure Subarea (Storage Coefficient = 0.036)	



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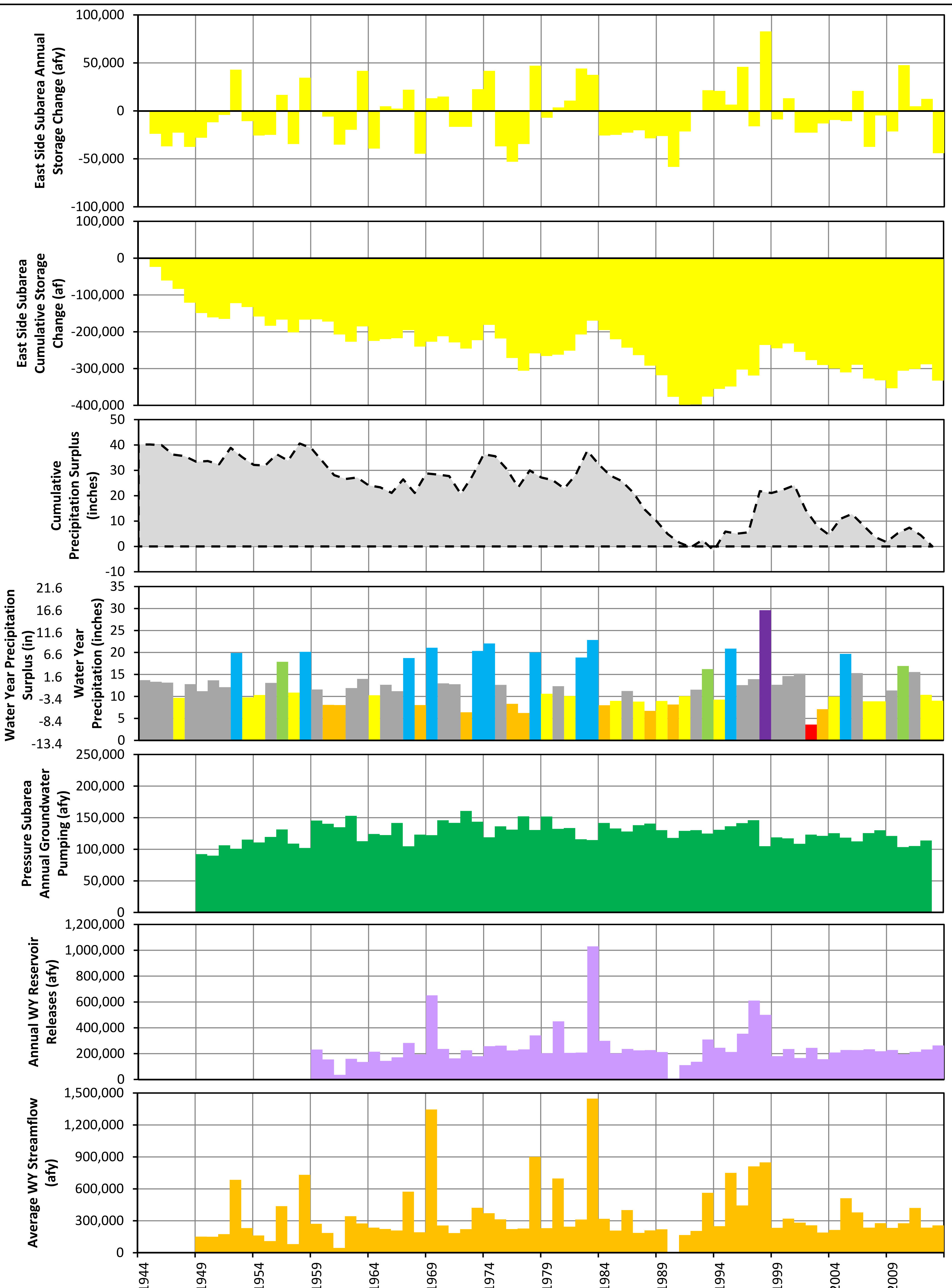
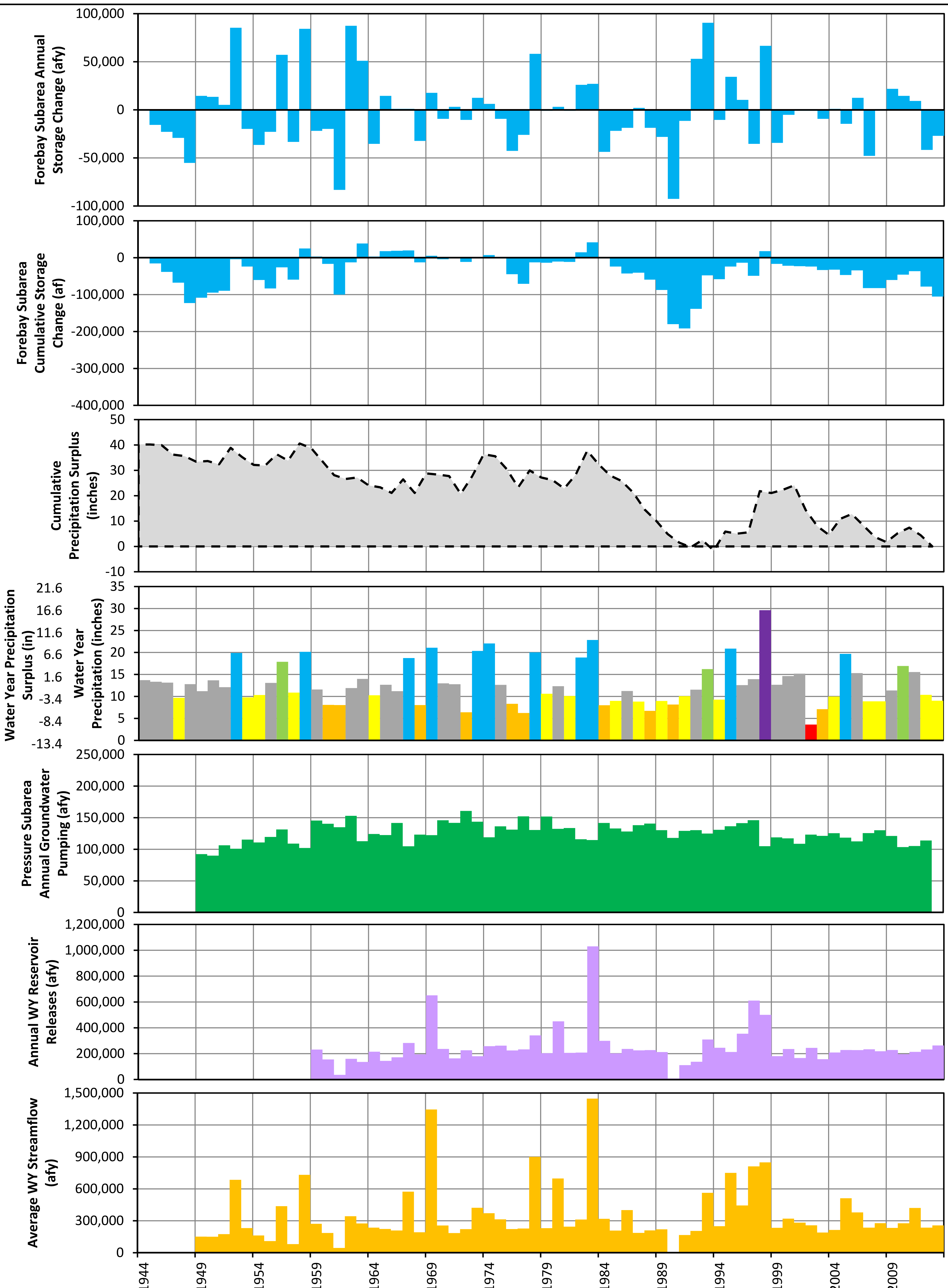
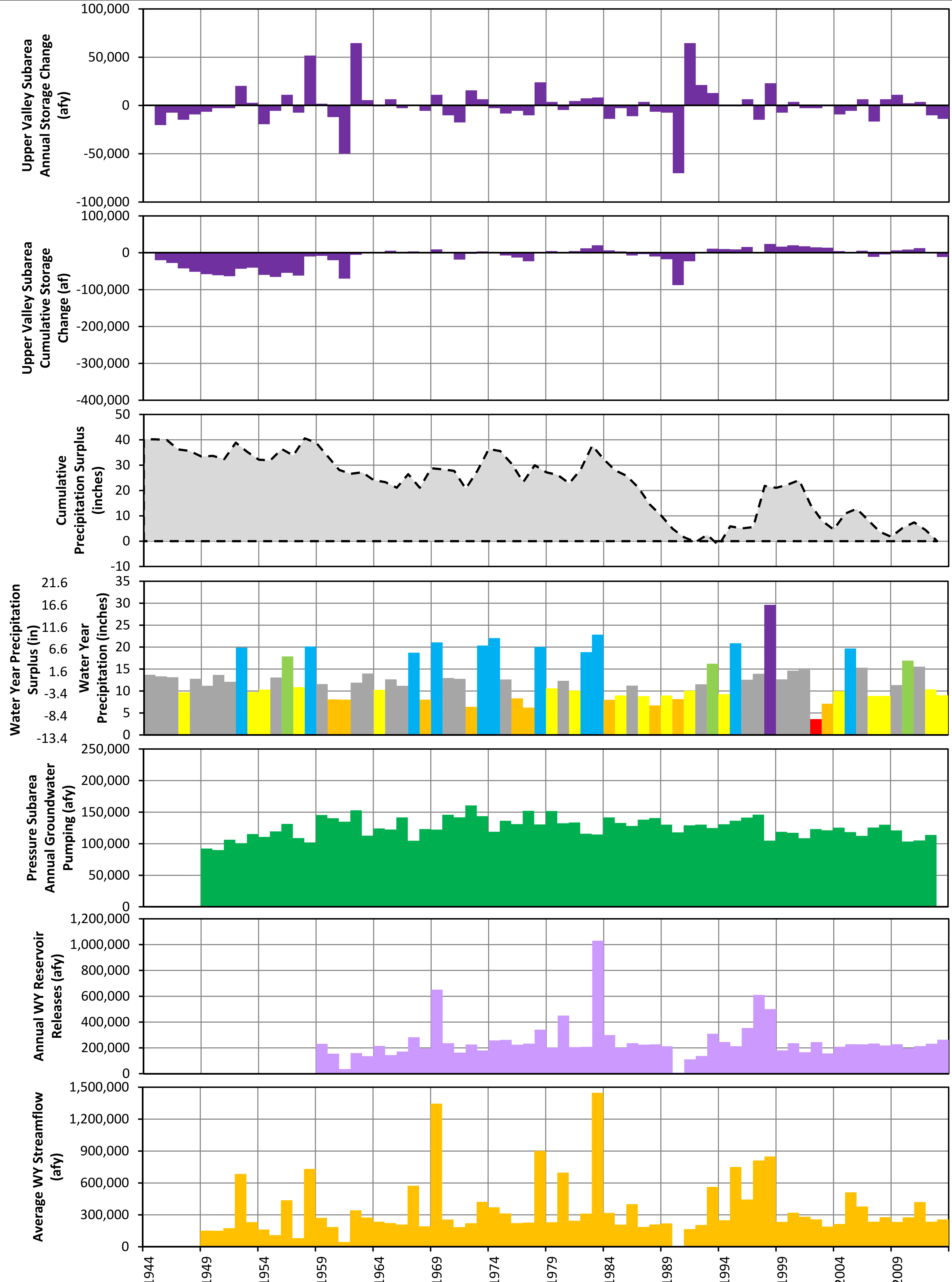
10/21/14	Salinas River Groundwater Basin Investigation	Figure 4b
PROJECT 146430	TITLE Storage Change in the Pressure Subarea (Storage Coefficient = 0.004)	



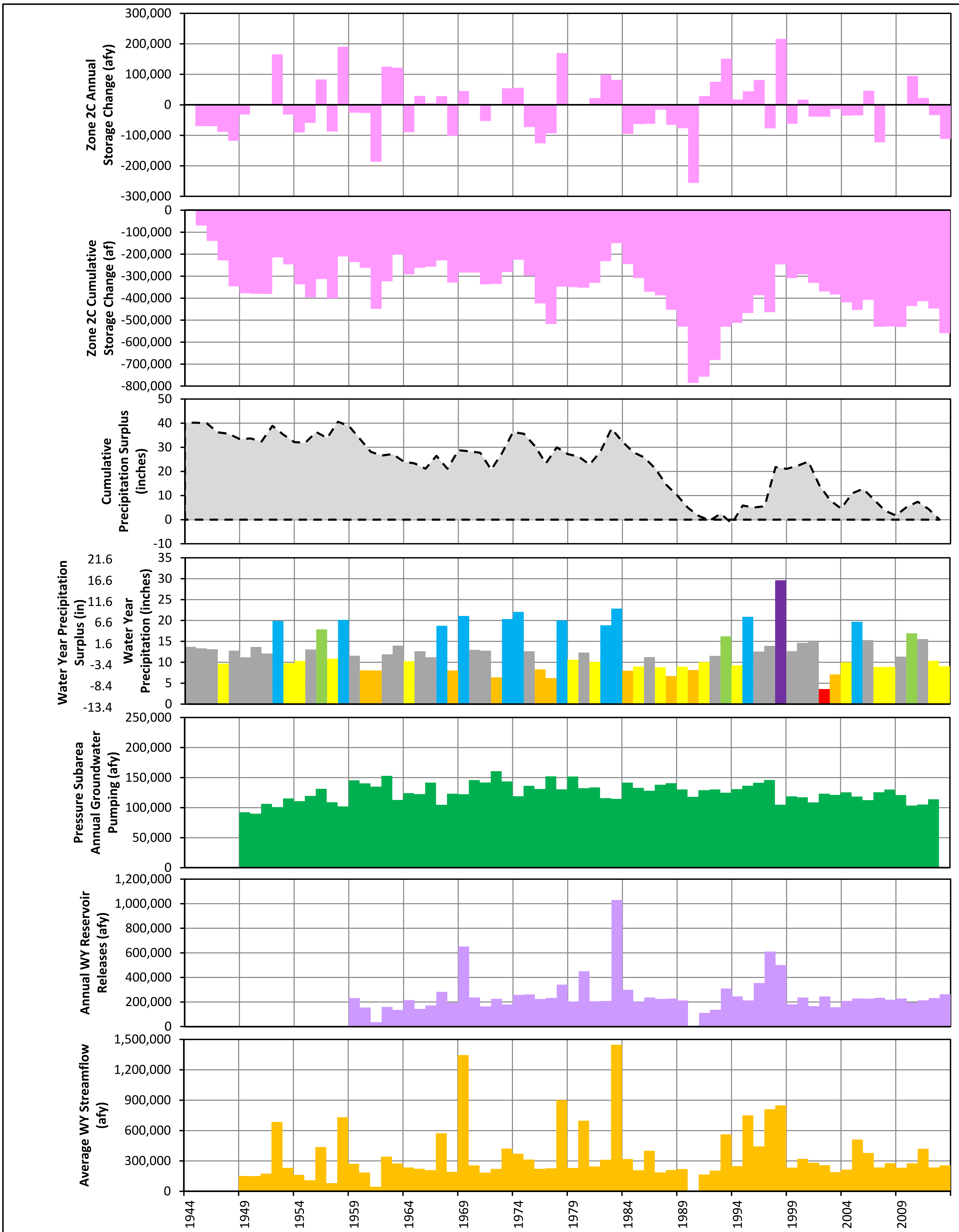
Brown AND Caldwell	DATE 10/21/14	SITE Salinas River Groundwater Basin Investigation	Figure 5
	PROJECT 146430	TITLE Storage Change in the East Side Subarea	



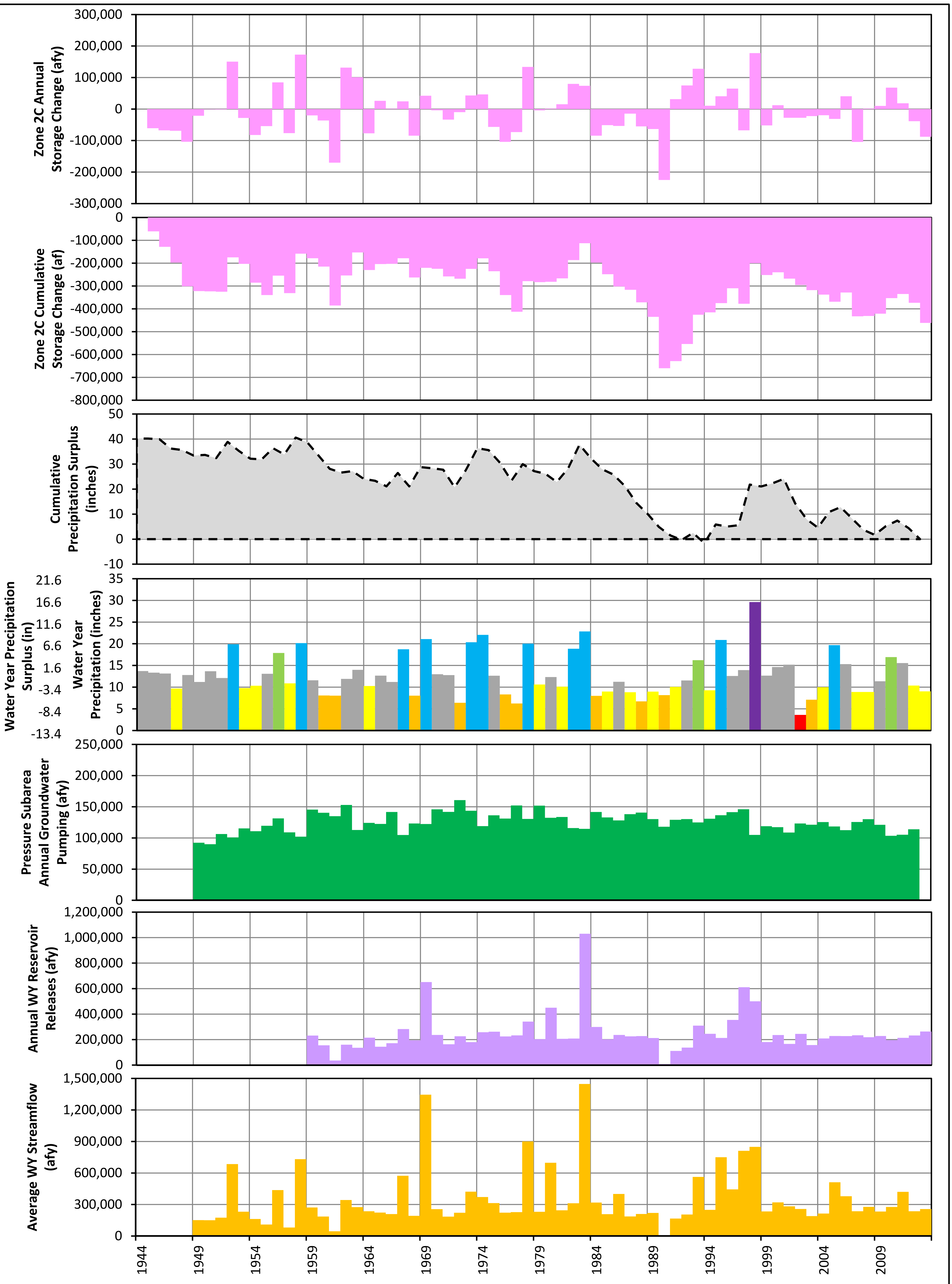
Brown AND Caldwell	DATE 10/21/14	SITE Salinas River Groundwater Basin Investigation	Figure 6
	PROJECT 146430	TITLE Storage Change in the Forebay Subarea	



Brown AND Caldwell	DATE 10/21/14	SITE Salinas River Groundwater Basin Investigation	Figure 7
	PROJECT 146430	TITLE Storage Change in the Upper Valley Subarea	



Brown AND Caldwell	DATE 10/21/14	SITE Salinas River Groundwater Basin Investigation	Figure 8a
	PROJECT 146430	TITLE Storage Change in Zone 2C (Pressure Subarea Storage Coefficient = 0.036)	



Brown AND Caldwell	DATE 10/21/14	SITE Salinas River Groundwater Basin Investigation	Figure 8b
	PROJECT 146430	TITLE Storage Change in Zone 2C (Pressure Subarea Storage Coefficient = 0.004)	

Reservoir releases (which started in WY 1959) are much more sporadic than extraction, and depend in part on the amount of precipitation in previous years. Particularly low release years (such as WY 1961 and WY 1990) correspond to steep declines in storage. These are not years of increased extraction. The highest release year, WY 1983, which was a VW year, actually saw a decline in storage. The linear correlation between reservoir releases and storage change has a p-value of 0.07 (the relationship is not statistically significant to the 95% confidence level) and an r^2 coefficient of 0.06. This indicates that there is not a strong relationship between these two variables.

The cumulative storage change over the period of record was compared with the cumulative precipitation surplus (Figure 4a). The effect of considering the cumulative storage change and precipitation surplus is to de-emphasize year-to-year variability and emphasize longer-term trends. The linear correlation between these two variables has a p-value of 1.4×10^{-17}, and an r^2 coefficient of 0.66, indicating a much better match compared to that between annual storage change and annual precipitation surplus. It must be noted that this comparison relies on the same data as the annual comparison, and so the relationship between cumulative storage change and precipitation cannot really be used as a predictive tool with any greater certainty than could the relationship between annual storage change and annual precipitation surplus.

As noted in Section 2.5.2, the period from WY 1984 to 1991 is the longest period of below-average rainfall years in the period of record. The cumulative precipitation surplus declined by about 36 inches over this period, and storage declined by a total of about 103,000 af, or about 13,000 afy. Every year during this period saw a decline in storage, ranging from about 1,800 to 34,900 afy. The provisional precipitation total of about 5.9 inches for WY 2014 discussed in Section 2.5.2 is somewhat lower than the precipitation total for WY 1988 (6.7 inches), a VD year, when storage declined in this subarea by about 11,800 af. WY 1984, another VD year with 8.0 inches of precipitation saw a storage decline of about 12,200 af; WY 1990, another VD year (8.2 inches of precipitation), saw a storage decline of about 34,900 af. It therefore seems reasonable to assume that continued years of precipitation well below average would result in storage declines on the order of 10,000 to 20,000 afy in the Pressure subarea.

As noted in Section 2.1, the storage coefficient used for the above analysis (0.036) is not representative of the confined conditions believed to be prevalent in the subarea, and a more representative storage coefficient is likely to be substantially lower than that used above. To provide an alternative calculation of storage change, a storage coefficient value of 0.004 was used, which was used by MWH (1997) for the 180-Foot Aquifer (see Section 2.4). Figure 4b shows the annual and cumulative storage changes for the Pressure subarea using this storage coefficient value. As expected, the storage changes using this approach are much smaller than those described above, with annual changes ranging from about -3,900 to +4,900, an average annual storage change of about -200 afy, and a cumulative storage change of about -12,200 af from 1944 to 2013. This represents a decrease in storage changes of about an order of magnitude compared to the storage changes shown on Figure 4a.

Because the storage coefficient is just a proportionality constant in Equation 1, the linear correlations between storage changes using the smaller value of storage coefficient and the independent variables have the exact same statistical significance as those discussed above, although the slope and intercept of the correlation lines change.

During the extended drought of WY 1984 to 1991, storage declined by about 200 to 3,900 af per year. Based on years similar to WY 2014, storage can be expected to decline by about 1,000 to 2,000 afy in the Pressure subarea under continued dry years.

3.2 East Side Subarea

The East Side subarea experienced annual storage changes estimated at between about -58,400 and +82,800 afy over the period from 1944 to 2013 (Figure 5). The cumulative storage change was negative over the entire period, reaching about -398,100 af in 1991 and ending at about -332,600 af in 2013. The average change in storage over the period of record was about -4,800 afy. Of the 70 years included in the analysis, 41 had negative storage change, 1 had no change, and 28 had positive change.

The trends in storage change in the East Side subarea are similar to those in the Pressure subarea, but greater in magnitude. Of the 70 years covered in the analysis, there were five with positive storage change in the Pressure subarea and negative storage change in the East Side subarea, three with negative change in the Pressure subarea and positive change in the East Side subarea, and one with no change in the Pressure subarea and negative change in the East Side subarea. Figure 9 shows a comparison between annual storage changes for the East Side and Pressure subareas; there is a very good correlation between the two ($r^2 = 0.81$, p-value = 5.8×10^{-26}), indicating that the factors driving storage change in the East Side subarea are likely the same as those driving change in the Pressure subarea. The annual storage changes are about twice as large on average in the East Side subarea as in the Pressure subarea (when the higher storage coefficient is used in the Pressure subarea calculation). The cumulative storage change in the East Side subarea (about -398,000 af by 2013) is about 2.8 times the cumulative storage change in the Pressure subarea (about -144,300 af).

As with the Pressure subarea, correlations of annual storage change with reservoir releases ($r^2 = 0.13$, p-value = 6.0×10^{-3}) and extraction ($r^2 = 0.02$, p-value = 0.32) are poor (although the correlation to reservoir releases is statistically significant). The correlation of annual storage change with annual precipitation surplus is slightly better for the East Side subarea than for the Pressure subarea ($r^2 = 0.54$, p-value = 4.4×10^{-13}). The correlation between cumulative storage change and cumulative precipitation surplus is also slightly better than for the Pressure subarea ($r^2 = 0.80$, p-value = 3.6×10^{-25}).

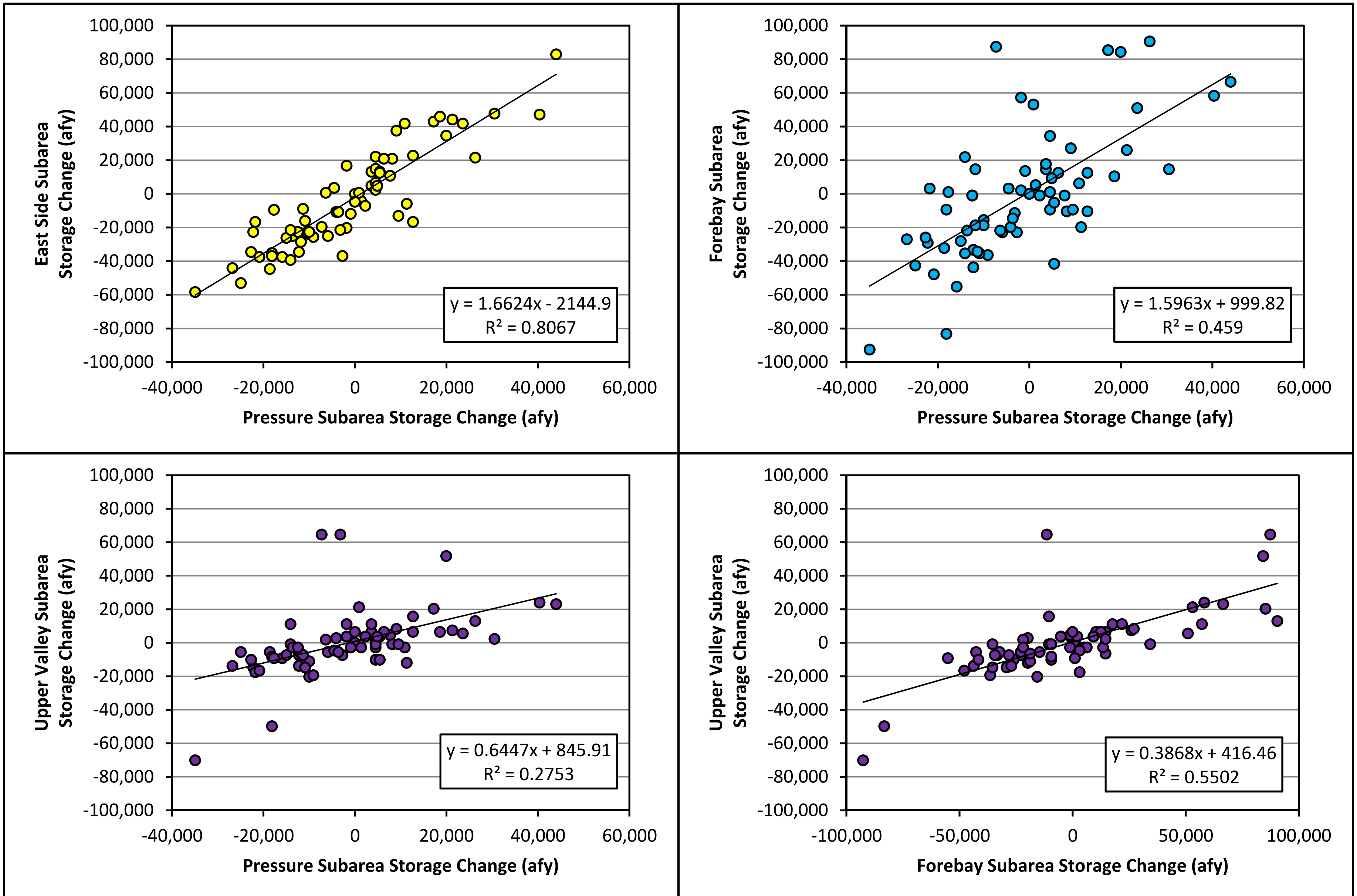
The cumulative storage decline over the period from WY 1984 to 1991 was about 228,300 af, or about 28,500 afy. Based on similar precipitation years during this period (see Section 3.1), the annual storage change for WY 2014 can be expected to be about -25,000 to -35,000 af.

3.3 Forebay Subarea

The Forebay subarea experienced annual storage changes estimated at between about -92,600 and +90,500 afy over the period from 1944 to 2013 (Figure 6). The cumulative storage change was negative over most of the period, with a maximum of about +41,600 af in 1983 and a minimum of about -191,500 af in 1991, and ended at about -105,200 af in 2013. The average change in storage over the period of record was about -1,500 afy. Of the 70 years included in the analysis, 38 had negative storage change, 2 had no change, and 30 had positive change.

The trends in storage change in the Forebay subarea are somewhat similar to those of the Pressure subarea, but much more variable from year to year and overall less negative (i.e. closer to zero). Over the 70-year period of the analysis, there were nine years with positive storage change in the Pressure subarea and negative storage change in the Forebay subarea and nine years with negative change in the Pressure subarea and positive change in the Forebay subarea; the total number of positive, zero, and negative storage change years is the same for the two subareas.

Figure 9 shows that the correlation between annual storage changes in the Pressure and Forebay subareas is not as good as between the Pressure and East Side subareas, although it is still significant ($r^2 = 0.35$, p-value = 5.8×10^{-8}). In particular, the Forebay subarea experiences very large (positive and negative) storage changes during years when the storage change in the Pressure subarea is much smaller. This may indicate that the processes governing storage change in the Forebay subarea are different from those operating in the Pressure subarea.



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	PROJECT 146430	TITLE Storage Change Correlations Between Subareas	

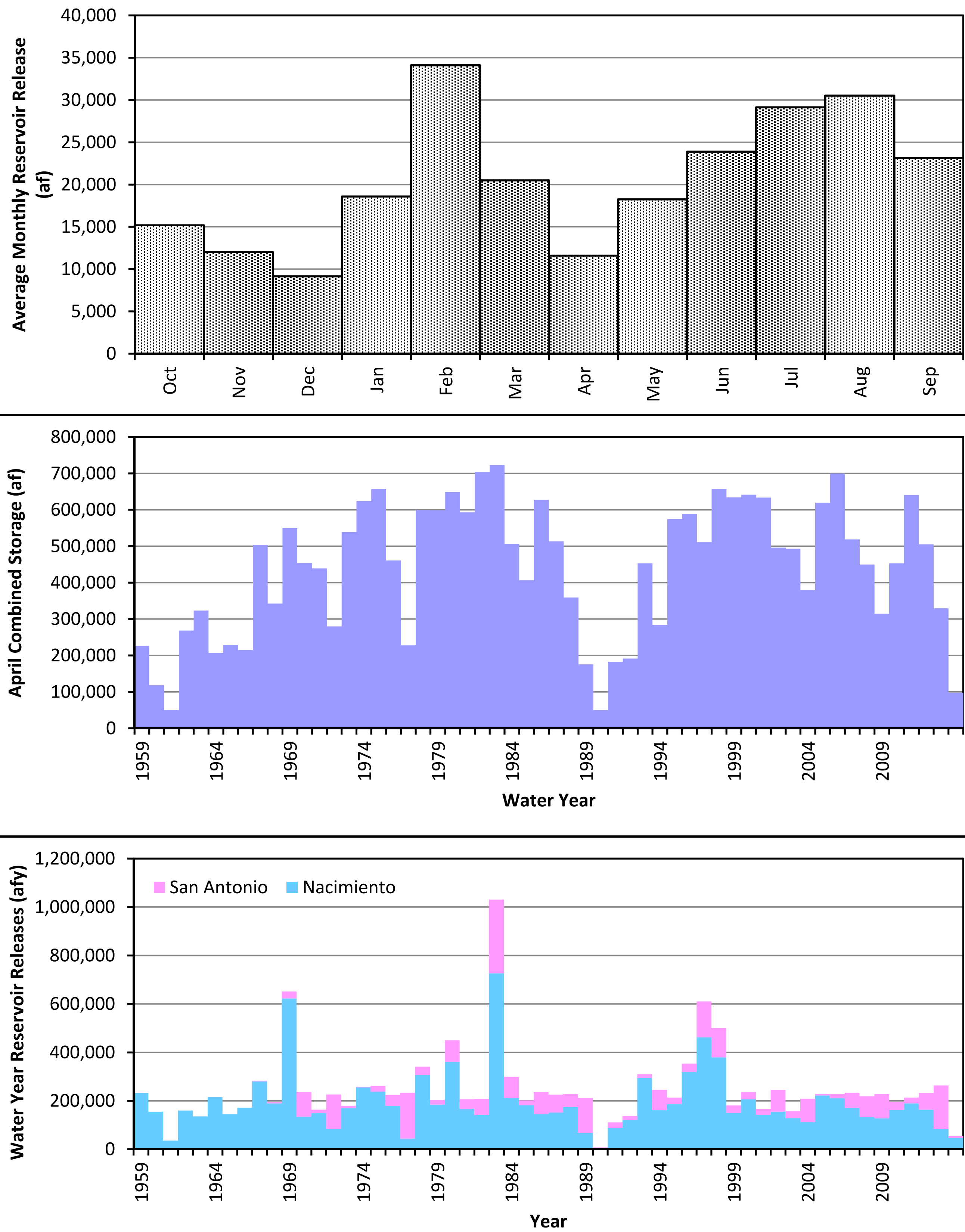
As can be seen in Figure 6, the magnitude of annual storage changes is frequently much larger in the Forebay subarea than in the Pressure subarea, particularly early in the period of record. Large positive storage changes occurred in wet years, such as WYs 1952 (VW), 1956 (W), 1958 (VW), 1978 (VW), 1993 (W), and 1998 (EW), each of which followed one or more years of normal or dry conditions. Additionally, WYs 1962, 1963, and 1992 (all N) saw large positive storage changes without having abnormally high precipitation; these years followed periods when storage change was highly negative during dry conditions (VD WYs 1960 and 1961 for the early example and 1984 to 1991 for the late example). On the other hand, VW WYs 1967, 1969, 1973, and 1974 saw only modest storage increases (less than 20,000 af in each year), and occurred during a period of several years of normal to above average precipitation. This indicates that storage has typically declined during dry periods in the Forebay subarea, but that a year or two of wet (and even normal) conditions have historically been sufficient to build storage back up. This recovery took longer after the drought covering WYs 1984 to 1991, when the cumulative storage change did not return to zero until WY 1998 (EW). Additionally, the cumulative storage change has been negative since WY 1999, despite several N to VW years occurring during this period. Of note is the fact that the cumulative storage change never gets above about 41,600 af, and tends to not remain positive for very long at any given time, indicating that the subarea was approximately at its storage capacity at the beginning of the period of record.

Groundwater extraction is higher on average in the Forebay subarea than in the Pressure and East Side subareas, averaging about 154,800 afy. Pumping before about 1980 was somewhat higher (167,700 afy) compared to the period from 1980 on (142,800 afy). Overall, the correlation between annual storage change and extraction is poor ($r^2 = 0.07$, p-value = 3.9×10^{-2}), though just barely significant. The same is true of the correlation between annual storage change and reservoir releases ($r^2 = 0.06$, p-value = 6.6×10^{-2}). Years of abnormally high reservoir releases (such as WYs 1969 and 1983) do not result in abnormally large storage changes (about 17,700 and 27,100 af, respectively). This is likely due to the fact that these large reservoir releases only occur during exceptionally wet periods (when the reservoirs are full), when the cumulative storage change is approximately zero and the subarea is already at or near its storage capacity. On the other hand, years of very small reservoir releases (such as WYs 1961 and 1990) saw by far the largest negative storage changes over the entire period of record (-83,200 and -92,600 af, respectively), indicating that normal reservoir releases are instrumental to keeping the Forebay subarea storage at or near its capacity. In both of the cases of small reservoir releases, the large negative storage change was made up for by several years of normal releases in subsequent years.

As noted above, the correlation between annual storage change and annual precipitation surplus in the Forebay subarea is not as good as in the Pressure and East Side subareas. The correlation between the cumulative storage change and cumulative precipitation surplus is much worse than in those subareas (r^2 = 0.18, p-value = 2.2×10^{-4}). This is due in no small part to the fact that the cumulative storage change in the Forebay subarea remains near zero for much of the period of record, unlike the large negative cumulative storage changes in the Pressure and East Side subareas.

The cumulative storage decline over the period from WY 1984 to 1991 was about 43,400 af, or about 5,400 afy. Based on similar precipitation years during this period (see Section 5.4.1), the annual storage change for WY 2014 can be expected to be about -10,000 to -15,000 af. However, if reservoir releases are very low over the coming years, the storage decline may be much greater in magnitude, on the order of -80,000 to -90,000 af, as occurred in WYs 1961 and 1990. To determine if this is likely, a brief discussion of historical reservoir storage and releases is warranted.

Reservoir operations at the Nacimiento and San Antonio Reservoirs are controlled by the Agency, and the reservoirs are used for flood control, Basin recharge, and offsetting of groundwater pumping near the coast. This is reflected in the distribution of average monthly releases since the reservoirs began operating (WY 1959 for Nacimiento and WY 1967 for San Antonio), shown in Figure 10. There are two peaks in the distribution, one in February and another in August. February, when streamflow is highest due to winter



Brown AND Caldwell	DATE 10/21/14	SITE Salinas River Groundwater Basin Investigation	Figure 10
	PROJECT 146430	TITLE Reservoir Release Time Series	

precipitation, has relatively high release volumes for flood control. August, when the irrigation season is at its peak, has relatively high release volumes to offset pumping along the coast and to stabilize water levels in the Forebay and Upper Valley subareas.

Of particular interest are the conditions that have previously led to very small historical releases from the reservoirs. Figure 10 includes a chart of April reservoir storage (on average, the highest storage month of the year) that can be compared against the reservoir release time series given on Figure 10. The two years of lowest reservoir releases, WYs 1961 and 1990, correspond to the two years of lowest April reservoir storage. A linear relationship exists between annual reservoir releases and April storage ($r^2 = 0.22$, p-value = 2.7×10^{-4}), particularly below April storage volumes of about 500,000 af. In fact, between April storage volumes of about 100,000 and 500,000 af, the reservoir release volume is fairly steady around 200,000 afy, with a slight increase with increasing April storage. However, when the April storage is very low, about 50,000 af (as occurred in WYs 1961 and 1990), releases have been correspondingly low.

The April 2014 storage volume was about 97,200 af, the third-lowest volume on record but not as low as the volumes of WYs 1961 and 1990. However, if dry conditions continue for additional years, it is reasonable to expect that the April reservoir storage may decline to even lower levels, and that reservoir releases may therefore be very small, leading to large storage declines in the Forebay subarea. As noted above, historical large groundwater storage declines have been recovered over a period of several years once climatic conditions returned to normal. The total WY 2014 reservoir release was about 55,000 af, the third-lowest release on record (following WYs 1990 and 1961). WYs 1990 and 1961 saw storage declines of more than 80,000 af each in this subarea, indicating that the storage loss during WY 2014 may be quite large, and that additional dry years could result in further substantial storage declines.

3.4 Upper Valley Subarea

The Upper Valley subarea experienced annual storage changes estimated at between about -70,100 to +64,600 afy over the period from 1944 to 2013 (Figure 7). The cumulative storage change was negative over most of the period, with a maximum of about +24,000 af in 1998 and a minimum of about -87,700 af in 1990 and ending at about -11,500 af in 2013. The average change in storage over the period of record was about -200 afy. Of the 70 years included in the analysis, 40 had negative storage change, 1 had no change, and 29 had positive change.

Figure 7 shows that the storage change trends in the Upper Valley subarea are generally similar to those of the Forebay subarea, and unlike the trends in the Pressure and East Side subareas; this is also displayed on Figure 9, which includes scatterplots of annual storage changes in the Upper Valley subarea versus annual storage changes in both the Pressure and Forebay subareas. The correlations between annual storage change and annual precipitation surplus ($r^2 = 0.12$, p-value = 3.3×10^{-3}), reservoir releases ($r^2 = 0.03$, p-value = 2.4×10^{-1}), and extraction ($r^2 = 0.01$, p-value = 4.2×10^{-1}) are quite poor, and only the correlation with annual precipitation surplus is statistically significant. The correlation between cumulative storage change and cumulative precipitation surplus is also poor, the worst of any of the subareas ($r^2 = 0.11$, p-value = 4.5×10^{-3}), and in fact has a slight negative slope, indicating that times of lower cumulative storage correspond to times of higher cumulative precipitation surplus (this is due to the fact that most of the years of negative cumulative storage in the Upper Valley subarea occurred during the period prior to the operation of the Nacimiento Reservoir, when the cumulative precipitation surplus was quite high, but reservoir releases were not available to recover storage declines in the Upper Valley subarea).

Since the Nacimiento Reservoir began operating, the cumulative storage change in the Upper Valley subarea has hovered around zero. The only time since then that the cumulative storage change has been as far as 50,000 af below zero was WY 1990, when there was almost no water released from the reservoirs (storage change during that year was about -70,100 af). WY 1961, when there was also very little water released from the reservoir, saw a storage change of about -49,800 af. As for the Forebay subarea, comparison of the annual storage change time series to the reservoir release time series demonstrates that these years of small reservoir release correspond to the largest negative annual storage changes (Figure 7). In the Upper Valley subarea, the cumulative storage change rises back to about zero even more quickly than in the Forebay subarea after these declines.

The general response of storage in the Upper Valley subarea can be expected to be similar to that of the Forebay subarea, although smaller in magnitude. If the period from WYs 1984 to 1991 is taken as a guide, storage change in the Upper Valley subarea can be expected to be about -5,000 to -15,000 afy under continued dry conditions. However, if reservoir releases decline to very low levels, the magnitude of storage change may be larger, similar to the -70,100 af change that occurred in WY 1990. As with the Forebay subarea, any large negative storage changes are likely to be refilled in subsequent wetter climatic conditions. As noted above, the WY 2014 storage release was only about 55,000 af. The two years on the record with lower release than this (WYs 1990 and 1961) saw storage declines in this subarea of about 50,000 to 70,000 af, indicating that the storage loss during WY 2014 may be quite large, and that additional dry years could result in further substantial storage declines.

3.5 Entire Study Area

Together, the four subareas discussed above make up the bulk of Zone 2C. This area experienced annual storage changes estimated at between about -256,100 and +216,500 afy over the period from 1944 to 2013 (Figure 8a; note that this relies on the larger value of storage coefficient for the Pressure subarea). The cumulative storage change was negative over the entire period, reaching about -785,500 af in 1990 and ending at about -559,100 af in 2013. The average change in storage over the period of record was about -8,000 afy. Of the 70 years included in the analysis, 41 had negative storage change, 1 had no change, and 28 had positive change.

Because the storage change patterns are very different in the northern part of Zone 2C (the Pressure and East Side subareas) and the southern part (the Forebay and Upper Valley subareas), describing the response of Zone 2C as a whole is less straightforward than describing the response of the individual subareas. However, the storage change in the entire Zone 2C is dominated by the pattern in the East Side subarea, as this is where the largest storage changes occur.

The correlations of annual storage change with annual precipitation surplus ($r^2 = 0.46$, p-value = 1.2×10^{-10}) and reservoir releases ($r^2 = 0.10$, p-value = 2.2×10^{-2}) are slightly worse than those in the East Side subarea, while the correlation with extraction ($r^2 = 0.06$, p-value = 5.0×10^{-2}) is slightly better. The correlation between cumulative storage change and cumulative precipitation surplus ($r^2 = 0.61$, p-value = 2.1×10^{-15}) is also slightly worse than in the East Side subarea, and comparable to the correlation in the Pressure subarea.

As with the Forebay and Upper Valley subareas, strong responses can be observed in the time series of annual storage changes during WYs 1961 and 1990, when reservoir releases were very low (Figure 8a). The magnitude of storage change during these two years was greater in the Forebay (Figure 6) and Upper Valley (Figure 7) subareas than in the Pressure (Figure 4a) and East Side (Figure 5) subareas, indicating that the overall Zone 2C storage response to very low release years is felt most strongly in the Forebay and Upper Valley subareas.

Based on the analyses for the individual subareas, it is likely that Zone 2C as a whole may experience between about 50,000 to 85,000 afy of storage loss in future dry years, comparable to other past dry years (Figure 8a). However, if reservoir releases are curtailed, as occurred in WYs 1961 and 1990, storage losses can be expected to be much larger in magnitude, due mostly to losses in the Forebay and Upper Valley subareas. In that case, the total magnitude of storage loss in Zone 2C may be on the order of about 185,000 to 215,000 afy in future dry years, a level of storage loss that has only been experienced during years of very small reservoir release. The time series of cumulative storage change (Figure 8a) indicates that the large storage losses experienced during these years were compensated for in subsequent years when climatic conditions returned to normal.

Using the smaller value of storage coefficient for the Pressure subarea (see Section 3.1), the Zone 2C annual storage change has ranged from about -225,000 to +177,000 afy. The cumulative storage change was negative over the entire period of record, reaching a maximum loss of about 660,000 af in 1990 before ending at about 462,000 af in 2013 (Figure 8b). In general, the pattern of changes shown on Figure 8b is very similar to that shown on Figure 8a, since the greatest changes were experienced in the East Side subarea.

Of the 70 years included in the analysis, 40 had negative storage change, 1 had no change, and 29 had positive change. Because the storage coefficient is simply a proportionality constant in Equation 1, the regression statistics are the same as described above, although the slopes and intercepts of the linear regressions are different.

Based on the analysis for individual subareas, it is likely that Zone 2C as a whole will experience between about 40,000 to 65,000 afy of storage loss in future dry years (Figure 8b). However, if reservoir releases are curtailed, the storage loss may be much greater, on the order of about 175,000 to 195,000 afy.

Section 4: Data Gaps

In the course of performing this analysis, several data gaps were identified. Filling in these gaps would improve the accuracy of this and other analyses in the study area by improving knowledge of the study area hydrogeology.

As mentioned in Section 2.1, the storage coefficients used for this analysis represent average values for individual subareas and were taken from existing studies. The analysis of the Pressure subarea shows the effect of uncertainty in the storage coefficient, with storage change varying by about an order of magnitude depending on the value of the storage coefficient used. The larger storage coefficient value for this subarea, provided by MCWRA, is the simple average of three storage coefficient values reported by DWR (2003) from a numerical groundwater flow model (Yates, 1988) that treated the Pressure subarea as a single layer, without differentiating the individual aquifers. It seems likely that the actual storage coefficient in the Pressure subarea is smaller than that used in this analysis, and quite variable considering the heterogeneous nature of the aquifer (as demonstrated by cross-sections in Kennedy/Jenks, 2004). However, few aquifer tests have been performed in the study area, limiting the amount of independent data that could be used to more accurately estimate the values and variability of storage coefficients throughout the study area. In this TM, the value provided by MCWRA was used to calculate storage change, and an alternate calculation was performed using a storage coefficient value considered more representative of confined conditions.

As noted in Brown and Caldwell (2014), while groundwater extraction data are available for a large number of wells throughout the study area, construction information is generally not known, meaning that it is often not known from what particular aquifers a well is drawing water. This limits the capacity for an analysis like this one to be extended to estimate storage changes in individual aquifers.

The three-dimensional extents of the aquifers and aquitards in the subareas of the study area are not known with any great accuracy, This limits the accuracy of estimates of the total volume of groundwater in storage, for which the saturated volume of the aquifer must be known (whereas the change in storage depends only on the storage coefficient; although the storage coefficient is a vertically integrated parameter, and therefore depends directly on aquifer thickness, its value is typically estimated directly during aquifer tests, without having to know the thickness of the aquifer).

In addition, the specific yield of confined aquifers is typically unknown, since the groundwater head must be lowered below the top of the aquifer to estimate this parameter, a typically undesirable condition. The specific yield is a parameter that quantifies the volume of water released from a unit volume of the aquifer if the pores are allowed to drain under gravity. Therefore, this parameter must be estimated to calculate the total volume of extractable groundwater in storage.

Section 5: Summary and Conclusions

This TM discussed the trends of storage change in Zone 2C and its component subareas. Storage change is driven by different processes in different parts of Zone 2C, with the response in the Pressure and East Side subareas driven largely by precipitation and the response in the Forebay and Upper Valley subareas driven by a combination of precipitation and reservoir releases.

The Pressure subarea has experienced cumulative storage losses on the order of about 109,700 af (Figure 4a) or about 12,200 af (Figure 4b), depending on the storage coefficient used. The cumulative storage loss in the East Side subarea has been much larger (about 332,600 af; Figure 5) The cumulative storage change has been negative over the entire period of record in both these subareas, covering 1944 to 2013. Storage changes have been of greater magnitude in the East Side subarea than in the Pressure subarea. Annual storage change is reasonably well-correlated to annual precipitation surplus at the Salinas Municipal Airport station.

The Forebay and Upper Valley subareas have experienced much smaller cumulative storage losses, hovering around zero for much of the period of record and ending at about 105,200 af (Figure 6) and 11,500 af (Figure 7), respectively. Annual storage change is not as well-correlated to annual precipitation surplus in these subareas. Of the considered variables (precipitation surplus, reservoir releases, and groundwater extraction), precipitation surplus is still the most highly-correlated variable. However, an analysis of the time series of storage change indicates that large positive storage changes occur during normal and wetter years if preceded by years with negative storage changes (i.e. storage increases whenever there is storage capacity in the aquifers of these subareas). Over the period of record, cumulative storage changes hovered around zero except in the Forebay subarea during the WYs 1984 to 1991 drought and since WY 1999.

The dry period of WYs 1984 to 1991 can be instructive for predicting how storage is likely to change under continued dry conditions. During this period, storage declined by a total of about 607,300 af over the entirety of Zone 2C, an average of about 75,900 afy, with a very large proportion of the decline (about 256,100 af) occurring just during WY 1991, when reservoir releases were very small. Estimates of potential storage change in continued dry years (see Section 3.5) varied from about 50,000 to 85,000 afy if normal reservoir operations continue, and about 185,000 to 215,000 afy if reservoir releases are severely curtailed. An alternative analysis relying on a more realistic value of storage coefficient in the Pressure subarea indicated smaller storage changes, with losses estimated to vary from about 40,000 to 65,000 afy if normal reservoir operations continue, and about 175,000 to 195,000 afy if reservoir releases are severely curtailed. Current reservoir storage levels are not quite as low as in previous years of very low delivery, but are close; WY 2014 had the third-lowest April storage in the record, and the third-lowest total release volume. This shows that reservoir releases can be expected to be very low in coming years, unless enough precipitation reaches the area to replenish reservoir storage levels.

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