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Reconstructing the natural hydrology of the San Francisco Bay-Delta watershed

P. Fox[1], P. H. Hutton[2], D. J. Howes[3], A. J. Draper[4], and L. Sears[5]

[1]Consulting Engineer, Rockledge, FL, USA
[2]Principal Engineer, Metropolitan Water District of Southern California, Sacramento, CA, USA
[3]Assistant Professor, Irrigation Training and Research Center, BioResource and Agricultural Engineering Department, California Polytechnic State University, San Luis Obispo, USA
[4]Principal Engineer, MWH, Sacramento, CA, USA
[5]GIS Specialist, Beaverton, OR, USA

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Correspondence to: D. J. Howes (djhowes@calpoly.edu)

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Abstract

The San Francisco Estuary, composed of San Francisco Bay and the Sacramento–San Joaquin River Delta, is the largest estuary along the Pacific coast of the United States. The tributary watersheds of California's Central Valley are the principal sources of freshwater flow into the San Francisco Bay-Delta estuary. The Delta serves as one of the principal hubs of California's water system, which delivers 45 % of the water used statewide to 25 million residents and 16 000 km^2 of farmland.

The development of California, from small-scale human settlements that co-existed with an environment rich in native vegetation to the eighth largest economy in the world was facilitated by reconfiguring the state's water resources to serve new uses: agriculture, industry, and a burgeoning population. The redistribution of water from native vegetation to other uses was accompanied by significant declines in native aquatic species that rely on the San Francisco Bay-Delta system. These declines have been attributed to a variety of causes, including reduction in the amount of freshwater reaching the San Francisco Bay-Delta watershed (Delta outflow); decreased sediment loads; increased nutrient loads; changes in nutrient stoichiometry; contaminants; introduced species; habitat degradation and loss; and shifts in the ocean–atmosphere system, among others. Among these stressors, only the volume of Delta outflow has been regulated in an effort to address the decline in aquatic species.

As native species evolved under natural landscape conditions, prior to European settlement in the mid-18th century, we evaluated the impact of landscape changes on the amount of Delta outflow. We reconstructed the natural landscape and used water balances to estimate the long-term annual average Delta outflow that would have occurred under natural landscape conditions if the climate from 1922 to 2009 were to repeat. These outflows are referred to as "natural" Delta outflows and are the first reported estimate of natural Delta outflow. We then compared these "natural" Delta outflows with current Delta outflows for the same climate and the existing landscape, including its re-engineered system of reservoirs, canals, aqueducts and pumping plants.

This analysis shows that the long-term, annual average Delta outflow under natural landscape conditions is equal to current Delta outflow because the amount of water currently used by farms, cities, and others is about equal to the amount of water formerly used by native vegetation. The development of water resources in California's Central Valley transferred water formerly used by native vegetation to new beneficial uses without reducing the long-term annual average supply to the San Francisco Bay-Delta estuary. Thus, it is unlikely that reductions in annual average Delta outflow have caused the decline in native freshwater aquatic species.

1 Introduction

The Central Valley of California is a 60 to 100 km wide broad flat alluvial plain, stretching over 750 km from north to south and covering about 58 000 km^2 (containing the irrigated land from south of Redding to south of Bakersfield in Fig. 1). This valley is entirely surrounded by mountains except for a narrow gap on its western edge through which the combined Sacramento and San Joaquin Rivers flow to the Pacific Ocean through San Francisco Bay (Fig. 1). This valley is the agricultural heartland of the United States, producing over 360 products and more than half of the country's vegetables, fruits and nuts. It is often considered the most productive agricultural region in the world, a status achieved by significantly re-engineering the natural landscape.

The northern portion of the Central Valley, referred to in this work as the Valley Floor (Fig. 2), is the major source of freshwater to the San Francisco Bay-Delta system, the largest estuary along the Pacific coast of North America and the home to a rich ecosystem. It is also the major source of freshwater that sustains most of the agricultural production and population of California. The Sacramento River from the north and the San Joaquin River from the south flow toward each other, joining in the Delta. These rivers are the principal freshwater supply for the San Francisco Bay-Delta system as well as 45 % of the water used statewide by 25 million residents and 16 000 km^2 of farmland.

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Declines in native aquatic species have been documented in the San Francisco Bay-Delta system over the last several decades (Jassby et al., 1995; MacNally et al., 2010; Thomson et al., 2010). Many aquatic species have been classified as endangered, threatened, and species of concern, e.g., Sacramento River winter-run Chinook salmon, Delta smelt, Sacramento Splittail, Longfin smelt, Southern green sturgeon (Lund et al., 2007). These declines have been attributed to several factors including reduced volume and altered timing of freshwater flows from the tributary watersheds (Delta outflow); decreased sediment loads; increased nutrient loads; changes in nutrient stoichiometry; contaminants; introduced species; habitat degradation and loss; and shifts in the ocean–atmosphere system (Luoma and Nichols, 1993; Jassby et al., 1995; Bennett and Moyle, 1996; MacNally et al., 2010; Glibert, 2010; Glibert et al., 2011; Miller et al., 2012; Cloern and Jassby, 2012).

However, among these, only Delta outflow has been directly or indirectly regulated in an effort to stem the decline in aquatic species as it is generally believed that reduced outflows are directly related to reduced species abundance. This study investigates whether the volume of freshwater flow reaching the San Francisco Bay-Delta system has been reduced by development within the tributary watershed and thus is a contributing factor to species declines.

The native species of concern evolved and thrived under natural landscape conditions, or those that existed prior to European settlement starting in the mid-18th century. These undisturbed conditions are referred to in this work as “natural” conditions, meaning undisturbed by western civilization. Thus, “natural” Delta outflows are those that would have occurred with “natural” landscape conditions.

The natural landscape included immense inland marshes located in natural flood basins along major rivers (Alexander et al., 1874; Hall, 1887; Garone, 2011), lush riparian forests on river levees (Katibah, 1984), and vast swaths of grasslands interwoven with vernal pools and immense valley oaks in park-like savannas that extended from the floodplains to the oak- and pine-covered foothills (Holland, 1978; Burcham, 1957; Dutzi, 1978). This landscape was fed by periodic overflows of the rivers into natural

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flood basins along the major rivers. Figure 3 is a cross-section through the Valley Floor that illustrates the major features of this natural landscape.

This landscape was dramatically altered, starting in the mid-18th century, to support new land and water uses. The native vegetation was largely replaced by cultivated crops, the flood basins were drained, the rivers were confined between levees, headwater reservoirs was built to store floodwaters, and an extensive system of canals and aqueducts were built to move water from its point of origin to distant locations. In this study, we estimate long-term annual average Delta outflow under natural landscape conditions (referred to as “natural” Delta outflow) using a water balance. We then compare natural Delta outflow with Delta outflow under current conditions for the same climatic conditions. This is the first estimate of natural Delta outflow into the San Francisco Bay-Delta estuary.

2 Study area background

Prior to development, starting in the mid-18th century, the channels of the major rivers did not have adequate capacity to carry normal winter rainfall runoff and spring snowmelt (Grunsky, 1929; CA State Engineer, 1908). The rivers overflowed their banks into vast natural flood basins flanking both sides of the Sacramento and San Joaquin Rivers (Hall, 1880; Grunsky, 1929). Sediment deposited as the rivers spread out over the floodplain and built up natural levees along the river channels (Fig. 3). These natural levees were much larger and more developed along the Sacramento River than along the San Joaquin River (Hall, 1880).

The natural levees were lined with lush riparian forest. The floodplains contained large expanses of tule marsh, seasonal wetlands, vernal pools, grasslands, lakes, sloughs and other landforms that slowed the passage of flood waters (Whipple et al., 2012; Garone, 2011; Holmes and Eckmann, 1912) (Fig. 4). Groundwater generally moved from recharge areas along the sides of the valley towards topographically lower areas in the central part of the valley, where it was depleted through marsh, vernal

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pool, and riparian forest evapotranspiration (TBI, 1998; Bertoldi et al., 1991; Williamson et al., 1989; Davis et al., 1959).

Grasslands interspersed with vernal pools (seasonal wetlands) stretched from the edge of the floodplain to the foothills, generally overlying relatively impermeable hardpans and claypans that supported perched water tables. This habitat once occupied nearly all level lands between the foothills and floodplain and was the dominant vegetation under natural conditions, supplied by perched aquifers, overland runoff from the foothills, and precipitation (Fig. 4).

This natural landscape, summarized in Fig. 4, was radically modified, starting in the mid-18th century, to make it suitable for agricultural (Smith and Verrill, 1998) and urban uses (Fig. 5), creating the world's largest water system supporting the eighth largest economy in the world. The native vegetation was removed, river channels were dredged and rip-rapped, levees were raised, the flood basins were drained, bypasses were installed to route flood waters directly into the Delta, and head-stream reservoirs were built to replace side-stream storage, provide protection from floods, and generate electricity. Massive hydraulic works were built to move water from areas of relative abundance to areas of relative scarcity, throughout the state, including to Los Angeles and the San Francisco Bay Area. The heart of this system is the tributary watersheds of the Valley Floor in the Central Valley of California (Figs. 1 and 2). The history of these changes have been documented elsewhere (Kelley, 1959, 1989; Bain et al., 1966; Kahrl, 1979; Thompson, 1957; Hundley, 2001; Olmstead and Rhode, 2004; CDWR, 2013b).

3 Methods

Annual average Delta outflow was estimated under natural landscape conditions (natural Delta outflow) using a conventional water balance. The results of this calculation are compared with two estimates of Delta outflow by the California Department of Water

Resources (CDWR): (1) current Delta outflow (CDWR, 2012) and (2) unimpaired Delta outflow (CDWR, 2007).

"Unimpaired" outflows are rim inflows from the surrounding mountain ranges, modified or "unimpaired" to remove impacts of upstream alterations that are routed through the existing system of channels and bypasses into the Delta (Fig. 2), without any losses or modifications on the way and with no recognition of the natural landscape (CDWR, 2007). These "unimpaired" outflows are frequently misused as a surrogate for "natural" Delta outflow (Cloern and Jassby, 2012; Dynesius and Nilsson, 1994). All three of these estimates are based on the level-of-development methodology and the climate over the period 1922 to 2009 to facilitate direct comparisons.

3.1 Level of development methodology

These three estimates of Delta outflow – natural, current and unimpaired – were estimated using a synthetic multi-year hydrologic sequence utilizing a "level of development" approach (Draper et al., 2004). This method routes the same amount of water (rim inflows plus precipitation) over a defined historical period assuming "frozen" conditions such as land use, flood control and water supply facility operations, and environmental regulations. In other words, this method simulates river flows under a repeat of historical climate, but holding land use and facility operations constant.

A historical hydrologic sequence may be generated to represent development as it existed in a particular year (i.e., "1990 level of development"), as it exists today (i.e., "current level of development"), or as it may exist under a projected scenario (i.e., "future level of development"). This approach allows us to estimate the impact of anthropogenic changes on natural Delta outflow by comparing a "natural" level of development with a "current" level of development.

Thus, our estimate of natural outflow is not an estimate of actual flows that occurred under Paleolithic or more recent conditions prior to European settlement (Ingram et al., 1996; Malamud-Roam et al., 2006; Meko et al., 2001). Rather, our natural Delta outflow calculation is an estimate that assumes the contemporary precipitation and inflow

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pattern to the Valley Floor with the Valley Floor in a natural or undeveloped state, i.e., before flood control facilities, levees, land reclamation, irrigation projects, imports, etc.

Natural outflow calculations were performed on a monthly basis assuming long term climatic conditions observed over an 88 year period (1922 to 2009). The calculations assume a conventional California October through September water year. Water balances were calculated around the portion of the Central Valley that drains into San Francisco Bay (referred to as the "Valley Floor") as shown in Fig. 2.

3.2 Natural delta outflow

Natural Delta outflow was calculated using a conventional water balance as the difference between water supply and water use:

$$\text{Natural Delta Outflow} = \text{Water Supply} - \text{Water Use} \quad (1)$$

"Natural" Delta outflows are the outflows that would result if the climate for the period 1922 to 2009 were to occur under "natural" landscape conditions. "Natural" landscape conditions are those that existed prior to the advent of European settlement, starting in the mid-18th century, including native vegetation (Fig. 4) and natural landforms such as stream-side flood basins and low levees.

The water supply is the sum of rim inflows from the surrounding mountain ranges into the Valley Floor plus precipitation on the Valley Floor, adjusted to remove impairments such as diversions. The only losses of water under natural conditions were evaporation from water surfaces and evapotranspiration by native vegetation. Water that is not evaporated or evapotranspired flows out of the Delta into San Francisco Bay and is referred to here as "Delta outflow."

Equation (1) assumes that the long-term, annual average change in groundwater storage would have been zero under pre-development conditions. This assumption would not significantly affect long-term annual average calculations as the year-to-year fluctuations of groundwater exchanges are insignificant compared to average surface water flows. However, it would affect seasonal flow patterns, which is the subject of

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ongoing work. Net groundwater depletions under pre-development conditions are approximately zero and unimportant to the overall annual water balance (Gleick, 1987).

Water balances are reported for three hydrologic regions that comprise the Valley Floor: the Sacramento Basin, the San Joaquin Basin, and the Delta (Fig. 2). Water balances were calculated at a finer resolution for sixteen subsets of the Valley Floor, referred to as "planning areas" (CDWR, 2005a, b) shown on Fig. 2.

The results of these conventional water balance calculations are compared with current Delta outflow (CDWR, 2012) and a surrogate for natural outflow, unimpaired outflow (CDWR, 2007), estimated based on the level-of-development methodology.

3.3 Natural water supply

The water supply used in the natural water balances was estimated as the sum of rim inflows around the periphery of the Valley Floor plus precipitation that falls on the Valley Floor. The long-term annual average natural water supply is 50.1 billion $m^3 yr^{-1}$, comprising 34.2 billion $m^3 yr^{-1}$ from rim inflows and 15.9 billion $m^3 yr^{-1}$ from precipitation over the Valley Floor.

The Valley Floor boundary is defined by the drainage basins of the gages used to determine valley rim inflows, adjusted (i.e., "unimpaired") to remove the effects of upstream storage regulation, imports and exports. Rim inflows are defined as the natural water supply from the surrounding mountains and other watersheds to the Valley Floor. The rim inflows were compiled for undeveloped and developed watersheds from several sources that cover different portions of the study area.

Rim inflows have been affected by changes in land use and forest management and by loss of natural meadows. Agricultural and urban development represents a relatively small portion (about five percent) of the rim watersheds. While low elevation hardwoods and chaparral have been lost and annual grassland areas have increased (Thorne et al., 2008), much of the rim watersheds remain characterized by conifer forest. Forest management practices, which have resulted in denser forest stands compared to pre-development conditions, may significantly affect runoff timing and volume (Bales

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et al., 2011; CDWR, 2013b). Denser forest canopy prevents snow from reaching the ground and leads to greater evapotranspiration and earlier snowmelt (CDWR, 2013b). However, scientific evidence necessary to quantify relationships between forest management and water supply has been inconclusive. Therefore, our work assumes natural inflows from the rim watersheds are equal to historical inflows adjusted to remove the effects of upstream storage regulation, imports and exports (i.e., unimpaired inflows).

Historical flow records were generated from US Geological Survey (USGS) and California Department of Water Resources (CDWR) gage data and extended through linear correlation with gaged flows in nearby watersheds. Rim inflows from ungaged watersheds were estimated from adjacent gaged watersheds based on relative drainage area and average annual precipitation.

Unimpaired flows (CDWR, 2013a) from developed rim watersheds in the Sacramento and San Joaquin hydrologic regions were assumed to equal natural inflows. Similarly, unimpaired flows from the rim watershed south of the Valley Floor (i.e., the Tulare Lake hydrologic region) were assumed to be equal to natural inflows (CDWR, 2012). Minimal groundwater flow from the Sierra Nevada and Coastal Range to the Valley Floor is assumed, due to the presence of bedrock and high surface slopes (Armstrong and Stidd, 1967; Gleick, 1987; Williamson et al., 1989).

In addition to rim inflows from surrounding mountain watersheds, precipitation falling directly on the Valley Floor contributes to the water supply. Precipitation was calculated for each planning area within the Valley Floor using distributed grids obtained from the PRISM Climate Group at Oregon State University (Daly et al., 2000; Daly and Bryant, 2013; PRISM Climate Group, 2013).

3.4 Natural water use

The pre-development Valley Floor was a diverse ecosystem of immense inland marshes, lush riparian forests, and vast swaths of grasslands interwoven with vernal pools and immense valley oaks in park-like savannas that extended from the floodplains to the oak- and pine-covered foothills (Bryan, 1923; Davis et al., 1959; Thomp-

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son, 1961, 1977; Roberts et al., 1977; Dutzi, 1978; Warner and Hendrix, 1985; TBI, 1998; Cunningham, 2010; Garone, 2011; Whipple et al., 2012).

Under natural conditions, the only water use was evapotranspiration by natural vegetation and evaporation from water surfaces such as lakes, rivers, and sloughs. We estimated the amount of water used by natural vegetation from the areal extent and evapotranspiration rate for each type of vegetation. We also estimated evaporation from lakes, rivers, and sloughs based on the area and evaporation rates from these bodies of water.

Estimating the water used by natural vegetation requires information on the vegetation evapotranspiration rate (ET_v) and the areal extent of vegetation (A_v). The volume of water used by natural vegetation is then estimated in Eq. (2) as the product of ET_v and A_v summed over all planning areas i and vegetation types j:

$$ET = \sum_{i,j} (ET_v \times A_v) \quad (2)$$

The same method was applied to evapotranspiration from free water surfaces such as lakes, ponds, sloughs, and river channels. The remainder of the section discusses how ET_v and A_v were estimated.

3.4.1 Evapotranspiration

The reference crop method was used to estimate evapotranspiration by natural vegetation (Howes and Pasquet, 2013; Howes et al., 2015). As shown in Eq. (3), the evapotranspiration rate is related to the potential evapotranspiration (ET_o) for a standardized grass reference crop grown under idealized conditions multiplied by a vegetation coefficient (K_v) that accounts for canopy/plant characteristics:

$$ET_v = ET_o \times K_v \quad (3)$$

Two methods were used to estimate K_v, depending upon the available water supply used by various vegetation categories. The methods used to develop the K_v and ET_v

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used in this study are discussed in detail in Howes et al. (2015). The methods are briefly summarized in the following paragraphs.

For non-stressed vegetation with a continuous water supply throughout the growing season, K_v was estimated from published studies of actual monthly (or more frequent) ET_v using a grass reference evapotranspiration (ET_o) (Howes et al., 2015). The ET_o used to derive the K_v values for this study was computed using the Standardized Penman–Monteith equation (Allen et al., 2005) when a full set of meteorological data was available; otherwise, the Hargreaves equation was used. The accuracy of this method was confirmed for permanent wetlands and riparian forest using actual evapotranspiration measured using remote sensing at two sites in central California (Howes et al., 2015).

For vegetation depending solely on precipitation (chaparral and a portion of the grasslands and valley/foothill hardwood), a daily soil water balance using the dual-crop coefficient method (Allen et al., 1998) was used to estimate ET_v and K_v over the 88 year study period (Howes et al., 2015). The ET_v values directly from the daily soil water balance were used in Eq. (2) for vegetation types reliant solely on precipitation. Since the daily soil water balance accounts for variable precipitation, the ET_v from vegetation reliant on precipitation varies from year to year. As a reference, the long term annual average K_v values for these vegetation types were calculated from daily soil water balances for each planning area and are summarized in Table 1.

The K_v values summarized in Table 1 for non-water stressed vegetation were used in Eq. (3) to estimate monthly average ET_v for vegetation types that had access to full year-round water supply by planning area. Long-term average ET_v values for all vegetation types are shown in Table 2 (Howes et al., 2015).

3.4.2 Vegetation areas

The vegetation present on the Valley Floor under natural conditions included rain-fed and perennial grasslands, vernal pools, permanent and seasonal wetlands, valley/foothill hardwood, riparian forest, saltbush, and chaparral (Howes et al., 2015; Bar-

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bour et al., 1993; Garone, 2011; Küchler, 1977). The areal extent of each type of vegetation was estimated from historic maps and contemporary estimates based on historic sources (Hall, 1887; Burcham, 1957; Küchler, 1977; Roberts et al., 1977; Dutzi, 1978; Fox, 1987; TBI, 1998; CSU Chico, 2003; Garone, 2011; Whipple et al., 2012; Fox and Sears, 2014), supplemented by early soil surveys for vernals pools (Holmes et al., 1915; Nelson et al., 1918; Strahorn et al., 1911; Lapham et al., 1909; Sweet et al., 1909; Holmes and Eckmann, 1912; Mann et al., 1911; Lapham and Holmes, 1908; Lapham et al., 1904; Watson et al., 1929).

Most of these vegetation maps focused on a single type of vegetation so we were unable to use them as our primary source. Further, we were unable to piece the more limited coverage maps together in any meaningful way as they used different vegetation classification systems and different study areas; even this collection of maps did not cover the entire Valley Floor study area. Thus, we based our natural vegetation estimates on the California State University at Chico ("CSU Chico") pre-1900 map, which covered most of the Valley Floor.

The CSU Chico study reviewed and digitized approximately 700 historic maps from numerous collections in public libraries. These sources were pulled together in a series of maps, including a "Pre-1900 Historic Vegetation Map." We used the pre-1900 Historic Vegetation Map as our base map, modified to cover the entire Valley Floor using Küchler (1977) and to further subdivide some of its vegetation classifications to match available evapotranspiration information.

CSU Chico characterized its pre-1900 map as "the best available historical vegetation information for the pre-1900 period" noting it provided "a snapshot of the most likely pre Euro–American vegetation cover" (CSU Chico, 2003). This map has been cited by others as representing natural vegetation (Bolger et al., 2011; Vaghti and Greco, 2007). It is based on a patchwork of sources, scales, and dates, with the earliest source map dating to 1874.

The accuracy of the CSU Chico pre-1900 map was confirmed to the extent feasible using GIS overlays with other available natural vegetation maps (Hall, 1887; Roberts

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et al., 1977; Dutzi, 1978; Fox, 1987; TBI, 1998; Garone, 2011; Whipple et al., 2012). Original shapefiles were used where available (Whipple et al., 2012; TBI, 1998; Küchler, 1977; CSU Chico, 2003). Other maps were scanned (400-dpi full color scanner), the scanned versions were georeferenced using various data layers (e.g., county, township), and the map features were digitized by hand using editing features in ArcMap. ArcMap's geoprocessing tools were used to determine vegetation areas (Fox and Sears, 2014).

However, as the CSU Chico maps and other sources were based on maps prepared after significant modifications to the landscape had already occurred, they may underestimate some types of natural vegetation (Thompson, 1957; Whipple et al., 2012; CSG, 1862). It follows that reliance on these maps may underestimate evapotranspiration and thereby overestimate natural Delta outflow. Riparian forests, for example, were cleared early to make way for cities and farms and harvested to supply fuel for steamboats traversing the rivers in support of the Gold Rush (Whipple et al., 2012). Widespread conversion of wetlands into agricultural uses began in the 1850s when they were leveed, drained, cleared, leveled or filled; water entering them was impounded, diverted, or drained; and sloughs and crevasses closed to dry out the land (Whipple et al., 2012; Frayer et al., 1989; CSG, 1862). The great wheat bonanza that transformed much of the Central Valley into farmland was well underway by 1874, the date of the earliest historic map in the collection considered by CSU Chico.

The results of our natural vegetation area analysis, based on available historic maps and soil surveys, are summarized in Fig. 4 and Table 3. These areas represent the starting point for our natural flow estimate. We call this starting point "Case I".

Case I represents long-term annual average conditions. These areas are not representative of individual years due to climate-driven variations, which primarily affected grasslands and wetlands. Area size, especially of rainfed grasslands and vernal pools, likely varied from year to year with the amount of precipitation falling on the Valley Floor and surrounding mountains.

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3.4.3 Sensitivity analysis

A sensitively analysis was performed to address the uncertainity in both natural vegetation areas and evapotranspiration rates. The areal extent of most types of vegetation was not measured or even observed by botanists in its natural state. Further, the water used by some classes of natural vegetation, such as vernal pools and valley oak savannas, has never been measured in the Valley Floor while the natural water supply is largely based on measurements of rim watershed stream flows or impairments thereof and precipitation. Thus, we formulated a series of cases, in which land use was varied, to explore the range in natural vegetation water use. The cases were selected to address key uncertainties associated with classifying vegetation areas. The eight cases we studied are summarized in Table 4.

As grasslands (including vernal pools) and valley/foothill hardwood classifications represent the greatest portions of the Valley floor (see Table 3), our cases focus on these two vegetation classifications. The extent of permanent wetlands, the next largest vegetation classification in the Valley Floor, was extensively surveyed in the 1850s (CSG, 1856, 1862; Anonymous, 1861; Flushman, 2002; Thompson, 1957) and is considered to be accurately estimated in Case I (Table 3). Further, the evapotranspiration from these wetlands has been well studied (Howes et al., 2015). Thus, we have confidence in our estimates of water use by permanent wetlands.

Grasslands occupied about half of the Valley Floor area or about 16 000 km^2 out of 34 000 km^2 (Table 3). The composition of these grasslands (e.g., the fraction that was perennial, rainfed, and vernal pool) is unknown, as rapid and widespread modifications occurred before any botanical study (Heady et al., 1992; Holmes and Rice, 1996; Holstein, 2001; Burcham, 1957; Garone, 2011). Some have attempted to estimate vernal pool area (Holland, 1978, 1998; Holland and Hollander, 2007), but we are not aware of any attempts to estimate the area of perennial and rainfed grasslands.

There is significant controversy over the original composition of grasslands. Some argue pristine grasslands were perennial bunchgrasses (Heady, 1988; Küchler, 1977;

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Bartolome et al., 2007) while others argue they were dominated by annual forbs (Schiffman, 2007; Holstein, 2001). A discussion of this controversy is provided in Garone (2011). Finally, large expanses of lands classified as “grasslands” by others (Küchler, 1977; Fox, 1987; TBI, 1998; CSU Chico, 2003) were probably vernal pool seasonal wetlands supported by perched aquifers (Zedler, 2003; Holland and Hollander, 2007; Fox and Sears, 2014). Due to these unknowns and controversies, we used six cases to explore the effect of grassland composition on natural water use, the base case compared to five variants.

In Case I, all grassland areas outside of the floodplain were classified as either vernal pool (based on soil surveys) or rainfed grassland, as shown in Fig. 4 and Table 3. We then varied the rainfed portion to assume it was vernal pool (Case II) and perennial grassland (Case III). Case IV is similar to Case III, except that all San Joaquin Basin grasslands were classified as rainfed. We discounted the scenario of grasslands being rainfed valley-wide as unlikely, given that our work and the work of Holland and Hollander (2007) established that a significant fraction of the Valley Floor was vernal pool habitat. Some of these grassland areas, particularly within the flood basins, were likely seasonal wetlands or lakes and ponds (Whipple et al., 2012) with higher water uses, but we had no basis for estimating these areas.

It was generally assumed that vegetation areas are constant from year to year in cases I to IV, which is reasonable for a long-term annual average. However, this assumption is an over-simplification when applied to individual years because vegetation area likely varied in response to climate, especially the amount and timing of precipitation and resulting riverbank overflow. The floodplain boundary, for example, would have varied significantly depending on the amount and timing of runoff, which would have affected vegetation both inside and outside of the floodplain. In July 1853, for example, engineers surveying a route for a railroad in the San Joaquin Valley reported: “The river [San Joaquin] had overflowed its banks, and the valley was one vast sheet of water, from 25 to 30 miles broad, and approaching within four to five miles of the hills” (Williamson, 1853). The average floodplain boundary (CDPW, 1931a, b) was typically

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over 20 miles from these hills. We used the average floodplain boundary to estimate some vegetation types, such as seasonal wetlands within "other floodplain habitat," which would yield inaccuracies when used for individual years.

Grasslands are the vegetation type most likely to respond significantly to climate. Thus, in Cases V and VI, the mix of rainfed and perennial grasslands was varied based on the volume of rim inflow to the Sacramento and San Joaquin basins. We believe Cases V and VI most closely represent water use under natural conditions as it is likely that vegetation varied in this fashion. It is likely that seasonal wetlands varied in a similar fashion, extending further outside of the flood basins in wet years than in dry or critical (Whipple et al., 2012). However, we did not have sufficient data to evaluate this case.

We defined two additional vegetation area cases to explore the uncertainty of natural Delta outflow due to evapotranspiration and areal extent of valley foothill hardwoods (Case VII) and wetlands (Case VIII).

Case VII was included to explore the effect of valley/foothill hardwoods composition on natural Delta outflow. This case primarily affects Sacramento Basin outflow as 86 % of the hardwood vegetation, or 5300 km^2, are in this basin. This vegetation class was subdivided into foothill hardwood, present at higher elevations with deeper water tables, and valley oak savannas, present in the Valley Floor where water tables were shallow, for purposes of estimating evapotranspiration (Howes et al., 2015). Foothill hardwoods likely relied on soil moisture as the water table was generally deeper at these higher elevation areas than on the Valley Floor. Valley oak savannas, on the other hand, had deep root systems (Howes et al., 2015) that tapped the shallower groundwater at lower elevations (Bertoldi et al., 1991; Bryan, 1915; Kooser et al., 1861).

We had no basis for reliably subdividing valley/foothill hardwood land areas into subclasses. Küchler (1977) suggests about 65 % was foothill hardwoods. Thus, we evaluated a range. In Case I, we assumed that 100 % of valley/foothill hardwood was foothill hardwood. In Case VII, we assumed 100 % was valley oak savanna, holding all other land areas constant as in Table 3.

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Case VIII classifies San Joaquin Basin seasonal wetlands as rainfed grasslands. Soil surveys, eyewitness accounts, and the basin's relatively dry hydrology suggest that rainfed grasslands (rather than seasonal wetland) is a plausible alternate vegetation classification.

4 Results

The water balance methodology described previously was used to estimate annual average Delta outflow under natural conditions for each year of the 88 year hydrologic sequence (1922–2009). A long-term annual average was computed from individual yearly results and compared with CDWR's (2012, 2007) estimates of long-term annual average Delta outflow under current conditions and unimpaired conditions for a similar period of record.

The results of our natural Delta outflow water balances for eight land use cases are summarized in Table 5 and illustrated in Fig. 6. Under natural conditions, native vegetation used 27.1 to 36.1 billion $m^3 yr^{-1}$ of the natural water supply, falling as precipitation in the mountain ranges surrounding the Valley Floor and on the Valley Floor itself. This amounts to 54 to 72 % of the total supply of 50.1 billion $m^3 yr^{-1}$. The water that was not evapotranspired or evaporated, ranging from 14.0 to 23.0 billion $m^3 yr^{-1}$, flowed into the Delta and San Francisco Bay. These results are consistent with those reported by others (Shelton, 1987; Bolger et al., 2011; Fox, 1987).

We believe that Cases V and VI, in which the mix of rainfed and perennial grasslands was varied based on the volume of rim inflow to the Sacramento and San Joaquin basins, most closely represent water use under natural conditions. In these cases, native vegetation used 29.6 to 30.8 billion $m^3 yr^{-1}$ or about 60 % of the natural supply. In these cases, about 40 % of the natural supply was consumed by the grassland-vernal pool complex occupying the area between the foothills and the floodplain. About 34 % of the natural supply was consumed by permanent and seasonal wetlands, largely within the floodplain. The balance of the natural supply was consumed by riparian

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vegetation (14 %), foothill hardwoods (9 %), and saltbush, chaparral, and open water surfaces (3 %).

In comparison, the current-level, long-term annual average Delta outflow is 19.5 billion $m^3 yr^{-1}$ (CDWR, 2012). This estimate was developed using a reservoir system operations model (Draper et al., 2004) and assumes a 2011 level of development for an 82 year hydrologic sequence (1922 to 2003). The current long-term annual average water supply of 51.6 billion $m^3 yr^{-1}$ estimated by CDWR (2012) exceeds the natural water supply in our analysis by 1.5 billion $m^3 yr^{-1}$ due to (1) groundwater overdraft of 0.9 billion $m^3 yr^{-1}$ in the Sacramento and San Joaquin Basins and (2) Sacramento River Basin imports of 0.6 billion $m^3 yr^{-1}$ from the U. S. Bureau of Reclamation Trinity River Diversion Project, a project that transfers water from Lewiston Reservoir through the Clear Creek Tunnel to the Sacramento River (CDWR, 2012). Thus, 62 % of the current water supply or 31.9 billion $m^3 yr^{-1}$ is consumed by irrigation, municipal, industrial, and other uses under current conditions, based on the 2011 level of development.

The long-term annual average current level Delta outflow of 19.5 billion $m^3 yr^{-1}$ falls within the range of estimated natural outflows shown in Table 5 for the same period of record (14.0 to 23.0 billion $m^3 yr^{-1}$). The current level water balance indicates that 62 % of the water supply is currently consumed by irrigation, municipal, industrial, and other uses (CDWR, 2013b). This estimate is roughly the midpoint of the range of estimated natural water use (54 to 72 %) and indistinguishable from our best estimates of natural outflow in cases V and VI (60 %).

Thus, current and natural Delta outflows, when reported for the same climatic conditions, are very similar because natural vegetation used nearly as much water (27.1 to 36.1 billion $m^3 yr^{-1}$) as is consumed currently (26.0 billion $m^3 yr^{-1}$) for agriculture, municipal, industrial, and other uses. Further, the current and natural Delta outflow estimates are statistically indistinguishable due to uncertainties described elsewhere.

In sum, reconfiguring the natural water supply to accommodate new land uses (e.g., compare Fig. 4 with Fig. 5), mitigate flooding, and redistribute the water supply in time and space has not changed the annual average amount of freshwater reaching San

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Francisco Bay from the Central Valley, when controlled for climate. This is the case because natural vegetation (Fig. 4) consumed about as much water as is currently used by the new land uses within the Valley Floor (Fig. 5) as well as outside of it.

We believe our natural Delta outflow estimates were based on conservative assumptions that will tend to underestimate evapotranspiration and thus overestimate natural Delta outflows. Noteworthy conservative assumptions include: (1) all of the permanent wetlands is assumed to be “large stand”, thereby ignoring higher water-using “small stand” wetlands and (2) the maps and soil surveys used to estimate natural vegetation areas underestimate the extent of some types of natural vegetation, such as wetlands and vernal pools, as significant modifications had been made to the landscape prior to the date of its earliest source (1874).

5 Discussion

This study shows that long-term annual average current and natural outflows fall within the same range, when controlled for climatic conditions. This occurs as the amount of water currently used from Valley Floor watersheds for agriculture, domestic, industrial, and other uses is about equal to the amount of water that would be used if the existing engineered system were replaced by natural vegetation.

An estimate of natural Delta outflows is important as reduction in the volume of freshwater reaching the San Francisco Bay-Delta Estuary due to the current level of development has frequently been advanced as one of the causes for the decline in abundance of native species. Further, estimates of hypothetical natural outflow (so-called “unimpaired” outflows) have been proposed to regulate current Delta outflows in an effort to restore ecological health of the estuary. However, prior to our work, no one had attempted to estimate natural outflows. This work indicates that restoring flows to annual average natural outflows are unlikely to restore ecosystem health because they are indistinguishable from annual average current outflows.

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The reduced outflow hypothesis advanced by some as a cause of declines in native fish abundance is typically based on "unimpaired" flows of 34.3 billion $m^3 yr^{-1}$ published by CDWR (2007). These "unimpaired" flows are hypothetical flows that never existed. They assume the same water supply (50.1 billion $m^3 yr^{-1}$) as our natural water balance, but current landscape conditions. Thus, unimpaired flows are not natural flows. CDWR (2007) differentiates "unimpaired" Delta outflow from "natural" Delta outflow by characterizing them as:

> runoff that would have occurred had water flow remained unaltered in rivers and streams instead of stored in reservoir, imported, exported, or diverted. The data is a measure of the total water supply available for all uses after removing the impacts of most upstream alterations as they occurred over the years. Alterations such as channel improvements, levees, and flood bypasses are assumed to exist.

The long-term annual average unimpaired Delta outflow estimate of 34.3 billion $m^3 yr^{-1}$ assumes the same rim inflows and Valley Floor precipitation used in our natural water balances in Table 5. However, rather than reducing water supply to account for water use associated with the full extent of natural vegetation in the Valley Floor, the unimpaired outflow calculation assumes that water use upstream of the Delta is limited to only Valley Floor precipitation (CDWR, 2007).

Thus, the unimpaired outflow calculation effectively assumes rim inflows pass through the Valley Floor and arrive in the Delta in the current system of channel improvements, levees and flood bypasses (i.e., the difference between the natural water supply of 50.1 billion $m^3 yr^{-1}$ and Valley Floor precipitation of 15.9 billion $m^3 yr^{-1}$ is 34.2 billion $m^3 yr^{-1}$). Thus, by definition, unimpaired Delta outflow calculations provide a high estimate when used as a surrogate for natural Delta outflow.

In spite of CDWR's caveats of its theoretical calculation of "unimpaired" Delta outflow from natural Delta outflow, unimpaired outflows have frequently been used as a surrogate measure of natural conditions, presumably because an estimate of natural Delta outflow was unavailable prior to this work. For example, Dynesius and Nilsson

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(1994) argue that the Bay-Delta watershed is "strongly affected" by fragmentation due to the difference between current Delta outflow and the Delta's reported "virgin mean annual discharge" of 34.8 billion $m^3 yr^{-1}$, a quantity roughly equivalent to CDWR's long-term annual average unimpaired Delta outflow calculation published by CDWR at the time of this work. More recently, the California State Water Resources Control Board (CSWRCB, 2010) submitted a report to the state legislature suggesting a flow criterion of 75 % of unimpaired Delta outflow from January through June "in order to preserve the attributes of the natural variable system to which native fish species are adapted". This suggested criterion was based on fishery protection alone and did not consider other beneficial uses of water in the estuary.

Native aquatic species evolved under natural landscape conditions. A comparison of Figs. 4 and 5 demonstrates that very little of the natural landscape remains. Thus, habitat restoration should be an important ingredient in restoring these species. An estimate of natural Delta outflow is important to guide future restoration planning activities.

The Comprehensive Everglades Restoration Plan (CERP), for example, used natural system modeling to gain a better understanding of south Florida's hydrology prior to drainage and development. CERP, which was designed to restore the Everglades ecosystem while maintaining adequate flood protection and water supply for south Florida, is using insights gained by this modeling effort, in combination with other adaptive management tools, to formulate restoration plans and set targets (SFWMD, 2014).

California's Bay Delta Conservation Plan, another such planning activity, envisions a reversal of the Delta's ecosystem decline through protection and creation of approximately 590 km^2 of aquatic and terrestrial habitat (CDWR & USBR, 2013). By reconnecting floodplains, developing new marshes, and returning riverbanks to a more natural state, the plan is designed to boost food supplies and provide greater protection for native fisheries.

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6 Conclusions and recommendations

This study found that the amount of water from the Valley Floor watershed currently consumed for agriculture, domestic, industrial, and other uses is roughly equal to the amount of water formerly used by native vegetation in this same watershed. Thus, Delta outflow, or the amount of freshwater reaching San Francisco Bay, is about the same under current conditions as under natural conditions, when controlled for climate.

This finding, which used a conventional water balance methodology and assumed contemporary climatic conditions for both natural and current landscapes, suggests that human disturbances to the landscape and hydrologic cycle have not significantly reduced the annual average volume of freshwater flows entering San Francisco Bay through the Delta. Rather, development has simply redistributed flows from natural vegetation to other beneficial uses. Thus, it is unlikely that reduced annual average freshwater flows have contributed to ecosystem decline in the estuary.

Another key finding of this study is that "unimpaired" Delta outflow calculations significantly overestimate natural Delta outflow as they fail to include consumptive use by natural vegetation in the Valley Floor. Therefore, unimpaired Delta outflow calculations should not be used as a surrogate measure of natural conditions or to set flow standards to restore ecosystem health.

Several limitations associated with this work point to areas for future research. The simple water balance methodology utilized in this paper is an appropriate reconnaissance-level step in reconstructing the natural hydrology of a complex system. However, this simple approach is unable to explore several important and relevant questions.

First, our analysis only considers long-term annual averages and does not evaluate inter- and intra-annual variability of natural Delta outflow. Ecosystems respond to flows at time scales much shorter than annual. Thus, future work should consider these shorter time scales.

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Second, our analysis does not account for complex interactions between groundwater and surface water. These interactions would place important limits on water availability to vegetation in a natural landscape on a shorter time scale.

Third, many vegetation land areas likely varied with the wetness of the year. We attempted to address this using a sensitivity analysis in which grassland/vernal pools areas were varied as a function of rim inflows and other assumptions.

Finally, we assumed natural evapotranspiration rates for vegetation types with a continuous water supply, e.g., permanent wetlands, are constant over the period of record. They likely varied as a function of climate. Future work should include a sensitivity analysis of vegetation coefficient ranges such as those shown in Howes et al. (2015).

We recommend future research in several areas of historical landscape ecology, hydrology and estuarine hydrodynamics to address these limitations to support on-going regulatory and habitat restoration activities in the San Francisco Bay-Delta watershed, including:

- refined natural vegetation mapping in the Sacramento and San Joaquin Basins, following work in the Delta reported by Whipple et al. (2012);
- evapotranspiration from vernal pools and seasonal wetlands;
- interactions between groundwater and surface water under natural conditions;
- inter- and intra-annual variability of natural Delta outflows;
- natural watershed geomorphology; and
- natural estuarine salinity transport.

We recommend that integrated groundwater-surface water models, digital elevation models and hydrodynamic models be developed to support this research. Several collaborative efforts are currently underway to develop such models (Draper, 2014; Kadir and Huang, 2014; Grossinger et al., 2014; Fleenor et al., 2014; DeGeorge and Andrews, 2014). Finally, we recommend future research be conducted to compare the

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evolution of the San Francisco Bay-Delta watershed with other watersheds around the world.

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References

Alexander, B. S., Mendell, G. H., and Davidson, G.: Report of the Board of Commissioners on the Irrigation of the San Joaquin, Tulare, and Sacramento Valleys of the State of California, 43rd Congress, 1st Session, House of Representation, Ex. Doc. No. 290, Government Printing Office, Washington, 1874.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop Evapotranspiration: guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper No. 56, Food and Agricultural Organization of the United Nations, Rome, Italy, 1998.

Allen, R. G., Walter, I. A., Elliott, R. L., Howell, T. A., Itenfisu, D., Jensen, M. E., and Snyder, R. L. (Eds.): The ASCE Standardized Reference Evapotranspiration Equation, ASCE, Reston, Virginia, 2005.

Anonymous: Commissioners and Surveyor-General's Instructions to the County Surveyors of California, California State Printing Office, Sacramento, CA, USA, 1861.

Armstrong, C. F. and Stidd, C. K.: A moisture–balance profile on the Sierra Nevada, J. Hydrol., 5, 258–268, 1967.

Bain, J. S., Caves, R. E., and Margolis, J.: Northern California's Water Industry: The Comparative Efficiency of Public Enterprise in Developing a Scarce Natural Resource, Published for Resources for the Future, Inc., The Johns Hopkins Press, Baltimore, MD, 1966.

Bales, R. C., Battles, J. J., Chen, Y., Conklin, M. H., Holst, E., O'Hara, K. L., Saksa, P., and Stewart, W.: Forests and Water in the Sierra Nevada: Sierra Nevada Watershed Ecosystem Enhancement Project, report number 11.1, Sierra Nevada Research Institute, 2011.

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Barbour, M. G., Pavlik, B., Drysdale, F., and Lindstrom, S.: California's changing landscapes, Diversity and Conservation of California Vegetation, California Native Plant Society, Sacramento, CA, 1993.
Bartolome, J. W., Barry, W. J., Griggs, T., and Hopkinson, P.: Valley grasslands, Chapter 14, in: Terrestrial Vegetation of California, edited by: Barbour, M. G., Keeler-Wolf, T., and Schoenheer, A. A., University of California Press, Berkeley, 367–393, 2007.
Bennett, W. A. and Moyle, P. B.: Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento–San Joaquin estuary, in: San Francisco Bay: The Ecosystem, edited by: Hollibaugh, J. T., Pacific Division of the American Association for the Advancement of Science, 519–542.
Bertoldi, G. L., Johnston, R. J., and Evenson, K. D.: Ground Water in the Central Valley, California – A Summary Report, U. S. Geological Survey Professional Paper 1401-A, United States Government Printing Office, Washington, D.C., USA, 1991.
Bolger, B. L., Park, Y.-J., Unger, A. J. A., and Sudicky, E. A.: Simulating the pre-development hydrologic conditions in the San Joaquin Valley, California, J. Hydrol., 411, 322–330, 2011.
Bryan, K.: Groundwater for Irrigation in the Sacramento Valley, California, U. S. Geological Survey Water-Supply Paper 375-A, United States Government Printing Office, Washington, D.C., USA, 1915.
Bryan, K.: Geology and Ground-Water Resources of the Sacramento Valley, California, U. S. Geological Survey Water-Supply Paper 495, United States Government Printing Office, Washington, D.C., USA, 1923.
Burcham, L. T.: California Range Land: An Historical–Ecological Study of the Range Resource of California, CA Department of Natural Resources, Division of Forestry, 1957.
California Department of Public Works (CDPW): Sacramento River Basin, Bulletin No. 26, Sacramento, CA, USA, 1931a.
California Department of Public Works (CDPW): San Joaquin River Basin, Bulletin No. 29, Sacramento, CA, USA, 1931b.
California Department of Water Resources (CDWR): California State Water Project Atlas, Sacramento, CA, USA, 1999.
California Department of Water Resources (CDWR): California Planning Areas, Prepared by Scott Hayes, 31 October 2005, available at: http://www.waterplan.water.ca.gov/docs/maps/pa-web.pdf (last access: 15 January 2015), 2005a.

HESSD
12, 3847–3892, 2015

California Department of Water Resources (CDWR): California Detailed Analysis Units, Prepared by Scott Hayes, 31 October 2005, available at: http://www.waterplan.water.ca.gov/docs/maps/dau-web.pdf (last access: 15 January 2015), 2005b.

California Department of Water Resources (CDWR): California Central Valley Unimpaired Flow Data, 4th edn., Draft, Bay-Delta Office, California Department of Water Resources, Sacramento, CA, May 2007.

California Department of Water Resources (CDWR): The State Water Project Final Delivery Reliability Report 2011, available at: http://baydeltaoffice.water.ca.gov/swpreliability/FINAL_2011_DRR.pdf (last access: 1 March 2015), 2012.

California Department of Water Resources (CDWR): California Data Exchange Center, Chronological Reconstructed Sacramento and San Joaquin Valley Water Year Hydrologic Classification Indices, available at: http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST (last access: 8 April 2015), 2013a.

California Department of Water Resources (CDWR): California Water Plan, Update 2013, Bulletin 160-13, Sacramento, CA, USA, 2013b.

California Department of Water Resources and U. S. Department of the Interior, Bureau of Reclamation (CDWR & USBR): Bay Delta Conservation Plan, Public Draft, November 2013, available at: http://baydeltaconservationplan.com (last access: 3 February 2015), 2013.

California State Engineer: Report of the State Engineer of the State of California, Sacramento, CA, USA, 11 May 1907 to 30 November 1908.

California State Water Resources Control Board (CSWRCB): Development of Flow Criteria for the Sacramento–San Joaquin Delta Ecosystem, Prepared Pursuant to the Sacramento–San Joaquin Delta Reform Act of 2009, Sacramento, CA, USA, August 2010.

California State University (CSU) Chico: The Central Valley Historic Mapping Project, Chico, CA, USA, April 2003.

California Surveyor-General (CSG): Annual Report of the Surveyor-General of the State of California. Document No. 5, In Senate, Session of 1856, Sacramento, available at: http://www.slc.ca.gov/Reports/Surveyors_General/reports/Marlette_1855.pdf (last access: 7 April 2015), 1856.

California Surveyor-General (CSG): Annual Report of the Surveyor-General of California for the Year 1862, Sacramento, available at: http://www.slc.ca.gov/Reports/surveyors_general/reports/houghton_1862.pdf (last access: 7 April 2015), 1862.

HESSD
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Cloern, J. E. and Jassby, A. D.: Drivers of change in estuarine-coastal ecosystems: discoveries from four decades of study in San Francisco Bay, Rev. Geophys., 50, 1–33, 2012.
Crampton, B.: Grasses in California, University of California Press, Berkeley, 1974.
Cunningham, L.: A State of Change: Forgotten Landscapes of California, Heyday, Berkeley, CA, 2010.
Daly, C. and Bryant, K.: The PRISM climate and weather system – an introduction, PRISM Climate Group, Northwest Alliance for Computational Science & Engineering, Oregon State University, Corvallis, OR, USA, available at: http://www.prism.oregonstate.edu/documents/PRISM_history_jun2013.pdf (last access: 7 April 2015), 2013.
Daly, C., Taylor, G. H., Gibson, W. P., Parzybok, T. W., Johnson, G. L., and Pasteris, P. A.: High-quality spatial climate data sets for the United States and beyond, Trans. ASAE, 6, 1957–1962, 2000.
Davis, G. H., Green, J. H., Olmsted, F. H., and Brown, D. W.: Ground-water conditions and storage capacity in the San Joaquin Valley, California, U. S. Geological Survey Water Supply Paper 1469, United States Government Printing Office, Washington, D.C., USA, 1959.
DeGeorge, J. and Andrews, S.: Natural Delta Hydrodynamic Model Development, Presented at the 8th Biennial Bay-Delta Science Conference, Sacramento, C A., 28–30 October, p. 38, available at: http://scienceconf2014.deltacouncil.ca.gov/sites/default/files/uploads/OralAbstractsFull.pdf (last access: 7 April 2015), 2014.
Draper, A.: Natural flow monthly routing model, Presented at the California Water and Environmental Modeling Forum Annual Meeting, Folsom, CA, 24–26 February, p. 36, available at: http://www.cwemf.org/AnnualMeeting/2014Abstracts.pdf (last access: 7 April 2015), 2014.
Draper, A. J., Munevar, A., Arora, S. K., Reyes, E., Parker, N. L., Chung, F. I., and Peterson, L. E.: CalSim: generalized model for reservoir system analysis, J. Water Res. Pl. ASCE, 6, 480–489, 2004.
Dutzi, E. J.: Valley Oaks in the Sacramento Valley: Past and Present Distribution, Master of Arts Thesis in Geography, University of California, Davis, 1978.
Dynesius, M. and Nilsson, C.: Fragmentation and flow regulation of river systems in the northern third of the world, Science, 266, 753–762, 1994.
Fleenor, W., Whipple, A., Bell, A., Lay, M., Grossinger, R., Safran, S., and Beagle, J.: Generating a historical Delta bathymetric-topographical digital elevation model (Part II) Data Interpolation, Presented at the California Water and Environmental Modeling Forum Annual Meeting,

Folsom, CA, 24–26 February, p. 39, available at: http://www.cwemf.org/ (last access: 7 April 2015), 2014.
Flushman, B. S.: Water Boundaries: Demystifying Land Boundaries Adjacent to Tidal or Navigable Waters, John Wiley & Sons, Inc., New York, NY, USA, 2002.
Fox, J. P.: Freshwater Inflow to San Francisco Bay Under Natural Conditions, Appendix 2, SWC Exhibit No. 262, Calif. State Water Resources Hearings on the Bay-Delta, Dec. 1987, Sacramento, CA, USA, 1987.
Fox, J. P. and Sears, L.: Natural Vegetation in the Central Valley of California, Project Report Prepared for San Luis Delta Mendota Water Authority and the State Water Contractors, San Luis Delta Mendota Water Authority and State Water Contractors, Sacramento, CA, USA, 2014.
Frayer, W. E., Peters, D. D., and Pywell, H. R.: Wetlands of the California Central Valley, Status and Trends – 1939 to mid-1980s, US Fish and Wildlife Service Report, U.S. Fish and Wildlife Service, Region 1, Portland, OR, USA, June 1989.
Garone, P.: The Fall and Rise of the Wetlands of California's Great Central Valley, University of California Press, Berkeley, 2011.
Gleick, P. H.: The development and testing of a water balance model for climate impact assessment: modeling the Sacramento Basin, Water Resour. Res., 6, 1049–1061, 1987.
Glibert, P. M.: Long-term changes in nutrient loading and stoichiometry and their relationships with changes in the food web and dominant Pelagic fish species in the San Francisco Estuary, California, Rev. Fish. Sci., 18, 211–232, 2010.
Glibert, P. M., Fullerton, D., Burkholder, J. M., Cornwell, J. C., and Kana, T. M.: Ecological stoichiometry, biogeochemical cycling, invasive species, and aquatic food webs: San Francisco estuary and comparative systems, Rev. Fish. Sci., 4, 358–417, 2011.
Grossinger, R., Safran, S., Beagle, J., DeGeorge, J., Fleenor, W., Whipple, A., Bell, A., and Lay, M.: Generating a historical Delta bathymetric-topographical digital elevation model (Part I) data collection and development, Presented at the California Water and Environmental Modeling Forum Annual Meeting, Folsom, CA, 24–26 February, available at: http://www.cwemf.org/AnnualMeeting/2014Abstracts.pdf (last access: 7 April 2015), 2014.
Grunsky, C. E.: The relief outlets and by-passes of the Sacramento Valley flood-control project, Trans. ASCE, 93, 791–811, 1929.
Hall, W. H.: Report of the State Engineer to the Legislature of California, Session of 1880, Part 2, California State Printer, Sacramento, CA, USA, 1880.

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Hall, W. H.: Topographical and Irrigation Map of the Great Central Valley of California Embracing the Sacramento, San Joaquin, Tulare and Kern Valleys and the Bordering Foothills, California State Engineering Department, Sacramento, CA, USA, 1887.
Heady, H. E., Bartolome, J. W., and Pitt, M. D.: California prairie, in: Natural Grasslands, edited by: Copland, R. T., Elsevier, New York, 313–332, 1992.
Heady, H. F.: Valley grasslands, Chapter 14, in: Terrestrial Vegetation of California, edited by: Barbour, M. G., and Major, J., John Wiley & Sons Inc., New York, NY, USA, 491–513, 1988.
Holland, R. F.: The Geographic and Edaphic Distribution of Vernal Pools in the Great Central Valley, California, California Native Plant Society Special Publications No. 4, California Native Plant Society, Fair Oaks, CA, USA, 1978.
Holland, R. F.: Changes in Great Valley Vernal Pool Distribution from 1989 to 1997, available at: http://www.dfg.ca.gov/biogeodata/wetlands/pdfs/Holland_ChangesInGreatValleyVernalPoolDistribution.pdf (last access: 9 April 2015), California Department of Fish and Game, 1998.
Holland, R. F.: GIS shape files for Holland vernal pool map, email from Holland, R. to Sears, L., 4 December 2013.
Holland, R. F. and Hollander, A. D.: Hogwallow biogeography before gracias, in: Vernal Pool Landscapes, Studies from the Herbarium, edited by: Schlising, R. A. and Alexander, D. G., California State University, Chico, Number 14, 2007.
Holmes, L. C. and Eckmann, E. C.: Soil Survey of the Red Bluff Area, California, U. S. Department of Agriculture, Bureau of Soils, 1912.
Holmes, L. C., Nelson, J. W., and Party: Reconnaissance Soil Survey of the Sacramento Valley, California, U. S. Department of Agriculture, Bureau of Soils, 1915.
Holmes, T. H. and Rice, K. J.: Patterns of growth and soil-water utilization in some exotic annuals and native perennial bunchgrasses of California, Ann. Bot., 78, 233–243, 1996.
Holstein, G.: Pre-agricultural grassland in Central California, Madroño, 4, 253–264, 2001.
Howes, D. J. and Pasquet, M.: Grass reference based vegetation coefficients for estimating evapotranspiration for a variety of natural vegetation, U. S. Committee on Irrigation and Drainage, Proc. of October 2013 Conference, Denver, CO, 22–25 October, 181–194, 2013.
Howes, D., Fox, J. P., and Hutton, P.: Evapotranspiration from Natural Vegetation in the Central Valley of California: Monthly Grass Reference-Based Vegetation Coefficients and the Dual Crop Coefficient Approach, J. Hydrol. Eng., doi:10.1061/(ASCE)HE.1943-5584.0001162, in press, 2015.

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Hundley Jr., N.: The Great Thirst, University of California Press, Berkeley, 2001.
Ingram, B. L., Conrad, M. E., and Ingle, J. C.: Stable isotope record of late Holocene salinity and river discharge in San Francisco Bay, California, Earth Planet. Sci. Lett., 141, 237–247, 1996.
Jassby, A. D., Kimmerer, W. J., Monismith, S. G., Armor, C., Cloern, J. E., Powell, T. M., Schubel, J. R., and Vendlinski, T. J.: Isohaline position as a habitat indicator for estuary populations, Ecol. Appl., 1, 272–289, 1995.
Kadir, K. and Huang, G.: Simulated 1922–2009 daily inflows to the Sacramento–San Joaquin Delta under predevelopment conditions using precipitation-runoff models and C2VSIM: preliminary results, Presented at the California Water and Environmental Modeling Forum Annual Meeting, Folsom, CA, 24–26 February, p. 38, available at: http://www.cwemf.org/AnnualMeeting/2014Abstracts.pdf (last access: 7 April 2015), 2014.
Katibah, E. F.: A brief history of riparian forests in the Central Valley of California, in: California Riparian Forests, edited by: Warner, R. E. and Hendrix, K. M., University of California Press, Berkeley, 23–29, 1984.
Kahrl, W. L.: The California Water Atlas, State of California, Prepared by the Governor's Office of Planning and Research in Cooperation with the CA DWR, Sacramento, CA, USA, 1979.
Kelley, R. L.: Gold vs. grain: The hydraulic mining controversy in California's Sacramento Valley: a chapter in the decline of the concept of laissez faire, Arthur H. Clark Company, Glendale, CA, USA, 327 pp., 1959.
Kelley, R.: Battling the Inland Sea: Flood, Public Policy and the Sacramento Valley, University of California Press, Berkeley, CA, 1989.
Kooser, B. P., Seabough, S., and Sargent, F. L.: Notes of trips of the San Joaquin Valley Agricultural Society's visiting committee on orchards and vineyards, Reports of Committees, Committees Nos. 1 and 2 on Farms and Orchards, Trans. S. J. V. Agr. Soc., 258–298, 1861.
Küchler, A. W.: Natural vegetation of California, pocket map, in: Terrestrial Vegetation of California, edited by: Barbour, M. G., Major, J., John Wiley & Sons, Inc., New York, NY, USA, 909–938, 1977.
Lapham, M. H. and Holmes, L. C.: Soil Survey of the Redding Area, California, U. S. Department of Agriculture, Bureau of Soils, 1908.
Lapham, M. H., Root, A. S., and Mackie, W. W.: Soil Survey of the Sacramento Area, California, U.S. Department of Agricultural Field Operations Bureau of Soils, United States Government Printing Office, Washington, D.C., USA, 1904.

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Lapham, M. H., Sweet, A. T., Strahorn, A. T., and Holmes, L. C.: Soil Survey of the Colusa Area, California, U. S. Department of Agriculture, Bureau of Soils, U.S. Department of Agricultural Field Operations Bureau of Soils, United States Government Printing Office, Washington, D.C., USA, 1909.

Lund, J., Hanak, E., Fleenor, W., Howitt, R., Mount, J., and Moyle, P.: Envisioning Futures for the Sacramento–San Joaquin Delta, Public Policy Institute of California, San Francisco, CA, 2007.

Luoma, S. N. and Nichols, F. H.: Challenges in detecting contaminant effects on an estuarine ecosystem affected by many different disturbances: San Francisco Bay, U. S. Geological Survey Toxic Substances Hydrology Program, Proc. Tech. Mtng., Colorado Springs, Colorado, 20–24 September 1993, Water–Resources Investigations Report 94-4015, 1993.

MacNally, R., Thomson, J. R., Kimmerer, W. J., Feyrer, F., Newman, K. B., Sih, A., Bennett, W. A., Brown, L., Fleishman, E., Culberson, S. D., and Castillo, G.: Analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR), Ecol. Appl., 20, 1417–1430, 2010.

Malamud-Roam, F. P., Ingram, B. L., Hughes, M., and Florsheim, J. L.: Holocen paleoclimate records from a large California estuarine system and its watershed region: linking watershed climate and bay conditions, Q. Sci. Rev., 13–14, 1570–1598, 2006.

Meko, D. M., Therrell, M. D., Baisan, C. H., and Hughes, M. K.: Sacramento River flow reconstructed to A.D. 869 from tree rings, J. Am. Water Res. As., 4, 1029–1038, 2001.

Miller, W. J., Bryan, F. J., Manly, D., Murphy, D., Fullerton, D., and Ramey, R. R.: An investigation of factors affecting the decline of Delta Smelt (*Hypomesus transpacificus*) in the Sacramento–San Joaquin Estuary, Rev. Fish. Sci., 1, 1–19, 2012.

Nelson, J. W., Guernsey, J. E., Holmes, L. C., and Eckmann, E. C.: Reconnaissance Soil Survey of the Lower San Joaquin Valley, California, U. S. Department of Agriculture, Bureau of Soils, 1918.

Olmstead, A. L. and Rhode, P. W.: The evolution of California agriculture 1850–2000, in: California Agriculture: Dimensions and Issues, edited by: Siebert, J. B., University of California Press, available at: http://giannini.ucop.edu/CalAgBook/Chap1.pdf (last access: 8 April 2015), 2004.

PRISM Climate Group: Descriptions of PRISM Spatial Climate Datasets for the Conterminous United States, available at: http://www.prism.oregonstate.edu/documents/PRISM_datasets_aug2013.pdf (last access: 9 April 2015), 2013.

HESSD
12, 3847–3892, 2015
Reconstructing the natural hydrology of the San Francisco Bay-Delta watershed
P. Fox et al.

Roberts, W. G., Howe, J. G., and Major, J.: A survey of riparian forest flora and fauna in California, in: Riparian Forests in California: their Ecology and Conservation, edited by: Sands, A., A Symposium Sponsored by Institute of Ecology, University of California, Davis and Davis Audubon Society Institute of Ecology, Publication No. 15, 14 May 1977.

Schiffman, P. M.: Species composition at the time of first european settlement, in: California Grasslands: Ecology and Management, edited by: Stromberg, M. R., Corbin, J. D., and D'Antonio, C. M., University of California Press, Berkeley, 52–56, 2007.

Shelton, M. L.: Irrigation induced change in fegetation and evapotranspiration in the Central Valley of California, Landscape Ecol., 2, 95–105, 1987.

Smith, D. W. and Verrill, W. L.: Vernal pool-soil–landform relationships in the Central Valley, California, in: Witham, C. W., Bauder, E. T., Belk, D., Ferren Jr., W. R., and Ornduff, R. (eds.): Ecology, Conservation, and Management of Vernal Pool Ecosystems, Proc. from a 1996 Conference. California Native Plant Society, Sacramento, CA, 19–21 June, 15–23, 1998.

South Florida Water Management District (SFWMD): Natural System Regional Simulation Model (NSRSM) Fact Sheet, available at: http://sfwmd.gov (last access: 5 February 2015), West Palm Beach, Florida, USA, 2014.

Strahorn, A. T., Mackie, W. W., Westover, H. L., Holmes, L. C., and Van Duyne, C.: Soil survey of Marysville Area, California, U. S. Department of Agriculture, Bureau of Soils, 1911.

Sweet, A. T., Warner, J. F., and Holmes, L. C.: Soil Survey of the Modesto–Turlock Area, California, With a Brief Report on a Reconnaissance Soil Survey of the Region East of the Area, U. S. Dept. of Agriculture, Bureau of Soils, 1909.

The Bay Institute (TBI): From the Sierra to the Sea: The Ecological History of the San Francisco Bay-Delta Watershed, The Bay Institute of San Francisco, Novato, CA, USA, 1998.

Thompson, K.: The settlement geography of the Sacramento–San Joaquin Delta, California, PhD Dissertation, Stanford University, 1957.

Thompson, K.: Riparian forests of the Sacramento Valley, California, Ann. Assoc. Am. Geogr., 3, 294–315, 1961.

Thompson, K.: Riparian forests of the Sacramento Valley, California, in: Riparian Forests in California: Their Ecology and Conservation, edited by: Sands, A., A Symposium Sponsored by Institute of Ecology, University of California, Davis and Davis Audubon Society, Institute of Ecology Publication, No. 15, 1977.

Thomson, J. R., Kimmerer, W. J., Brown, L., Newman, K. B., MacNally, R., Bennett, W. A., Feyrer, F., and Fleishman, E.: Bayesian change-point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary, Ecol. Appl. 20, 1431–1448, 2010.

Thorne, J. H., Morgan, B. J., and Kennedy, J. A.: Vegetation change over sixty years in the Central Sierra Nevada, California, USA, Madroño, 3, 223–237, 2008.

Vaghti, M. G. and Greco, S. E.: Riparian vegetation of the Great Valley, in: Terrestrial Vegetation of California, 3rd edn., edited by: Barbour, M. G., Keeler-Wolf, T., and Schoenherr, A. A., University of California Press, Berkeley, 425–455, 2007.

Warner, R. E. and Hendrix, K. M.: Riparian Resources of the Central Valley and California Desert, Final Draft. Department of Fish & Game, 1985.

Watson, E. B., Glassey, T. W., Storie, R. E., and Cosby, S. W.: Soil survey of the Chico area, California, U. S. Department of Agriculture, Bureau of Chemistry and Soils, Series 1925, Number 4, 1929.

Whipple, A. A., Grossinger, R. M., Rankin, D., Stanford, B., and Askevold, R. A.: Sacramento–San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process, Publication 672, San Francisco Estuary Institute (SFEI) – Aquatic Science Center, Richmond, CA, 2012.

Williamson, A. K., Prudic, D. E., and Swain, L. A.: Ground-water flow in the Central Valley, California. U. S. Geological Survey Professional Paper 1401-D, United States Government Printing Office, Washington, D.C., USA, 1989.

Williamson, R. S.: Report of exploration in California for railroad routes to connect with the routes near the 35th and 32d parallels of north latitude, in: Reports of Explorations and Surveys, to Ascertain the Most Practicable and Economical Route for a Railroad from the Mississippi River to the Pacific Ocean, United States War Dept., Henry, Joseph, 1797–1878, Baird, Spencer Fullerton, 1823–1887, United States Army, Washington, A. O. P. Nicholson, printer, 1853.

Zedler, P. H.: Vernal pools and the concept of “Isolated Wetlands”, Wetlands, 3, 597–607, 2003.

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Table 1. Monthly vegetation coefficients (K_v) for non-water stressed and rainfed vegetation (Howes et al., 2015).

Vegetation	Month Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfed Grassland[a]	0.78	0.72	0.64	0.58	0.35	0.06	0.00	0.00	0.03	0.16	0.47	0.73
Perennial Grassland	0.55	0.55	0.60	0.95	1.00	1.05	1.10	1.15	1.10	1.00	0.85	0.85
Vernal Pool	0.65	0.70	0.80	1.00	1.05	0.85	0.50	0.15	0.10	0.10	0.25	0.60
Large Stand Wetland	0.70	0.70	0.80	1.00	1.05	1.20	1.20	1.20	1.05	1.10	1.00	0.75
Small Stand Wetland	1.00	1.10	1.50	1.50	1.60	1.70	1.90	1.60	1.50	1.20	1.15	1.00
Foothill Hardwood[a]	0.80	0.77	0.69	0.61	0.52	0.20	0.01	0.01	0.03	0.15	0.46	0.71
Valley Oak Savanna[a]	0.80	0.77	0.69	0.62	0.54	0.40	0.40	0.40	0.40	0.41	0.55	0.71
Seasonal Wetland	0.70	0.70	0.80	1.00	1.05	1.10	1.10	1.15	0.75	0.80	0.80	0.75
Riparian Forest	0.80	0.80	0.80	0.80	0.90	1.00	1.10	1.20	1.20	1.15	1.00	0.85
Saltbush	0.30	0.30	0.30	0.35	0.45	0.50	0.60	0.55	0.45	0.35	0.40	0.35
Chaparral[a]	0.55	0.61	0.54	0.40	0.22	0.03	0.01	0.01	0.03	0.14	0.40	0.57
Aquatic Surface	0.65	0.70	0.75	0.80	1.05	1.05	1.05	1.05	1.05	1.00	0.80	0.60

[a] Evapotranspiration from rainfed vegetation was estimated from a daily soil water balance. Valley oak savanna K_v during the summer and fall was estimated to be 0.4 to account for groundwater contribution. The vegetation coefficients shown are averages over the 88 year period and all Valley Floor planning areas.

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Table 2. Annual average evapotranspiration rates ET_v ($cm\,yr^{-1}$).

Basin	Planning Area	Rainfed Grassland	Perennial Grassland	Vernal Pool	Large Stand Wetland	Small Stand Wetland	Seasonal Wetland	Foothill Hardwood	Valley Oak Savanna	Riparian Forest	Saltbush	Chaparral	Aquatic Surface
Sacramento	502	39.1	130.1	75.3	139.5	204.3	131.1	45.1	67.1	134.1	60.2	29.5	127.4
	503	39.1	130.1	75.3	139.5	204.3	131.1	45.1	67.1	134.1	60.2	29.5	127.4
	504	34.0	128.9	73.9	137.8	201.7	129.4	40.2	64.0	132.5	59.6	28.8	125.8
	505	32.8	135.9	77.9	145.1	212.5	136.2	40.2	67.1	139.6	62.7	24.7	132.5
	506	32.4	135.0	77.7	144.2	211.3	135.5	39.8	67.1	138.7	62.3	25.0	131.7
	507	35.2	139.2	80.1	148.7	217.9	139.7	42.7	70.1	143.0	64.3	26.9	135.8
	508	36.6	143.3	82.3	152.4	222.5	140.2	42.7	73.2	146.3	67.1	27.4	140.2
	509	32.8	135.9	77.9	145.1	212.5	136.2	40.2	67.1	139.6	62.7	24.7	132.5
Delta	510	31.2	136.8	78.5	146.0	213.8	137.0	38.6	67.1	140.4	63.1	23.2	133.3
	602	27.2	121.3	70.3	129.5	189.8	121.8	33.3	57.9	124.6	55.9	19.3	118.3
San Joaquin	511	34.8	143.3	81.8	153.0	224.1	143.5	42.6	73.2	147.1	66.2	26.4	139.7
	601	27.4	113.5	65.5	121.1	177.4	113.9	32.3	54.9	116.6	52.3	19.0	110.6
	603	33.7	142.7	81.9	152.3	223.3	143.0	41.5	70.1	146.4	65.9	25.5	139.1
	604	30.5	137.2	79.2	149.4	213.4	134.1	39.6	67.1	140.2	64.0	24.4	134.1
	605	24.4	134.1	79.2	146.3	213.4	134.1	30.5	61.0	140.2	64.0	18.3	131.1
	606	24.0	135.6	78.4	144.7	212.1	136.1	31.2	61.0	139.2	62.6	17.4	132.2
	607	29.3	140.2	80.9	149.6	219.5	140.6	36.8	67.1	143.8	64.7	21.6	136.7
	608	28.9	144.6	83.8	154.3	226.4	145.0	36.6	70.1	148.2	66.7	21.5	141.0
	609	29.0	152.1	87.5	162.2	238.0	152.2	37.2	70.1	155.8	70.2	22.0	148.2
	610	29.0	152.1	87.5	162.2	238.0	152.2	37.2	70.1	155.8	70.2	22.0	148.2

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Table 3. Area of natural vegetation (A_v) by planning area within the Valley Floor, Case I (Hectares).

Valley	Planning Area	Rainfed Grasslands	Vernal Pool	Permanent Wetland	Seasonal Wetland	Valley/ Foothill Hardwood	Riparian Forest	Saltbush	Chaparral	Aquatic Surface	Total
Sacramento	502	0	0	0	0	692	0	0	0	0	692
	503	114 308	25 046	7	2	130 205	33 271	0	7478	1253	311 570
	504	52 570	433	96	977	78 027	34 720	0	39	807	167 667
	505	0	0	0	0	31	0	0	2170	0	2201
	506	140 301	94 683	50 395	19 679	71 054	43 383	0	9541	2429	431 466
	507	19 523	33 515	60 751	102 700	75 491	80 467	0	0	3274	375 721
	508	7289	3712	0	0	86 369	5407	0	0	590	103 368
	509	65 863	42 392	27 454	5395	58 148	25 913	0	22 000	610	247 775
	511	18 066	74 895	20 989	25 425	51 101	17 408	0	0	3116	211 000
Delta	510	718	4263	91 810	10 550	21	760	0	0	5240	113 361
	602	25 265	8533	115 385	9128	34	594	0	0	2858	161 798
San Joaquin	601	3885	3874	0	2	0	1	0	0	274	8037
	603	47 777	59 435	5117	55 734	80 998	16 614	0	157	629	266 461
	604	1098	0	0	0	741	311	0	0	0	2149
	605	4924	406	0	0	0	0	0	0	0	5331
	606	83 099	70 915	12 084	57 570	0	1281	41 405	32	1136	267 523
	607	69 411	64 097	3295	9099	1355	10 574	0	0	820	158 651
	608	66 786	51 142	3037	4945	1689	12 797	0	0	478	140 873
	609	123 728	242 041	17 323	18 450	501	8462	8099	0	1258	419 863
	610	6547	376	0	0	67	4	0	0	0	6995
Total		851 158	779 758	407 744	319 657	636 525	291 966	49 505	41 416	24 771	3 402 501

Note: Case I assumes: (1) no perennial grasslands; (2) all permanent wetlands are large stand; and (3) all valley/foothill hardwoods are foothill hardwoods.

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Table 4. Water Balance Cases.

Case	Grassland Assumptions Sacramento and Delta Basins	San Joaquin Basin	Hardwood Assumptions
Grasslands – Constant Area			
I	Mix of rainfed grassland and vernal pools	Mix of rainfed grassland and vernal pools	Foothill
II	Vernal pools	Vernal pools	Foothill
III	Mix of perennial grassland and vernal pools	Mix of perennial grassland and vernal pools	Foothill
IV	Mix of perennial grassland and vernal pools	Rainfed grassland	Foothill
Grasslands – Variable Area			
V	Mix of rainfed and perennial grassland and vernal pools[a]	Mix of rainfed and perennial grassland and vernal pools[a]	Foothill
VI	Mix of rainfed and perennial grassland[b]	Mix of rainfed and perennial grassland[b]	Foothill
Other			
VII	Mix of rainfed grassland and vernal pools	Mix of rainfed grassland and vernal pools	Valley Oak Savanna
VIII	Mix of perennial grassland and vernal pools	Rainfed grassland[c]	Foothill

[a] Vegetation areas are identical to Case I, except grassland areas not classified as vernal pools are assumed to be a mix of rainfed and perennial grassland that varies from year to year based on the annual runoff volume as measured by the Eight River Index (CDWR, 2013a). Grassland areas are assumed to be perennial in the wettest year, rainfed in the driest year, and for all other years, the mix is assumed to vary linearly with annual runoff volume between the wettest year and driest year.
[b] Vegetation areas are identical to Case I, except vernal pools are assumed to be a mix of rainfed and perennial grassland. Aggregate grasslands are assumed to be perennial in the wettest year, rainfed in the driest year, and for all other years, the mix is assumed to vary linearly with annual runoff volume between the wettest year and driest year.
[c] Vegetation areas are identical to Case IV, except seasonal wetlands within the floodplain are assumed to be rainfed grasslands.

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Table 5. Natural water balance 1922–2009 Valley Floor (billion $m^3\,yr^{-1}$).

Water Supply		Water Use (billion $m^3\,yr^{-1}$)							
Inflow	34.2	Grasslands – Constant Area				Grasslands – Variable Area		Other Vegetation	
Precipitation	15.9								
Total Water Supply	50.1	Case I	Case II	Case III	Case IV	Case V	Case VI	Case VII	Case VIII
Sacramento Basin									
Rainfed Grasslands		1.5	0.0	0.0	0.0	0.9	1.5	1.5	0.0
Perennial Grasslands		0.0	0.0	5.6	5.6	2.1	3.6	0.0	5.6
Vernal Pool		2.2	5.4	2.2	2.2	2.2	0.0	2.2	2.2
Large Stand Wetland		2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Seasonal Wetland		2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Foothill Hardwood		2.3	2.3	2.3	2.3	2.3	2.3	0.0	2.3
Valley Oak Savanna		0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.0
Riparian Forest		3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Saltbush		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chaparral		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aquatic Surface		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		14.2	**15.9**	**18.2**	**18.2**	**15.7**	**15.5**	**15.5**	**18.2**
Delta									
Rainfed Grassland		0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0
Perennial Grassland		0.0	0.0	0.4	0.4	0.1	0.1	0.0	0.4
Vernal Pool		0.1	0.3	0.1	0.1	0.1	0.0	0.1	0.1
Large Stand Wetland		2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Seasonal Wetland		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Foothill Hardwood		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Valley Oak Savanna		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Riparian Forest		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Saltbush		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chaparral		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aquatic Surface		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		3.5	**3.5**	**3.7**	**3.7**	**3.5**	**3.5**	**3.5**	**3.7**

Table 5. Continued.

Water Supply		Water Use (billion $m^3 yr^{-1}$)							
Inflow	34.2	Grasslands – Constant Area				Grasslands – Variable Area		Other Vegetation	
Precipitation	15.9								
Total Water Supply	50.1	Case I	Case II	Case III	Case IV	Case V	Case VI	Case VII	Case VIII
San Joaquin Basin									
Rainfed Grasslands		1.1	0.0	0.0	2.6	0.7	1.5	1.1	3.0
Perennial Grasslands		0.0	0.0	5.8	0.0	2.2	5.1	0.0	0.0
Vernal Pools		4.2	7.5	4.2	0.0	4.2	0.0	4.2	0.0
Large Stand Wetlands		0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Seasonal Wetland		2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.0
Foothill Hardwoods		0.4	0.4	0.4	0.4	0.4	0.4	0.0	0.4
Valley Oak Savanna		0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0
Riparian Forest		0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Saltbush		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Chaparral		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aquatic Surface		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		9.5	**11.7**	**14.2**	**6.8**	**11.3**	**10.7**	**9.7**	**5.2**
Total Water Use		**27.1**	**31.1**	**36.1**	**28.7**	**30.4**	**29.7**	**28.7**	**27.1**
Delta Outflow = Total Water Supply – Total Water Use		**23.0**	**19.0**	**14.0**	**21.4**	**19.6**	**20.4**	**21.4**	**23.0**

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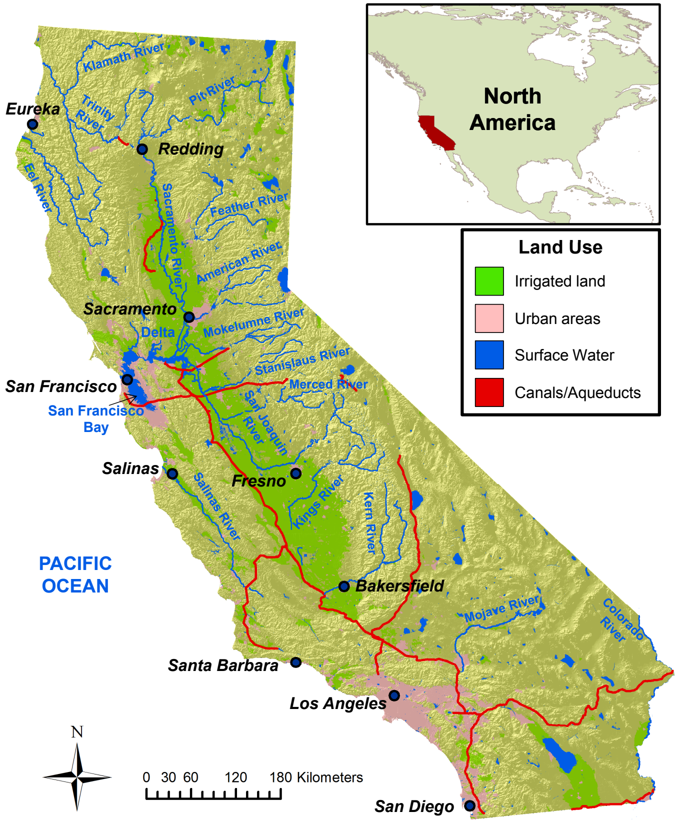

Figure 1. California, current land classifications, and major tributaries feeding into and through the Central Valley.

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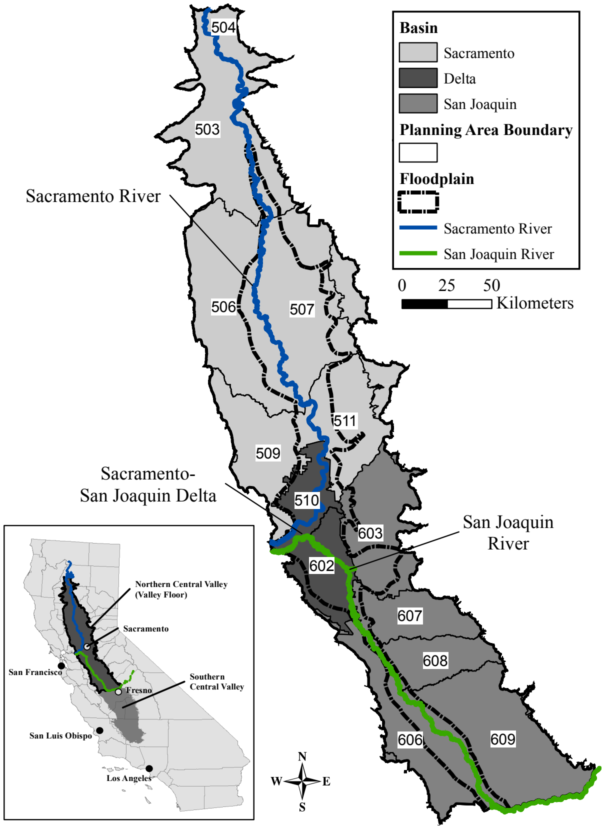

Figure 2. Valley Floor Study Area showing the area that water use calculations were conducted by planning area and summarized by hydrologic basin. Planning Areas 502, 505, 508, 601, 604, 605 and 610 within the Valley Floor are too small to show on this map. Planning area boundaries were defined by CDWR (2005a, b).

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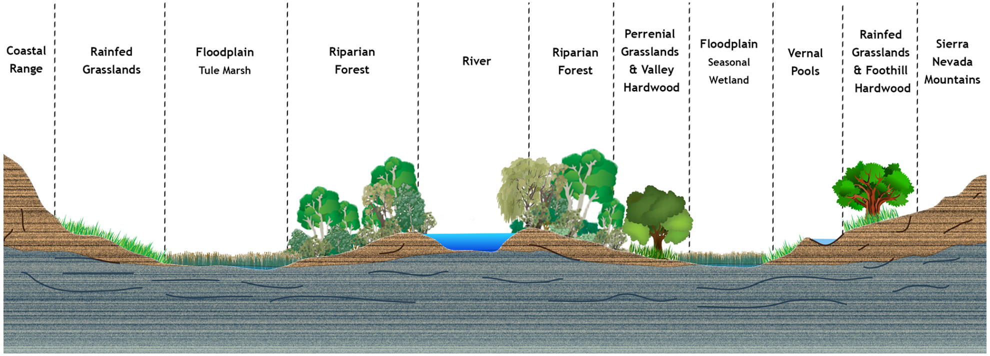

Figure 3. Illustrated cross section of the valley floor under natural conditions.

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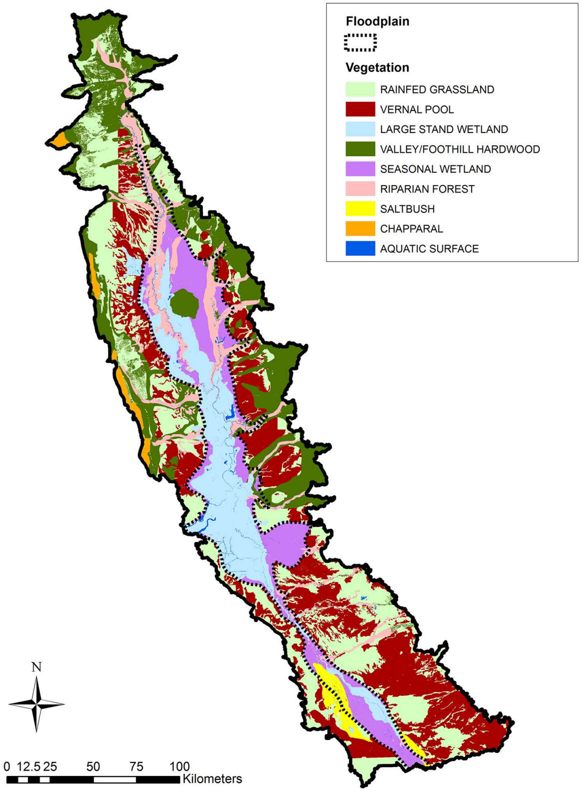

Figure 4. Natural vegetation in the Valley Floor map portraying the areal extent of natural vegetation based on the "Case I" definition of grassland composition (i.e., all grassland area outside of the floodplain was classified as either vernal pool or rainfed grassland). Although this map represents a composite of several maps, the primary source of information comes from CSU Chico's pre-1900 Historic Vegetation Map (CSU Chico, 2003).

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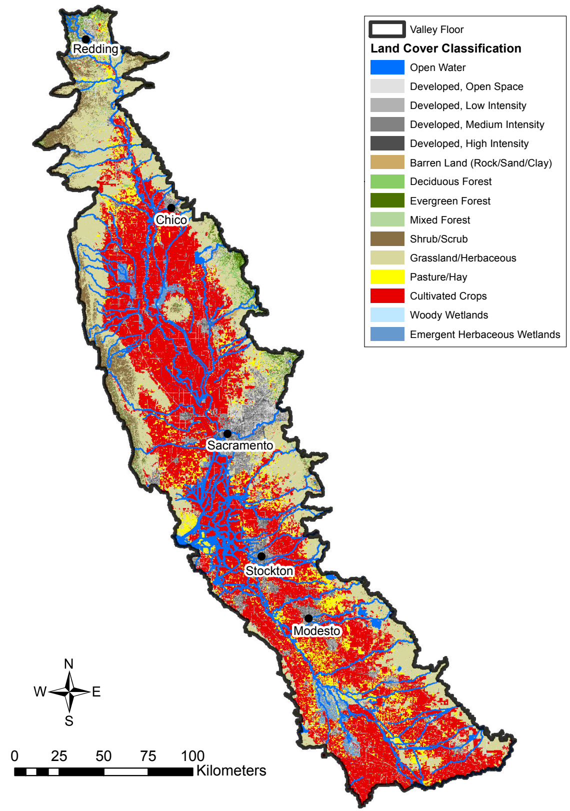

Figure 5. Current land use on the Valley Floor.

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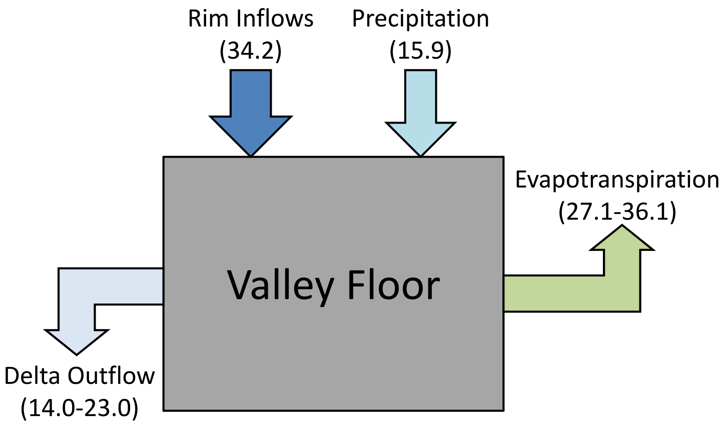

Figure 6. Schematic showing the average (1922–2009) natural water balance results (billion $m^3\,yr^{-1}$).

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Reconstructing the natural hydrology of the San Francisco Bay-Delta watershed

P. Fox et al.

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