APPENDIX 2

FRESHWATER INFLOW TO SAN FRANCISCO BAY UNDER NATURAL CONDITIONS

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FRESHWATER INFLOW TO SAN FRANCISCO BAY UNDER NATURAL CONDITIONS

Freshwater inflow to San Francisco Bay from the Delta is presently about the same as it was under natural conditions. Drainage, reclamation, flood control, and water development in the Central Valley have not significantly affected the quantity of freshwater reaching San Francisco Bay. Early development in the Valley increased outflows while subsequent development reduced them to about their initial level. Evaporative water losses from the original marshes and riparian forests in the Central Valley exceeded present in-basin use and exports by about 10 percent. The monthly distribution of flow into San Francisco Bay was much more uniform under natural conditions than it is presently, and winter and spring pulse flows that are common today were probably rare under natural conditions.

The results of our analyses are summarized in Figure 1, which shows changes in Delta outflow as the Valley develops. We have also plotted along the bottom of this chart the historic events that were responsible for the changes. Early development in the Valley increased Delta outflow from 13 million ac-ft/yr around 1770 to about 28 million ac-ft/yr between 1850 and 1900. The increase occurred primarily because high water-using vegetation (tule marsh, riparian forest) was replaced by lower water-using crops and urban areas. This native vegetation used over 17 million ac-ft/yr of water, more than is presently exported from and used within the Central Valley. The increase in water yield that occurred when native vegetation was removed was subsequently used primarily for agriculture and domestic water supply, returning freshwater inflow to about the amount that naturally reached San Francisco Bay.

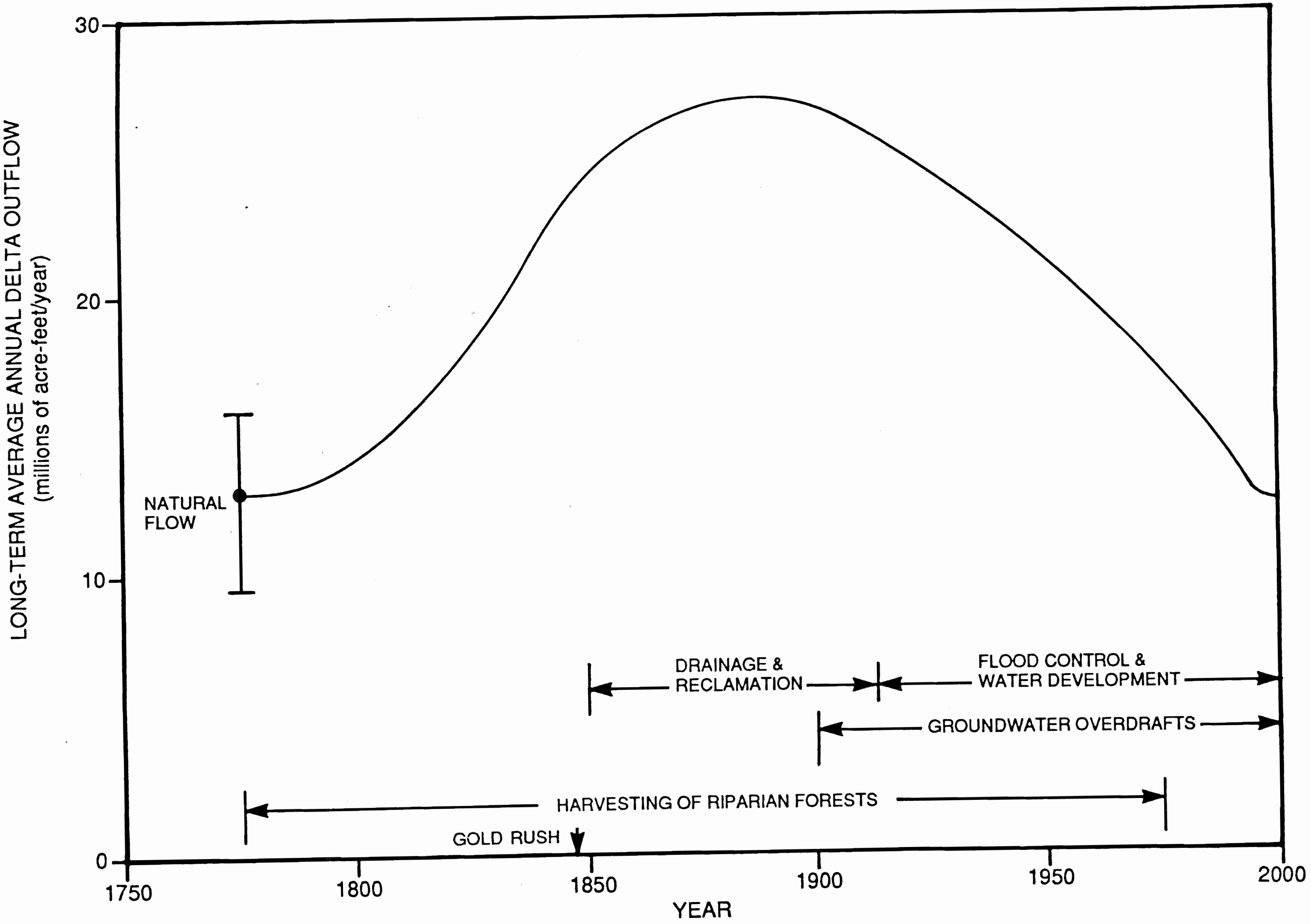

FIGURE 1. Summary of Historic Changes in Delta Outflows.

Originally, the trough of the Central Valley functioned as a reservoir filling and draining every year. Tule marshes choked these natural reservoirs and riparian forests lined the stream channels along the Valley floor. This natural vegetation took advantage of the plentiful supply of water, using far more than the irrigated crops that replaced them.

When the Central Valley was developed, the natural flood basins were drained, the tule marshes and riparian forest were replaced by irrigated crops, and the upslope forests were harvested. The original languid, slow moving, quasi-lake-like environment in the Central Valley was transformed into the highly channelized system with very short hydraulic residence times and high velocities that we know today. The principal result of upstream development has been to replace Valley reservoirs with man-made upstream reservoir storage and evaporative water losses by natural vegetation with consumptive use by agricultural crops and humans.

In this report, we estimate freshwater inflow to San Francisco Bay from tributary drainages in the Central Valley. Natural flows are defined here as those that occurred in a virgin, undisturbed state, prior to any significant human intervention. We use as our starting point the unimpaired flows calculated by the California Department of Water Resources [DWR 1987]. These estimates did not include the high evaporative water losses from natural vegetation, and they assumed present channel configurations.

THE NATURAL LANDSCAPE

The physical geography and vegetation in upstream drainages to San Francisco Bay (Sacramento Basin, the Delta region, and the San Joaquin Basin) were massively altered during early settlement and development of the Valley. This section describes the natural hydrology and primitive vegetation of the Valley and outlines its transformation into the system we know today. We have organized our discussion around the principal geomorphic features of the Valley as delineated by Bryan (1923, p. 9) — riverlands, flood basins, Delta islands, and plains. These features are shown in a schematic cross section of the Valley in Figure 2. Moving from the main rivers (Sacramento, San Joaquin) outwards are found the riverlands, flood basins, and plains.

In the following sections, we focus our discussion on the Central Valley because we intend, in the analyses that follow, to estimate freshwater inflow to the Bay using a water balance around this area. This region also contributes about 99 percent of the freshwater to the Bay. The Central Valley comprises about 20,000 square miles and extends from near Red Bluff in the north to near Bakersfield in the south, a distance of about 400 miles. The average width of the Valley is about 50 miles. We emphasize the area north of Fresno and the San Joaquin River because over 99 percent of the water of interest originates in that area. We include the Tulare Lake Basin overflow as an inflow to the Central Valley.

Riverlands and Riparian Forests

The riverlands, the flood plains immediately adjacent to rivers and streams, and their riparian forests were one of the most prominent features of the Valley. They appeared as winding ribbons of green against a monotonously flat plain and were thus extensively described by early visitors [e.g., Farquhar 1932a]. In most parts of the Valley, the riverlands comprised banks of flood-borne sediments that were locally known as "rim lands" or "natural levees." These levees occurred along the Sacramento River from Red Bluff downstream and were most extensively developed in the river's middle reach from Ord Ferry to Sacramento. They were also present along the entire length of the San Joaquin River [Davis et al. 1959, p.27], though they were less well developed there because peak flows were typically less, thus limiting their ability to pick up and carry sediment for great distances [Katibah 1984]. Natural levees were also present in most Delta channels and along major

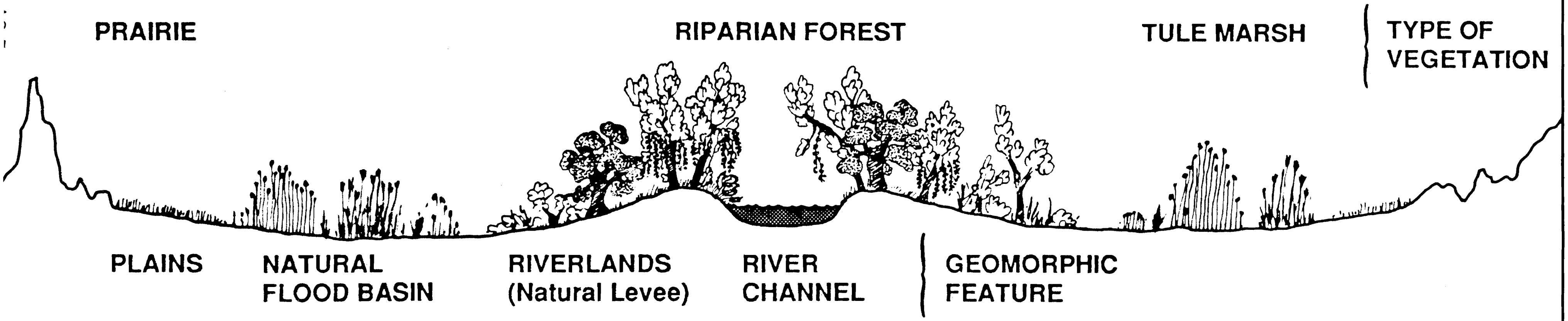

FIGURE 2. Typical Cross Section of Central Valley (Not to Scale) Showing Principal Geomorphic Features and Natural Vegetation.

tributaries, including the Feather, Tuolumne, Stanislaus, Merced, Mokelumne, Fresno, and Cosumnes Rivers. They rose some 10 to 30 feet above the normal water level and extended several miles back from the river's edge [Bryan 1923; Davis et al. 1959].

These levees confined the main streams to their regular channels when water levels were at low to moderate stages. They also prevented overland runoff from the foothills and Valley floor from entering the main channels. When winter and spring runoff were high, however, the natural levees were overtopped by annual flood flows. The levees also were more or less discontinuous, and breaks were common along the main river, allowing flood flows to escape the main channels and fill the natural basins flanking the main-stem rivers [Bryan 1923].

The natural levees were formed by repeated overflows of sediment-laden river water onto adjacent lands and occur where the valley slope is lowest and the duration of overbank flow is highest. The coarse, sandy material deposited close to the channel (sandy loams) gradually built-up, forming broad slopes that fall gently away from the river. In the Sacramento Valley, these flood plains are occupied by soils of the Columbia series [Holmes et al. 1916] and in the San Joaquin Valley, by soils of the Hanford loam series [Nelson et al. 1918]. Because they are primarily coarse sediment, these levees are extremely porous and transmit water readily.

These riverlands supported riparian forest habitat, which included Fremont cottonwood, box elder, valley oak, and various species of willow. Many shrubs, including buttonbush, honeysuckle, wild rose, and berry were also common [Bakker 1971; Jepson 1893; Thompson 1961; Roberts et al. 1977; Hoover 1935; Conard et al. 1977; Warner 1984]. Thompson (1961) has chronicled the eye witness accounts of riparian forests in the Sacramento Valley, and Landrum (1938) has provided similar information on the San Joaquin Valley. The areal extent of this vegetation has also been mapped [Kuchler 1977; Roberts et al. 1977] and is shown on Figure 3.

These riverlands were more extensively altered by man than any other natural landscape in California [Bakker 1971], and they were one of the first major losses in the natural environment [Katibah 1984; Scott and Marquiss 1984]. Limited use of these forests probably occurred during the first settlement of the Valley around 1820 and slowly increased until the Gold Rush in 1849, when such use greatly accelerated [Katibah 1984]. Estimates based upon historic accounts indicate that 775,000 to 800,000 acres of riparian forest were present in the Sacramento Valley [Smith 1977; Roberts et al. 1977; Michny 1980] around 1850. By 1972, only 12,000 acres remained [Roberts et al. 1977].

Since the riparian forests were the only significant woody vegetation on the Valley floor, they were used by early settlers for fencing, lumber, and fuel [Thompson 1961]. Steamships transporting miners and supplies upriver were heavy users of local wood fuel. In the decades following the Gold Rush, many settlers turned to farming. This agricultural development began on the natural levees because they were higher and less subject to flooding [Scott and Marquiss 1984]. Most of these lands were converted to orchards and annual row crops [McGill 1975]. Additional losses of riparian forests were caused by streambank stabilization, channelization, gravel and gold mining, and grazing [Roberts et al. 1977; Warner 1984].

The removal of riparian vegetation from the riverlands significantly altered the hydrology of the Central Valley. It is well known that forests and brush reduce stream flow and decrease maximum daily discharge and normal flood peaks [e.g., Hoyt and Troxell 1932; Love 1955; Lewis 1968; Robinson 1952; Hibbert 1971; Turner and Skibitzke 1951]. Riparian vegetation is deep rooted and uses large quantities of water [Robinson 1958; Young and Blaney 1942]. The vegetative canopy and understory also intercept precipitation, storing it for subsequent use and evaporation, thereby altering the seasonal distribution of runoff [Lewis 1968].

Natural Flood Basins and Tule Marsh

The flood basins are shallow troughs that lie between the low plains and the natural levees along both sides of the Sacramento River and San Joaquin Rivers (Figure 2). They stretched from below Red Bluff on the Sacramento south to Bakersfield in the Tulare Lake Basin, and in wet years the entire Valley was a veritable inland sea. The early history of the Valley is rife with descriptions of the floods, starting with the great flood of 1805, which allegedly covered the entire Valley except the Sutter Buttes. The flood history of the Valley has been reviewed by several writers [Thompson 1960; Simpson and Meyer 1951; Gilbert 1879; Small 1929; Grunsky 1929].

The boundaries of these ancient flood plains (or overflowed lands, as they have often been called), are shown on Figure 3. These shallow flood basins were locally known as "tules" because of the heavy growth of tules (Spanish for reed), or rushes, which they supported [Bryan 1923, p. 39]. They were the lowest and flattest parts of the valley, they had no direct surface outlets, and they gently sloped toward the center and toward the downstream end, slowly draining into the main river channels after the flood wave had passed.

In times of ordinary high water, they were filled by overland flow that poured across the low plains in broad sheets and was trapped in the flood basins by the higher natural levees along the rivers. The basins were also filled by rivers that discharged into them either through definite channels or directly over natural levees. Many of the tributaries were not connected directly with the main rivers. They drained into the flood basins through a welter of channels, losing themselves "in the intricate plexus of sloughs which meander through the tule-land bordering the main river"

[Ransome 1896]. The hydrology of each individual flood basin is described elsewhere [Hall 1880; Bryan 1923; DPW 1931a; DPW 1931c; Davis et al. 1959; Grunsky 1929].

The existence of these flood basins was documented by early explorers and settlers [e.g., Gilbert 1879; Thompson 1960]. Fages, the first Spanish explorer to describe the Valley, wrote in 1773 that "it is all a labyrinth of lakes and tulares, and the River San Francisco (original name of the Sacramento and San Joaquin Rivers), divided into several branches winding in the middle of the plains, now enters and flows out of the lakes until very near to the place where it empties into the estuary of the river" [Bolton 1931]. Lieutenant Charles Wilkes, U.S.N., one of the first Americans to report on the Valley, wrote following an expedition in August and September 1841 that "according to the testimony of the Indians, the whole country was annually innundated" [Wilkes 1850, p. 189].

State Engineer Wm. Ham. Hall, in the first scientific treatise on the hydrology of the Valley, wrote that "in the natural state of the stream the waters of the Sacramento River, at time of ordinary flood, just overtopped the banks ...." Hall went on to define "ordinary flood" as that which "passes through the channel and over the low lands once, and perhaps twice, each winter or spring, except in seasons of drought, occurring once or twice every ten years" [Hall 1880, pps. 10-11].

Some of the flood waters that were captured in these basins seeped into the alluvial aquifers and natural levees , some drained directly back into the main channels, some was evapotranspired by the natural vegetation in the basins, and the balance was evaporated from the large surface area, many times that of present-day reservoirs. The precise distribution of these floodwaters is unknown. One estimate of drainange back into the stream channel was presented by DPW (1931b).

Since portions of these natural flood basins contained standing water and water-logged soils year-round (e.g., Grunsky 1929, p. 796; Bryan 1923), they were home to extensive areas of freshwater marshes. The estimated extent of the tule marshes is shown in Figure 3. As shown by this map, these marshes are sandwiched between the prairie and the riparian forest, and their outer limit approximately follows the natural flood basin boundaries throughout their range. Since these two boundaries were determined from different data sets and physical concepts [see DPW 1931a, 1931c; Kuchler 1964], it is striking how closely they match and is confirming evidence that both are reasonable estimates of natural conditions.

These marshes are probably the most neglected habitat type in California and have received scant botanical attention. Studies by botanists began with W.L. Jepson (1893, 1975). They have subsequently only been studied by Hoover (1935), Mason (1957), and more recently by the USGS [Atwater 1980; Atwater and Belknap 1980; Atwater et al. 1979]. The characteristic vegetation in these marshes included sedges, cattails, rushes, reeds, and other types of aquatic herbaceous vegetation [Mason 1957; Bakker 1971]. The common tule (*Scirpus acutus*), the cattail (*Typha latifolia*), and a variety of other Scirpus species were the most common plants [Hoover 1935; Atwater 1980].

The existence of these marshes is amply documented in writings of early explorers of the Central Valley, who described difficulties in getting their pack animals across the Central Valley due to the extensive marshlands (e.g., Farquhar 1932a, p. 118-119). The marshes are also shown on the maps prepared by the early explorers [reviewed by Landrum 1938] and on early maps prepared by the U.S. Department of Agriculture [Holmes et al. 1916] and the U.S. Geological Survey [Bryan 1923, Plate IV].

The evidence suggests that tule marshes were present year round, even during droughts. We reviewed diaries and correspondence from these early explorations and compiled (Table 1) eye witness descriptions of the tule marshes. We subsequently determined the year type (dry, normal, wet) from precipitation records [Anon. 1886; Graumlich 1987]. These analyses indicate that tule marshes were present throughout the Valley under all types of hydrologic conditions, including drought. Present day accounts also suggest that these marshes did not dry up. Bryan (1923), describing conditions observed during the dry period of 1912-13, wrote that, "In spite of the so-called Tule Canal, which traverses Yolo Basin ..., the basin contains some water even in the dry season..." (ibid., p.43).

The water supply for most of the freshwater marshes is believed to have been springs, groundwater, sloughs, and overflow from the main channels through breaks in the natural levies. Springs were common in the Valley under natural conditions. Assistant State Engineer Grunsky [Grunsky 1929 p. 793] reported that there were many places with "a large outflow in springs. These springs have a fairly constant flow throughout the year ...." In the Sacramento Valley, groundwater was within 1 foot of the surface in much of the area supporting marsh habitat. Elsewhere, where the marshes were underlain by clayey soils, they were probably supplied by sloughs that communicated with surface streams and/or groundwater. In the Delta, marshes had a constant, year-round water supply from groundwater discharge and drainage from upslope flood basins. Some riparian species in the Delta and lower Sacramento River have even been reported to grow much larger than elsewhere due to their abundant water supply [Jepson 1893], and remnant wetlands of the Delta today produce extraordinary amounts of organic matter [Atwater and Belknap 1980].

After the riparian forest, the natural flood basins (or tule lands), were developed next. These lands had been regarded as wastelands by early settlers, who avoided

TABLE 1

EYE WITNESS ACCOUNTS OF TULE MARSH IN THE CENTRAL VALLEY

Observer/Date	Year Type[a]	Reference
Sacramento Valley		
April 1817 Arguello	Dry	Cook (1960), p.276
March 1833 John Work	Wet	Maloney (1945), p.35
September/October 1849 Lt. Derby	Normal	Farquhar (1932a), p.252
Delta Area		
April 1772 Fages	Normal	Treutlein (1972), p.335
August 1775 Canizares	Dry	Eldredge (1909), p.65-69
April 1776 Father Font	Dry	Bolton (1933), p. 388
October 1811 Abella	Below Normal	Cook (1960), p.261
August 1837 Vallejo	Above Normal	Cook (1962), p.190
September 1846/47(?) Bryant	Above Normal	Bryant (1967),p.300-301
San Joaquin Valley		
September 1806 Moraga	Below Normal	Cutter (1950), p.101,125
September 1808 Moraga	Below Normal	Ibid., p.124-125
August/October 1810 Moraga/Father Viader	Below Normal	Ibid., p.157-158; Cook (1962), p.260
May 1817 Father Duran	Dry	Chapman (1911), p.35
September 1846/47(?) Bryant	Above Normal	Bryant (1967), p.302
July 1853 Lt. Williamson	Wet	Williamson (1855) p.10, 191-192
Tulare Lake Basin		
October 1814 Father Cabot	Dry	Cutter (1950), p.205
September-November 1815 Various observers	Dry	Cutter (1950), p.208-226
1849/1850 J.W. Audubon	Normal/Wet	Audubon (1906), p.184
April/May 1850 Lt. Derby	Wet	Farquhar (1932b), p.252

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[a] For the period prior to 1850, Graumlich's (1987) data for the Southern Valleys is used, which included the Sacramento Valley. For the period 1850 to 1887, precipitation records at Sacramento (Anon. 1886) are used.

them due to the difficulties they presented — for not only was the terrain nearly impossible to cross, but recurrent outbreaks of "swamp fever" (or ague) claimed Indians and settlers alike. Thus, interest in reclaiming the swamps did not develop until after the 1850 Arkansas Act, in which the Federal government transferred ownership of all "swamp and overflowed lands" to the State on the condition that they be drained. California followed with a series of Acts and statutes, culminating in the 1868 Green Act, which created regular reclamation districts [Adams 1904].

Reclamation, even with the force of these Acts, was still painfully slow because it was technically difficult and costly, about $5.00/acre [Tide Land Reclamation Co. 1869]. No coherent reclamation program ever developed, and the disorganized and senseless manner in which it was carried out was the scandal of the era [Manson 1888; Adams 1904]. Sherman Island in the Delta was one of the first successful reclamation projects [Tide Land Reclamation Co. 1869], and by 1884, 1,270 miles of levees had been built on the Sacramento and its tributaries and on the San Joaquin below the mouth of the Stanislaus [Grunsky cited in Manson 1884]. By 1910, 300,000 acres of land in the Valley were reclaimed and by 1918, this figure has risen to 700,000 acres [Karl 1979]. By 1920 to 1930, most of the Delta marshes were leveed and reclaimed for farming [Atwater et al. 1979; Thompson 1957, pp. 208-238].

This river levee program, however, was mostly unsuccessful in containing the flood waters [Manson 1884; Scott and Marquiss 1984]. The first plan for flood control in the Sacramento Valley was developed in 1880 [Hall 1880], but implementation was slow due to its great cost, complexity, and political controversy. With the federal government's involvement, the Sacramento Flood Control Project, the first in the U.S., was completed between 1928 and 1944. This massive project included 980 miles of levees; 7 weirs or control structures; 3 drainage pumping plants; 438 miles of channels and canals; 7 bypasses, 95 miles in length and encompassing an area of 101,000 acres; 5 low-water check dams; 31 bridges; and 50 miles of collecting canals and seepage ditches [Karl 1079]. This massive public works project was followed by flood control features of the Central Valley Project in 1944. Nevertheless, flooding remains a concern in the Valley, and extensive damage occurred during the 1986 floods.

Leveeing the rivers and draining and reclaiming the marshes redistributed and increased freshwater inflow to San Francisco Bay. The natural flood basins and their marshes had provided extensive surface and subsurface storage for flood waters. The basins and marshes absorbed flood energy and reduced water velocities, partially explaining the absence of currents noted by early explorers [e.g., Bolton 1933, p. 369]. After the marshes were reclaimed and river levees constructed, flood flows that formerly spilled over the much lower natural levees were routed directly through the river channels into the Bay. This increased flood peaks [Grunsky 1929, p. 793], creating the now-famous "pulses", or high winter-spring discharges from the Delta that stratify most of the Bay. The quantity of water reaching the Bay was also increased because vegetation, which used copious quantities of water, was removed.

The Delta

These flood basins included most of the Delta, which because of its unique features merits separate commentary. In its original condition, the Delta was a vast, flat water-soaked marsh, lying near sea level [Bryan 1923; Atwater et al. 1979; Dachnowski-Stokes 1936]. It was subject to periodic overflows at high stages of the rivers and was traversed by an ever-changing network of channels and sloughs that divided the marsh into islands.

As noted by Bryan (1923, p.44), "Under natural conditions these islands were covered with water throughout a large part of the year and were always flooded at high river stages. The tide raised and lowered the level of the water over large areas..." Most of these channels had natural levees that sloped away from the channels towards the centers of the islands. Each island had a saucer-shaped surface and under natural conditions was swampy in the interior [Bryan 1923, p.10].

"Peat" and "muck" form the majority of the soils in the Delta and upstream areas, as mapped and defined by the U.S. Department of Agriculture [Nelson et al. 1918; Holmes et al. 1916; Cosby 1941]. These soils were very important in the natural hydrology of the basin [Dachnowski-Stokes 1935] because they could store water for subsequent use by native vegetation. The types of peat found in the Delta can absorb seven times their weight in water and have an absorptive capacity of 2.6 to 3 acre-feet of water per acre-foot of peat [Dachnowski-Stokes 1935, p.175].

Plains and Prairie

The area stretching from the flood basins to the foothills, known locally as the plains (Figure 2), did not play as large a role in the natural hydrology as the riverlands and flood basins. These lands were sparsely vegetated with low water-using plants similar to present day vegetation. Thus, the role they played in the hydrology of the Valley is probably not very different today than under natural conditions.

The plains were smooth and nearly level lands that were formed as flood waters spread over them, leaving behind thin deposits of silt. The vegetation in the plains was prairie, as defined by Kuchler (1977) (Figure 3). The dominant species was bunchgrass (*Stipa pulchra*) [Barbour and Major 1977, p.495]. Numerous annuals and perennial grasses were associated with *Stipa* species, as listed in Barbour and Major, as well as plants with bulbs and annuals in the Compositae, Cruciferae, and other families. Hoover (1935), describing the San Joaquin Valley, noted that "one of the most striking features of the flora of the open plains of the valley in the primitive condition was the scarcity of grasses over large areas." Fremont, in his Memoirs, described the plains as "unbroken fields of yellow and orange colored flowers, varieties of *Layia* and *Escholtzia California*..." [Fremont 1964, p.18]. Some areas in the plains, primarily north of the Delta, contained alkaline patches that supported saltbush (Figure 3).

The vegetation of the plains was swiftly altered, partly by accident, partly to accommodate grazing. Today, the herbaceous cover of the plains is dominated by annual plants, many of them introduced. In parts of the San Joaquin Valley, for instance, it has been found that more than half of the herbaceous cover is comprised of alien species, mainly from the Old World [Burcham 1957].

Groundwater

The occurrence and depth to groundwater are important considerations in evaluating the natural hydrology of the Central Valley The tule marshes would have required vast areas of water-logged soils and standing water for most of the year, and the riparian forest would have required groundwater within reach of their root systems. Our examination of the available data indicates that the riparian forest's water supply was stream flow, bank storage in the natural levees, and groundwaters. The marshes, on the other hand, were located in areas where the groundwater table was at the surface, in areas underlain by clayey soils that were supplied by sloughs, or in areas that were tidally inundated year round (the Delta). Our calculations indicate that enough water to supply the marshes was stored annually in surface soil horizons. Additional water was supplied from streams via sloughs.

Studies on groundwater hydrology of the Central Valley were reviewed recently [Page 1986]. The earliest studies were conducted by the U.S. Geological Survey between 1905 and 1913 [Bryan 1923; Mendenhall et al. 1916]. We focus on these early studies, since significant pumping for irrigation was present during later work [e.g., Olmsted and Davis 1961; Davis et al. 1959].

Under natural conditions in the Valley, groundwater aquifers were filled by precipitation falling on the foothills and plains and by flood waters that filled the natural flood basins flanking the main channels. Originally, "there (was) no adequate outlet for ground waters of the Great Valley..." [Mendenhall et al. 1916, p.28] so they escaped by "capillarity" and evaporation along the valley axis [Mendenhall et al. 1916; Bryan 1923, p.85; Hilgard 1892]. This water slowly moved downslope toward the main channels, stagnating in the valley trough. It discharged "into seeps and sloughs in the basin lands where the water evaporated; by evaporation from moist lands where the groundwater stands less than about 8 feet from the surface; and by transpiration where the groundwater is within reach of the root of plants" [Bryan 1923, p.85], forming alkali deposits.

The areas that supported marshes in the Valley were and are bordered by patches of alkaline soils in most areas. These patches delineate the areas within which groundwaters used to emerge at the surface where the marshes were located. The origin, composition, and location of these salt deposits are presented elsewhere [Hilgard 1892; Kuchler 1977; Holmes et al. 1916; Nelson et al. 1918; Bryan 1923, p.85]. These areas supported saltbush, and the largest concentration of such regions was located in the San Joaquin and Tulare Lake basins (Figure 3). These deposits are greater in extent in the San Joaquin valley because the higher precipitation to the north continuously washed the deposits away in most areas [Bryan 1923, p.86].

Bryan (1923), in his classic work on groundwater conditions in the Sacramento Valley, reported that it was "remarkable for the large area in which the water table stands close to the surface. During the summers of 1912 and 1913 — two dry years — the depth to water in more than 80 per cent of the valley was less than 25 feet. " (ibid. p.82).

In describing the location of groundwater in the flood basins, Bryan (1923) goes on to report that in dry years, over large parts of the American, Sutter, and Yolo flood basins and adjacent riverlands, that the depth to water "ranges from a maximum of 20 feet along the river bank [where the riparian forest was] to only a few inches in parts of the basins [where the marshes were]. In the basins, the maximum depth is 6 feet in the very driest years." (ibid, p. 83).

FRESHWATER INFLOW TO THE BAY

We have calculated the freshwater inflow to San Francisco Bay from a water balance around the portion of the Central Valley that drains into the Bay. The geographic boundary and areas used in our analysis are shown on Figure 4. The portion of the Central Valley that drains into the Bay is Area 2, which comprises the Sacramento Valley (Area 2a), the Delta and upslope areas (Area 2b), and the San Joaquin Valley (Area 2c). These boundaries are the same as used by the DWR in their unimpaired flow studies [DWR 1987].

The water balance we performed around the Central Valley can be expressed as follows:

$$\text{Delta Outflow} = \text{Water Supply} - \text{Water Use by Native Vegetation}$$

The total water supply is equal to the sum of unimpaired rim inflows, Tulare Lake Basin overflow, and precipitation on the valley floor. We have not included evaporative losses from flooded areas because most of these areas supported native vegetation. Evaporative water losses from flooded areas with no vegetation are probably small. We have also assumed that over the long term, the net change in basin storage (groundwater, bank storage, natural flood basins, marshes) is zero. Any water that was stored during one season would subsequently be used by native

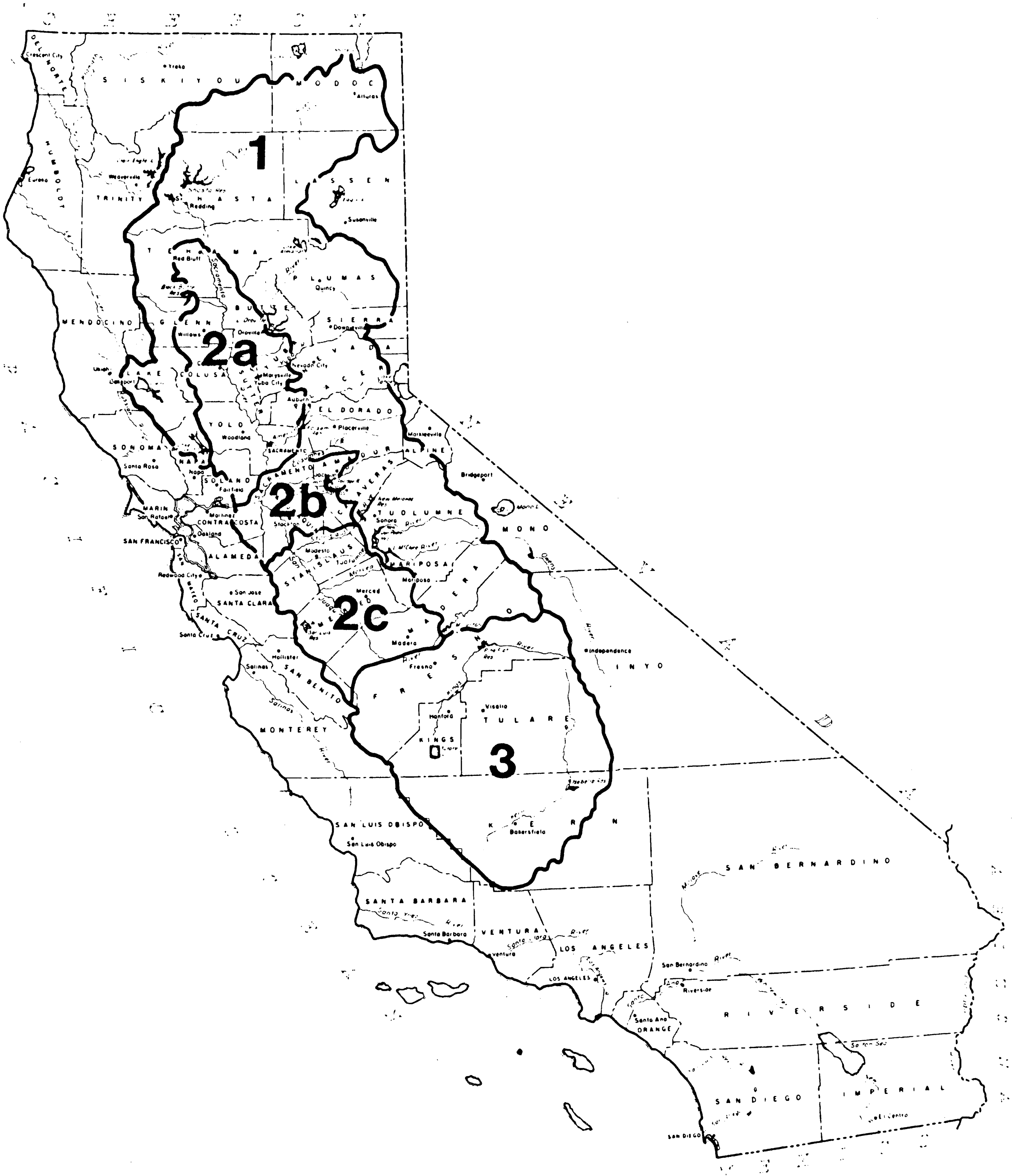

FIGURE 4. Hydrologic Units Used in Calculating Freshwater Inflow to San Francisco Bay Under Natural Conditions.

vegetation or would be released at a later time as channel flow. Our calculations are for long-term, average annual conditions.

The results of our water balance are presented in Table 2. Each element of the water balance (first column) is described and discussed in subsequent sections. This table shows the quantity of water from each source (rim inflow, Tulare Lake Basin inflow, valley floor precipitation) and the amount used by each principal type of vegetation in the Valley. We have used a range for vegetative water use because the consumptive use would have varied in different parts of the Valley.

This table shows that under natural conditions, an average of 38.8 million acre feet of water were available each year. From 51 to 80 percent of this supply was consumptively used by native vegetation and the balance entered San Francisco Bay. Slightly more than one-third of the water was evapotranspired by the riparian forests that lined all of the major streams. The balance was used by tule marshes in the natural flood basins and by prairie vegetation, in the expansive plains. The remaining 7.8 to 18.9 million acre feet annually flowed through the Delta into San Francisco Bay.

Our estimates of net water use and Delta outflow under natural conditions are compared with equivalent quantities for the "unimpaired" case and the 1990 level of development on Figure 5. Our estimates of natural net water use on this figure are the mid-points of the ranges presented in Table 2. "Unimpaired" flows are those calculated by the DWR in Exhibit 26 [DWR 1987]. These flows assume present channel configurations, no diversions, or exports, and no tule marsh or riparian forest water use. They assume that the natural flood basins and their marshes have been drained, that levees and channel bypasses are in place, and that the Valley water supply and runoff have the same characteristics as foothill areas. Although these unimpaired flows certainly never existed, their magnitude may have been

TABLE 2

FRESHWATER INFLOW TO SAN FRANCISCO BAY CALCULATED FROM A WATER BALANCE AROUND THE CENTRAL VALLEY

Element in Water Balance		Long-term Average Annual Water (millions of ac-ft/yr)
Water Supply		
Unimpaired Rim Inflow		28.2
Tulare Lake Basin Inflow		0.2
Precipitation on Valley Floor		10.5
	Total	38.8
Water Use by Native Vegetation		
Riparian Forest		8.6 – 11.5
Tule Marsh		5.7 – 8.5
Prairie		5.6 – 11.0
	Total	19.9 – 31.0
Freshwater Inflow to San Francisco Bay under Natural Conditions		7.8 – 18.9

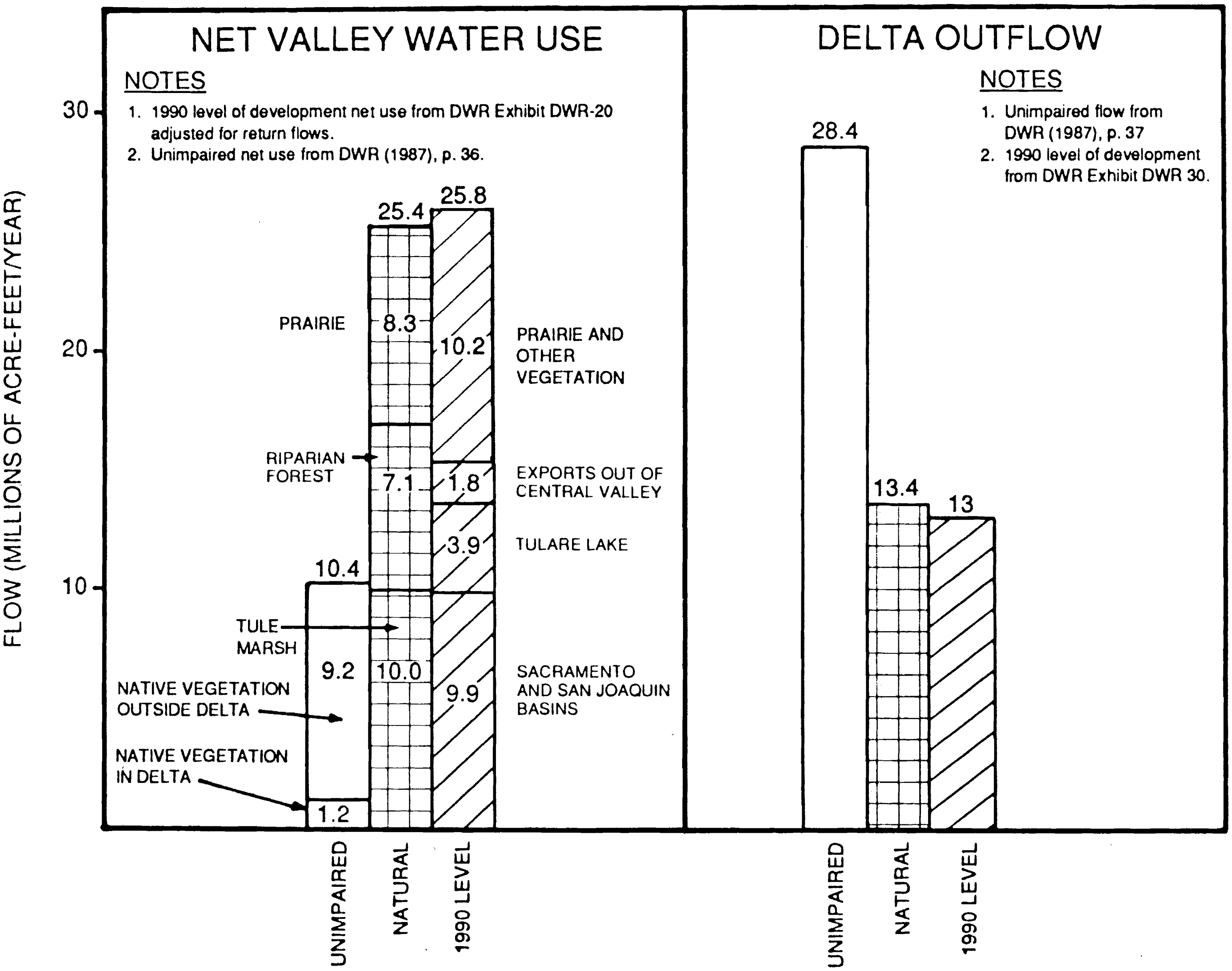

FIGURE 5. Comparison of Unimpaired, Natural, and 1990-Level-of-Development Net Water Use and Delta Outflow.

approached sometime between 1850 and 1900 (Figure 1). Considerable additional work is required to determine what the maximum outflow may have been and when it would have occurred.

Figure 5 indicates that evaporative water losses from the original marshes and riparian forests (17.1 million ac-ft/yr) were about 10 percent greater than present in-basin use and exports (15.6 million ac-ft/yr). This means that more water was used under natural conditions in the Central Valley than is used in this area today. During the first half century of California's statehood, the water supply and river flows were increased by removing the riparian forests, draining the swamps, and channelizing the streams. During the second half century, this increased supply was developed for agricultural and domestic use (Figure 1).

Figure 5 also shows that Delta outflow today is very close to what we estimate it was under natural conditions. Our calculations indicate that Delta outflow was 7.8 to 18.9 million ac-ft/yr under natural conditions, while the DWR has estimated that Delta outflow for the 1990 level of development will be 13 million ac-ft/yr [DWR Exhibit No. 30, D1485 Delta Standards], well within our range.

The following sections present the data and assumptions used to calculate the water balance discussed above.

Rim Inflows

Rim inflows are the total quantity of water from Area 1 (Figure 4) under natural conditions. They were calculated from DWR's unimpaired flow data [DWR 1987] by subtracting valley floor contributions [DWR Areas 1,12,24,17,23] from total Delta inflow (ibid., p. 35).

Land Areas

Land areas were used in a number of calculations in this work. All of the relevant areas used in our calculations are summarized in Table 3. Areas are also outlined on the map shown in Figure 3.

Flood Basins

The flood basin areas were used to calculate active groundwater storage capacity and as a rough check on the accuracy of tule marsh acreages. These areas were determined by planimetering from maps reported in DPW Bulletin 26 and 29 [DPW 1931a, 1931c] that were prepared from surveys and maps by State Engineer Wm. Ham. Hall (1880). Our estimates indicate that about 3.1 million acres of land were subject to annual innundation and that about 2.2 million acres of this was tributary to the Bay. However, even larger areas, extending into the plains, were innundated in wet years [Hall 1880, p. 8]. Our flood basin areas include the channel areas and natural levee areas, which were usually higher than the flood water level. Channel surface areas are also summarized in Table 3 from the early literature.

Tule Marsh

We planimetered the tule marsh area from Kuchler's natural vegetation map (1977), correcting it for areas that others have reported as riparian forest [Thomas et al. 1977]. These estimates indicate that there were 1.6 million acres of tule marsh in the Central Valley, and about 1 million acres were tributary to the Bay. These estimates generally compare favorably with those cited in literature prior to 1900. For example, Manson, one of Ham. Hall's assistants, wrote in 1884 that swamp lands situated on the lower San Joaquin and Sacramento rivers and their tributaries, including the Delta, encompassed about 1 million acres [Manson 1884, p. 88].

TABLE 3

LAND AREAS

Drainage Basin (Figure 4)	Total Area (1,000 acres)						
	Flood Basin Area[a]	Channel Surface Area	Riparian Forest[f]	Tule Marsh[g]	Prairie[h]	Salt-Bush[h]	Total Valley Floor[i]
Sacramento Basin (2a)	1,256	24[b]	938	295	2,256	0	3,489
Delta (2b)	588	37[c]	198	397	700	0	1,295
San Joaquin Basin (2c)	345	7[d]	298	254	2,392	148	3,092
Tulare Basin (3)	936	3[e]	515	643[j]	4,027	1,298	6,503

[a] Determined by planimetering the overflowed land area from Plate LXXIII [DPW 1931c] and Plate VII [DPW 1931a]. This area includes channel surface area and natural levees.

[b] From Hall (1880), p. 7. May include some channels in northern Delta.

[c] From DPW (1931b), p. 70, notes to table.

[d] Estimated by multiply channel area in Sacramento Basin by the ratio of the unimpaired flow from the San Joaquin Basin (6861 TAF) to that from the Sacramento Basin (24,800 TAF) for the period 1889-1929 [DPW 1931a, Table 5; DPW 1931c, Table 5).

[e] Estimated as in (d), but using unimpaired flow of Tulare Basin for 1889-1929 (3,510 TAF).

[f] Planimetered from Kuchler (1977) and Roberts et al. (1977). Kuchler was used for forest along tributaries and for all areas south of the Merced River while Roberts was used for forest along the main channels (Sacramento, San Joaquin Rivers).

[g] Planimetered from Kuchler (1977). Areas corrected for riparian forest along main channels as shown by Roberts et al. (1977).

[h] Planimetered from Kuchler (1977).

[i] Planimetered from Kuchler (1977). Corresponds to boundary defined by Blue Oak-Digger Pine forest and California Prairie (*Stipa* spp.). This area is the sum of riparian forest, tule marsh, prairie, and saltbush in all basins except Tulare. The Tulare Lake Basin has small quantities of other types of native vegetation that we did not consider here.

[j] Under natural conditions, the Tulare Valley contained a series of lakes interconnected by sloughs. The marsh and lake area varied greatly, according to historical accounts. This area is assumed to about equal the sum of marsh plus lake under average conditions.

Riparian Forest

Our riparian forest area was determined by planimetering from Robert's (1977) and Kuchler's (1977) natural vegetation maps. We used Roberts for forest areas along the main river channels (Sacramento, San Joaquin Rivers), which Kuchler showed incorrectly as tule marsh. We used Kuchler for forest along tributary streams, which Roberts underestimated by restricting the habitat to Columbia and Hanford loam soils. Our estimates indicate that there were about 1.9 million acres of riparian forest in the Central Valley, and 1.4 million acres of this were tributary to the Bay. Our estimates compare favorably with early estimates [Smith 1977; Michny 1980] but are high compared to present-day estimates derived from soil profiles. Katibah (1984) estimated that there were 921,600 acres of riparian forests in the Central Valley, and Roberts et al. (1977) estimated that there were some 771,600 acres north of the Merced River. In both cases, the forests were mapped according to soil profiles and were restricted to loams.

Precipitation on the Valley Floor

Precipitation falling on the valley floor was calculated by multiplying the area of the valley floor (Table 3) by the area-weighted average annual precipitation in feet/year. The valley floor precipitation volume for each basin (2a,2b,2c) is presented in Table 4, and the precipitation is listed in footnote (b) to that table.

The valley floor areas that we used in our calculations were obtained by planimetering from Kuchler's (1977) Natural Vegetation Map the area defined by the boundary between blue oak-digger pine forest and prairie. The area-weighted precipitation values that we used for each area (Areas 2a,2b,2c) were obtained from Schreiner (1987). They were calculated by planimetering from the annual average isohyetal precipitation map for the Central Valley for the period 1911-1960 prepared by J.D. Goodrich. The total basin areas used in these calculations were those used

TABLE 4

ELEMENTS OF WATER USE AND WATER SUPPLY BY BASIN

	Natural Vegetation Water Use (1,000 ac-ft/yr)[a]				
			Prairie		
Basin	Riparian Forest	Tule Marsh	Grasslands	Saltbush	Valley Floor Precipitation[b] (1,000 ac-ft/yr)
Sacramento Valley (2a)	5,628 – 7,504	1,770 – 2,655	2,256 – 4,512	0	5,902
Delta Valley (2b)	1,188 – 1,584	2,382 – 3,573	700 – 1,400	0	1,640
San Joaquin Valley (2c)	1,788 – 2,384	1,524 – 2,286	2,392 – 4,784	296	2,937
Totals	8,604 – 11,472	5,676 – 8,514	5,348 – 10,696	296	10,479

[a] Water use was calculated by multiplying the total land area from Table 3 by the water use. The water use used in the calculations is as follows: riparian forest: 6 to 8 ac-ft/ac; tule marsh: 6 to 9 ac-ft/ac; grasslands: 1 ac-ft/ac; saltbush: 2 ac-ft/ac.

[b] Precipitation was calculated by multiplying the total valley floor area from Table 3 by the area - weighted average precipitation for the period 1911-60 from J.D. Goodrich's (1966) isohyetal map for the Central Valley [Schreiner 1987]. The precipitation values are; Sacramento Valley - 20.3 in.; Delta area - 15.2 in.; San Joaquin Valley - 11.4 in.

by DWR in its consumptive use studies. These precipitation estimates include some foothill areas where precipitation is higher than on the valley floor. Therefore, our average precipitation values (Table 4) are slightly (<5 percent) larger than actual precipitation falling on the valley floor area. This would slightly overestimate natural Delta outflow.

Water Use by Native Vegetation

Water used by native vegetation was estimated by multiplying the area of each type of vegetation by a consumptive use value [Blaney 1954; Jensen 1973]. The areas that we used in these calculations were summarized in Table 3. The resulting water use for each type of vegetation by basin was summarized in Table 4.

This section discusses the consumptive use factors we used to estimate native vegetative water use. Normally, riparian forests and aquatic macrophytes transpire at the so-called potential rate due to the fact that their roots are continuously immersed in water. However, prairie grasses depend upon available soil moisture, and their actual evapotranspiration was probably less than the potential amount. Thus, we have selected potential evapotranspiration factors (ET) for wetland vegetation and actual (field) values for prairie vegetation.

Riparian Forest

The consumptive use of water by riparian vegetation has been determined in studies designed to save water by removing phreatophytes from along streams and canals in arid areas [e.g., Muckel 1966; Robinson 1952; Blaney 1956]. Most relevant studies have been reviewed and summarized elsewhere [Robinson 1958; Young and Blaney 1942]. Water use estimates for the principal types of vegetation occurring in Central Valley riparian forests are summarized in Table 5.

TABLE 5

WATER USE BY COMMON RIPARIAN VEGETATION IN THE CENTRAL VALLEY

Vegetation	Annual Water Use (ac-ft/ac)	Location	Reference
Field Studies			
Canyon-bottom	7.5[a]	Coldwater Canyon, CA	Blaney (1933)
Moist-land vegetation	9.4[b]	Temescal Canyon, CA	Blaney et al. (1930)
River-bottom brush	4.2	Prado, CA	White (1932)
Tank Studies			
Willows	4.4	Santa Ana, CA	Blaney et al. (1930)
Willows	2.9	Not reported	DPW (1931b)
Cottonwoods	5.2 – 7.7[c]	San Luis Rey, CA	Blaney (1957, 1961)
Alders	5.0	Santa Ana, CA	Muckel (1966)
Cottonwoods	7.6[c]	Safford Valley, AZ	Gatewood et al. (1950)

[a] Reported for the 4-month period July-October 1932 and converted to a 12-month basis using the monthly distribution of water use reported for willows (DPW) 1931b).

[b] Reported for the month of May 1929 and converted to a 12-month basis using the monthly distribution of water use for willows [DPW 1931b].

[c] Range depends on depth to groundwater, which varied from 3 to 4 feet at San Luis Rey and was 7 feet at Safford Valley.

In our estimates of evaporative water losses from riparian forests, we used an evapotranspiration (ET) range of 6 to 8 ac-ft/ac. The lower limit was calculated by weighting the water use for willows (4.4 ac-ft/ac), cottonwoods (7.7 ac-ft/ac), and river-bottom brush (4.2 ac-ft/ac) by the relative densities reported by Conrad et al. (1977) for a riparian forest along the Sacramento River (cottonwood=0.44; willows=0.20; all other=0.36). These densities are generally consistent with abundances reported by others [e.g. Warner 1984]. Our upper limit of 8 ac-ft/ac is the average of field measurements made for canyon-bottom and moist-land vegetation (Table 5).

Tule Marsh

Investigations on the consumptive use of water by aquatic macrophytes have been conducted for nearly a century, yielding a variety of contradictory results. Initially, studies were conducted in isolated tanks, which yielded rates that were up to 300 percent higher than evaporation from a free water surface [Otis 1914]. Later, it was learned that it was important to surround the tanks with similar vegetation to simulate the environment in large swampy areas [Young and Blaney 1942, p.25]. This reduced evaporation due to the insulation from surrounding vegetation.

Several other factors are now recognized as affecting water use by marsh vegetation. Canopy surface geometry (i.e., the actual surface from which water evaporates) plays an important role in evaporation from marshes. Generally, small or narrow canopies such as occur along rivers, streams, canals, and sloughs can have evaporative water losses several times greater than those from comparable open water surfaces [Blaney 1961, p.39; Anderson and Idso 1987, p. 1041]. Evaporative losses from extensive vegetative canopies such as occur in large marshes are much lower, depending upon a number of other factors, including humidity, winds, length of growing season, depth of water, age of plants, and height of canopy. Evaporative water losses from tall canopies, which are characteristic of tule marsh areas (tules and other marsh vegetation typically grow to 5 - 6 feet), are enhanced by atmospheric turbulence. A recent study reported that "evaporative water loss from a tall canopy such as cattails (*Typha latifolia*) may be as much as 40 percent greater than that from a comparable open water surface." (ibid, p. 1041). Reliable measurements of up to 90 percent greater than from a free water surface have been reported for tule marsh in California [Young and Blaney 1942; Young 1938].

We reviewed measurements of water use by tules and cattails in marsh environments similar to those of the Central Valley, and the relevant values are summarized in Table 6. Most of these values were measured in tanks (i.e., lysimeters) that were properly surrounded by native vegetation. We eliminated literature values with the following characteristics: (a) less than 12 months of data were reported; (b) abnormal growth or other anomalous conditions were described; (c) salt-water marsh (high salinity reduces evaporation).

From Table 6 and the additional considerations we summarize here, we have selected a range of 6 to 9 ac-ft/yr for tule marsh water use. The lower end of the range is probably representative of areas with lower evaporation rates (e.g., northern Sacramento Valley) and areas that lacked a full year-round water supply (i.e., probably only in Tulare Lake Basin). The upper end of the range applies to areas with a high evaporation rate (e.g., parts of Delta, San Joaquin Valley) and a full year-round supply of water (e.g., the Delta).

Our range of 6 to 9 ac-ft/ac was derived from the ratio between marsh evapotranspiration and pan evaporation first published by Young [Young 1938; Young and Blaney 1942; Anderson and Idso 1987]. The ratio of tule and cattail evapotranspiration to pan evaporation is about 1.4 and can be as high as 1.9. Since pan evaporation in the Central Valley ranges from about 5.0 to 6.5 ac-ft/ac [DWR 1979], the corresponding marsh evaporation would be 7 to 9 ac-ft/ac, which is well

TABLE 6

WATER USE BY TULES AND CATTAILS

Location	Type of Marsh	Annual Water Use (ac-ft/ac)[d]	Reference
King Island, Delta	freshwater tidal marsh	7.4 – 13.0[a]	Stout (1929-35)
Victorville, CA (Mojave River)	desert inland marsh	6.5 – 7.0	Young and Blaney (1942)
Mesilla Valley, NM (Rio Grande River)	freshwater marsh	10.1	Young and Blaney (1942)
Bonner's Ferry, ID	inland marsh	5.1	Robinson (1952)
Antioch, Delta	freshwater (?) tidal marsh	5.8[b]	Blaney and Muckel (1955)
Clarksburg, Delta	freshwater tidal marsh	9.6[c]	DPW (1931b)

[a] Value for third year of growth. Range corresponds to two different tank configurations.

[b] Calculated based on limited experiments at Joice Island in Suisun Marsh.

[c] Experiments conducted in isolated tanks and values adjusted by multiplying by a factor of about 0.5.

[d] All values measured in tank experiments in which tanks were set in natural environment unless otherwise stated.

within the range of reported evapotranspiration values (Table 6). We lowered the minimum to 6 ac-ft/ac because several of the reported values (Table 6) are around 6 ac-ft/ac.

We believe that this range is conservative and may understate the actual water use in natural Central Valley marshes. Many of the marshes in the Central Valley were supplied by sloughs, as discussed previously. The Delta, in particular, had some 37,000 acres of sloughs, and the extensive tule marsh south of the Merced River was a complex maze of sloughs. Water use by marsh vegetation growing along sloughs can be several times higher than by those growing deep within an expansive marsh [Blaney 1961, p.39; Anderson and Idso 1987, p.1041]. Actual measurements with tules and cattails suggest that water use in these fringe areas is about 20 ac-ft/ac [Young and Blaney 1942]. We have made no effort to estimate these edge effects, but they could be significant in marshes that are fed by sloughs.

Prairie

The majority of the land area in the Central Valley plains was formerly prairie (Table 3), and it initially supported a vigorous livestock industry [Burcham 1956]. Today, much of it is farmed. As discussed previously, this area was covered with a bunchgrass (*Stipa* spp.) community that included many forbs. The more alkaline soils in the Valley, located in area of groundwater discharge, supported saltbush [Kuchler 1977; Barbour and Major 1977].

We reviewed measurements of water use by vegetation similar to that occurring in the Central Valley prairie. Relevant values are summarized from the literature in Table 7. This table indicates that native prairie uses from 0.8 to 1.8 ac-ft/ac of water, or about 1.3 ac-ft/ac on the average. Saltgrass, which was common in the Valley [Barbour and Major 1977] can use larger quantities of water, up to 5 ac-ft/ac

TABLE 7

WATER USE BY NATURAL VEGETATION COMMON IN THE CENTRAL VALLEY PRAIRIE

Vegetation	Annual Water Use	Location	Reference
Field Studies			
Native brush	1.4 – 1.8	San Bernadino, CA	Young and Blaney (1942)
Native brush	1.5	Muscoy,CA	Young and Blaney (1942)
Native brush	1.2	Claremont, CA	Young and Blaney (1942)
Native brush	1.6	Palmer Canyon, CA	Young and Blaney (1942)
Native grass and weeds	0.8	San Bernadino, CA	Young and Blaney (1942)
Native grass and weeds	1.2	Cucamonga, CA	Young and Blaney (1942)
Native grass and weeds	1.0	Anaheim, CA	Young and Blaney (1942)
Native grass and weeds	1.1	Ontario, CA	Young and Blaney (1942)
Native grass and weeds	1.1	Wineville, CA	Young and Blaney (1942)
Saltgrass	2.1	Owens Valley, CA	Lee (1912)
Annual grasses, forbes, and legumes	1.2	Placer County, CA	Lewis (1968)
Tank Studies			
Saltgrass	1.1 – 3.6	Santa Ana, CA	Young and Blaney (1941)
Saltgrass	1.1 – 4.1	Owens Valley, CA	Young and Blaney (1942)
Saltgrass	2.6	Isleta, NM	Young and Blaney (1942)
Saltgrass	0.8 – 4.0	Los Griegos, NM	Young and Blaney (1942)
Annual grasses	0.8 – 1.2	Placer County, CA	Lewis (1968)
Grass	1.2	San Luis Rey, CA	Blaney (1957)
Grasslands	0.9 – 2.9	Sierra Ancha, AZ	Rich (1951)
Grasses	2.2	Sierra Ancha, AZ	Rich (1951)

[Robinson 1958]. In our analyses, we used a range of 1 to 2 ac-ft/ac for all prairie as defined by Kuchler (1977).

About 148,000 acres of saltbush (*Atriplex polycarpa*) were also present in the plains region of the San Joaquin Valley. Since we did not find water use measurements for this species, we used the mean consumptive use value (2 ac-ft/ac) determined for saltgrass (Table 7).

Native Vegetation Water Supply

The natural water supply that we described in the section, The Natural Landscape, could have supported the native vegetation that we have described. In the Sacramento valley, we believe that the principal water supply to marshes and riparian forests was a high groundwater table, springs, and bank storage. In the San Joaquin valley, the principal supply for the marshes was groundwater that was discharged through sloughs and springs.

The riparian forests were located on the permeable natural levees where channel seepage was continuously present and groundwater was within 20 feet of the surface. The predominant riparian forest species (i.e., cottonwoods, willows) have typical rooting depths of 15 to 30 feet [Robinson 1958, p.62,64], and valley oak, which were common in other areas, are known to draw water from depths in excess of 40 feet [Lewis and Burgy 1964].

Tules and other marsh vegetation, on the other hand, have shallow root systems, typically in the form of rhizomes [Jepson 1975; Mason 1957; Correll and Correll 1972; Beetle 1941]. The common cattail is reported to extend its rhizomes over a diameter of 10 feet in a single growing season and to produce aerial shoots 4 to 48 inches long (Yeo 1964). These plants probably only grew in areas where the groundwater table was within 5 feet of the surface or in regions with a surface water supply (i.e., via sloughs or springs). An examination of early maps reveals that marshes were located in areas where the groundwater table was at the surface and where soils were reported to have high absorptive capacities [e.g., Forbes 1931, Plate B-I]. Areas underlain by clayey soils that supported tule marsh were typically criss-crossed by complex assemblages of sloughs [e.g., see Bryan 1923, Plate IV; Holmes et al. 1916, Soil Map; Mendenhall et al. 1916, Plate I].

Under natural conditions, surface storage in the flood basins and groundwater storage in the underlying aquifers probably operated in concert to supply native vegetation. Today, this is practiced by spreading water on the land to recharge aquifers and is known as "conjunctive use" [DWR 1983, p.77]. Water was stored during wet periods and used during dry periods.

We investigated the potential groundwater available for native vegetation in each basin (Figure 4, Areas 2a, 2b, 2c) and found that enough water was present in storage in the top 10 feet of soil beneath the flood basins to support marshes using up to 9 ac-ft/ac of water for at least one year everywhere except in the San Joaquin Basin. There, groundwater was adequate to only support marshes at a rate of 6 ac-ft/ac. However, we believe that groundwater storage was not the sole source of water for any of the marshes. The sloughs, which were typically deeper than the main channels, and springs could also have transported surface waters into the marsh areas. Additionally, some flood water from the Sacramento River moved into the San Joaquin Valley through Delta sloughs (e.g., DPW 1931b).

Tulare Lake Basin Overflow

Under natural conditions, and through the present, water was and is exchanged between the Tulare Lake Basin (Area 3, Figure 4) and the San Joaquin Basin (Area 2c) during flood flows. Most people currently believe that the flow was from the Tulare Lake Basin into the San Joaquin Basin and hence into the Bay, because that is the direction of flow today. Many early maps of the Valley show a continuous ribbon of water running from the Delta south to the lakes of the Tulare Basin [Landrum 1938]. Fremont remarked that the Tulare lakes and the San Joaquin River in the rainy season made a "continuous stream from the head of the valley to the bay." [Fremont 1964,p.14]. However, the amount of water passing across this boundary and the direction of flow are subject to considerable conjecture.

We used DWR's estimate of the Tulare Lake Basin overflow [DWR 1987, p.33] in our natural flow calculations (Table 2). This value (174 TAF/yr) is actually the historic USGS flow measurements at James Bypass on the Fresno Slough, which connects the two drainages. These flows probably have little, if any relationship to flows that may have occurred under natural conditions.

Our calculations suggest that over the long-term, the net water exchange between the two basins was nearly zero. Drought was more common in the Tulare Lake Basin than to the north, and these lakes were often reported as dry by early explorers. Under many conditions, water moved from the San Joaquin Basin into the Tulare Lake Basin, or in the opposite direction. Nevertheless, we adopt DWR's estimate in an effort to be conservative. We reviewed the literature in an attempt to resolve the uncertainty surrounding this overflow. We also calculated a water balance for the Tulare Lake Basin. This work indicates that the long-term net exchange of water between these basins was about equal to zero.

Natural Geography and Hydrology

The San Joaquin and Tulare Lake drainage basins are separated by a natural ridge or barrier that lies immediately to the south of the San Joaquin River. Tulare, Kern, Buena Vista, and other small lakes were located in a depression south of this ridge. Normally, the San Joaquin River system drains north into the Bay, and the Tulare system drained south into these lakes. The lakes were connected by sloughs and formerly were filled by flow from the east-side tributaries, primarily the Kings and Kern Rivers. These lakes no longer exist because they were drained and reclaimed for farming. The overflow area was and remains a complex network of sloughs, the principal one being Fresno Slough.

The overflow lands bordering the slough were of nearly uniform width, averaging about 5.4 miles [Davis et al. 1959, p. 28]. The slough itself, under natural conditions, has been reported to be "like a canal...and very deep near the San Joaquin, but eight to ten miles from this river it divides up into numerous channels, which become intricate and ramified as they enter the lake." [Williamson 1853, p.192]. It was "about forty miles in length...and about two hundred and forty feet in width...." in April 1850 [Farquhar 1932b], a very wet year in the Valley [Anonym. 1886].

Under natural conditions, the Kings River discharged into this lowland area. Part of the flow moved south to Tulare Lake, which formerly covered an area varying from a few square miles in dry years to about 760 square miles in wet ones [DPW 1931c, p.76]. Part may also have moved north through Fresno Slough into the San Joaquin Basin under some conditions. Apparently, the flood waters had to raise the surface of the lake to an elevation of 205 to 210 feet from a low of 176 feet before any water moved northward into Fresno Slough and the San Joaquin River (ibid., p.483).

Historic Accounts

Contemporary technical descriptions generally indicate that transfer of water only occurred during periods of high flow in winter and spring and that there was no constant flow direction, the flow sometimes being south and sometimes north. In the earliest technical description of note, Coulter, an English scientist, reported that "The Tule Lakes are now known not to exceed 100 miles in total length, being fordable in the dry season in places; ...they discharge, during a considerable portion of the year, very little, if any, water into San Francisco. It is only immediately after the rainy season, which is usually ended by February, and during the thaw of the snow ...that there is any considerable discharge of water from them in this direction" [Coulter 1835, p.60]. Fremont, in his Memoirs, also reported flow into the San Joaquin, remarking that "In times of high water, the lake discharges into the Joaquin, making a continuous water line through the whole extent of the valley." Both of these observations, and many others like them, were based on hearsay or memory, rather than actual first-hand observations.

Later technical descriptions by professionals working in the area reported flow moving predominantly from north to south, into the Tulare Lake Basin. Lieutenant Derby explored the "Tulares Valley" in 1850, which was a wet year, in search of a site for a military outpost [Farquhar 1932b] and attempted to cross between the basins at the site of Fresno Slough in April of that year. He reported that the ground between the lake and the San Joaquin was "entirely cut up by small sloughs which had overflowed in every direction, making the country a perfect swamp....We were engaged...in getting through the mire, crossing no less than eight distinct sloughs, one of which we were obliged to raft over. In all of these sloughs a strong current was running southwest, or from the San Joaquin river to the lake."

In 1853, the U.S. War Department undertook surveys for a railroad route from the Mississippi River to the Pacific Coast. Blake, the geologist on this mission, described the overflow area, noting that "when the level of the river is greatly raised by freshets it overflows its banks, and the water passes to the lakes by this slough. At seasons of low water, all communication between the river and lake is prevented by a bar at the mouth of the slough." [Williamson 1853, p.192].

Others have reported that water was exchanged between the two basins through subsurface flow. The Irrigation Congress, reporting on field work for canals in the

San Joaquin and Tulare Lake Basins, speculated that "the San Joaquin receives an important accession of volume from underground drainage — probably from the Tulare Lake drainage." [Anonym. 1873, p.8]. However, most accounts of groundwater in this area indicate that it was "stagnant" [Mendenhall et al. 1916], discharging at the surface. Additionally, groundwater contours of the Valley [e.g., Ingerson 1941; Mendenhall et al. 1916], indicate that groundwater predominantly moved downslope toward the valley trough, rather than along the axis of the valley. We were unable to locate any authoritative accounts of groundwater exchange along a north-south axis or any that allowed us to eliminate this potential exchange.

Tulare Lake Basin Water Balance

We also calculated a water balance around the valley floor of the Tulare Lake Basin, using the same procedure described previously for the entire Central Valley. The results of this water balance are presented in Table 8. All of the factors and assumptions used in the analysis are listed on the table in the column headed "source/assumptions."

We used different consumptive use factors in the Tulare Lake Basin than in the north because climatic and hydrologic conditions there are distinct. This area is "desert-like and barren....during the summer and autumn..." when it is reported to be "without green vegetation...and gives unobstructed passage to steady currents of air.." [Blake 1856, p.1]. Thus, we used consumptive use factors for grassland and saltbush that were 50 percent less than we used in areas to the north.

We also used a combined tule marsh/lake evaporation rate of 6 ac-ft/ac. During wet cycles, extensive freshwater lakes were formed, which in dry cycles were partially drained and their lower levels replaced by marshes [Forbes 1941, p.17]. Thus, the ratio of lake surface area to marsh was constantly changing under natural conditions. Therefore, we used a mean tule marsh/lake evaporation rate of 6 ac-

TABLE 8

TULARE LAKE BASIN WATER BALANCE FOR NATURAL CONDITIONS

Element in Water Balance	Long-term, Average Annual Water (millions of ac-ft/yr)	Source/Assumptions
Water Supply		
Rim Inflow	3.5	For period 1889-1929; DPW Bull. 29 (1931), Table 5
Precipitation on Valley Floor	4.5	Valley floor area (6,503 x 10^3 acres) times average precipitation (8.3 in.) from Schreiner (1987)
TOTAL SUPPLY	**8.0**	
Water Use		
Riparian Forest (Valley oak)	0.9	Forest area (515 x 10^3 acres) times evapotranspiration (1.7 ac-ft/ac) from Lewis (1968)
Prairie	2.0	Prairie area (4,027 x 10^3 acres) times evapotranspiration (0.5 ac-ft/ac) based on 50% of the mean (Table 7)
Saltbush	1.3	Saltbush area (1,298 x 10^3 acres) times evapotranspiration (1 ac-ft/ac) estimated as 50% of the average saltgrass use (Table 7)
Tule Marsh/Lake Evaporation	3.9	Total area (643 x 10^3 acres) times evapotranspiration (6 ac-ft/ac) from Table 6
TOTAL USE	**8.1**	
IMBALANCE	**-0.1**	

ft/ac. This is 40 percent greater than lake evaporation [Anderson and Idso 1987], which Forbes estimated to be 4.4 ft/yr [Forbes 1931, p. 541].

We found that for natural conditions, water use in the basin slightly exceeded in-basin supply by about 100,000 ac-ft/yr over the long-term. This suggests that the Tulare Lake Basin may have had an unidentified water supply, which we believe was surface and subsurface overflow from the San Joaquin Basin into the Tulare Lake Basin. Within the limits of error for this type of analysis, this suggests that the Tulare Lake Basin overflow did not contribute large quantities of water to San Francisco Bay. However, it is certainly possible that, during very wet years, a larger quantity of water could have been exchanged, depending upon the volume of water stored in the natural lakes just before the flood flows began. A conservative upper bound for this overflow is the total rim inflow for the basin or 3.5 million ac-ft/yr (Table 8). If the overflow were on the average this large, which we believe is physically impossible, it would not change any of the conclusions presented here.

RECOMMENDATIONS

The concepts and calculations presented here should be viewed as a first step in estimating what the natural inflows to San Francisco Bay may have been. Estimates such as these are difficult to make due to the absence of quantitative measurements, and considerable additional work is required to refine our first attempts. We recommend the following additional studies and analyses:

1) Water use by tule marshes and riparian forests that were indigenous to the Central Valley should be measured in field studies in preserved wetland areas.

2) The ecology and hydrology of freshwater marshes such as those that were common throughout the Central Valley have never been studied in a

comprehensive manner. Field studies in preserved wetlands should be conducted to determine, among other things, the source of water, the volume of water storage, species distribution and abundance, and the effect of floods and droughts on marsh productivity. The excellent research conducted in Europe and the USSR on mires, bogs, and swamps should be used as a guide [e.g., Ivanov 1981].

3) Daily salinity and tidal data have been collected at the Presidio, at the Golden Gate, since 1855. This information should be analyzed to confirm the concepts presented here. Historic changes in Delta outflow (Figure 1) should be reflected in tidal and salinity records at this site. Some of the tidal data have been reported elsewhere [Smith 1980], and we believe the increase in tidal height from 1860 to 1885 shown in these records reflects increased Delta outflows from the extensive harvesting of riparian forest and draining of swamps that occurred then [Meade and Emery 1971].

4) An extensive body of technical information exists in pre-1900 State and Federal reports, which were then published as appendices to congressional proceedings. Many of these have been abstracted and tabulated in bibliographies on the State [e.g., Cowan and Cowan 1933; Hasse 1908]. A thorough search and synthesis of this material may yield additional information that could further clarify the natural system.

5) Eye witness accounts can also provide valuable information. Many of the original journals and maps are archived in the Bancroft Library on the University of California's Berkeley campus. Additional diaries and journals of early explorers and settlers should be consulted to determine the response of the natural system to droughts and floods. Events of interest should be compiled and tabulated in a consistent format and classified by

year type (wet, dry) using the excellent climatological research that is available [e.g., Graumlich 1987; Lamb 1977; Lynch 1931].

6) Existing natural vegetation maps of California [Kuchler 1977; Roberts et al. 1977] should be revised using historic accounts as presented in journals, diaries, and early technical reports appended to congressional proceedings.

7) Our analyses have focused on the effect of changes in valley floor vegetation on Delta outflow. The influence of changes in upslope vegetation on freshwater inflow to the Bay should also be explored. Some important additional areas to investigate include timber harvesting in the Sierra and Coastal range forests, converting chaparral to grassland, and the accidental introduction of annual grasses into the prairie.

8) A reservoir operations study should be performed on the Central Valley and its ancient storage reservoirs - the natural flood basins and groundwater aquifers - to determine the monthly distribution of flows under natural conditions.

9) The surface area of the natural flood basins was much greater than the surface area of man-made reservoirs that replaced them. This means that under natural conditions, water surface evaporation was much greater than it is today. This was not considered in this work. It should be evaluated in future studies.

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