Natural Flow Routing Model

TECHNICAL MEMORANDUM, Final

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for the State Water Contractors, San Luis and Delta-Mendota Water Authority, and Metropolitan Water District of Southern California

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Abbreviations and Acronyms

C2VSim	California Central Valley Groundwater-Surface Water Simulation Model
CDEC	California Data Exchange Center
cfs	cubic feet per second
Chico State	California State University, Chico
DAU	Detailed Analysis Unit
Delta	Sacramento-San Joaquin Delta
DSA	Depletion Study Areas
DWR	California Department of Water Resources
ET	Evapotranspiration
ET_o	reference crop evapotranspiration
HUC	Hydrologic Unit Code
km	kilometer
MAF	million acre-feet
M&I	municipal and industrial
MWD	Metropolitan Water District of Southern California
NatFM	Natural Flow Project Monthly Routing Model
NFP	Natural Flow Project
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
RM	River Mile
SFEI	San Francisco Estuary Institute
SLDMWA	San Luis and Delta-Mendota Water Authority
SOW	Scope of Work
SWC	State Water Contractors
TAF	thousand acre-feet
TM	Technical Memorandum
USGS	U.S. Geological Survey

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Chapter 1
Introduction

Human activities have dramatically affected inflows to the Sacramento-San Joaquin Delta (Delta). Upstream storage regulation has changed the monthly flow pattern. Diversions for irrigation and municipal and industrial (M&I) purposes have depleted streamflows. Changes in land use have affected the amount and timing of surface runoff. Groundwater pumping has impacted groundwater elevations and groundwater inflows to streams and rivers. Additionally, flood control measures and an extensive network of levees have ended the natural cycle of bank overflows and detention storage.

This Technical Memorandum (TM) describes the Natural Flow Project (NFP) Monthly Routing Model (NatFM) that was developed under separate contracts with the State Water Contractors (SWC), San Luis and Delta-Mendota Water Agency (SLDMWA), and Metropolitan Water District of Southern California (MWD). The purpose of this work is to estimate the inflows to the Delta and the net Delta outflows that would have occurred in the absence of human activity for an 88-year period spanning water years 1922 through 2009. These "natural" flows are significantly different from unimpaired flows that are sometimes used as their surrogate.[1]

The NatFM is a simple spreadsheet-based water balance that accounts for both surface water and groundwater flow components within the Sacramento River and San Joaquin River hydrologic regions[2] and accounts for land-use-based evaporative depletions. The NatFM allows the user to perform sensitivity analyses by changing key model input parameters.

This TM was prepared as part of Task 10 (Model Documentation) of the Scope of Work (SOW), dated July 1, 2013.[3] Chapter 5 serves as the User Manual for the NatFM. Chapter 6 describes the supporting input files.

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[1] Unimpaired flow is a term used to describe the natural flow of a river without anthropogenic influences such as regulations, diversions, or artificial recharge.

[2] In the 1960s, DWR subdivided the Central Valley into three hydrologic regions: Sacramento River, San Joaquin River, and Tulare Lake. These regions were in turn disaggregated into Planning Areas, and then Detailed Analysis Units (DAU). Over the past 50 years, DAUs have become DWR's standard unit for collecting and reporting land-use data, preparing water budgets, and making projections for land-use change and urban growth for the California Water Plan. The Delta lies partly in the Sacramento River and partly in the San Joaquin River hydrologic regions.

[3] *A Model to Estimate Delta Inflows and Outflow Under Natural Conditions*. San Luis & Delta-Mendota Water Authority Consultant Master Service Agreement, Task Order MWH 2013-01.

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Chapter 2
Data Sources

The NatFM divides the Sacramento River and San Joaquin River hydrologic regions into rim watersheds and valley floor watersheds. The rim watersheds comprise the foothills and mountains that surround the Central Valley. These watersheds are relatively undeveloped, and changes in land use over time have not significantly affected the natural outflow. However, storage regulation in many rim watersheds has changed the seasonal pattern of stream flows.[4] Additionally, trans-watershed imports and exports have increased flows in some rim watersheds, while depleting flows in adjacent rim watersheds.

Valley floor watersheds, located downstream from the rim watersheds, cover the floor of the Sacramento and San Joaquin valleys and the entire Delta. These lands have been extensively developed for irrigated agriculture and include major urban centers. Both surface water and groundwater flows are significantly affected by these developments.

To develop a water balance for the flows that would have occurred under natural conditions, the NatFM further divides the valley floor watersheds, as follows:

- Lands located downstream from the rim watersheds, but are upslope of the Central Valley groundwater aquifer.
- Lands overlaying the Central Valley alluvial aquifer system.
- The Delta

Figure 2-1 shows the valley floor watershed divided into areas located in the Sacramento River and San Joaquin River hydrologic regions. The Delta (shown in blue) spans both hydrologic regions. The figure also shows DWR Planning Areas within the valley floor which were used to develop estimates of evapotranspiration (ET) (described later). The outer extent of floodplain (delineated in red) was taken from *Sacramento River Basin, Bulletin 26* (DPW, 1931a) and *San Joaquin River Basin Bulletin 29* (DPW, 1931b).[5]

The NatFM calculates the monthly flows that would have occurred from October 1921 through September 2009 under natural conditions. The following sections describe the major data inputs and data sources.

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[4] Significant evaporative losses are associated with the larger reservoirs.

[5] The NatFM does not use this floodplain boundary, rather the model determines the flooded area based on a monthly water accounting of water stored in the low-lying detention basins. This storage varies monthly and annually depending on over-bank spills, rainfall-runoff, infiltration, ET, and discharge back to the river.

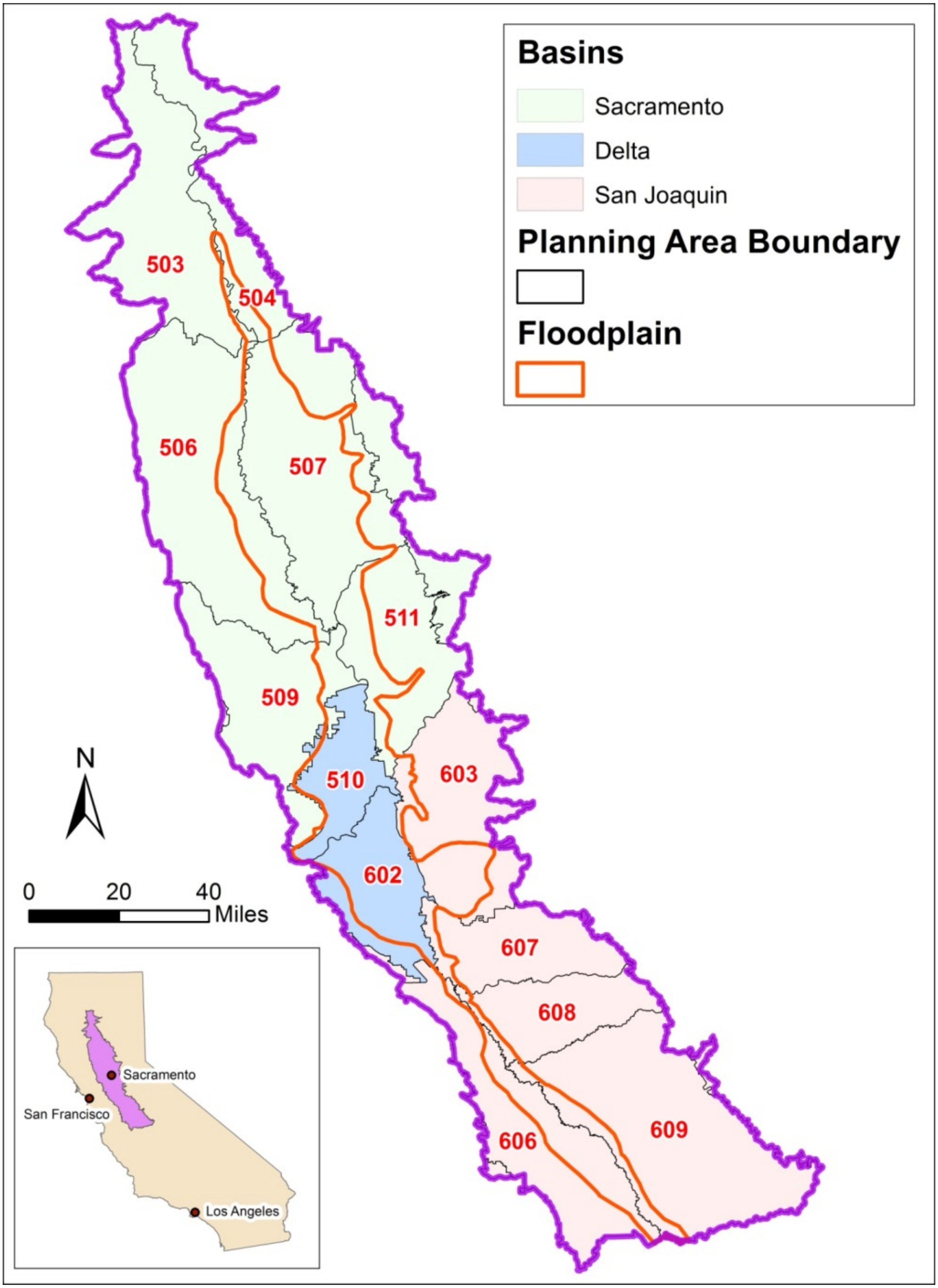

Figure 2-1. Rim and Valley Watersheds

Rim Watersheds

Data requirements for the rim watersheds include historical gage stream flows, historical storage regulation, and stream imports and exports.

There is no precise boundary between the rim and valley watersheds. Elevation is an imprecise indicator because of valley grades, and the presence of terraces and side valleys. In general, the borders of the Central Valley are defined where alluvial soils merge with bedrock features and where foothill woodland dominates the landscape. The NatFM defines the boundary of Central Valley according to stream gage locations and foothill dams, where historical stream flows are known. This flow-based boundary typically lies slightly upslope of the deep alluvial soils of the Central Valley.

Rim watersheds were delineated using CalWater 2.2.1[6] and the U.S. Geological Survey (USGS) Watershed Boundary Dataset.[7] Additionally, some watersheds were digitized manually using USGS 1:24,000 topographic maps. Outflow points from these watersheds typically coincide with major dams or stream gage locations. Natural flows from the rim watersheds to the valley floor were calculated in two steps: first, the historical flows were determined; second, the historical flows were unimpaired for any historical storage regulation and diversions. For all rim watersheds, the unimpaired flows are considered equal to the natural flows, i.e., land-use changes in the rim watersheds and its effect on streamflows are ignored. For watersheds with little or no water regulation facilities, the historical and unimpaired flows are equal.

Historical flows from each rim watershed were calculated using one of four methods, as follows:

- **Direct gage measurement** – Stream gage data exist at the watershed outflow point for entire period of simulation.
- **Streamflow correlation** – Stream gage data exist at the watershed outflow point for only part of the period of simulation. These gage data were extended through linear correlation with streamflow records from adjacent watersheds. In some watersheds (e.g., Butte Creek), stream gage data were adjusted to account for upstream interbasin imports and exports.
- **Proportionality** – No gage data exist for the watershed. It is assumed that runoff is proportional to the product of drainage area and average annual precipitation depth over

[6] The California Interagency Watershed Mapping Committee (IWMC) has worked since the mid-1990s to delineate California's watersheds. The IWMC is responsible for all interagency watershed mapping and data set creation in the State, including CalWater 2.2.1. CalWater is the official State of California watershed map and GIS data set. It is officially known as the California Interagency Watershed Map of 1999 (CalWater Version 2.2.1), and usually referred to simply as CalWater 2.2.1.

[7] The USGS has divided and subdivided the U.S. into successively smaller watersheds, termed hydrologic units. Each hydrologic unit is identified by a unique hydrologic unit code (HUC). The smallest watersheds (level 6) are defined as part of the Watershed Boundary Dataset. This dataset contains the most current, the highest resolution, and the most detailed delineation of the watershed boundaries.

the watershed. Flow is determined through association of the watershed with a similar, but gaged watershed and the use of multiplicative factors representing the ratio of watershed areas and ratio of precipitation depths.

- **Mass balance** – Typically, this method is used when watersheds have significant storage regulation. Reservoir operating records of dam releases and reservoir storage, together with estimated reservoir evaporation, are used to estimate inflows to the reservoir.

For the more complex watersheds, unimpaired flows were obtained from the California Department of Water Resources (DWR) Division of Snow Surveys as published on the California Data Exchange Center (CDEC) (DWR, 2013c). The average annual unimpaired flow from the rim watersheds to the valley floor for water years 1922 – 2009 is 27.6 million acre-feet (MAF).

Valley Floor Watersheds

Data requirements for the valley floor watersheds include land use under natural conditions, precipitation, and evapotranspiration (ET) for the various land-use classifications.

Delineation

The total area of the valley floor watersheds is equal to the combined area of the Sacramento River and San Joaquin River hydrologic regions, less the area of the rim watersheds described above. The valley floor watersheds, including the Delta, cover an area of approximately 8.5 million acres. The majority of these lands are underlain by the Central Valley groundwater aquifer, and are represented in the NatFM by 16 subregions. Initially, the subregions used by the NatFM corresponded to the subregions of the California Central Valley Groundwater-Surface Water Simulation (C2VSim) model (DWR, 2013a).[8] The C2VSim subregions, in-turn, are based on DWR's Depletion Study Areas (DSA). Subsequently, delineations for Subregion 3 (Colusa Basin), Subregion 4 (Butte Basin), Subregion 5 (Sutter Basin), and Subregion 6 (Yolo Basin) were modified to match the boundaries of the natural flood basins of the Sacramento Valley. The delineation of Subregion 9 was adjusted to match the Delta as defined by DWR for planning purposes.[9] To improve the simulation of flows in particular streams, and flows across the

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[8] C2VSim is an application of the IWFM code to the Central Valley. It includes a distributed quasi 3-dimensional finite element model of the Central Valley groundwater aquifer. The historical run of C2VSim simulates historical conditions for water years 1922 – 2009 using a monthly timestep.

[9] The official boundary of the Delta, the Legal Delta, was defined in 1959 and covers approximately 738,000 acres. The Delta, as defined for CalSim II, is known as the "Delta Service Area." The boundary lines of this area were defined in a DWR Central District Office report called Sacramento-San Joaquin Delta Area Land Use Survey Data (DWR, 1965). The most prominent difference between the Legal Delta and Delta Service Area is that the Legal Delta includes the towns of Pittsburg and Antioch; the Delta Service Area does not. Over the years, various estimates of land area for the Delta Service Area have been reported. Table III of the 1965 Central District Office report, mentioned above, lists the Delta Service Area as comprising 678,549 acres. The Consumptive Use (CU) models,eight which have been developed for the Delta, use a slightly lower combined estimate of 678,200 acres, as reported in Joint DWR and WPRS Delta Channel Depletion Analysis (DWR and WRPS, 1981). In 2006, a new model called DETAW was developed by the University of California at Davis (UC Davis) to estimate consumptive water demands within the Delta (Kadir, 2006). To define the boundary of the Delta, the original 142 subareas for the Delta Island Consumptive Use (DICU) model were digitized from a printed schematic; no computer-aided design (CAD) schematic or

floodplain, Subregion 5 was divided into 5a and 5b; Subregion 8 was divided into 8a and 8b; and Subregion 10 was divided into 10a and 10b. The final areas of the subregions used in the NatFM are presented in **Table 2-1**.

Land Use

Under natural conditions the floor of the Central Valley consisted of open water, marshes, alkali sinks, riparian forest, grassland, and savanna (Küchler, 1977). These different communities are loosely associated with elevation. For the purposes of estimating evaporative depletion of water supplies, the natural vegetation of the valley floor was divided into set of seven land-use classes. Under natural conditions, the most expansive land-use class was **Grassland**. Grasslands once covered all well-drained areas in the Central Valley and are still the dominant vegetation, although the native species have been replaced (Fox et al., 2014). For the purposes of estimating ET, the Grassland land-use class is divided into three subclasses. Grasslands that depended on rainfall to meet their water demands are referred to as **Rainfed Grassland**. Grasslands located in areas with a high water table or in areas prone to flooding that resulted in year-round water supplies are assumed to be **Perennial Grassland**. The last subclass is **Vernal Pool**. Vernal pools are seasonal grasslands that typically are supported by a perched groundwater table. This subclass was introduced towards the end of the NFP and is not considered explicitly in the NatFM.

Under natural conditions, much of the flood basins in the Sacramento and San Joaquin valleys and Delta contained large expanses of marsh and seasonal and tidal wetlands. Wetlands are divided into two subclasses: **Seasonal Wetland** and **Permanent Wetland**. Permanent wetlands, predominantly tule marshes, were located in the overflow basins, in the tidal channels of the Delta, and throughout the valley floor floodplain where there was adequate water supply and drainage characteristics to permit saturation of the soil (Fox et al., 2014).

The **Riparian** land-use class refers to riparian forest located adjacent to freshwater bodies. These riparian forests were predominantly found on the higher ground of natural levees adjacent to the Sacramento and San Joaquin rivers and their tributaries. They were primarily winter-deciduous species including sycamore, elder, cottonwood, willow, and valley oak. Riparian vegetation obtains moisture from groundwater or from water percolating downwards through the streambed. It is unlikely that the riparian vegetation experienced water stress, except under very severe drought.

Geographical Information System (GIS) layer could be found or located. The digitized map was rectified into a GIS layer. This area was further disaggregated into 168 subareas (Kadir, 2006). The resulting total area is 679,699 acres; approximately 0.2 percent larger than the previous estimate used for CalSim II.

Table 2-1. Natural Flow Model Subregions in the Valley Watersheds

NatFM Subregion	Description	C2VSim Subregion[1]	DSA	Area (acres)
1	Redding Basin	1	58	329,000
2	Northern Sacramento Valley	2	10	699,000
3	Colusa Basin	3/4	12/15	817,000
4	Butte Basin	4/5	15/69	309,000
5a	Left Bank of the Feather River	5	15/69	194,000
5b	Sutter Basin	4/5	69	324,000
6	Yolo Basin	6	65	615,000
7	American Basin	7	70	349,000
8a	Eastside Streams (Mokelumne watershed)	8	59	453,000
8b	Eastside Streams (Calaveras watershed)	8	59	453,000
9	Sacramento-San Joaquin Delta	9	54/55	680,000
10a	Westside San Joaquin Valley - North	10	49A	157,000
10b	Westside San Joaquin Valley - South	10	49A	510,000
11	Eastside San Joaquin Valley - North	11	49B	413,000
12	Eastside San Joaquin Valley - Center	12	49C	340,000
13	Eastside San Joaquin Valley - South	13	49D	1,036,000
Subtotal				7,680,000
14	Sacramento Valley foothills	N/A	N/A	768,000
15	Eastside Stream foothills	N/A	N/A	63,000
16	San Joaquin Valley foothills	N/A	N/A	28,000
Subtotal				859,000
Total				8,549,000

Note:
[1] Correspondence is approximate for Subregions 3,4,5,6, and 9.
Key:
C2VSim = California Central Valley Groundwater Surface Water Simulation Model
DSA = Depletion Study Area
N/A = not applicable

The **Hardwood** land-use class includes the foothill woodlands and savannas that were primarily located on the rim of the valley floor. The woodlands consisted of drought tolerant species such as pine and oak. The deep-rooted oaks were capable of tapping groundwater to sustain growth during the summer and fall. Savanna's are differentiated from woodland when the tree canopy becomes less dense so that the underlying grassland becomes the dominant community. These grasslands would be dependent on soil moisture from precipitation.

The **Chaparral** land-use class refers to dense communities of drought-tolerant evergreen shrubs, including manzanita and sage scrub. It was principally located on the westside of the Central Valley at higher elevations outside of the floodplain.

Saltbush is a broad-leaved evergreen and/or deciduous shrub associated with alkali soils. These xerophyte species principally occupied poorly drained soils in the arid parts of the Tulare Lake basin and small areas on the westside of the San Joaquin Valley (Shelton, 1987). The alkali soils are formed at the bottom of basins where water remains standing for long periods or the subsurface is moist from a high groundwater table.

The **Aquatic** land-use class covers all forms of shallow water, including streams, distributaries, lakes, sloughs, and tidal channels. Depletion from this land-use class is from open water evaporation rather than ET. Land that is temporarily flooded from over-bank river flows or from a high groundwater table are not included under the aquatic land-use class. ET from these temporarily flooded lands is calculated according to the land-use class being flooded.

The NatFM does not explicitly differentiate between perennial and rainfed grasslands. Neither does the model differentiate between permanent and seasonal wetlands. A priori, grasslands and wetlands are considered perennial/permanent. However, in months or in areas where water is a limiting factor, ET is reduced to zero and it is assumed that the vegetation “dies-back”; new growth (and associated ET) does not occur until the onset of the winter rains, or until other sources of water become available.

Land Area

The land area associated with each land use class is based on mapping performed by Küchler (1977) and California State University, Chico (Chico State) (2003),[10] as interpreted by Fox et al. (2014). **Table 2-2** presents the areas for each land-use class assumed for the NatFM. **Figure 2-2** shows the location of these land-use classes under natural conditions.

The San Francisco Estuary Institute (SFEI) has undertaken a very detailed analysis of natural land use in the Delta (Whipple et al., 2012). This work was used to validate the land use performed by Küchler and Chico State. However, SFEI mapping was not used directly for the NatFM.

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[10] In 2001, the US Fish and Wildlife Service (USFWS) and the U.S. Bureau of Reclamation (Reclamation) contracted with the California State University, Chico Research Foundation (Chico State) to develop a set of historical natural vegetation maps for the Central Valley of California. Natural vegetation was divided into eight classes: valley foothill hardwood, chaparral, grassland, riparian, alkali desert scrub, wetlands, aquatic, and other floodplain habitat. A series of geographic information system (GIS) layers were created to quantify vegetation changes over the last 100 years. Land-use layers include the pre-1900, 1940, 1960, and 1990 eras.

Table 2-2. Natural Land Use

NatFM Subregion	Area by Land Use Class (acres)							
	Aquatic	All Grassland	Saltbush	Chaparral	Riparian	Hardwood	All Wetland	Total
1	0	97,000	0	0	33,000	198,000	0	329,000
2	5,000	370,000	0	0	139,000	181,000	3,000	699,000
3	6,000	477,000	0	0	102,000	61,000	172,000	817,000
4	2,000	25,000	0	0	70,000	61,000	152,000	309,000
5a	2,000	75,000	0	0	46,000	25,000	45,000	194,000
5b	3,000	21,000	0	0	75,000	21,000	204,000	324,000
6	4,000	319,000	0	0	55,000	89,000	148,000	615,000
7	6,000	146,000	0	0	29,000	88,000	81,000	349,000
Delta	21,000	96,000	0	0	3,000	0	559,000	680,000
8a	1,000	206,000	0	0	38,000	127,000	81,000	453,000
8b	1,000	206,000	0	0	38,000	127,000	81,000	453,000
10a	1,000	124,000	0	0	2,000	0	30,000	157,000
10b	2,000	268,000	102,000	0	1,000	0	138,000	510,000
11	2,000	344,000	0	0	33,000	3,000	30,000	413,000
12	1,000	283,000	0	0	32,000	4,000	21,000	340,000
13	3,000	899,000	21,000	0	18,000	1,000	95,000	1,037,000
Subtotal	**61,000**	**3,955,000**	**123,000**	**0**	**715,000**	**986,000**	**1,840,000**	**7,680,000**
Sacramento Valley foothills	1,000	98,000	0	102,000	28,000	587,000	-48,000	768,000
Eastside Stream foothills	0	63,000	0	0	0	0	0	63,000
San Joaquin Valley foothills	0	37,000	-1,000	0	-4,000	2,000	-6,000	28,000
Subtotal	**1,000**	**198,000**	**-1,000**	**102,000**	**25,000**	**588,000**	**-54,000**	**859,000**
Total	**62,000**	**4,153,000**	**122,000**	**102,000**	**739,000**	**1,574,000**	**1,786,000**	**8,538,000**

Note:
Negative values are caused by minor inconsistencies between rim, valley, and Delta watershed definitions and boundaries used by C2VSim to define the extent of the Central Valley alluvial aquifer.

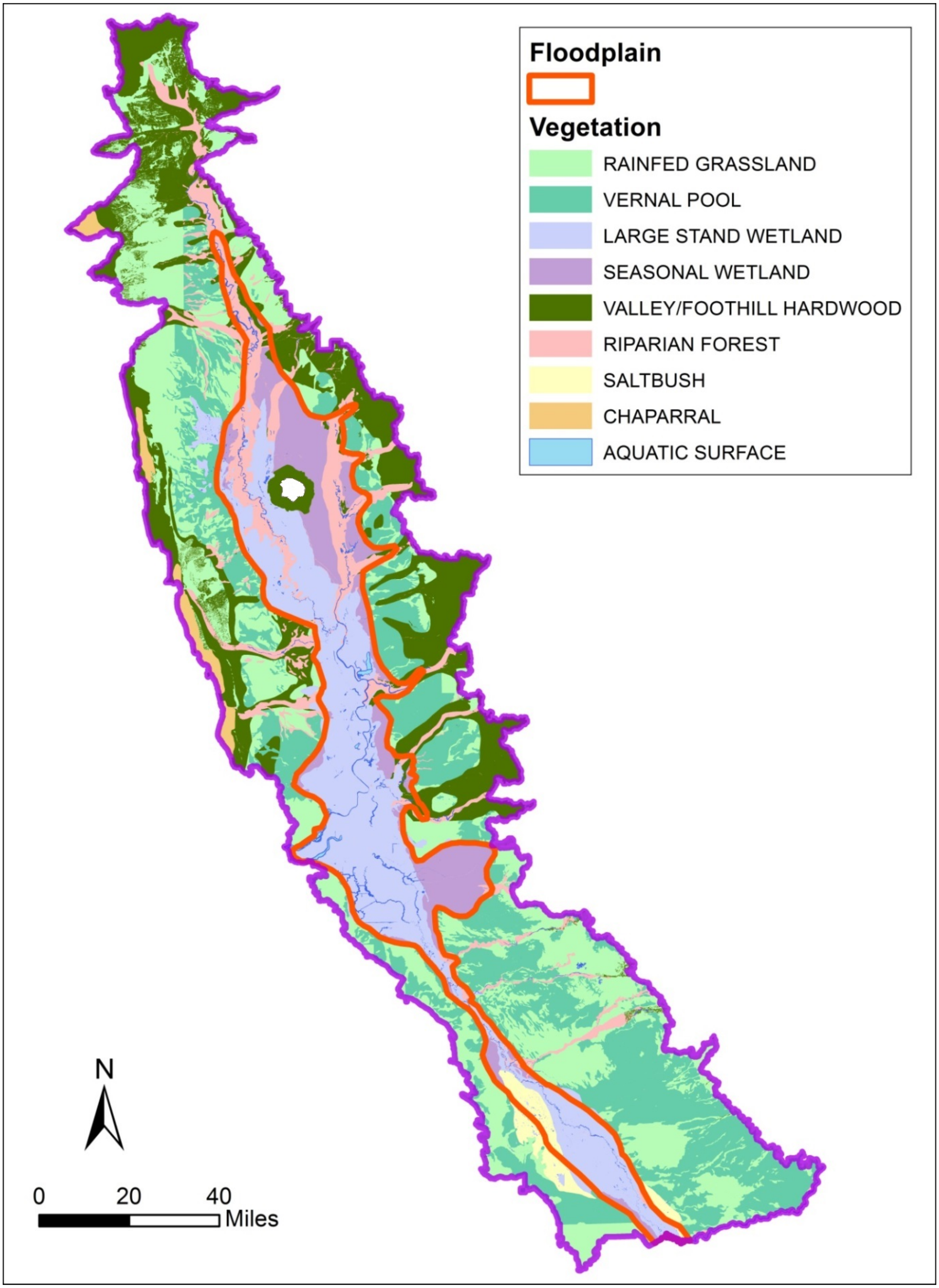

Figure 2-2. Natural Vegetation within the Valley Watersheds

Precipitation

Two sources of precipitation data were used for the NatFM. These sources are described in the following sections. **Table 2-3** presents average monthly precipitation by NatFM subregion for the 88 years 1922 through 2009.

Sacramento and San Joaquin Valleys

Monthly precipitation data for the NatFM subregions were developed using monthly distributed precipitation rates obtained from the PRISM Climate Group at Oregon State University (PRISM, 2013). Precipitation rates from a 2 kilometer (km) by 2 km PRISM grid were aggregated to each NatFM subregion.[11]

Sacramento-San Joaquin Delta

Monthly precipitation data for seven gaging stations in and adjacent to the Delta (Brentwood, Galt, Lodi, Rio Vista, Stockton, Davis, and Tracy-Carbona) were obtained or derived for water years 1922–2009. Precipitation data at the seven stations were used to develop area-weighted precipitation for the Delta Lowlands and Delta Uplands[12] using Thiessen polygons. **Table 2-4** presents the gage weighting factors. The long-term average annual precipitation is approximately 15.0 inches, which is equivalent to 0.85 MAF/year.

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[11] Precipitation data was obtained indirectly from DWR, rather than directly from PRISM. DWR had already processed PRISM grids for their C2VSim and CalSim models.

[12] Delta uplands includes all lands within the Delta at an elevation of 5.00 feet, or greater.

Table 2-3. Historical Average Monthly Precipitation

NatFM Subregion	Average Monthly and Average Annual Precipitation (inches) 1992-2009												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1	1.7	3.9	5.6	5.9	5.2	4.0	2.4	1.4	0.7	0.1	0.2	0.6	31.6
2	1.2	2.6	4.1	4.3	3.9	2.9	1.7	0.9	0.4	0.1	0.1	0.4	22.6
3	1.0	2.1	3.4	3.5	3.3	2.2	1.2	0.6	0.2	0.0	0.1	0.2	17.8
4	1.2	2.6	4.1	4.3	3.9	2.8	1.7	0.8	0.3	0.0	0.1	0.3	22.0
5a	1.3	2.8	4.0	4.3	3.9	3.1	1.8	0.8	0.3	0.0	0.1	0.3	22.5
5b	1.1	2.5	3.7	3.9	3.6	2.7	1.5	0.7	0.2	0.0	0.1	0.3	20.2
6	1.0	2.2	3.7	4.0	3.7	2.5	1.4	0.5	0.2	0.0	0.0	0.2	19.4
7	1.1	2.4	3.6	3.9	3.6	2.8	1.6	0.7	0.2	0.0	0.1	0.2	20.1
Delta	0.9	2.1	3.1	3.4	3.1	2.6	1.6	0.6	0.1	0.0	0.0	0.2	17.9
8a	0.9	2.1	3.1	3.4	3.1	2.6	1.6	0.6	0.1	0.0	0.0	0.2	17.9
8b	0.8	1.7	2.7	3.0	2.8	2.1	1.1	0.4	0.1	0.0	0.0	0.2	15.0
10a	0.5	1.2	1.8	2.1	1.9	1.6	0.9	0.4	0.1	0.0	0.0	0.2	10.6
10b	0.5	1.0	1.6	1.8	1.7	1.3	0.8	0.3	0.1	0.0	0.0	0.2	9.3
11	0.7	1.5	2.3	2.6	2.4	2.1	1.2	0.5	0.1	0.0	0.0	0.2	13.5
12	0.6	1.4	2.1	2.4	2.3	2.0	1.2	0.4	0.1	0.0	0.0	0.2	12.7
13	0.6	1.3	2.0	2.2	2.1	1.9	1.1	0.4	0.1	0.0	0.0	0.2	11.9
Sacramento Valley foothills	1.8	3.9	5.2	5.8	5.7	4.4	2.1	1.2	0.6	0.1	0.2	0.6	31.6
Eastside Stream foothills	0.9	2.1	3.1	3.4	3.1	2.6	1.6	0.6	0.1	0.0	0.0	0.2	17.9
San Joaquin Valley foothills	0.5	1.0	1.6	1.8	1.7	1.3	0.8	0.3	0.1	0.0	0.0	0.2	9.3

Table 2-4. Area-Weighting Factors for Delta Precipitation

Region	Precipitation Station						
	Brent-wood	Galt	Lodi	Rio Vista	Stockton	Davis	Tracy-Carbona
Lowlands (470,345 acres)	0.181	0.089	0.036	0.363	0.188	0.086	0.059
Uplands (209,354 acres)	0.188	0.100	0.025	0.067	0.073	0.235	0.313

Evapotranspiration

Monthly rates for historical reference crop evapotranspiration (ET_o) were obtained from DWR for Planning Areas covering the Central Valley.[13] These rates were calculated using the Hargreaves-Samani equation, which requires only limited input data; the equation computes ET_o as a function of minimum and maximum temperatures and extraterrestrial radiation (Orang et al., 2013).

To determine unit ET rates for the natural vegetation (ET_v), the land-use classes were split into two categories. The first category is for vegetation that is not subject to water stress and transpires at the maximum potential rate. This category includes Aquatic (open water), Permanent Wetland, Riparian, Permanent Grassland, and Saltbush. The second category is for vegetation that typically suffers from water stress in the summer and fall when lack of water limits ET. This second category includes Rainfed Grassland, Hardwood, and Seasonal Wetland. For the first category, Howes et al. (2014) developed 12 monthly K_v values for each land-use class, which relate ET for the particular land-use class to ET_o. For the second category, K_v values consist of monthly timeseries data calculated as the ratio of actual ET to ET_o. These K_v values incorporate the effects of water stress by considering the availability of precipitation stored in the root zone to meet ET.

ET_v data from Howes et al. (2014) were mapped to the various subregions considered by the NatFM. The mapping assumes that unit ET rates are uniform across each Planning Area. **Table 2-5** presents a summary of the ET_v data by land-use class.

Table 2-5. Average Monthly and Average Annual Evapotranspiration

Land-Use Class	Average Monthly and Average Annual ET (inches)[1] 1922-2009												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Aquatic	3.5	1.5	0.7	0.8	1.3	2.4	3.9	7.0	8.0	8.7	7.7	5.8	51.5
Chaparral	0.3	0.6	0.6	0.7	1.0	1.5	1.6	1.1	0.1	0.0	0.0	0.1	7.7
Grassland - Rainfed	0.5	0.8	0.9	1.0	1.4	2.1	2.8	2.2	0.4	0.0	0.0	0.2	12.3
Grassland – Permanent	3.6	1.6	1.1	0.7	1.1	2.0	4.7	6.8	8.3	9.4	8.7	6.2	54.2
Hardwood	0.7	0.9	0.9	1.1	1.5	2.3	3.1	3.9	1.9	0.1	0.1	0.2	16.7
Riparian	4.2	1.9	1.1	1.1	1.5	2.7	3.9	6.1	7.9	9.4	9.0	6.7	55.4
Saltbush	1.2	0.8	0.5	0.4	0.6	1.0	1.8	3.1	4.0	5.1	4.2	2.5	25.1
Wetland - Seasonal	2.9	1.8	1.2	1.3	1.9	3.2	4.7	6.5	8.8	9.5	8.8	4.3	54.9
Wetland - Permanent	3.8	1.9	0.9	0.9	1.3	2.6	4.1	6.9	9.0	9.8	8.6	5.7	55.5

Note:
[1] Area weighted values for 16 subregions (excluding the 3 regions within the foothills)
Key:
ET = evapotranspiration

[13] Planning Areas are used by DWR for reporting land and water use data as part of the California Water Plan (DWR, 2013d).

Chapter 3
Model Assumptions

This chapter briefly describes the major model assumptions. A more detailed description of these assumptions is presented in Chapter 5.

Rainfall-Runoff

Surface runoff refers to water flowing across the land surface as sheet flow or channel flow. It is also known as direct runoff. Different mechanisms have been described for the generation of surface runoff. Hortonian overland flow takes place when the rate of precipitation exceeds the surface infiltration capacity. Saturation overland flow occurs when the soil profile becomes saturated, and all additional precipitation is converted to surface runoff.

For the NatFM, surface runoff is calculated using a modified form of the Soil Conservation Service (SCS)[14] Curve Number method (SCS method). This method was developed in 1954 and is documented in Section 4 of the *National Engineering Handbook* (NEH-4), first published by the U.S. Department of Agriculture (USDA) in 1956. Empirical relationships were developed from rainfall-runoff data for a variety of watersheds, generally less than 1 square mile in area (SCS, 1972). Although the SCS method was developed for small, mildly sloping watersheds, it has been applied to much larger watersheds. Using the SCS CN method, runoff is determined as follows:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad \text{for } P > 0.2S \qquad \text{Eqn. 3-1}$$

where:

Q = surface runoff (inches)

P = precipitation (inches)

S = potential maximum retention (inches)

Equation 3-2 relates the potential maximum retention, S, to a curve number can be determined from information on soil type, hydrologic condition, land use, and antecedent moisture condition.

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[14] In 1994, the SCS changed its name to the National Resources Conservation Service (NRCS).

$$S = \frac{1000}{CN} - 10 \qquad \text{Eqn. 3-2}$$

The curve number is determined by soil type, hydrologic condition, land use, and antecedent moisture condition. The curve number, for convenience, varies from 0 to 100.[15] The retention parameter, described above, is for calculation of direct runoff and infiltration on a daily timestep. For monthly simulation, the maximum retention parameter, S, used in Equation 3-1 is replaced with αS. The parameter α is a coefficient, which depends on the amount of monthly rainfall, P (in inches), as follows:

$$\alpha = P^{0.4} \qquad \text{Eqn. 3-3}$$

Equation 3.3 was developed based on an analysis of rainfall station data and application of the SCS method on daily and monthly time scales. For the NatFM, additional runoff occurs when the soil profile is at or above field capacity and the average monthly precipitation rate exceeds the vertical hydraulic conductivity of the unsaturated layer below the root zone.

Soil Moisture Storage

The NatFM dynamically simulates soil moisture storage for 19 subregions. Soil moisture storage fluctuates between field capacity and the mid-point between field capacity and permanent wilting point. Soil moisture between these two limits is readily available to plants and vegetation. Depletion of soil moisture to the permanent wilting point is not simulated, neither is soil moisture storage between field capacity and saturation represented. The root zone is recharged from precipitation and flood water flowing across the land surface. Deep percolation from the root zone to the underlying aquifer only occurs after the root zone reaches field capacity. The NatFM tracks soil moisture for each land-use type and for each subregion. Two accounts are maintained for each land-use type: lands that are flooded and lands that are not flooded. The area of lands in these two accounts varies dynamically from month-to-month.

Evapotranspiration

Monthly rates of potential ET for each land-use class and for each subregion are inputs to the NatFM. Actual ET is calculated dynamically in the model as a function of soil moisture storage. For most land-use classes, actual ET is reduced to zero when the soil moisture storage falls below the readily available soil moisture. Exceptions to this rule are as follows:

- For the Aquatic land-use class, ET is always equal to the evaporation rate from shallow water.

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[15] Practical values for curve numbers lie within the range of 40 to 98.

- For the Riparian land-use class, actual ET is always equal to potential ET; once soil moisture storage is depleted, riparian ET is met from stream flows and/or groundwater.
- For the Hardwood land-use class, ET rates input to the NatFM already account for reduced ET during the summer and fall due to the lack of soil moisture;[16] actual ET is always equal to the input ET rate, groundwater is depleted by Hardwood ET once soil moisture storage falls below the readily available soil moisture.

ET associated with the Chaparral, Grassland, and Wetland land-use classes may be supported through the summer and fall under conditions of a high groundwater table, which is dynamically simulated in the model.

Groundwater

A set of 15 lumped-parameter groundwater models are used to simulate groundwater storage and the interaction with surface waters.[17] The lumped-parameter models are independent, i.e., hydraulically unconnected. Groundwater-surface water interactions are simulated using a stylized representation of the actual groundwater. Groundwater is represented as a wedge that slopes toward the stream/river. Groundwater is recharged from precipitation and flood flows over the floodplain and depleted through flow to the stream system and through ET from surface vegetation under conditions of a high water table. Groundwater flow to the river is dependent on the relative elevation between the groundwater and river stage. Calculation of groundwater flow is based on the Dupuit-Forcheimer assumptions, which assume that groundwater flows horizontally in an unconfined aquifer, and that the groundwater discharge is proportional to the saturated aquifer thickness.

Flood Routing

Under natural conditions, the channels of the Sacramento and San Joaquin rivers in the Central Valley had insufficient capacity to carry the heavy winter and spring flows generated by wet season precipitation and/or snowmelt. These rivers overflowed their banks in most years creating a system of swamps, marshes, and wetlands. Areas prone to frequent flooding were delineated by Hall (1887) and by the California Department of Public Works (DPW, 1931a; 1931b). The flow velocity in these lands was much reduced and finer material would drop-out of suspension forming the fine clay soils that typify the Colusa and Sutter basins in the Sacramento Valley. The bank-overflows caused the sediment carrying capacity of the rivers to diminish and over time the

[16] Hardwood consists of mixed oaks and grassland. ET from oaks is perennial; groundwater is assumed to be the source of water once the root zone soil moisture is depleted. ET from grasslands is dependent on the amount of precipitation stored in the root zone.

[17] Groundwater is not modeled for the Delta or for the 3 subregions comprised of lands located at the margin of the valley floor.

Sacramento and San Joaquin rivers built up their beds and formed natural levees composed of heavier, coarser material carried by the flood flows each year.

Sacramento Valley

Grunsky (1929) estimated that under natural conditions approximately 1 million acres or nearly 40 percent of lands within the Sacramento Valley were subject to flooding. At times of high river stage, over-bank spills from the Sacramento River and its tributaries flowed into low lying basins adjacent to the river. As river stage fell, water would drain back to the river through well-defined channels and sloughs.

The flood basins of the Sacramento Valley are described by Hall (1880), Manson and Grunsky (1895), and Grunsky (1929). These flood basins included the Butte, Sutter, American, and Sacramento basins on the left bank of the Sacramento River, and the Colusa and Yolo basins on the right bank of the river.

Butte Basin

The Butte Basin is located on the left bank of the Sacramento River, north of the Sutter-Buttes. Based on recent lidar data, no significant natural storage existed. Under natural conditions outflow from the basin was constricted to a narrow passage between the natural levee of the Sacramento River and the Sutter-Buttes. The following description is taken from Grunsky (1929):

> *At this contraction, Butte Slough, a break through river bank lands, forms an interconnection between the river and the basin. The water which flows over the east bank of the river above Butte Slough flowing in a network of channels and uniting with water from a number of streams which drain outlying portions of the Sierra Nevada region, reaches and fills the Butte Basin, the drainage from which, during river flood stages, goes south through the contracted low area between the river and Sutter Buttes already referred to. During a general flood stage of the river this basin holds a slow moving sea of water, 30 to 150 sq. miles* [19,200 to 96,000 acres] *in area, depending on the magnitude and origin of the flood waters. The volumetric contents of the basin cannot be given with precision because in times of flood the surface of the water in the basin has more or less slope depending upon the source from which its greatest accession of water.*

A similar description is given by Manson and Grunsky (1895):

> *This basin is a very broad, flat-bottomed depression, in which the water flows from north to south, until the rising of the Sacramento River, by discharging water through Butte Slough and across banks into the lower end of this basin (and into its outlet to the Sutter Basin), forms a water dam holding back the Butte Basin waters to a contour line of about 60 feet (above low water of Suisun Bay), or, if the basin be not already full, fills it to this height.*
>
> *The bottom of the basin has a gradual slope from north to south. It has a free outfall toward the south between the Buttes and Butte Slough, but the same is being rapidly choked by a dense growth of willow.*

During a general flood stage of the river the basin holds a slow moving sea of water from 30 to nearly 150 square miles in area, according to the amount of inflow to the basin.

The contents of the basin cannot be determined with precision, because in times of flood the water surface of the basin has more or less, slope, depending upon the locality from which it receives its greatest accession of water, and the high water-stages indicated around its margin may not have all prevailed at the same time.

When the outflow of the basin is checked at the lower end by a river stage above banks, its contents generally range between 5,000,000,000 and 20,000,000,000 cubic feet of water [115 to 459 TAF].

Sutter Basin

The Sutter Basin receives inflow indirectly from the Butte Basin and directly from the Sacramento and Feather rivers. Grunsky estimated the capacity of the Sutter Basin to be approximately 40 million cubic feet, equivalent to 0.9 MAF, covering an area of approximately 140 square miles. Drainage of the basin typically was not completed until fall, when the stage in the Sacramento River reached its lowest level. Drainage of the basin was "imperfect" and some parts of the basin would have stayed inundated year round. The following description is taken from Grunsky (1929):

The second basin on the east side of the river is Sutter Basin. This basin has a length from north to south of about 30 miles and an average width of 6 miles. The upper 10 miles thereof, however, has so much surface slope and lies so much higher than the more southerly portion, that, as soon as the inflow of water ceases, there is rapid drainage into the more depressed southerly portion, and submersion of basin lands does not there continue long. The unwatering of the more southerly basin lands being by drainage into Sacramento River near its confluence with the Feather River is a slow process. When the flood stage at the mouth of the Feather River is at Elevation 30 (above mean sea level), and the basin is full to this height (which is about 8 ft. below the flood-control project high-water stage), its surface has an area of nearly 140 sq. miles and its contents range from 25,000,000,000 to nearly 40,000,000,000 cu. ft., according to the momentary volume of inflow from the north. When, for example, in December, 1889, at its highest stage of the winter, the water in Sutter Basin amounted to 39,000,000,000,000 cu. ft., or four times the quantity which would fill the Sacramento River below Iron Canyon from a low-water to a high-water plane. The general elevation of the lowest portion of this basin is 19 to 20 ft. This is but little above the elevation of the low-water plane of the Sacramento River at the mouth of the Feather River. Complete drainage of the Sutter Basin as it was originally, was therefore a slow process.

The river does not fall to it seasonal lowest stage until in the autumn months, and drain-ways to it which Nature had provided, did not everywhere connect with the lowest spots. Drainage, therefore, was imperfect and water stood in some portions of the flood basin throughout the entire year. It is noted that by reason of its position between two rivers, this basin, before its reclamation, received water not only from the Sacramento, but also from the Feather River. While being filled and while discharging its contents, it has a profound effect on the flow of the Sacramento River below the Feather.

American Basin

The American Basin is located on the left bank of the Feather River and Sacramento River between the Bear and American rivers. The basin received flood water from the lower Bear River, the lower Feather River and the Sacramento River below Verona. Many small ephemeral streams also flowed into the basin. Grunsky (1929) estimated the capacity of the American Basin to be approximately 25 million cubic feet, equivalent to 0.6 MAF, covering a surface area of 110 square miles.[18] His description of the basin is as follows:

> *American Basin is the third east side basin. Its southerly or down-stream end is at the American River. Its northerly apex extends along the east side of the Feather River for some miles above its mouth. The basin has a surface extent, if measured by such a flood as that of December, 1889, of 110 sq. miles and, at that time, at its highest stage it contained 25,000,000,000 cu.ft. of water. Its water stage at its southerly end was controlled by the stage of the Sacramento River at the mouth of the American.*

Sacramento Basin

The Sacramento Basin consists of a long narrow depression located on the left bank of the Sacramento River below the City of Sacramento. The basin is divided into an upper or lower portion by a ridge of relatively high ground near the town of Freeport. Grunsky (1929) and Manson and Grunsky (1895) only briefly describe the basin as it was relatively well protected against flooding by the then existing flood control works. The lowest portion of the basin drained through ditches to Snodgrass Slough and subsequently into the Mokelumne River.

This Sacramento Basin is currently not represented in the NatFM as these lands are partly located within the Delta.

Colusa Basin

The Colusa Basin receives flood water from the Sacramento River and inflow from numerous small creeks that drain the Coast Range. The basin drains through Sycamore Slough and flood water discharged to the Sacramento River near the present town of Knights Landing. Grunsky (1929) estimated the capacity of the Colusa Basin to be approximately 45 million cubic feet, equivalent to 1.0 MAF. Grunsky's description of the basin is as follows:

> *Colusa Basin lies on the west side of Sacramento River, being separated from the Yolo Basin by a ridge of relatively high ground built out from the Coast Range to Sacramento River at Knights Landing (Grafton), by Cache Creek. This basin is long and comparatively narrow. Before the water was held back by levees, any general river flood stage converted the entire west side valley trough from a point in the latitude of Princeton to the ridge at Knights Landing to an inland sea nearly 50 miles long and 2 to 7 miles wide. Its water came from the west side over-bank flow of the river and from numerous small creeks which descend from the Coast Range. During flood conditions,*

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[18] Estimated under maximum flood conditions during December 1989.

when this basin was full, and water was flowing in it from north to south, its contents may at times have reached 45,000,000,000 cu.ft.

Some historical accounts divide the Colusa Basin into an upper and lower basin. The upper and lower basins were divided near the town of Meridian.

Yolo Basin

The Yolo Basin is the largest of the Sacramento Valley flood basins. In stretches from the Knights Landing Ridge to the lower end of Grand Island. Grunsky estimate its capacity to be approximately 50 million cubic feet, equivalent to 1.1 MAF. Cache and Putah creeks discharge into the basin. In the lower portion of the basin, east and south of Putah Creek, several lakes permanent lakes existed, including Washington Lake, Little Lake, and Big Lake. Grunsky's (1929) description of the basin is as follows:

Yolo Basin is the largest of the several flood basins along the Sacramento River. It extends from the ridge described at Knights Landing to Cache Slough at the lower end of Grand Island on the south. It has a length of more than 40 miles and an average width of 7 miles. At times of general inundation when water was flowing down the basin, its volumetric capacity, before being reduced by reclamation works, was about 50,000,000,000 cu.ft. Its surface extent may be noted as nearly 300 square miles. During the high water of 1889 (this being a flood for which the records permit approximation), the discharge from the lower end of the basin back into the Sacramento River through Cache Slough, its outlet channel, was more than twice the quantity of water which the river was carrying.

Storage and Elevation Data

Grunsky (1929) gives estimated flood storage in the various basins in the Sacramento Valley during the floods of December 1889. **Table 3-2** presents these data together with extracted form topographic maps prepared by Grunsky in 1989.

Table 3-2. Characteristics of Flood Control Basins in the Sacramento Valley

Basin	Basin		Flooded Land		Sacramento River at Basin Outflow		
	Maximum Storage	Maximum Area	Highest Elevation[3]	Lowest Elevation[4]	Natural Levee Height	High Water[2]	Low Water[1]
	MAF	Sq. Miles	feet	feet	feet	feet	feet
Butte[5]	4.7	150		50.0		62.7	43.2
Colusa	1.0		61	23.6	35.5	36.2	20.0
Sutter[6]	0.6	140	50	17.5	28.5	33.7	15.9
American	0.6	110	35	11.6	26.5	28.0	10.0
Sacramento	-	-	-	-	-	-	-
Yolo[7]	1.1	300	30	1.5	-	10.6	1.6

Source: Grunsky (1929) and 1895 survey maps prepared by M. Manson and C.E. Grunsky consulting engineers for A. H. Rose, the Commissioner of Public Works

Notes:
[1] Low water of 1878
[2] High water of 1879
[3] Highest elevation of lands shown subject to flooding in the basin.
[4] Lowest elevation corresponds to lands adjacent to the basin outflow point.
[5] High and low water for the Butte Basin correspond to levels recorded at the entrance to Butte Slough on the Sacramento River
[6] The range of elevations for the Sutter Basin are for lands adjacent to Butte Slough at the north end of the basin to low lands between the Sacramento and Feather rivers that may have been too low to completely drained through Sacramento Slough to the Sacramento River.
[7] The range of elevations for the Yolo Basin are for lands in the north of the basin, adjacent to the towns of Knights Landing and Fremont to lands at the confluence of Cache Slough and Steamboat Slough adjacent to Grand Island.
[8] "-" indicates no data available

Model Representation

The NatFM represents overbank flow in the Sacramento Valley at a total of six locations. Between Ord Ferry and Knights Landing, at high river stage Sacramento River water spills into the Colusa Basin to the west and into the Butte and Sutter basins to the east. Between Knights Landing and Sacramento, the Sacramento River spills into the Yolo Basin to the west and the American Basin to the east. Additionally, the NatFM represents a single bank overflow location on the Feather River, at Yuba City, where historically the river spilled over the right bank into Gilsizer Slough. Subsequently, floodwater flowed through the slough to the Sutter Basin.

Outflows from the flood basins are controlled by the stage in the Sacramento River. No outflow occurs until the river stage at the basin outlet falls below the flood water elevation. Once river stage falls below bank-full capacity, the flood basins are assumed to rapidly drain to river levee elevation. Thereafter, drainage is relatively slow. Outflow is modeled using a broad-crested weir equation; the outflow is a function of the flooded depth raised to the power of 1.5. Flood water also is depleted through surface infiltration and augmented by surface runoff.

Area-elevation-capacity relationships were derived for the Butte, Sutter, American, and Colusa basins based on Lidar data. The basin elevation is measured at the outflow for each basin: Butte Slough for the Butte Basin, Sacramento Slough for the Sutter Basin, Bannon Slough for the American Basin, and Sycamore Slough for the Colusa Basin. It was assumed that maximum storage in each basin occurred when the water elevation in the basin elevation was equal to the height of the natural levee in the Sacramento River at the basin outflow point. The NF Model assumed the following maximum storage values:

- Butte Basin: maximum storage 0.5 MAF

- Sutter Basin: maximum storage 0.9 MAF
- American Basin: maximum storage 0.6 MAF
- Colusa Basin: maximum storage 1.0 MAF

No natural storage regulation was modeled for the Yolo Basin. It was assumed that the flow characteristics of the basin were such that the basin quickly drained back to the Sacramento River after the passing of the initial flood wave. This assumption, together with a similar assumption for the Sacramento Basin on the left-bank of the river are partly the result of insufficient study funding to fully address the hydrodynamics of these two basins. Both basins lie partly within the Delta and basin outflow is influenced by tidal stage.

The frequency and duration of flooding under historical conditions is informative about the natural condition. Flood flow duration and ponding under natural conditions would have been longer; the existing flood levee system associated with the Yolo Bypass tending to concentrate flows and increase overland flow velocities. It is reasosable to assume that flood duration under historical conditions provides a lower bound to the duration of flooding that would have occurred under natural conditions.

Construction of the levees for the Yolo Bypass began in 1917, and the Fremont and Sacramento weirs were built in 1924 and 1917, respectively. The Deep Water Ship Channel that now runs along the eastern edge of the bypass was completed in 1963, decreasing the conveyance capacity of the southern reach of the bypass.

DWR maintains a gaging station at the Lisbon Weir that has recorded water levels in the Toe Drain in the southern part of the Bypass, downstream from Putah Creek, since 1935. These records reveal the historical magnitude, frequency, duration, and timing of inundation of the Bypass. Water level at the gage is tidally influenced and fluctuates between 0 and 4 feet above mean sea level during low flow periods. At a stage 8.5 feet above mean sea level (11.5 feet above the gage datum), flow in the upstream Toe Drain begins to spill out of the channel and inundate adjacent land. From 1935 through 1999 inundation occurred in 46 of the 65 years (Jones & Stokes, 2001). The cumulative seasonal duration of inundation ranged from 0 to 135 days. In 31 of the 46 years of inundation, the duration of flooding was greater than one month. The earliest recorded inundation began on October 14, 1962. However, inundation typically did not occur until mid-November. The latest recorded inundation ended on June 10, 1998.

The review of historical gage records suggest that the storage and outflow characteristics of the Yolo Basin, and probably the Sacramento Basin, may have a significant influence on the timing of Delta inflows under natural conditions and should be further investigated in the future.

Channel Capacities

The Sacramento and Feather rivers have been significantly affected by human activities in the 19th and 20th century. Uncontrolled hydraulic mining for gold in the mid-1800s caused a huge influx of sediment to these rivers and their tributaries and aggradation of the river bed up to 10-25 feet (Gilbert, 1917). In 1884, hydraulic mining was made illegal. Dams constructed in the 20th century capture sediment load and constructed levees confined flows to river channels and flood bypasses. Sediment loads decreased and the rivers started to degrade, eroding previously deposited hydraulic mining debris. Many researchers believe that present sediment loading on the Sacramento River is approaching its pre-gold rush value.

Early river flow estimates are given by Hall (1887). Grunsky (1929) estimated the bank-full capacity of the Sacramento River from Butte Slough to the Feather River confluence to be approximately 20,000 cfs under natural conditions. Below the Feather River, Grunsky estimated the natural channel capacity, prior to the effects of hydraulic mining, to be between 75,000 and 100,000 cfs.

Channel capacities were determined from a HEC-RAS analysis of the stage-discharge relationship for the Sacramento River at 3 locations: Sacramento River at Knights Landing, Sacramento River at Fremont Weir, and Sacramento River at Natomas East Main Drain Canal. The analysis is based on channel geometry from the 2002 Sacramento and San Joaquin River Basins Comprehensive Study.

San Joaquin Valley

Unlike the Sacramento Valley, there were no natural low-lying basins in the San Joaquin Valley although the valley was subject to frequent flooding. The characteristics of the San Joaquin River are described in the *Report of the Commissioner of Public Works to the Governor of California* (Manson and Grunsky, 1895).

> *The Upper San Joaquin River breaks from the Sierra Nevada foothills about 140 miles below the southeastern end of the San Joaquin Valley. It flows thence directly down the eastern valley slope in a broad gorge, half a mile to a mile wide, being flanked by narrow strips of bottom land, and, upon reaching the trough of the valley, turns abruptly to the northwest at Las Juntas. It falls from this point 156 feet in its course to the bay, and its length (measured along the main stream) is about 210 miles.*
>
> *It is flanked by strips of relatively low land, except at a few points, such as Grayson and San Joaquin City, where the high western plain slopes down to the river bank. The extensive east- and west-side low tracts are subject to frequent inundation. The capacity of the river channel falls far short of that which would be required to confine flood waters to a single channel, and the river water therefore spreads over large areas, flowing in innumerable sloughs or waterways, which sometimes are arms of the main stream, and again appear as continuations of the Coast Range or Sierra Nevada drainways, or may even appear as independent waterways without well-defined heads or mouths.*
>
> *The area of the country thus subject to frequent inundation along the upper San Joaquin River – that is, above the head of the Old River – is about 150 square miles. This entire region becomes a reservoir of slowly moving waters when the San Joaquin is in flood; and to the accumulation of waters along this portion of the river the fact is due that relatively small waterways at points just below have come so near being adequate to pass all the water of the many seasons of less than average rainfall since the reclamation work has been taken well in hand.*

Flooding in the lower San Joaquin Valley is described by Tinkham (1880) in a history of the City of Stockton.

> *In 1862 the entire county was two feet under water for two weeks, and it was noticed that a rich sediment was deposited on the soil, from one to three inches in depth. In 1872 only a portion of the city was under water, and floods are now an event of the past, as the city is graded above the highest water ever known.. The overflows are a benefit to the soil, and, as they frequently occur on the Calaveras near its banks, they give additional richness to the land.*

Model Representation

The NatFM simulates overbank flow for the reach of the San Joaquin River from (the town of) Mendota to Vernalis. Floodwater is withdrawn from the San Joaquin River at Mendota and the San Joaquin River at Newman (downstream from the Merced River) and routed parallel to the river to discharge into the south Delta. Within the San Joaquin Valley, no detention storage is represented; it is assumed that all flood water drains to the Delta in the same timestep.

The existing channel capacity of the San Joaquin River is considered a poor indicator of the river's pre-development channel capacity. Therefore, the default channel capacity for the NatFM is based on river geomorphology concepts. Bankfull flows are important for forming and maintaining stream channel cross-sectional area and habitat in alluvial streams. Bankfull stage is the stage at which water starts to flow over the floodplain. Bankfull flow is subject to minimum flow resistance and transports the most sediment over time. Bankfull events have been determined to have a recurrence interval of approximately 1.5 to 3.0 years (Leopold et al. 1964), but in streams with sharp peak flows and accentuated low flows, the channel capacity may be more influenced by less frequent, greater magnitude events (Gregory and Walling 1973).

A Log-Pearson Type III distribution was fitted to 89 years of unimpaired flow data, each point represented the maximum flow for a particular year, expressed as the average flow during the month. The unimpaired flow with a 1.5 years return period is approximately 5,000 cfs for the San Joaquin River at Millerton, increasing to 19,000 cfs for the San Joaquin River near Vernalis. These values are used as the default channel capacities for the San Joaquin River from Mendota to the Merced River, and from the Merced River to Vernalis, respectively.

Wetted-area flow relationships were determined from a one-dimensional steady-state flow analysis performed using HEC-RAS. Elevations for the San Joaquin Valley were taken from a topographic map published by Hall (1887).

Tulare Lake Basin

Under natural conditions, there was periodic exchange of surface water between the Tulare Lake and San Joaquin River hydrologic regions. Surface water was generally believed to flow from south to north from the Kings River fan through Fresno Slough and other smaller channels (DPW, 1931b). The Kings River fan in the east and the Los Gatos Creek fan to the west create a natural ridge which separates the majority of the Tulare Lake Hydrologic Region from the northern section. The elevation difference between the low point on this ridge and the San Joaquin River at Mendota is approximately 30 feet. Under natural conditions, except in very wet years, the ridge would have separated surface waters in the San Joaquin River and Tulare Lake hydrologic regions.

Similarly, a groundwater ridge would have divided most of the Tulare Lake Hydrologic Region from the San Joaquin River Hydrologic Region, maintained by recharge from the Kings and Kaweah rivers as they enter the floor of the valley. Except in very wet years, groundwater elevations would have sloped from these rivers northwards to the San Joaquin River and southwards to what was known as “Tache Lake”.

Historical accounts record that in exceptional wet years, such as 1862, Tache Lake spilled over the ridge, described above, and drained northwards through Fresno Slough to the San Joaquin River. The following description from the *Report of the Commissioner of Public Works to the Governor of California*, dated 1895, supports the assumption that flow from the Tulare Lake Hydrologic River into the San Joaquin River occurred infrequently:

> *Precipitation of moisture is so light throughout the southern portions of the Sierra Nevada Mountains, the upper parts of the San Joaquin Valley, and the eastern slope of the Coast Range, that the years in which more water has reached this part of the valley than is required to replace the amount annually evaporating from the surface of the San Joaquin Valley lakes have been rare. The entire drainage basin above Tulare Lake, including a part of the flow of Kings River, therefore becomes tributary to San Joaquin River only at long intervals. This can be best illustrated by a brief history of the fluctuations of the Tulare Lake water surface.*
>
> *After several wet winters preceding 1853 the lake was found full, though possibly not quite as high as in 1862 or in 1868.*
>
> *From 1853 until 1861 the low-water plane of the lake receded – at what rate each year cannot now be determined; but in 1861 the water surface was as low as 204 feet, if the testimony of some of the residents at the lake at that time, in reference to the rise of water the following winter, can be relied upon. The heavy rainfall of 1861 to 1862 caused the water surface of the lake to rise to the highest stage at which it has been known – 220 feet above low tide in Suisun Bay. Its area was increased from 300 to nearly 800 square miles. Its content were increased by 300,000,000,000 cubic feet [6.8 MAF] of water during this one winter.*

Model Representation

The Tulare Lake Hydrologic Region is not represented in the NatFM, except for a single surface inflow arc to the Mendota Pool (UI_JBP006). This inflow represents unimpaired flood flows from the James Bypass to the Mendota Pool originating from the Kings River. The source of this inflow is *California Central Valley Unimpaired Flow Data, Draft, Fifth Edition*, (DWR, 2012a). In very wet years, these unimpaired flow estimates may considerable underestimate the volume of water that would have spilled from the Tulare Lake Hydrologic Region into the San Joaquin River under natural conditions.

Chapter 4
Model Results

This chapter briefly describes NatFM results for the four geographical regions: Sacramento Valley, San Joaquin Valley, Eastside Streams, and Delta. Model results are compared to DWR unimpaired flows (DWR, 2012a). Groundwater results also are discussed. Model results are sensitive to many input parameters. Estimates of channel capacities under natural flows and the drainage characteristics of low-lying flood basins significantly affect simulated river flows. Model results presented in this chapter are for a set of input parameters calibrated to achieve a long-term average annual net Delta outflow of 18.7 MAF. This value coincides with Case I, presented by Fox et al. (2014). Model results should be interpreted as a plausible representation of flows under natural conditions, and not the exact flows that would have occurred. There remain many unknown factors that significantly influence model results.

Sacramento Valley Inflow to Delta

Unimpaired inflows from the rim watersheds to the floor of the Sacramento Valley, as computed for the NatFM, average **20.0 MAF/year** (see worksheet *Results Summary and Checks*). Precipitation over the valley floor contributes an additional **8.5 MAF/year**. ET from vegetation on the valley floor averages **11.0 MAF/year**.

For the calibrated input parameters, natural inflow to the Delta from the Sacramento Valley averages **16.0 MAF/year**. Rainfall-runoff on the valley floor, including accretions from small watersheds upslope from the alluvial aquifer, averages **1.5 MAF/year**. Groundwater inflow to the Sacramento Valley rivers and streams is negligible, as potential inflow is depleted by ET from riparian vegetation. Riparian vegetation depletes the stream flow by an average of **0.6 MAF/year**.

For the calibrated channel capacities, overbank spills average **15.7 MAF/year**. The calibrated channel capacities are significantly lower than the initial estimated values based on bank-full capacities; channel capacities were reduced to 40 percent of their initial estimated values to achieve sufficient flooding and subsequent groundwater recharge to support vegetative ET during the summer and early fall.[19] The reason for this apparent discrepancy may be the widespread occurrence of breaks in the natural levees (known as crevasses). Water poured through these break, flooding the adjacent lands.

[19] The need to lower channel capacities to match the expected Delta inflows suggest that either: (1) assumptions relating to vegetative ET or land use are incorrect, or (2) that some facet of natural conditions is not well represented in NatFM. DWR is currently developing a distributed integrated surface water groundwater model of natural conditions. Future planned comparisons of NatFM to the DWR distributed model may reveal aspects of NatFM that need additional calibration or improved representation.

Flood flows recharge the root zone and contribute to ET by an average of **5.3 MAF/year.** Groundwater recharge from flood waters averages **3.7 MAF/year.** The remaining portion of the flood water returns to the stream system and flows into the Delta.

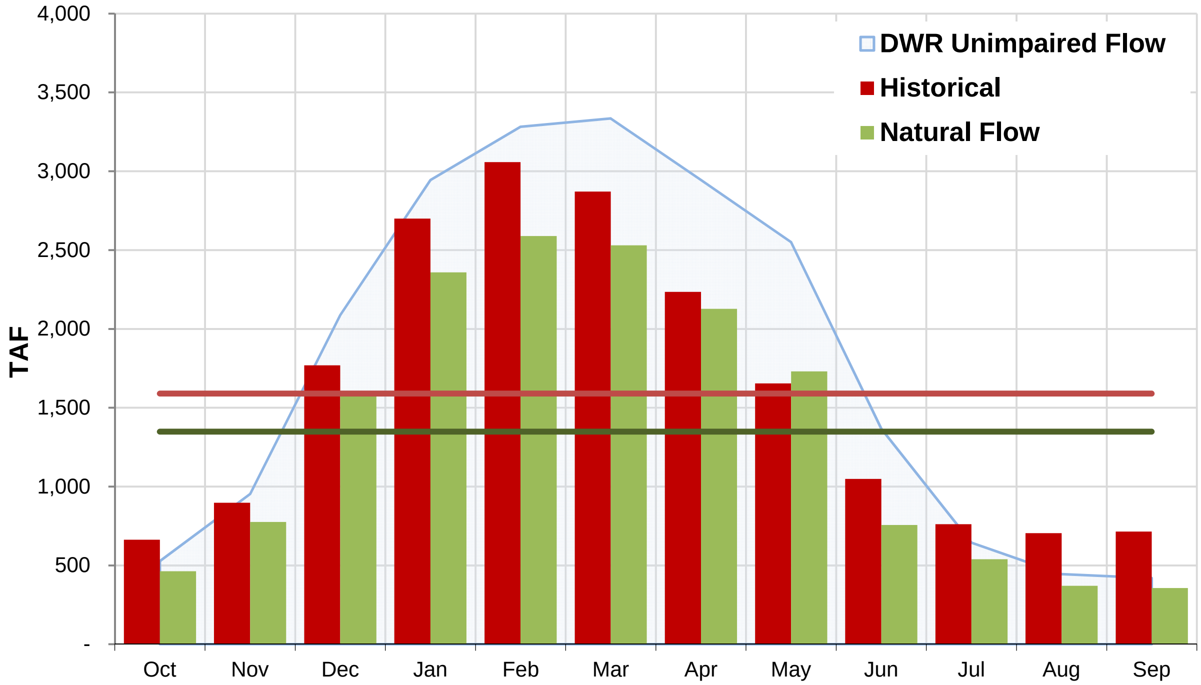

Figure 4-1. Sacramento Valley Average Monthly Inflow to Delta

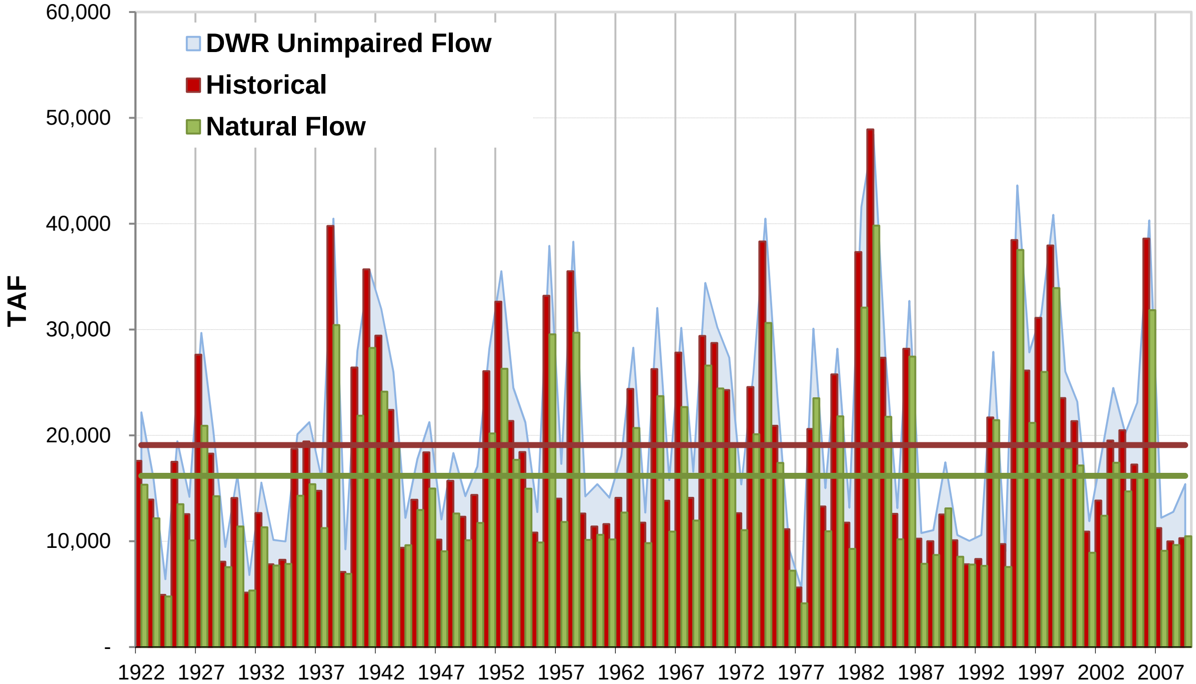

Figure 4-2. Sacramento Valley Average Annual Inflow to Delta

San Joaquin Valley Inflow to Delta

Unimpaired inflows from the rim watersheds to the San Joaquin Valley, as computed for the NatFM, average **6.2 MAF/year** (see worksheet *Results Summary and Checks*). Precipitation over the valley floor adds an additional **2.4 MAF/year**. ET from vegetation on the valley floor averages **5.0 MAF/year**.

The relatively low natural bank-full capacity of the San Joaquin River and the almost annual cycle of flooding dramatically attenuates the monthly peak of the annual hydrograph. For the calibrated channel capacities, overbank spills average **3.9 MAF/year**. For the calibrated input parameters, the average annual San Joaquin River flow near Vernalis is **3.7 MAF/year**. Rainfall-runoff on the valley floor, including accretions from small watersheds upslope from the alluvial aquifer, averages **0.1 MAF/year**. Groundwater inflow to the San Joaquin River is negligible, as potential inflow is depleted by ET from riparian vegetation. Riparian vegetation depletes the stream flow by an average of **0.2 MAF/year**.

For the calibrated channel capacities, overbank spills average **3.0 MAF/year**. This calibrated value is significantly higher than the initial value; channel capacities were reduced to 40 percent of their initial estimated values to achieve sufficient flooding and subsequent groundwater recharge to support vegetative ET during the summer and early fall. [20] Flood flows recharge the root zone and contribute to ET by an average of **1.0 MAF/year.** Groundwater recharge from flood waters averages **1.5 MAF/year.** The remaining portion of the flood water returns to the stream system and flows into the Delta.

[20] The need to lower channel capacities to match the expected Delta inflows suggest that either: (1) assumptions relating to vegetative ET or land use are incorrect, or (2) that some facet of natural conditions is not well represented in NatFM. DWR is currently developing a distributed integrated surface water groundwater model of natural conditions. Future planned comparisons of NatFM to the DWR distributed model may reveal aspects of NatFM that need additional calibration or improved representation.

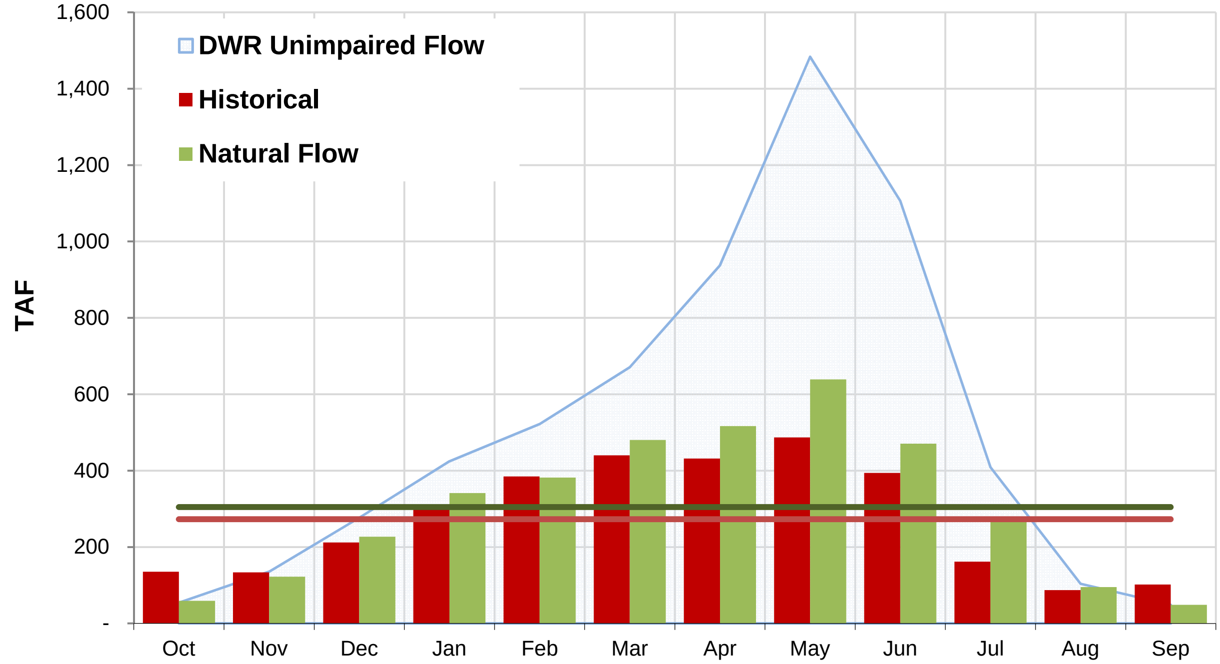

Figure 4-3. San Joaquin Valley Average Monthly Inflow to Delta

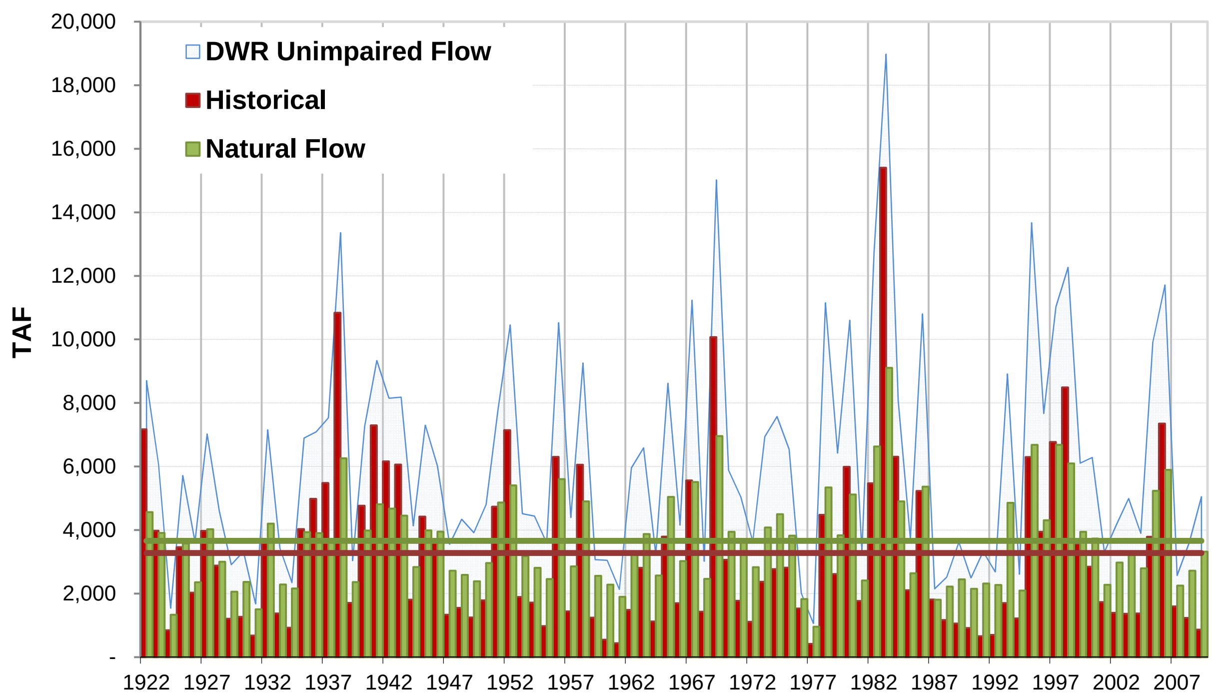

Figure 4-4. San Joaquin Valley Annual Inflow to Delta

Eastside Streams Inflow to Delta

For the NatFM, the principal components of the Eastside Streams are the Cosumnes, Mokelumne,[21] and Calaveras[22] rivers. Unimpaired inflows from the rim watersheds for these three streams averages **1.2 MAF/year** (Cosumnes River at Michigan Bar, Mokelumne River at Mokelumne Hill, and Calaveras River at New Hogan Dam). This represents approximately 86 percent of the total inflow of **1.5 MAF/year**. Precipitation over the valley floor part of the Eastside Streams adds an additional **1.4 MAF/year** (see worksheet *Results Summary and Checks*).

For the calibrated input parameters, the average annual flow from the Eastside Streams to the Delta is **1.1 MAF/year**. Groundwater inflow to the streams is negligible, as potential inflow is depleted by ET from riparian vegetation. Riparian vegetation depletes the stream flow by an average of **0.1 MAF/year**. Flood flows recharge the root zone and contribute to ET by an average of **0.2 MAF/year.** Groundwater recharge from flood waters averages **0.1 MAF/year.**

[21] The lower Mokelumne River stretches approximately 34 miles from Camanche Dam to its confluence with the San Joaquin River in the Delta. The Delta boundary crosses the Mokelumne River at River Mile [RM] 25, approximately 3 miles upstream from the mouth of the Cosumnes River and 2 miles upstream from the mouth of Dry Creek. Tidal influence extends to approximately 2.5 miles upstream from the Interstate 5 bridge near the town of Thornton (RM 18) and at times extends to the base of Lake Lodi (RM 34), a seasonally inundated reservoir at the town of Lodi (Merz and Setka, 2004)..

[22] The lower Calaveras River stretches approximately 43 miles from New Hogan Dam to its junction with the San Joaquin River. The Delta boundary crosses the Calaveras River at RM 4.

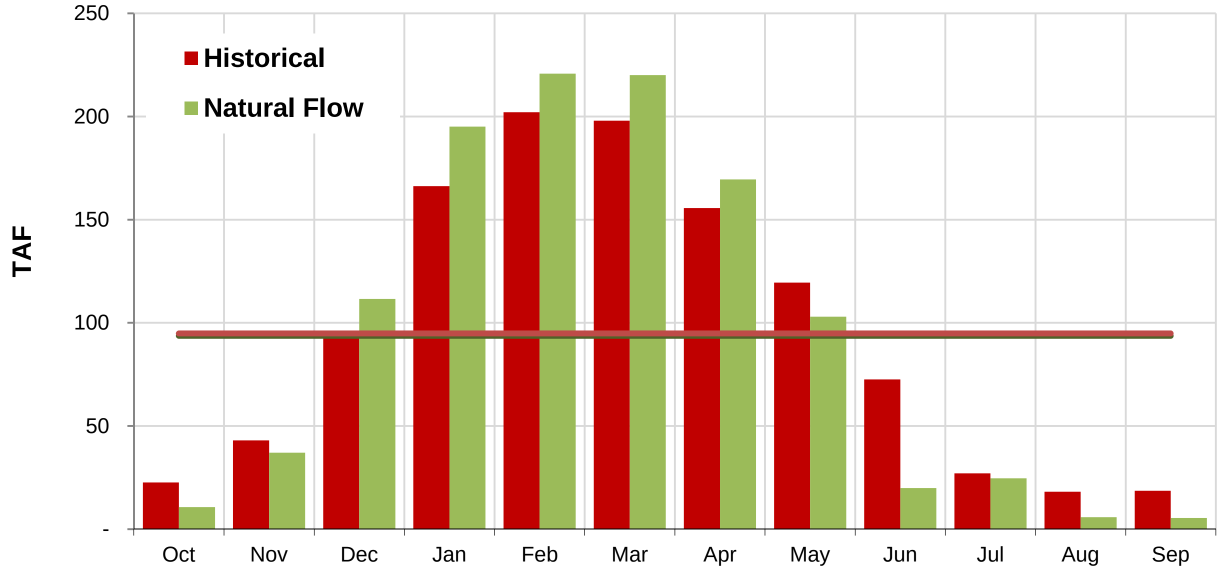

Figure 4-5. Eastside Streams Average Monthly Inflow to Delta

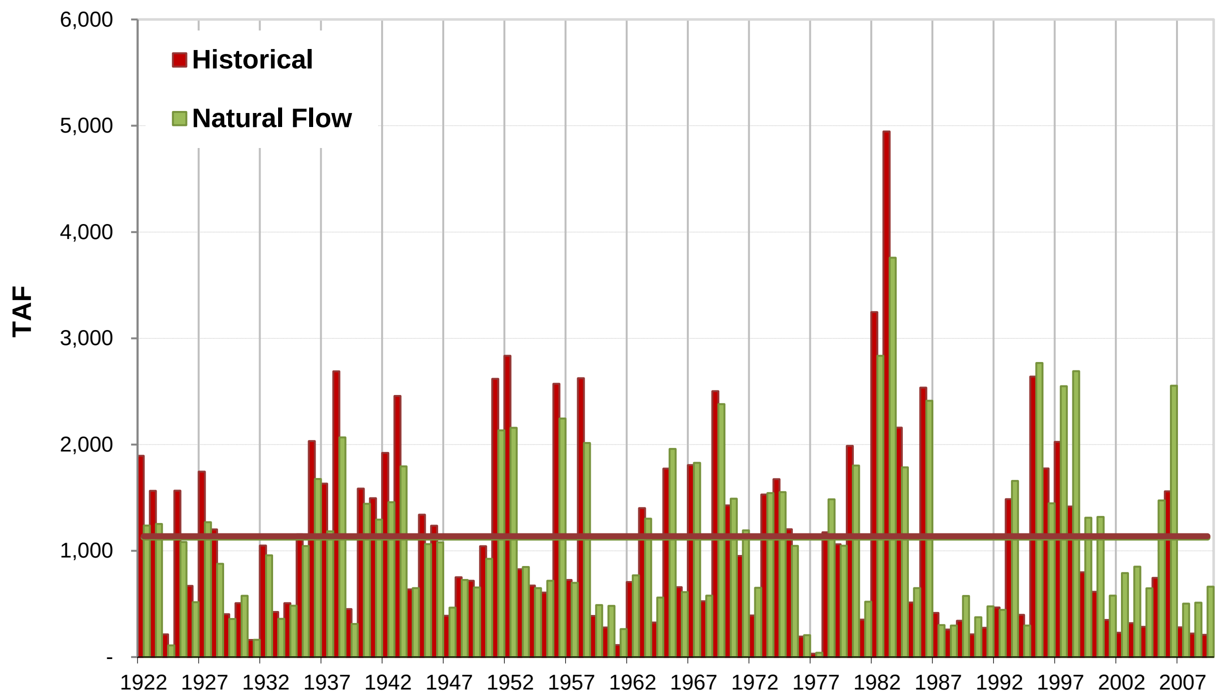

Figure 4-6. Eastside Streams Annual Inflow to Delta

Sacramento-San Joaquin Delta Channel Depletions

The NatFM calculates in-Delta effects on net Delta outflow using a simple volumetric balance between precipitation and consumptive use of water through soil moisture storage and ET. Within the Delta, flooding is not represented; groundwater is not modeled. The NatFM assumes that actual Delta ET equals potential ET as groundwater elevations are sufficiently high to support groundwater uptake by surface vegetation. The average annual precipitation over 679,699 acres is approximately 15.0 inches, equivalent to **0.9 MAF/year**. Average annual losses through ET are 51.7 inches, equivalent to **3.0 MAF/year**. The net Delta depletion, i.e. ET – precipitation, averages **2.1 MAF/year**.

As previously discussed, the storage characteristics of the Yolo and Sacramento basins is not modeled in the NatFM. However, storage of flood water in these basins may have had a significant affect on the timing of Delta inflows at a monthly time scale. It is recommended that the hydrodynamics of these basins under natural conditions is further investigated in future refinements of natural flow estimates.

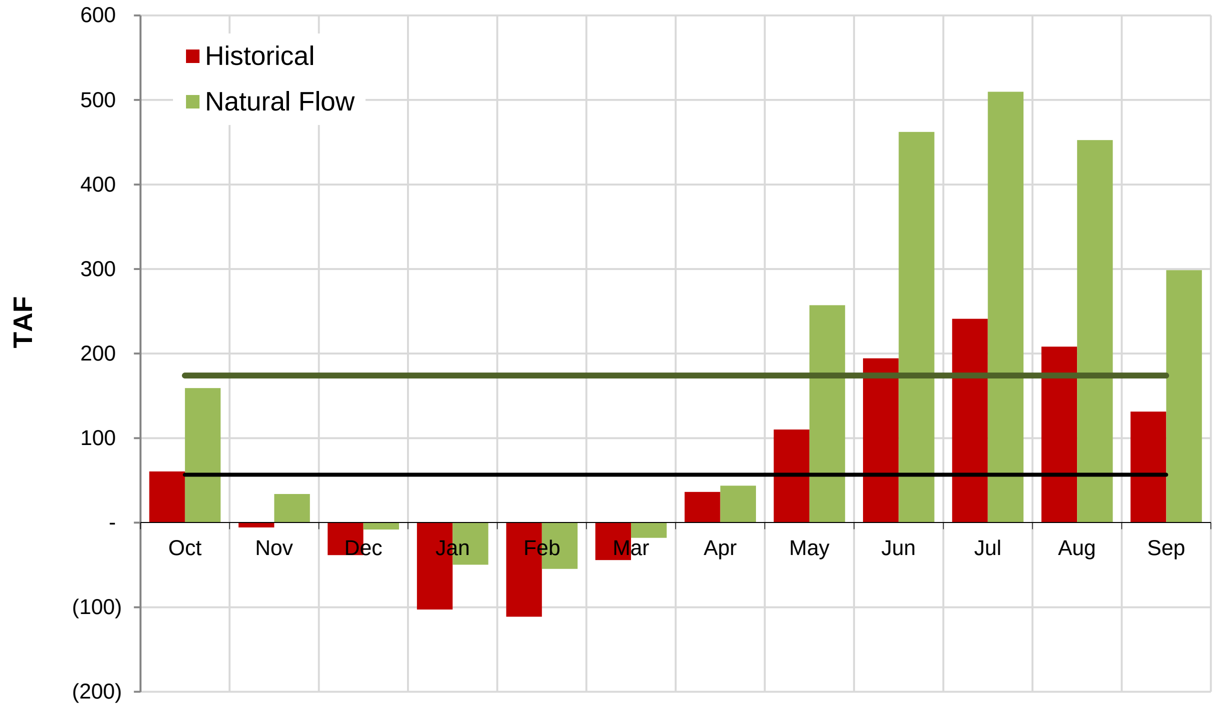

Figure 4-7. Average Monthly Net Delta Depletion

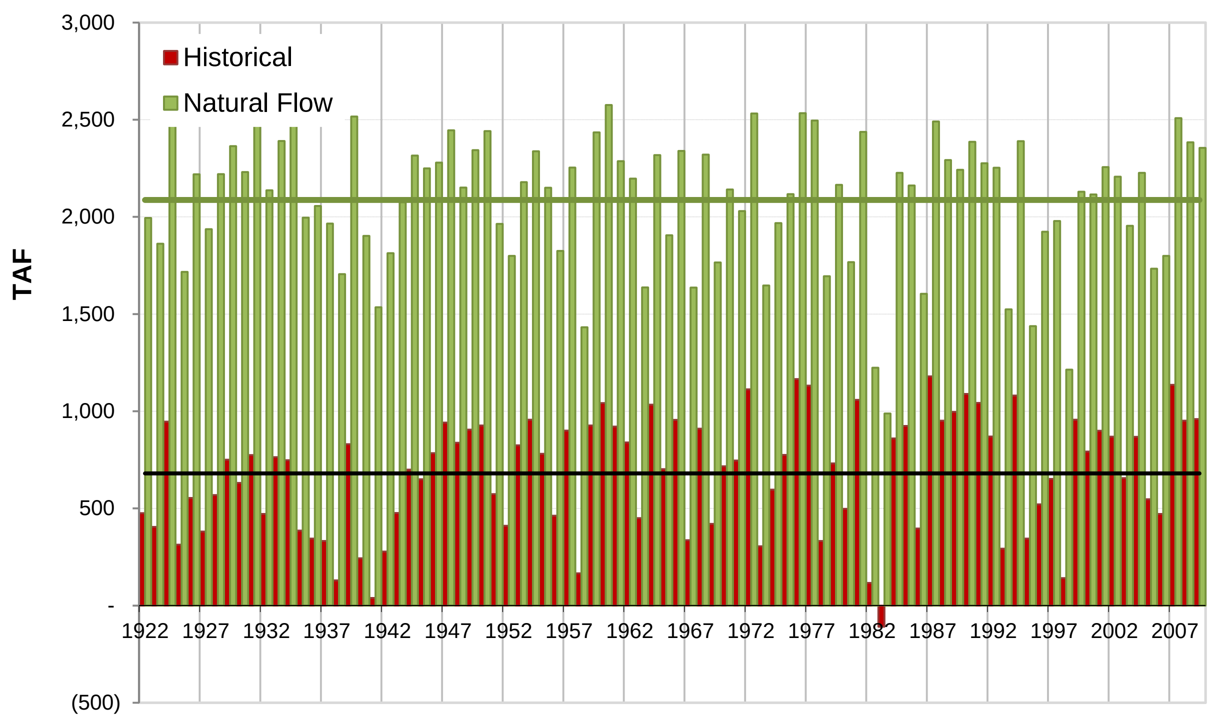

Figure 4-8. Annual Net Delta Depletion

Net Delta Outflow

Figures 4-9 and 4-10 compare the net Delta outflow as calculated by the NatFM compared to historical and unimpaired flows. The NatFM shows very low positive values for August and September. These are caused by the combination of low river flows and high Delta depletions in these months.

The seasonal pattern of net Delta outflow has changed significantly from the natural condition. The earliest flow measurements of rivers flows were made by Hall (1886).[23] Figure 4-11 compares the monthly pattern of net Delta outflow from NatFM with average monthly recorded flows for the Sacramento River at Collinsville from 1879 through 1885. These early estimates of Delta outflow may not be reliable. Additionally, by the 1880s, seasonal flow patterns had been significantly changed by the removal of natural vegetation, early flood control measures and the partial elimination of the natural flood basin storage, and the introduction of irrigated agriculture.

[23] William Hammond Hall served as California's first State Engineer from 1878 to 1889. During those years, Hall surveyed and undertook studies to improve navigation and drainage on the Sacramento and San Joaquin rivers, determine the effects of hydraulic mining, and assess the irrigation needs of the Central Valley. His survey team, working from boats, gauged and sounded large portions of the Sacramento, Feather, and American rivers. They installed an extensive system of permanent river gauging stations. Irrigation acreages and practices were recorded. Their efforts were summarized in five progress reports to the Legislature from 1878-1882. Hall's examinations still serve as the most extensive study of California's water systems to date, the scale of which, considering the fiscal situation of California's state government, is likely never to be matched (OAC, 2014).

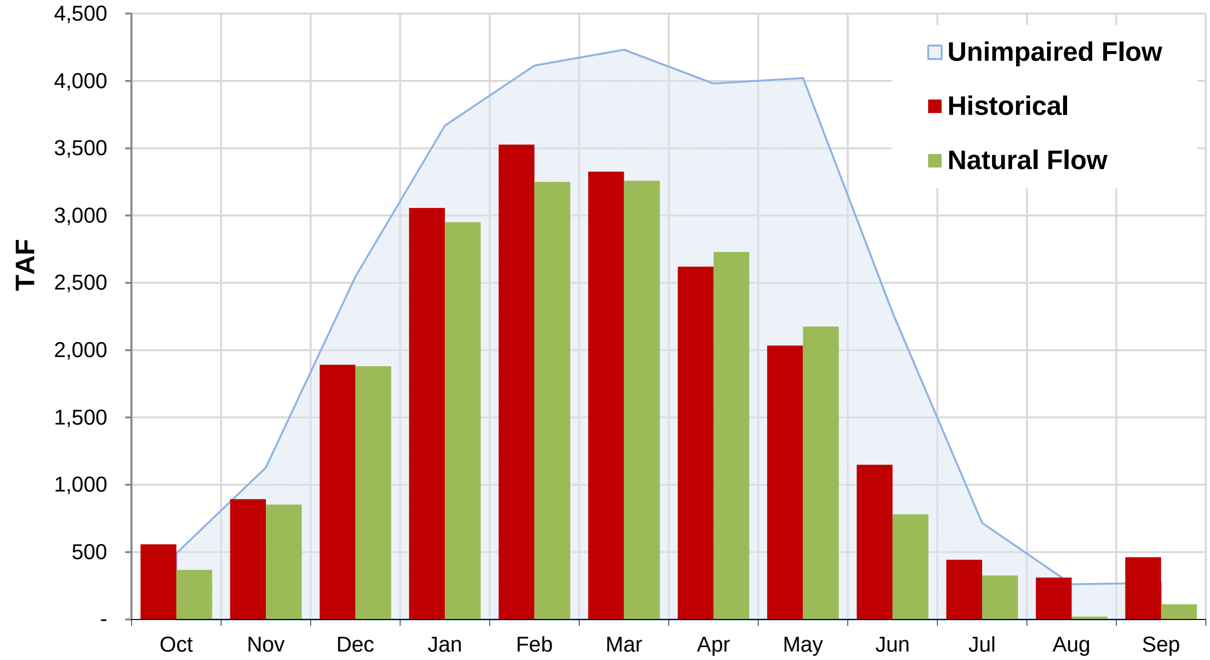

Figure 4-9. Average Monthly Net Delta Outflow

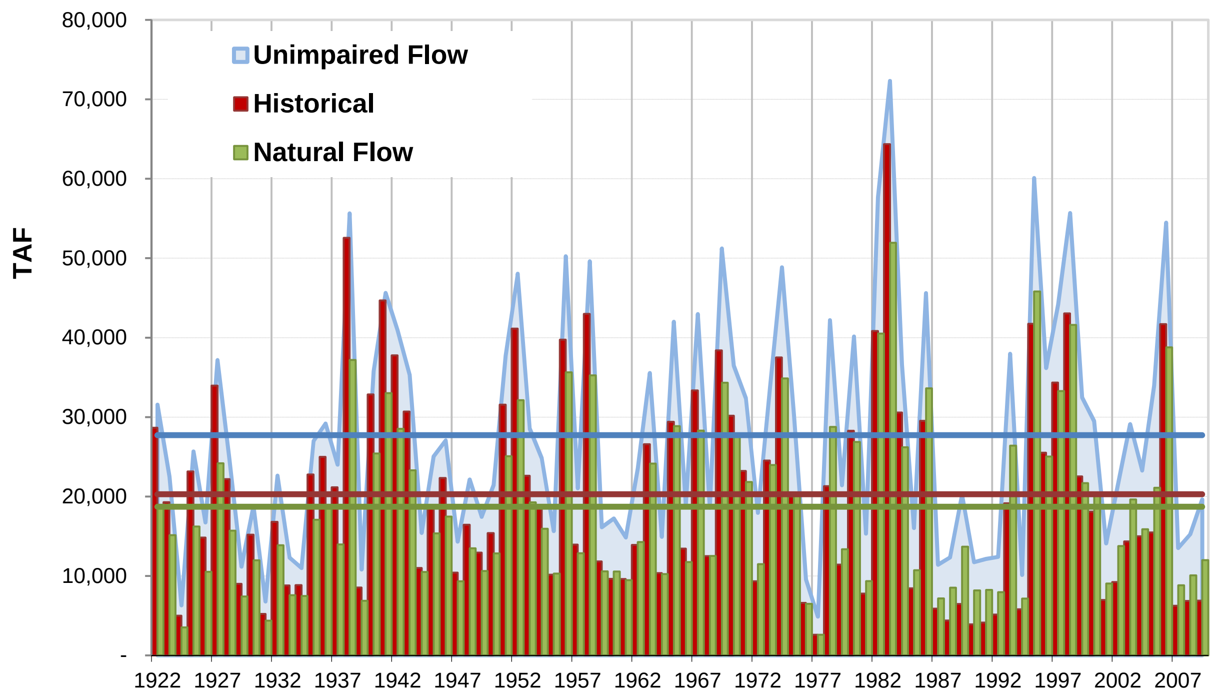

Figure 4-10. Annual Net Delta Outflow

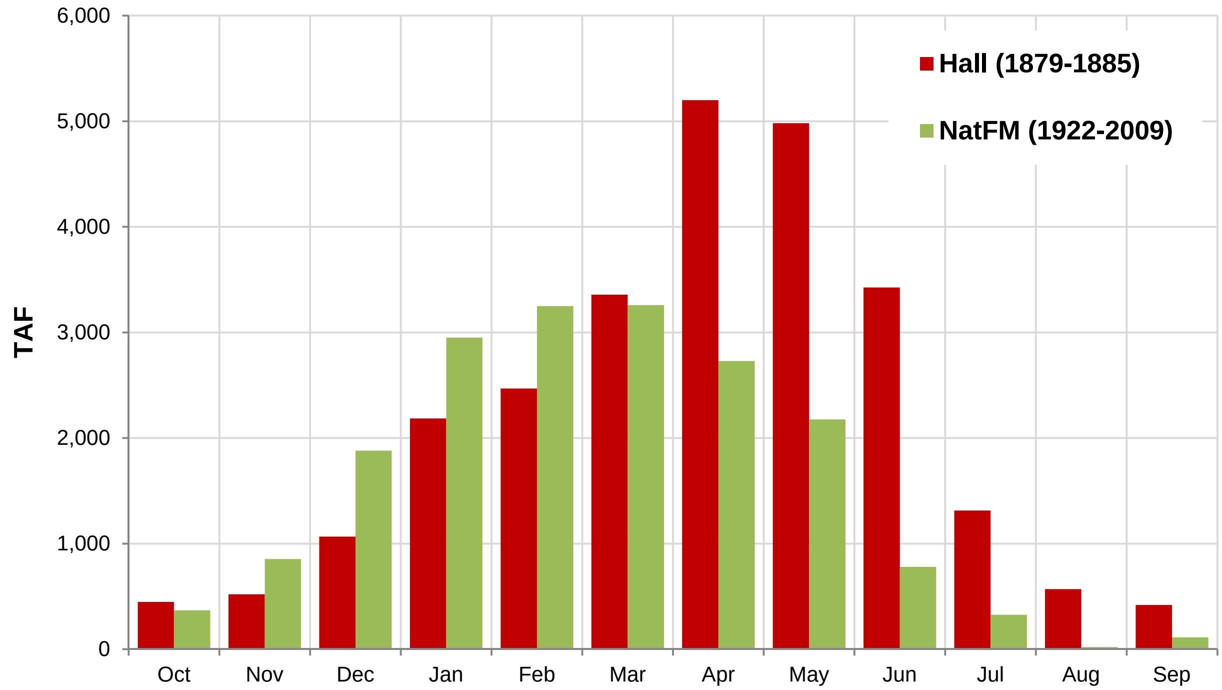

Figure 4-11. Average Monthly Net Delta Outflow

Existing Level of Development Flows

DWR and Reclamation have jointly developed a simulation model for performing planning studies related to CVP and SWP operations. The primary purpose of the model, known as CalSim II, is to evaluate the water supply reliability of the CVP and SWP at current or future levels of development (e.g., 2005, 2030), with and without various assumed future facilities, and with different modes of facility operations. Geographically, the model covers the drainage basin of the Delta (i.e., the Sacramento and San Joaquin valleys), CVP and SWP deliveries to the Tulare Basin, and SWP deliveries to the San Francisco Bay Area (Bay Area), Central Coast, and Southern California. River flows and associated water management facilities are simulated using a monthly time step. Land use, water infrastructure, water supply contracts, and regulatory requirements are held constant over the period of simulation, representing a fixed level of development. The historical flow record from October 1921 through September 2003, adjusted for the influence of land-use changes and upstream flow regulation, is used to represent the possible range of water supply conditions at the given level of development.

DWR has published CalSim II model results for an existing level of development (DWR, 2012b). Figures 4-12 through 4-21 compare simulated CalSim II results to reulst from NatFM for the same period (i.e., water years 1922–2003). The avergage annual net Delta outflow for existing conditions is **15.8 MAF**, compared to **18.7 MAF** for natural conditions.

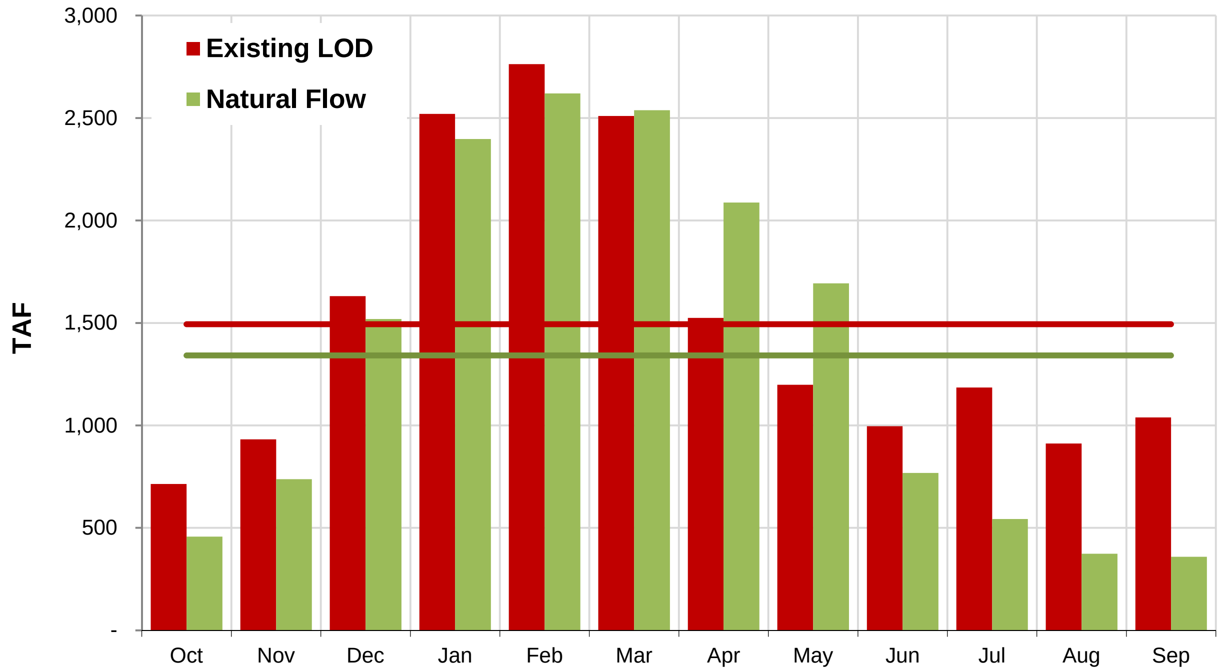

Figure 4-12. Sacramento Valley Average Monthly Inflow to Delta

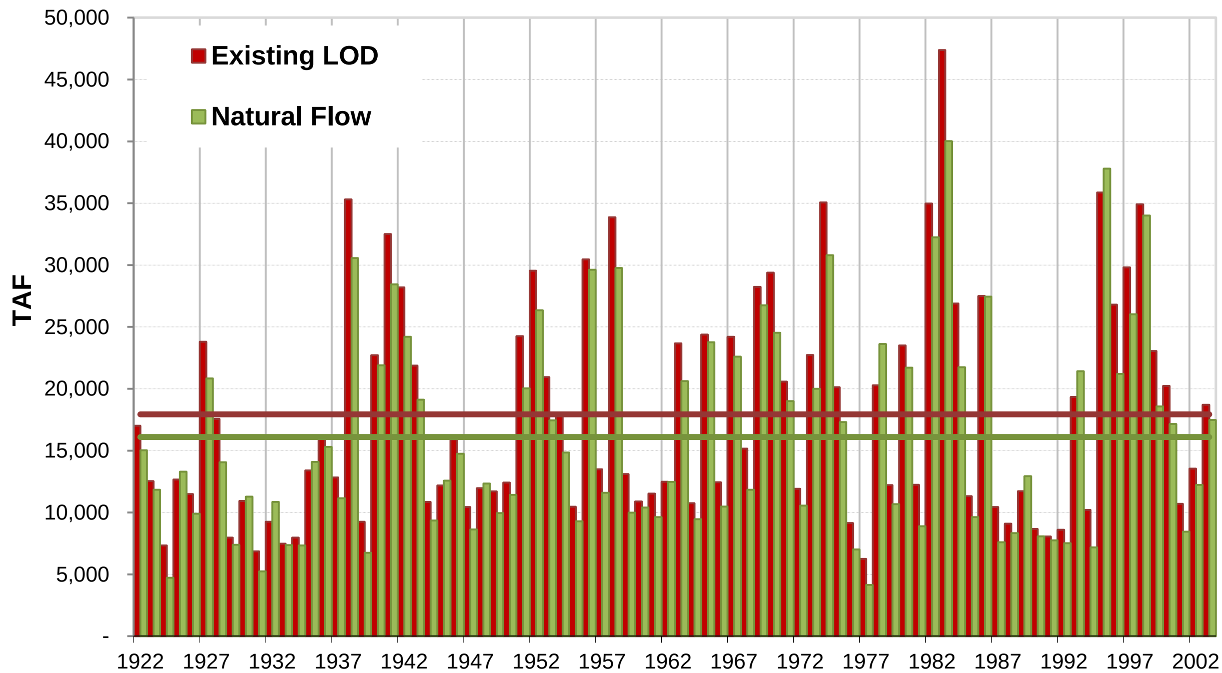

Figure 4-13. Sacramento Valley Average Annual Inflow to Delta

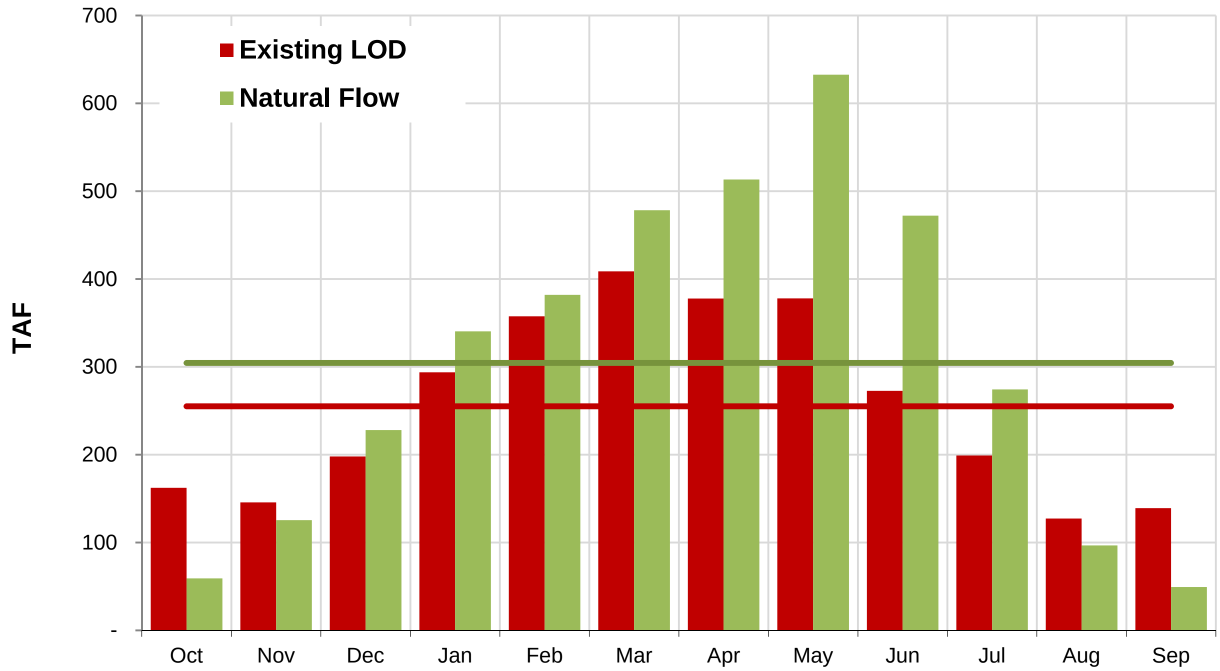

Figure 4-14. San Joaquin Valley Average Monthly Inflow to Delta

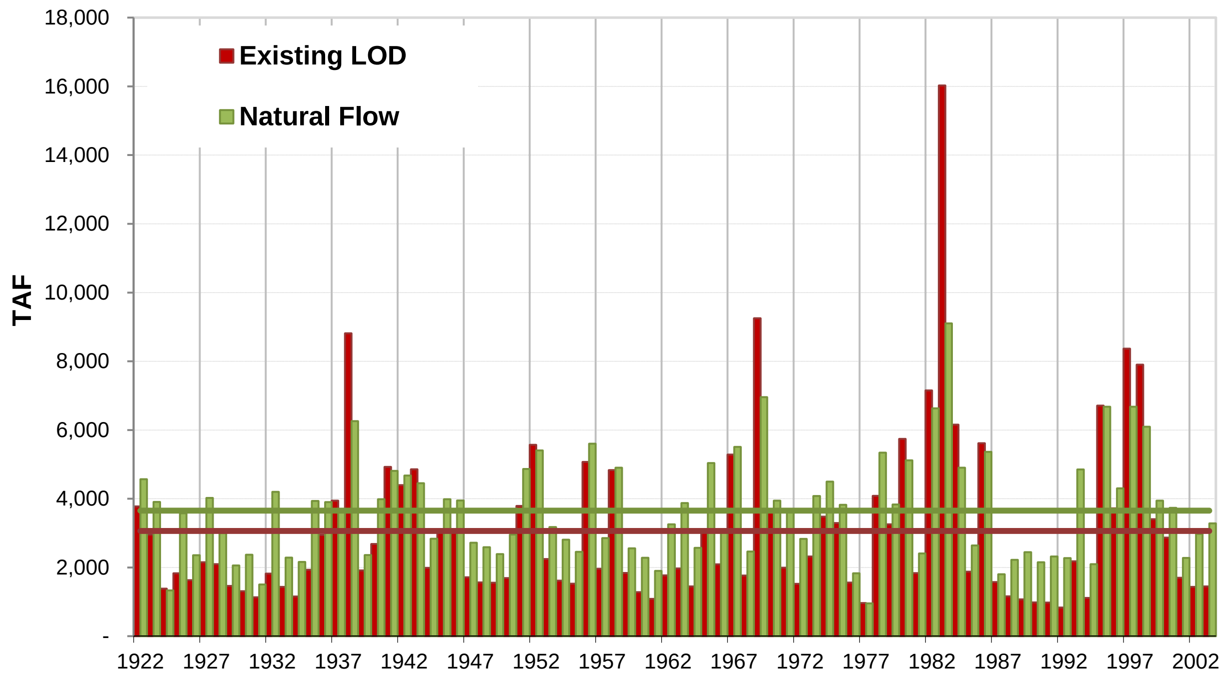

Figure 4-15. San Joaquin Valley Annual Inflow to Delta

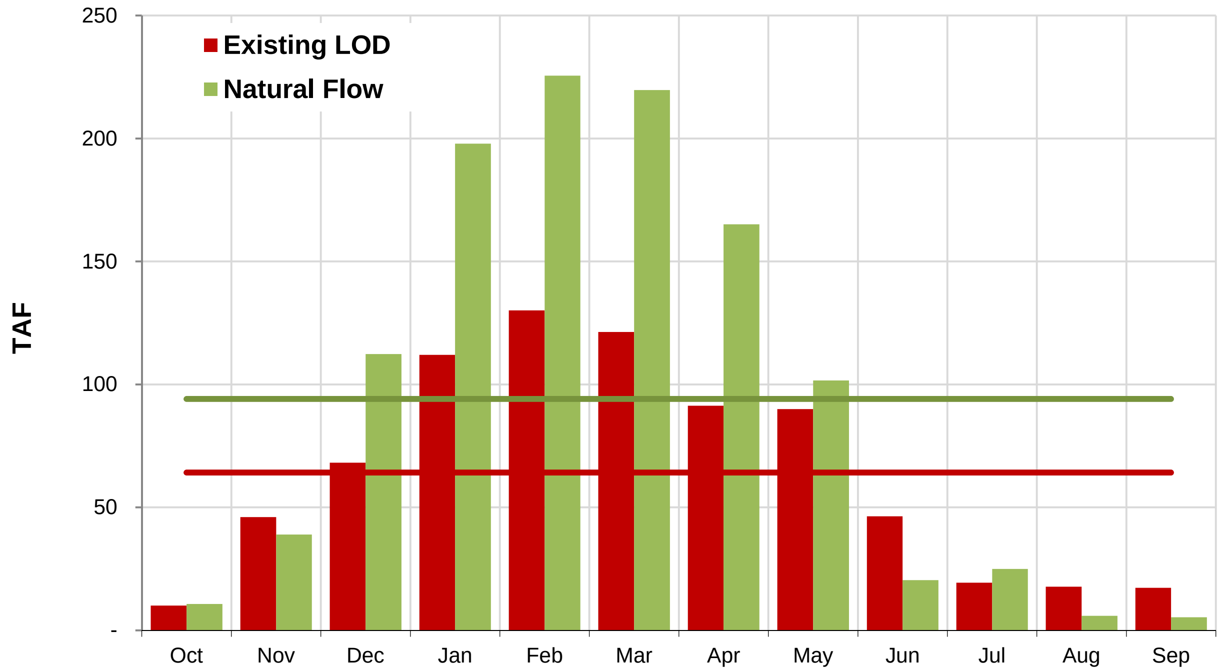

Figure 4-16. Eastside Streams Average Monthly Inflow to Delta

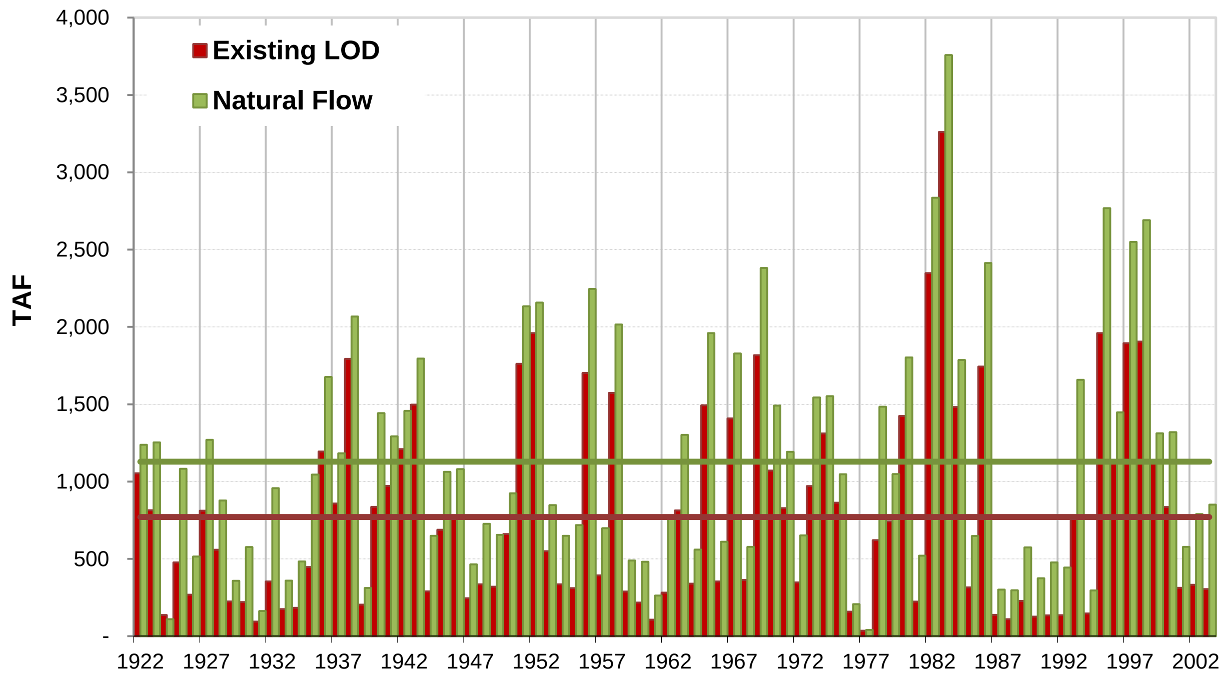

Figure 4-17. Eastside Streams Annual Inflow to Delta

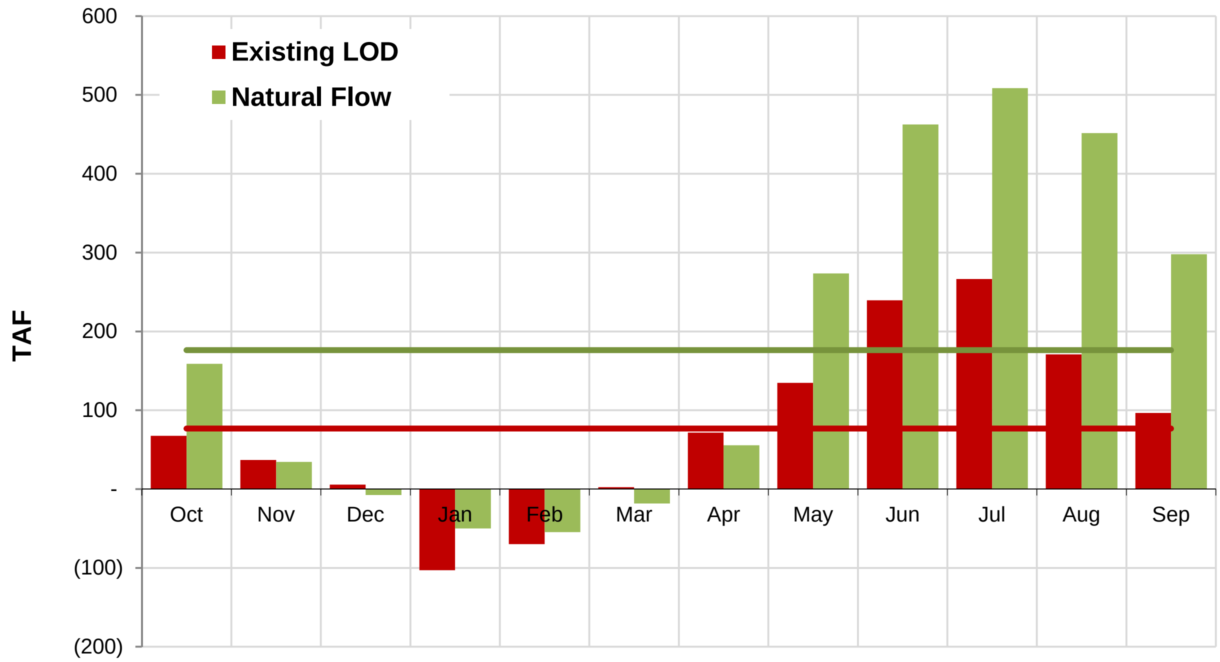

Figure 4-18. Average Monthly Net Delta Depletion

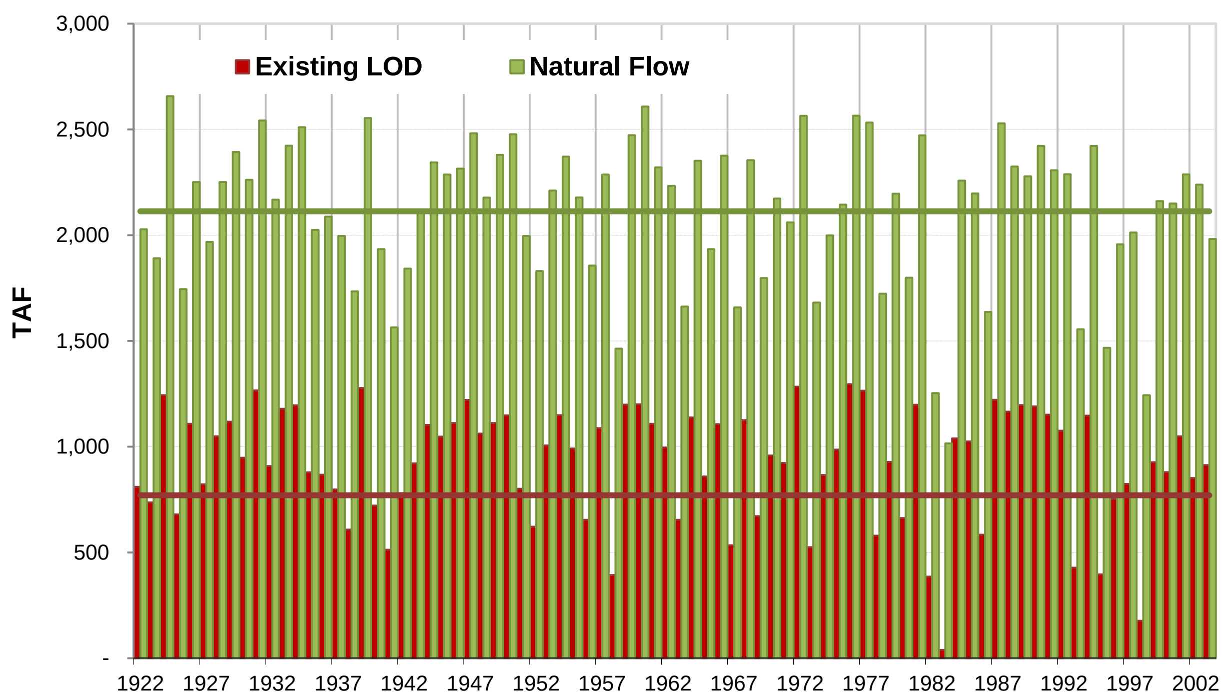

Figure 4-19. Annual Net Delta Depletion

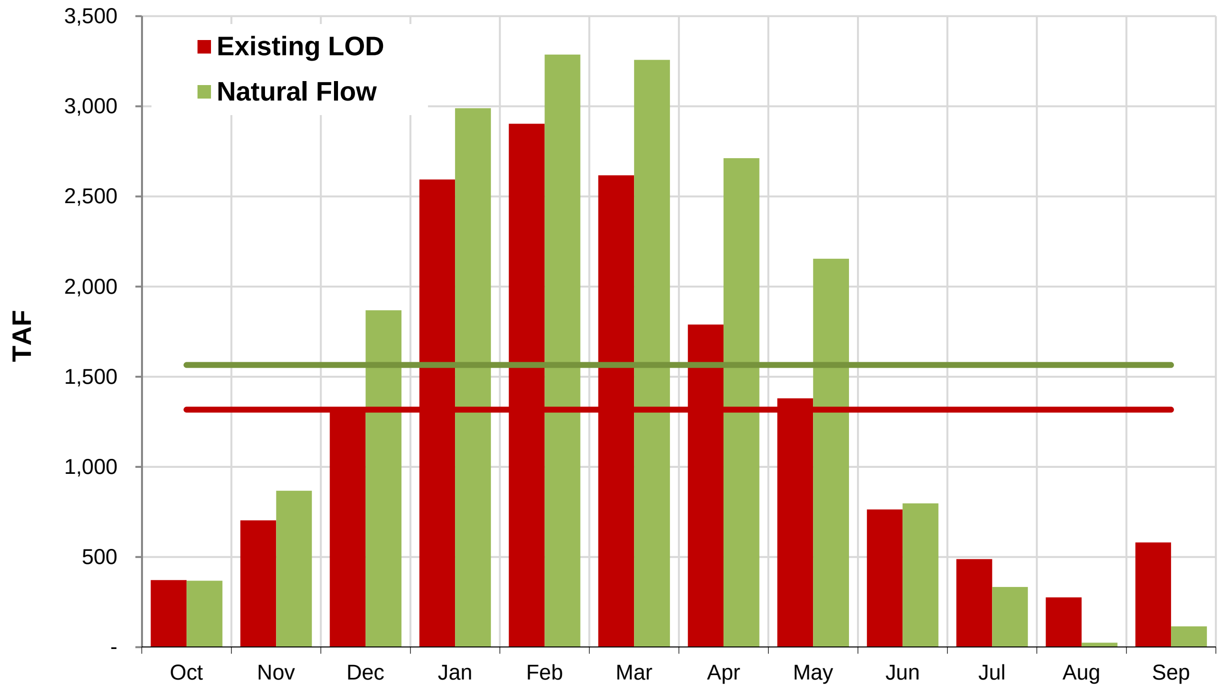

Figure 4-20. Average Monthly Net Delta Outflow

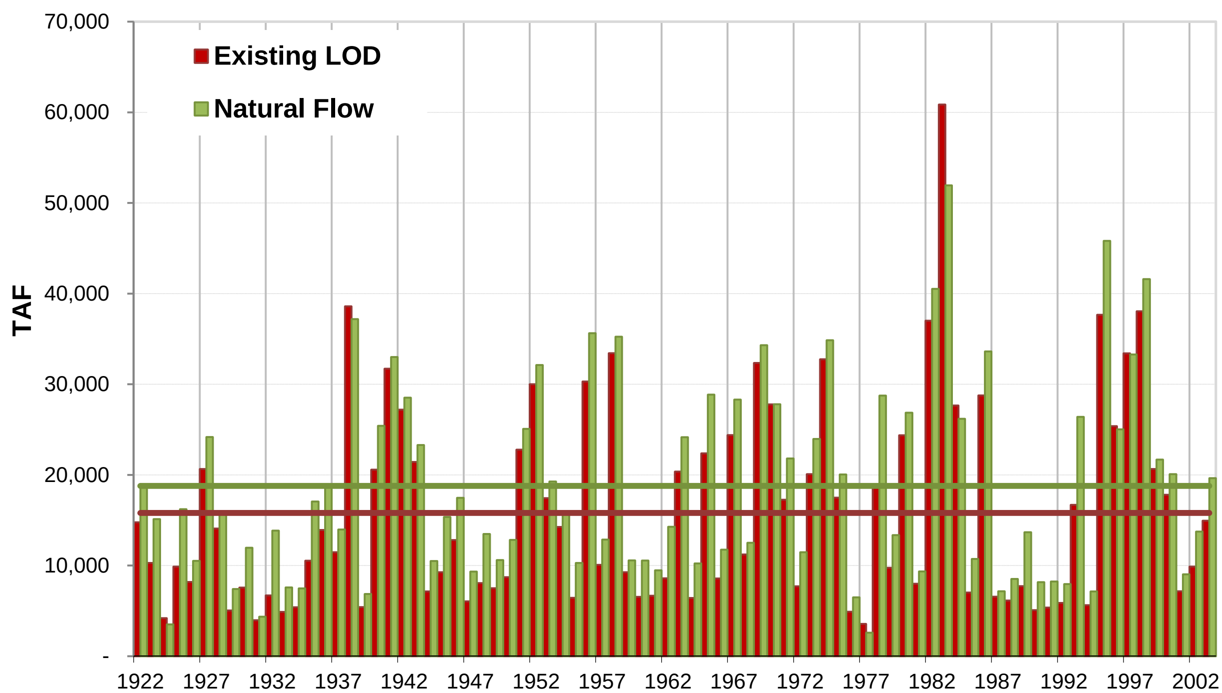

Figure 4-21. Annual Net Delta Outflow

Sensitivity Analysis

NatFM was originally envisaged as a spreadsheet accounting model of flows under natural conditions. Many simplifying assumptions were made about the nature of the seasonal cycle of overbank flows and detention storage, and the interaction between surface water and groundwater. The object was to create a simple parsimonious model that could capture the essence of the natural hydrology and have a great deal of explanatory power.

During the model development it became necessary to introduce additional model parameters to simulate aspects of groundwater uptake by surface vegetation and discharge to the river, which are not well represented by a lumped parameter formulation. Increasing the number of model parameters increases model complexity and partially detracts from the models ability to tell a simple story. Therefore, a sensitivity analysis was undertaken to validate the model and to identify key model determinants of Delta outflow. The following parameters were adjusted in the sensitivity analysis:

- Sacramento River and Feather River channel capacities
- San Joaquin River channel capacity
- Detention basin discharge coefficients
- Soil infiltration rate
- Groundwater saturated horizontal conductivity
- Vegetation ET
- Soil Conservation Service Curve Number
- Flooded Area for a given detention storage

The results of the sensitivity analysis are shown in **Figure 4-22.** The x-axis shows the percent change in the selected model parameters. The y-axis shows the the net Delta outflow. Changing a single parameter in the sensitivity analysis sometimes resulted in unstable groundwater conditions and either continually rising or falling groundwater storage during the period of simulation. Stabilizing groundwater would require adjustment of other model parameters. This was not done.

The results of the sensitivity analysis are indicative only. Many parameters are interdependent, so that changing the value of one parameter (e.g., maximum soil infiltration rate) will make net Delta outflow more sensitivitive to changes in other parameters (e.g., channel capacity).

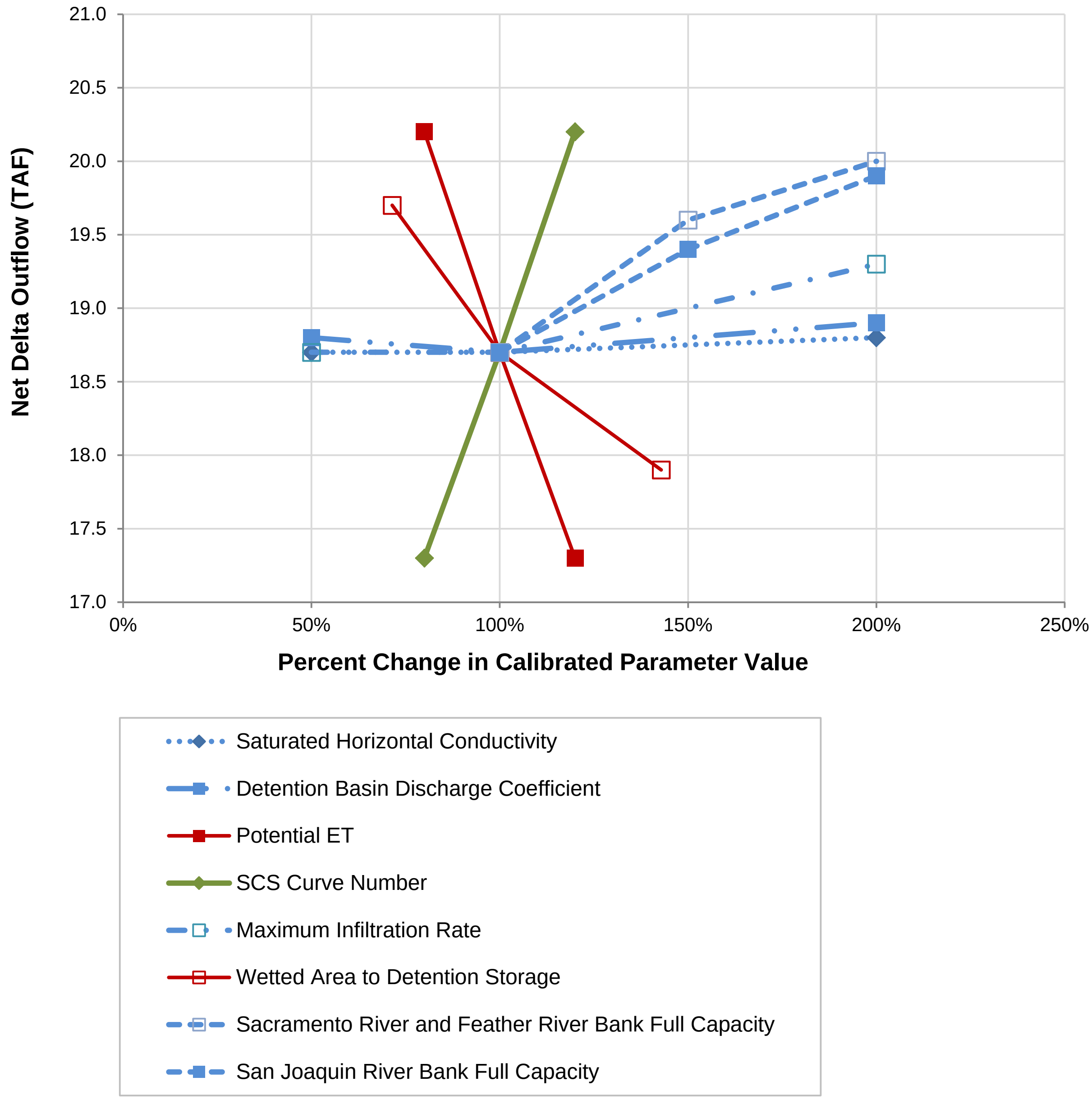

Figure 4-22. Sensitivity Analysis for Net Delta Outflow

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Chapter 5
Model Worksheets

This chapter describes each of the NatFM worksheets. The worksheets are described as they are contained in the workbook, from left to right. It is intended that these descriptions be read in conjunction with the NatFM. The NatFM is best viewed on a large external monitor. Because of its size, the NatFM may take several minutes to open and load into memory.

Worksheet 1: Version Control

The *Version Control* worksheet is for model documentation and version control purposes. Each worksheet in the workbook is listed and the purpose of the worksheet briefly stated. All file revisions are noted and dated. Any additional required file revisions also are noted. The worksheets can be categorized as follows:

- Worksheets 2-3: User defined inputs and sensitivity analysis.
- Worksheets 4: Summary table of average annual flows and mass balance checks.
- Worksheets 5-11: Summary charts of natural flows by geographical region and by type.
- Worksheets 12-15: Node-arc schematics for the Sacramento, San Joaquin, Eastside Streams, and Delta comparing historical and natural flows.
- Worksheets 16-30: Model inputs.
- Worksheet 31-32: Monthly and daily flow routing calculations based on mass balance.
- Worksheets 33-52: Calculation of monthly ET for model regions for each land-use class depending on water availability.
- Worksheets 53-69: Calculation of groundwater storage and stream-groundwater interaction.
- Worksheets 70-76: Model notes.

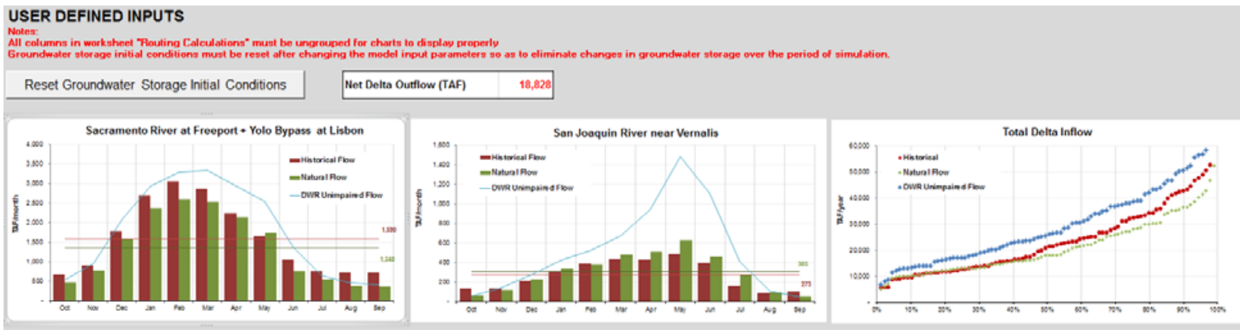
Worksheet 2: User Defined Input Assumptions

The worksheet *User Defined Input Assumptions* allows the user to change key input parameters. The worksheet consists of two parts: (1) charts that compare natural flows to historical and unimpaired flows; and (2) input parameters that affect the calculation of natural flows. Changing values of input parameters changes the natural flow data displayed in the charts. The following sections describe the various components of this worksheet.

Charts

The worksheet compares historical flows, natural flows, and DWR-computed unimpaired flows (DWR, 2012a). The comparison includes the following charts:

- Bar chart of average monthly inflows from the Sacramento Valley to the north Delta (sum of Sacramento River at Freeport and Yolo Bypass at the Lisbon Weir).
- Bar chart of average monthly inflows from the San Joaquin Valley to the south Delta (San Joaquin River near Vernalis).
- Exceedence plot of total Delta inflow.[24]



A box above the charts displays the long-term average annual net Delta outflow. This value is automatically updated as input parameters are changed.

Input Parameters

Input parameters that may be changed by the user include: channel capacity, detention storage characteristics, groundwater properties, vegetation coefficients for evapotranspiration (ET), vegetation rooting depths, and depression storage. These parameters are discussed in the sections below.

Initial Conditions for Groundwater Storage

The worksheet *User Defined Input Assumptions* contains a button (and associated macro) that determines the initial groundwater storage for each of the 15 groundwater basins so that there is no net change in storage over the period of simulation (1922–2009); end-of-month storage for September 1921 is set equal to end-of-month storage for October 2009.

[24] For the NatFM, total Delta inflow is the sum of Sacramento River at Freeport, Yolo Bypass at the Lisbon Weir, San Joaquin River near Vernalis, Eastside Streams (Cosumnes, Mokelumne, and Calaveras), Marsh Creek, and wastewater return flow from the Sacramento Regional Wastewater Treatment Plant.

The user should run the macro "Reset Groundwater Storage Initial Conditions" after making changes to parameter values on this worksheet. The macro may need to be run several times until the difference between beginning and ending groundwater storage is acceptable

Channel Capacity and Bank Overflow

Bank overflow is simulated for a limited number of river reaches of the Sacramento, Feather, and San Joaquin rivers. The overflow/spill locations include:

- Sacramento River between Ord Ferry and Knights Landing
- Sacramento River between Knights Landing and (the City of) Sacramento
- Feather River at Yuba City
- San Joaquin River from Mendota to Newman
- San Joaquin River from Newman to Vernalis

The volume of overbank flow is calculated as a constant fraction of the positive difference between the upstream river flow and the channel capacity. User-selected values for channel capacities (expressed as an average monthly flow in cubic feet per second [cfs]) are input in cells B40 to B45.[25] Parameter values entered in cells B48 to B54 control how much of the river flow in excess of its channel capacity spills over the left bank compared to the right bank. Typically, all flow in excess of the channel capacity is spilled. Default values are based on existing river channel capacity determined from a steady-state analysis for a river stage at the elevation of the outside levee toe. A multiplicative factor in cell H38 is used to scale the channel capacities during model calibration.

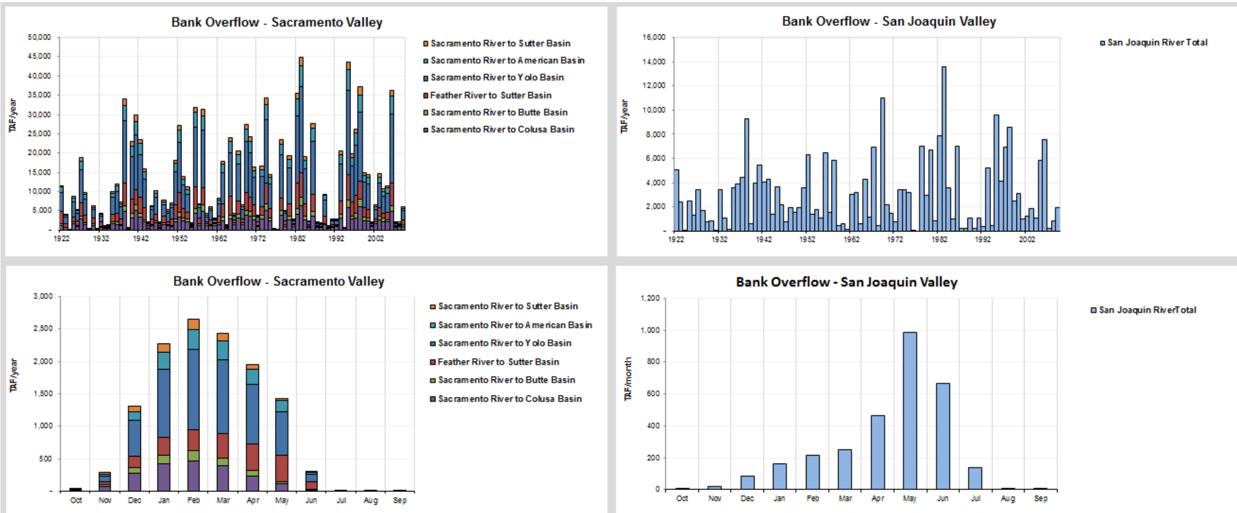
Channel Capacity - Bank Overflow

Channel	0.4 Channel Capacity (cfs)
Sacramento River channel capacity between Ord Ferry and Knights Landing	8,000
Sacramento River channel capacity between Knights Landing and Sacramento	20,000
Feather River channel capacity at Yuba City	8,000
San Joaquin River capacity between Mendota and Newman	2,000
San Joaquin River capacity between Newman and Vernalis	8,000
Yolo Bypass capacity - natural flood channel	0

Overbank Flow	Fraction of Total
Sacramento River to Colusa Basin	0.6
Sacramento River to Butte Basin	0.2
Sacramento River to Sutter Basin	0.2
Sacramento River to Yolo Basin	0.8
Sacramento River to American Basin	0.2
Feather River to Sutter Basin	0.7
Feather River to Left Bank	0.3

[25] For transparency, channel capacities are given defined names, which may be viewed in the Excel formula bar: SacCapacityOrdFerry, SacCapacitySacramento, FeatherCapacityYubaCity, ChannelCapacity_SanJoaquinRiver_MendotaToNewman, and ChannelCapacity_SanJoaquinRiver_NewmanToVernalis.

The worksheet *User Defined Input Assumptions* contains four charts of bank overflow/spills so that the user may appraise how changes to input parameters affect flooding. The charts present overbank flows for the Sacramento and San Joaquin valleys as annual timeseries and average monthly values.



Detention Storage

The NatFM represents detention storage in four natural basins of the Sacramento Valley: Butte, Colusa, Sutter, and American. The outflow from these basins is assumed to correspond to flow over a broad-crested weir, i.e., proportional to the upstream depth raised to the power of 1.5.[26] No outflow will occur until the downstream stage in the Sacramento River falls below the flood elevation in the basin. For the outflow from the Butte Basin to the Sutter Basin, the downstream stage is assumed to be zero and the outflow is assumed to be independent of storage in the Sutter Basin. No detention storage is modeled for the Yolo Basin, though flooding in the Yolo Basin is represented. On a monthly timestep the outflow from the Yolo Basin is equal to the inflow less water depleted through ET and infiltration. User-selected values for the discharge coefficients are entered in cells C121:C124.[27] The NatFM also defines maximum storage volumes for the four basins. Bank overflow that would raise the storage above these maximum values is returned to the river system in the same timestep.

The worksheet *User Defined Input Assumptions* contains charts of annual and average monthly surface water storage in the Sacramento Valley so that the user may appraise how changes to input parameters affect routing of floodwater across the floodplain.

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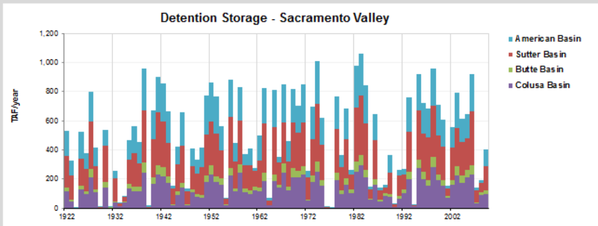
[26] There is considerable uncertainty regarding the form of the discharge equations.

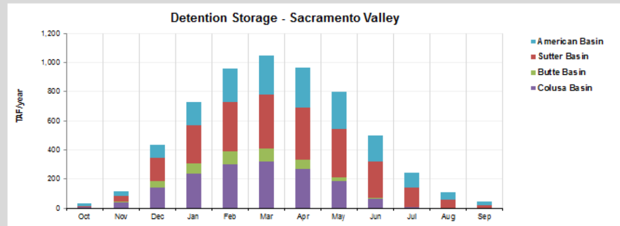
[27] For transparency, basin discharge coefficients are given defined names, which may be viewed in the Excel formula bar: ButteBasinDischargeCoefficient, ColusaBasinDischargeCoefficient, SutterBasinDischargeCoefficient, and AmericanBasinDischargeCoefficient.

Detention Storage

Basin	Discharge Coefficient	Maximum Storage (TAF)
Butte Basin	2.0	500
Colusa Basin	2.0	1000
Sutter Basin	2.0	900
American Basin	2.0	600

This table defines the discharge equation for the detention basins of the Sacramento Valley and their maximum storage (excess water is automatically routed back to the river in the same timestep). Outflow from the basins is assumed to correspond to flow over a broad crested weir, outflow is proportional to the storage depth raised to the power of 1.5.





Groundwater

A set of 15 lumped-parameter groundwater models are used to simulate groundwater interactions with surface waters. The lumped-parameter models are independent, i.e., hydraulically unconnected. Groundwater-surface water interactions are simulated using a stylized representation of the groundwater basins. Groundwater is represented as a wedge that is parallel to the stream/river. Groundwater flow to the river is dependent on the relative elevation between the groundwater table and the river stage. Groundwater is recharged from precipitation and flood flows over the floodplain and depleted through evapotranspiration (ET) under conditions of a high water table and flow to the stream system.

Input parameters for the lumped-parameter models are contained in in cells C160 to H175.[28] These parameters are as follows:

Hydraulic conductivity: a measure of the groundwater model's ability to transmit water represented in feet per day. DWR (2013a) report values from 6 – 100 feet per day for calibrating C2VSim (Layer 1), with an average value of 46 feet per day.

Width-to-breadth ratio: defines the shape of the groundwater model in plan view; the width is the length of the interface between the river and groundwater, the breath is the distance from the farthest edge of the aquifer to the river.

Specific yield: the porosity of the groundwater model, represented as a fractional volume (between 0 and 1). DWR (2013a) report values from 0.06 – 0.40 for calibrating C2VSim (Layer 1), with an average value of 0.19.

Seepage rate: the maximum infiltration rate in inches per month. DWR (2013a) report values from 4 – 12 inches per day for calibrating C2VSim (unsaturated layer).

Height for base flow only: the average groundwater elevation in feet measured above the river stage at which no vegetation has access to groundwater except for the Hardwood class.

[28] For transparency, default parameters for the 15 groundwater basins are given defined names, which may be viewed in the Excel formula bar: HydraulicConductivity, WidthtoBreadth, SpecificYield, SeepageRate, BaseFlowHeight, and RootZoneHeight.

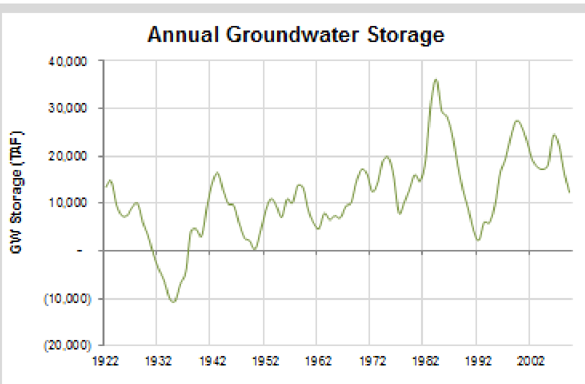
Height of root zone above datum: the average groundwater elevation in feet measured above the river stage at which all vegetation is assumed to have access to groundwater to meet ET.

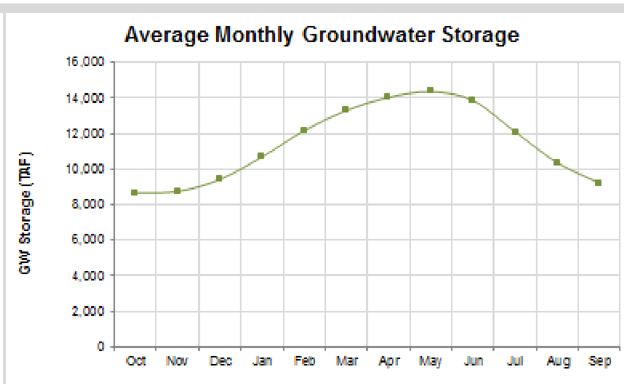
The worksheet also summarizes the beginning and ending storage for each groundwater basin. These are reported values and should not be edited.

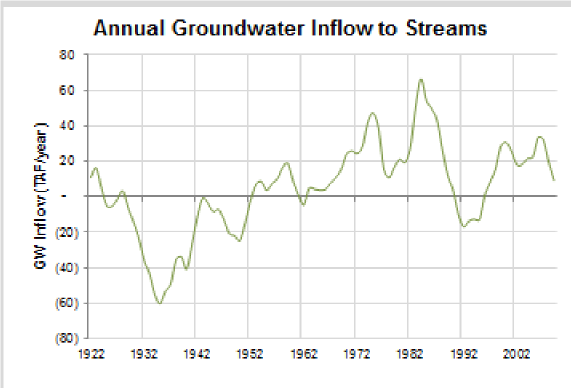
Groundwater

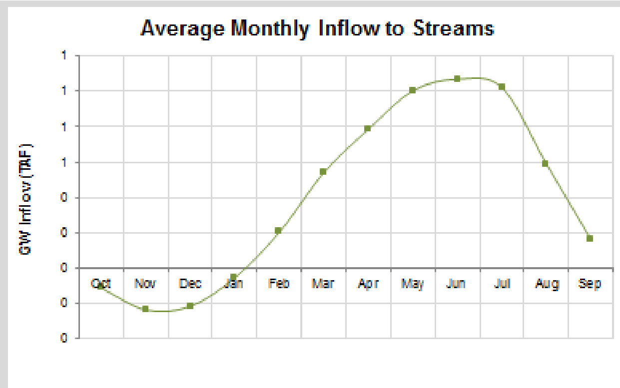
Basin	Hydraulic Conductivity	Width to Breadth Ratio	Specific Yield	Seepage Rate	Height for Base Flow Only	Height of Root Zone above Datum	Beginning Storage	Ending Storage	Difference
	(feet/day)	(none)	(none)	(inches/month)	(feet)	(feet)	(TAF)	(TAF)	(TAF)
Default	50.0	5.0	0.15	5.0	10.0	25.0	DO NOT EDIT		
1	50.0	5.0	0.15	5.0	10.0	25.0	513	513	0
2	50.0	5.0	0.15	5.0	10.0	25.0	10	10	0
3	50.0	5.0	0.15	20.0	10.0	25.0	272	272	0
4	50.0	5.0	0.15	15.0	10.0	25.0	8,718	8,819	102
5a	50.0	5.0	0.15	5.0	10.0	25.0	-610	-610	0
5b	50.0	5.0	0.15	10.0	10.0	25.0	91	85	-6
6	50.0	5.0	0.15	20.0	10.0	25.0	90	90	0
7	50.0	5.0	0.15	10.0	10.0	25.0	910	910	0
8a	50.0	5.0	0.15	5.0	10.0	25.0	226	226	0
8b	50.0	5.0	0.15	5.0	10.0	25.0	143	143	0
10a	50.0	5.0	0.15	5.0	10.0	25.0	118	118	0
10b	50.0	5.0	0.15	20.0	10.0	25.0	-921	-921	0
11	50.0	5.0	0.15	25.0	10.0	25.0	152	152	0
12	50.0	5.0	0.15	20.0	10.0	25.0	272	272	0
13	50.0	5.0	0.15	20.0	10.0	25.0	-71	-71	0
							9,910	10,007	96

The worksheet *User Defined Input Assumptions* contains four charts which summarize results from the lumped-parameter groundwater models: monthly timeseries of total groundwater storage, average monthly storage, monthly timeseries of groundwater inflow to the stream/river network, and average monthly inflow to the stream/river network.









Evapotranspiration

Crop ET under standard conditions (ET_c) is defined as the ET rate from disease-free, well-fertilized crops, grown in large fields, under optimum soil and water conditions, and achieving full production under given weather conditions. ET_c can be related to ET_o through crop coefficients as follows:

$$ET_c = K_c . ET_o$$

where:

ET_o = reference crop evapotranspiration [L/T]
ET_c = crop evapotranspiration under standard conditions [L/T]
K_c = crop coefficient [dimensionless]

Detailed discussion of methods to determine K_c and compute ET_o are provided by the Food and Agricultural Organization (FAO) *Irrigation and Drainage Paper 56* (Allen et al., 1998). For the NatFM, this methodology has been extended to natural vegetation. Crop/vegetation coefficients (K_v) are used to estimate ET from the natural landscape when soil moisture is not limiting. Vegetation coefficients are from Howes et al. (2014). Cells C210 to C217 allow the user to scale the vegetation coefficients by a constant factor for all months.[29]

Evapotranspiration - Grass Based Vegetation Coefficients

Habitat Type	Multiplier
Default	1.00
Aquatic	1.00
Grassland	1.00
Chaparral	1.00
Riparian	1.00
Hardwood	1.00
Wetland	1.00
Saltbush	1.00

For the Nat FM, crop/vegetation coefficients (Kv) are used to estimate ET from the natural landscape when soil moisture is not limiting. Vegetation coefficients arefrom Howes et al. (2014). This table allow the user to scale the vegetation coefficients by a constant factor, which is equivalent to scaling the refernce crop evapotranspiration.

[29] For transparency, multipliers for the vegetation coefficients are given defined names, which may be viewed in the Excel formula bar: AquaticETmultiplier, GrasslandETmultiplier, ChaparralETmultiplier, RiparianETmultiplier, HardwoodETmultiplier, WetlandETmultiplier, SaltbushETmultiplier.

Rooting Depth and Depth of Ponding

Rooting depths are defined for six land-use classes (Grassland, Saltbush, Chaparral, Riparian, Hardwood, and Wetland).[30] The rooting depth and soil water holding capacity define the amount of water that can be stored in the soil profile. Deep roots and high soil holding capacities increase the ability to store water in the root zone, and, therefore, to maintain ET rates during the summer and fall (ET diminishes with water stress, eventually leading to permanent wilting of the surface vegetation). The soil moisture available to the plant is typically defined as the soil moisture in the root zone between field capacity and permanent wilting point (i.e., the product of the root zone and soil water holding capacity). The water that is readily available to the plant (i.e., soil moisture contents that do not cause plant stress) is approximately 50 percent of the available soil moisture.

The default value for the available soil water holding capacity is 1.5 inches per foot of rooting depth. This value is based on DWR's Consumptive Use Model (DWR, 1967 and 1979).[31] Default rooting depths are from Howes et al. (2014). Grassland and Chaparral land-use classes are assumed to have a root depth of 24 inches; Riparian, Wetland, and Saltbush a depth of 48 inches; and Hardwood a depth of 72 inches.

Under natural conditions, much of the Central Valley was covered in dense vegetation. The NatFM assumes that precipitation and flood water recharge the root zone until the soil profile reached field capacity; subsequently surface water percolates downward to recharge the groundwater, as limited by the vertical infiltration rate (seepage rate). Any excess water ponds on the surface. As ponded depths increase, water begins to drain as sheet flow across the land surface. To simulate initial ponding on the land surface and depression storage before the onset of surface runoff, the user may specify a ponding depth for each of the vegetation classes. Initial ponding/depression storage, as a depth, is added to the available soil moisture in the root zone.[32] The maximum available water that may be stored in the root zone or in local depressions is contained in cells G225:G231. These cells are referenced in the calculation of ET (e.g., worksheet *ET Subregion 1 (DSA 58)*, cells AF4:AL4)

Rooting Depth and Depth of Ponding

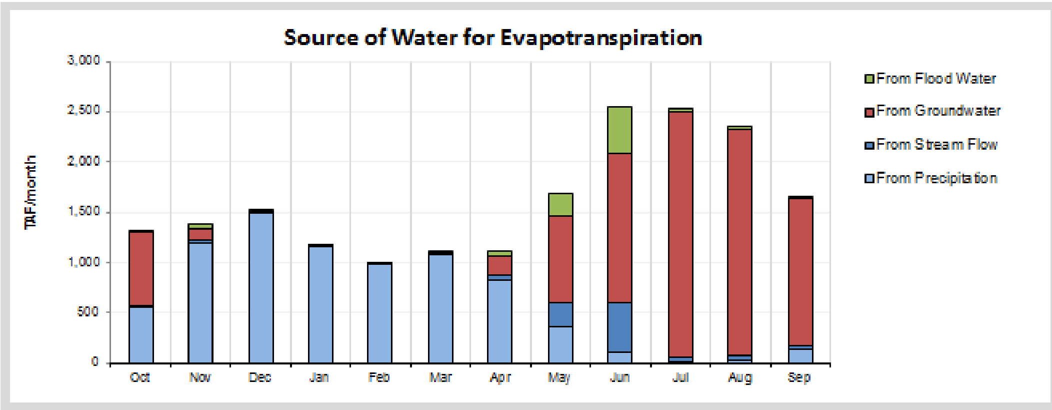
Habitat Type	Available Holding Capacity	Ponded Depth	Root Depth	Maximum Available Soil
	Inches/Foot	Inches	Inches	Inches
Rainfed Grassland	1.5	0	24	3
Aquatic	0	0	0	0
Grassland	1.5	0	24	3
Chaparral	1.5	0	24	3
Riparian	1.5	0	48	6
Hardwood	1.5	0	72	9
Wetland	1.5	0	48	6
Saltbush	1.5	0	48	6

[30] Rooting depths are not applicable to the Aquatic land use class.

[31] The Consumptive Use Model is used to derive agricultural water demands for CalSim II.

[32] This simple approach does not correctly model ponding/depression storage as this water is not subject to deep percolation losses. This approach may be refined in future versions of the Nat FM.

The worksheet *User Defined Input Assumptions* contains two charts of actual ET by source of water (precipitation, stream flow, flood water, and groundwater) so that the user may appraise how changes to input parameters affect ET. The charts present total valley-wide ET as annual timeseries and average monthly values.



Elevation-Area-Storage Characteristics for Flood Basins

The wetted area resulting from flood flows is calculated using storage-wetted area relationships based on both existing (for the Sacramento Valley) and historical (for the San Joaquin Valley) topographic maps. However, the area subject to flooding may be an underestimate because the NatFM does not represent: (1) multiple sites of overbank flow that would have occurred under natural conditions (overflow is typically aggregated to one location within a reach), (2) flooding along the minor rivers and streams, and (3) ponding in minor natural depressions and lakes. The factors in the cells C267 to C273 increase the wetted area by a multiplicative factor.[33]

Elevation-Area-Storage Characteristics for Flood Basins

Wetted Surface A	Multiplier
Default	1.50
Colusa	1.50
Butte	1.50
Sutter	1.50
American	1.50
Yolo	1.50
San Joaquin River	1.50

The wetted area resulting
existing and historical topo
represent the mutiple site
location within a reach), n
and lake. The factors in the

Source of Water for Riparian Vegetation

The NatFM assumes that ET from riparian vegetation is always met in full. Once soil moisture from precipitation is depleted, ET is met from either stream flows or groundwater. Cells C279 to C290 provide a toggle for switching between these two alternate supplemental sources of water. A value of 1 indicates that stream flows are tapped to meet ET; a value of 0 indicates that groundwater meets any supplemental ET requirements. Values are defined for each month. It is assumed that the winter and spring are characterized by high river flows and high river stage, and

[33] For transparency, multipliers for wetted area from flood flows are given defined names, which may be viewed in the Excel formula bar: FactorColusaWettedArea, FactorButteWettedArea, FactorSutterWettedArea, FactorAmericanWettedArea, FactorYoloWettedArea, and FactorSanJoaquinRiverWettedArea.

that under these conditions, the rivers recharge the underlying aquifer. Thus, during this period, riparian vegetation ET is assumed to be met from streamflow. Conversely, it is assumed that late summer and fall are periods of low river flow and low stage and groundwater inflow replenishes the rivers. Thus, during this period, riparian vegetation ET is assumed to be met from groundwater. The parameters for controlling the source of water for riparian ET are applied to all regions in the Sacramento and San Joaquin Valley.

Source of Water for Riparian Vegetation

Month	Surface Water	Groundwater
Oct	0.00	1.00
Nov	1.00	0.00
Dec	1.00	0.00
Jan	1.00	0.00
Feb	1.00	0.00
Mar	1.00	0.00
Apr	1.00	0.00
May	1.00	0.00
Jun	1.00	0.00
Jul	0.00	1.00
Aug	0.00	1.00
Sep	0.00	1.00

The model assumes that ET from riparain vegetation is always met in full. Once the soil mositure has been depleted, the model taps either stream flow or groundwater to meet ET. A value of 1.00 indicates stream flows are depleted to meet ET. A value of 0.00 indicates groundwater is depleted to meet ET. Values between 0 and 1 result in both sources of water being used to meet ET.

Groundwater Availability for Wetlands

Wetlands typically were located in the valley bottom in groundwater discharge areas. Cells C296 to C311 provide a toggle for making alternate assumptions about the availability of groundwater to meet ET for each region, once soil moisture from precipitation is depleted. A value of 1 indicates that groundwater is always available to meet ET, irrespective of groundwater storage/elevation. A value of 0 indicates groundwater is only available to meet ET under conditions of a high groundwater table. The default setting is 1.[34]

Groundwater Availability for Wetlands

Region	
Default	1.00
1	1.00
2	1.00
3	1.00
4	1.00
5a	1.00
5b	1.00
6	1.00
7	1.00
8a	0.00
8b	0.00
10a	1.00
10b	1.00
11	0.00
12	1.00
13	1.00

The model assumes that ET from wetlands is met only when there is sufficient water. Once the soil mositure has been depleted, the model taps groundwater to meet ET. A value of 1.00 indicates that groundwater is always available to meet ET. A value of 0.00 indicates groundwater is only available to meet ET under conditions of a high GW table.

[34] For transparency, the switch for the source of water for wetlands is given the defined name GWAvailabilityforWetlands.

Boundary Inflows to Groundwater Basins

The NatFM groundwater models include the ability to represent subsurface boundary inflows. Cell C318 provides a toggle for making alternate assumptions about these boundary inflows. A value of 1 preserves lateral groundwater boundary inflows as in the historical run of C2VSim. A value of 0 sets lateral groundwater boundary inflows to zero. The default setting is 0. The boundary between the rim and valley watersheds in the NatFM is typically upslope of the groundwater domain. Along this boundary, soils are assumed to be shallow and underlain by an impermeable layer, therefore, subsurface flows are minimal.[35]

Boundary Inflows to Groundwater Basins

0.00	A value of 1.00 preserves lateral groundwater boundary inflows as in the historical run of C2VSim. A value of 0.00 sets lateral groundwater boundary inflows to zero. Values between 0 and 1 result in partial implementation of boundary inflows.

Groundwater Recharge and Discharge Areas

In the NatFM, once soil moisture is depleted, further ET may be supported by groundwater. To help distinguish between groundwater recharge areas and groundwater discharge areas, cells C328 to C334 define the maximum fraction of the habitat type that can be supported by groundwater. For example, groundwater may always be too deep to support grasslands that are located adjacent to the foothills on relatively higher ground. A value of 0.75 for Grassland would indicate that 25 percent of grasslands are located on relatively higher ground; these are annual grasslands that die-back in the summer. The remaining 75 percent of grasslands located on relatively lower ground may have access to groundwater depending on groundwater storage, which is dynamically simulated.

Groundwater Recharge and Discharge Areas

Habitat Type	Maximum Fraction of Area having Access to Groundwater
Aquatic	N/A
Grassland	0.75
Chaparral	0
Riparian	N/A
Hardwood	N/A
Wetland	1.0
Saltbush	1.0

Once the soil moisture is depleted, further ET may be supported by groundwater. To help distinguish between groundwater recharge areas and groundwater discharge areas, this table defines the maximum fraction of the habitat type that can be supported by groundwater. For example, groundwater may always be too deep to support grasslands that are located adjacent to the foothills on realtively higher ground. A value of 0.75 for Grassland would indicate that 25% of grasslands are located on relatively higher ground; these are annual grasslands that die-back in the summer. The remaining 75% of grasslands located on relatively lower ground may have access to groundwater depending on the groundwater storage, which is dynamically simulated.

Direct Runoff SCS Curve Number Method

Runoff from precipitation is calculated using the Soil Conservation Service Curve Number (CN) method, modified to be applicable to a monthly time step. Cell B340 contains the default CN value is used for all land use types. The potential maximum retention or infiltration, S, is a function of CN and is calculated using the standard SCS equation. Additional runoff will occur if the infiltration, as calculated by the SCS CN method, exceeds the maximum infiltration of the soil as specified in the Groundwater Parameter table above.

[35] For transparency, the switch for boundary inflows is given the defined name GWBoundaryInflowFactor.

Direct Runoff SCS Curve Number Method

Habitat Type	CN	S
Default	60	6.67
Aquatic	N/A	
Grassland	60	6.67
Chaparral	60	6.67
Riparian	60	6.67
Hardwood	60	6.67
Wetland	60	6.67
Saltbush	60	6.67

Runoff from precipitation is calculated using the Soil Conservation Service Curve Number (CN) method, modified to be applicable to a monthly time step. A single CN value is used for all land use types, as indicated by the default value in red font. The potential maximum retention or infiltration, S, is a function of CN and is calculated using the standard SCS equation.
Additional runoff will occur if the infiltration, as calculated by the SCS CM method, exceeds the maximum infiltration of the soil as specified in the Groundwater Parameter table above.

Placeholder Flood Characteristics for Other Areas

During model calibration it was found that additional groundwater recharge was needed to stabilize groundwater elevations is some of the areas not subject to flooding. A table was created to allow the user to specify channel capacities for the Feather River, Mokelumne River, and Calaveras River that control flooding of subregions 5a, 8a, and 8b, respectively. The table also defines the fraction of the subregion that is prone to flooding.

Placeholder Flood Characteristics for Other Areas

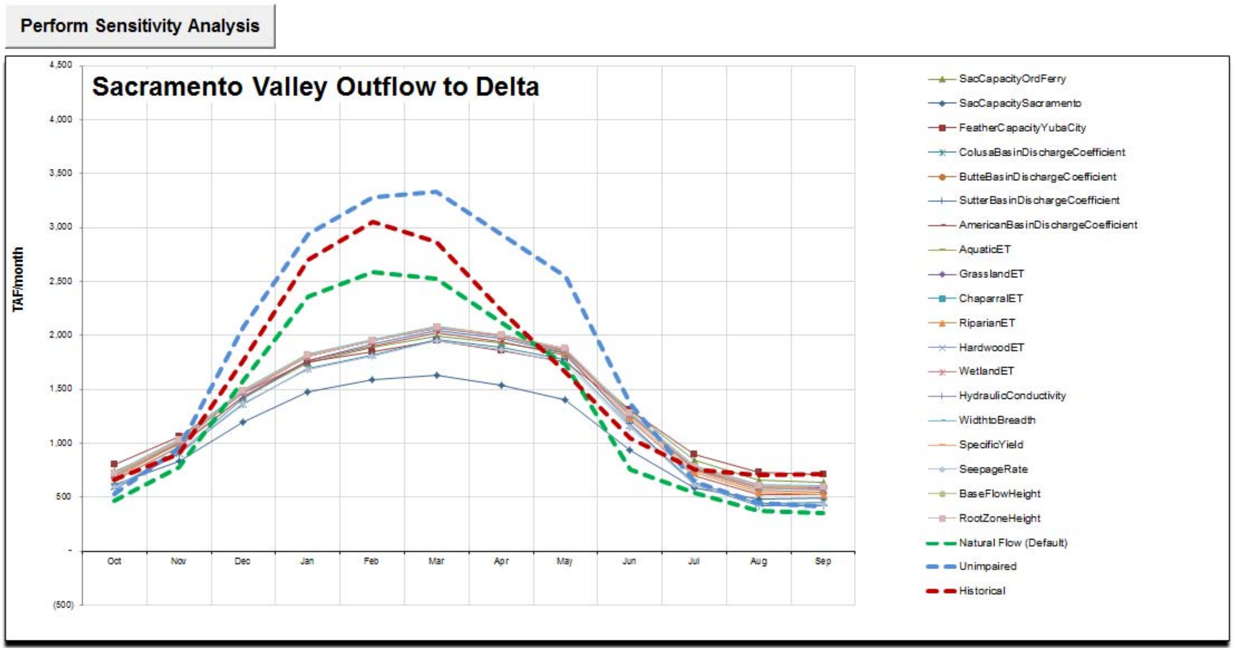
Region	Channel Capacity (cfs)	Fraction of Land
1	20,000	0.00
2	20,000	0.00
5a	8,000	0.50
8a	1000	0.50
8b	500	0.50

The table specifies channel capacities for the Feather River, Mokelumne River, and Calaveras River that control flooding of subregions 5a, 8a, and 8b, respectively. The table also defines the fraction of the subregion that is prone to flooding. These routines were not implemented for Subregions 1 and 2.

Worksheet 3: Sensitivity Analysis

The worksheet *Sensitivity Analysis* allows the user to conduct an automated sensitivity analysis for a standard set of input parameters. These parameters are listed in cells B8 to B29. Cells E8 to E29 contain a multiplier, which is input by the user, for performing the sensitivity. For example, cell B4 lists the parameter SacCapacityOrdFerry, which defines the capacity of the Sacramento River in the reach between Ord Ferry and Knights Landing. The parameter value is defined in the worksheet *User Defined Input Assumptions*, cell H40. If the user enters a multiplier value in the worksheet Sensitivity Analysis, cell E4 of 0.5, a sensitivity analysis will be performed wherein the channel capacity is 50 percent of its original value.

The sensitivity analysis is performed by pushing the button "Perform Sensitivity Analysis." Results from the sensitivity analysis are presented in the form of tables and charts showing average month Delta inflows from the Sacramento and San Joaquin valleys and the net Delta outflow. Values of 0 or 1 are entered into cells D8 to D29 to either include or exclude the input parameter in the analysis.



Worksheet 4: Results Summary and Checks

The worksheet *Results Summary and Checks* presents summary results for the Sacramento Valley, San Joaquin Valley, Eastside Streams, and Delta. Results are presented in the form of a water balance to provide a mass balance check on the flow routing calculations. Components of the average annual Delta inflow for the three geographical regions are given in cells C52, F52, and I52. Average annual Net Delta outflow is given in cell L38.

Summary and Mass Balance Checks

All values correspond to long-term average, water years 1922-2009. Values are in TAF/year.

Sacramento Valley	
Precipitation	
Precipitation over valley floor upslope of GW basins	2,024
Precipitation over valley floor on GW Basins	6,446
Natural Runoff	600
Natural Consumptive use of Precipitation	4,220
Natural Groundwater Recharge	1,626
Mass balance	**0**
Groundwater	
Natural Groundwater Recharge from precipitation	1,626
Natural Groundwater Recharge from flood flows	3,610
Natural Subsurface Boundary Inflow	0
Natural Groundwater inflow to stream system	3
Natural Evaporation from High Groundwater	5,232
Natural Change in Groundwater Storage	2
Mass balance	**-1**
Evapotranspiration	
Natural Consumptive Use (ET) of Precipitation	4,220
Natural Consumptive Use (ET) of Flood Flows	876
Natural Consumptive Use (ET) of Groundwater	5,232
Natural Consumptive Use (ET) of Stream Flow	624
Natural Total ET	**10,952**
Stream Flows	
Unimpaired Inflows	19,962
Accretion from valley floor upstream of GW basins	915
Natural Runoff	600
Natural Stream Depletion by Riparian Vegetation	624
Groundwater inflow to stream system	3
Natural Consumptive Use (ET) of Flood Flows	876
Natural Groundwater Recharge from flood flows	3,610
Natural Lake Evaporation (Clear Lake)	193
Detention Storage	0
Natural Outflow to Delta	16,178
Mass balance	**-1**
Inflows and Outflows	
Unimpaired Inflows	19,962
Accretion from valley floor upstream of GW basins	915
Precipitation over valley floor on GW Basins	6,446
Natural Subsurface Boundary Inflow	0
Natural Total ET	10,952
Natural Lake Evaporation (Clear Lake)	193
Natural Change in Groundwater Storage	2
Natural Outflow to Delta	**16,176**

San Joaquin Valley	
Precipitation	
Precipitation over valley floor upslope of GW basins	21
Precipitation over valley floor	2,384
Natural Runoff	106
Natural Consumptive use of Precipitation	1,962
Natural Groundwater Recharge	317
Mass balance	**0**
Groundwater	
Natural Groundwater Recharge from precipitation	317
Natural Groundwater Recharge from flood flows	1,481
Natural Subsurface Boundary Inflow	0
Natural Groundwater inflow to stream system	1
Natural Evaporation from High Groundwater	1,737
Natural Change in Groundwater Storage	0
Mass balance	**0**
Evapotranspiration	
Natural Consumptive Use (ET) of Precipitation	1,962
Natural Consumptive Use (ET) of Flood Flows	1,044
Natural Consumptive Use (ET) of Groundwater	1,737
Natural Consumptive Use (ET) of Stream Flow	154
Natural Total ET	**4,958**
Stream Flows	
Unimpaired Inflows	6,224
Accretion from valley floor upstream of GW basins	17
Natural Runoff	106
Natural Stream Depletion by Riparian Vegetation	154
Groundwater inflow to stream system	1
Natural Consumptive Use (ET) of Flood Flows	1,044
Natural Groundwater Recharge from flood flows	1,481
Natural Lake Evaporation	0
Detention Storage	0
Natural Outflow to Delta	3,631
Mass balance	**36**
Inflows and Outflows	
Unimpaired Inflows	6,224
Accretion from valley floor upstream of GW basins	17
Precipitation over valley floor	2,384
Natural Subsurface Boundary Inflow	0
Natural Total ET	4,958
Natural Lake Evaporation	0
Natural Change in Groundwater Storage	0
Natural Outflow to Delta	**3,667**

Eastside Streams	
Precipitation	
Precipitation over valley floor upslope of GW basins	94
Precipitation over valley floor	1,352
Natural Runoff	87
Natural Consumptive use of Precipitation	1,016
Natural Groundwater Recharge	248
Mass balance	**0**
Groundwater	
Natural Groundwater Recharge from precipitation	248
Natural Groundwater Recharge from flood flows	141
Natural Subsurface Boundary Inflow	0
Natural Groundwater inflow to stream system	1
Natural Evaporation from High Groundwater	388
Natural Change in Groundwater Storage	0
Mass balance	**0**
Evapotranspiration	
Natural Consumptive Use (ET) of Precipitation	1,016
Natural Consumptive Use (ET) of Flood Flows	214
Natural Consumptive Use (ET) of Groundwater	388
Natural Consumptive Use (ET) of Stream Flow	94
Natural Total ET	**1,713**
Stream Flows	
Unimpaired Inflows	1,453
Accretion from valley floor upstream of GW basins	31
Natural Runoff	87
Natural Stream Depletion by Riparian Vegetation	94
Groundwater inflow to stream system	1
Natural Consumptive Use (ET) of Flood Flows	214
Natural Groundwater Recharge from flood flows	141
Natural Lake Evaporation	0
Detention Storage	0
Natural Outflow to Delta	1,124
Mass balance	**0**
Inflows and Outflows	
Unimpaired Inflows	1,453
Accretion from valley floor upstream of GW basins	31
Precipitation over valley floor	1,352
Natural Subsurface Boundary Inflow	0
Natural Total ET	1,713
Natural Lake Evaporation	0
Natural Change in Groundwater Storage	0
Natural Outflow to Delta	**1,124**

Delta	Natural Flow NFP Data	Historical NFP Data	Historical DAYFLOW Data
Inflows			
Sacramento River at Freeport	10,459	16,053	16,000
Return Flow from Regional Wastewater Treatment Plant	0	78	
Yolo Bypass near Woodland	6,232	2,570	
Putah Creek near Davis	363	206	2,928
Sacramento Weir	0	14	
Westside Minor Streams less riparian ET	13	0	0
Losses from floodflows	-888		
San Joaquin River near Vernalis	3,631	3,274	3,274
Cosumnes River at Michigan Bar			359
Mokelumne River at Woodbridge	1,124	1,138	438
Miscellaneous Eastside Streams			319
Marsh Creek	14	14	
Total Delta Inflow	**20,947**	**23,340**	**23,390**
Exports			
Banks Pumping Plant	0	1,058	1,058
Jones Pumping Plant	0	1,316	1,316
Barker Slough Pumping Plant	0	10	10
CCWD Diversions	0	63	63
City of Antioch Diversions	0	0	0
Total Exports and Diversions	**0**	**2,447**	**2,447**
Accretions and Depletions			
Gross Channel Diversions	2,969	1,530	1,530
Precipitation	850	850	802
Tidal Inflows to Eastside Streams	0		
Net Channel Diversions	**2,119**	**680**	**728**
Net Delta Outflow			
Delta Outflow	**18,828**	**20,271**	**20,271**
Mass balance	**0**	**-50**	**-48**

Sacramento Valley

Results for the Sacramento Valley consist of three separate mass balances for precipitation, groundwater, and streamflows. Additionally, summaries of ET losses and system inflows and outflows are presented.

San Joaquin Valley

Results for the Sacramento Valley consist of three separate mass balances for precipitation, groundwater, and streamflows. Additionally, summaries of ET losses and system inflows and outflows are presented.

Eastside Streams

Results for the Sacramento Valley consist of three separate mass balances for precipitation, groundwater, and streamflows. Additionally, summaries of ET losses and system inflows and outflows are presented.

Delta

Results for the Delta comprise inflows, exports, depletions, and outflow. Natural flow data are compared to historical data, as used in the NatFM, and data from DWR's DayFlow program.

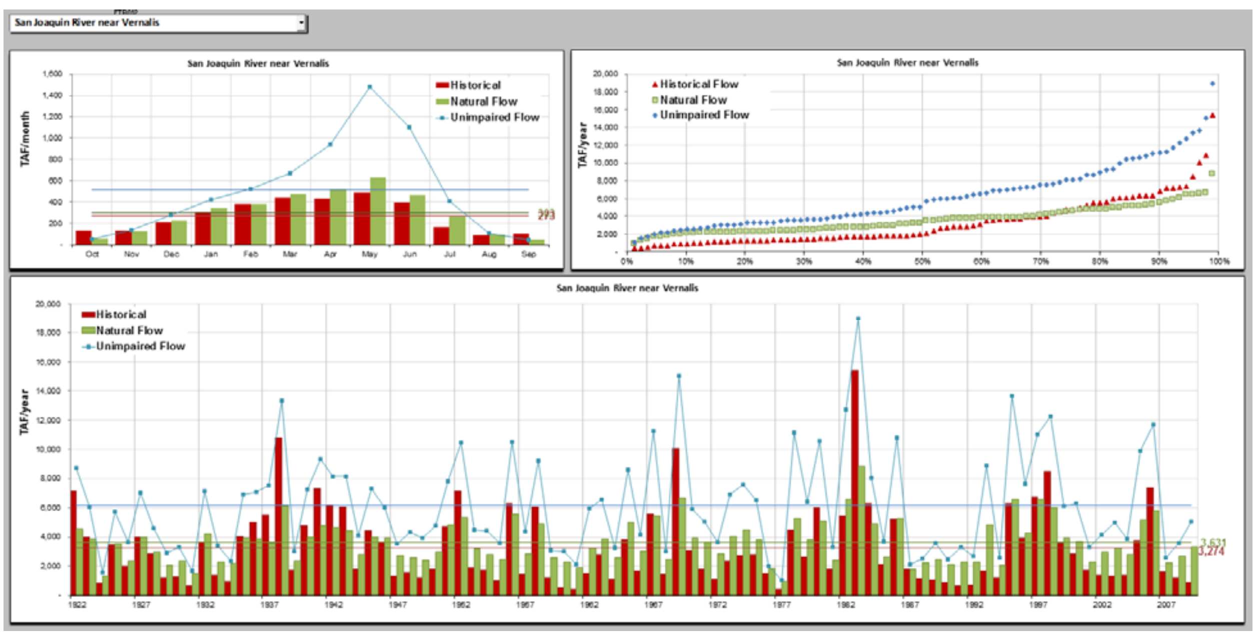
Worksheet 5: Results Charts River Flows

The worksheet *Result Charts River Flows* presents summary charts for key flows in the Sacramento and San Joaquin valleys and the Delta. The user may view charts for an initial selection of 27 flows using a dropdown box located in the upper top left of the spreadsheet. These flows are as follows:

- Sacramento River above Bend Bridge
- Stony Creek below Black Butte (missing historical data)
- Sacramento River at Butte City
- Sacramento River below Wilkins Slough
- Colusa Basin Outflow (negative indicates inflow to basin)
- Feather River at Oroville
- Yuba River at Smartville
- Yuba River near Marysville
- Bear River near Wheatland
- Feather River near Nicolaus
- Sacramento Slough near Karnak
- Sacramento River at Verona
- American River at Fair Oaks
- Sacramento River at Sacramento/Freeport

- Cache Creek at Yolo
- Yolo Bypass near Woodland
- Putah Creek near Davis
- Yolo Bypass outflow to Cache Slough
- Total Sacramento Valley Inflow to Delta
- Total Eastside Streams
- San Joaquin River below Friant Dam
- San Joaquin River upstream from Merced
- San Joaquin River near Newman (includes Merced Slough flood flows)
- San Joaquin River near Vernalis
- Tuolumne River below La Grange Dam
- Stanislaus River below Goodwin Dam
- Net Delta Outflow (calculated using 7-station average for precipitation, and area of 679,699 acres)

The charts compare historical and natural flows in the form of annual timeseries and average monthly values. Where available, the charts also present unimpaired flow data.



Worksheet 6: Result Charts Flooding

The worksheet *Result Charts Flooding* presents summary charts for the routing of flood water from the major rivers across the flood plain. The user may view charts for an initial selection of

17 flows using a dropdown box located in the upper top left of the spreadsheet. These flows are as follows:

- Butte Basin storage
- Sutter Basin storage
- Colusa Basin storage
- American Basin storage
- Sacramento Valley total storage
- Sacramento River overflow/spill to Colusa Basin
- Sacramento River overflow/spill to Butte Basin
- Sacramento River overflow/spill to Yolo Basin
- Sacramento River overflow/spill to Sutter Basin
- Sacramento River overflow/spill American Basin
- Feather River overflow/spill to Sutter Basin (through Gilsizer Slough)
- San Joaquin River left bank overflow/spill Mendota to Merced
- San Joaquin River right bank overflow/spill Mendota to Merced
- San Joaquin River left bank overflow/spill Merced to Vernalis[36]
- San Joaquin River right bank overflow/spill Merced to Vernalis
- San Joaquin River total overflow/spill

The charts compare historical and natural flows in the form of annual timeseries and average monthly values. Results for detention storage are average annual values.

[36] For routing purposes all flood water from overbank spills occurring upstream from the Merced confluence is returned to the river at the confluence and may respell over the banks.

Worksheet 7: Result Charts Groundwater

The worksheet *Result Charts Groundwater* presents summary charts for key groundwater components. The user may view charts for an initial selection of 6 groundwater timeseries using a dropdown box located in the upper top left of the spreadsheet. The options are as follows:

- Groundwater storage
- Groundwater inflow to streams and rivers
- Groundwater average elevation
- Groundwater ET (by surface vegetation)
- Groundwater ET under conditions of a low water table[37]
- Groundwater ET under conditions of a high water table[38]

The charts show natural flow data in the form of monthly and annual timeseries and average monthly values. Where available, the charts also present unimpaired flow data. Annual timeseries data for storage are average storage values for the year.

[37] Under a low water table, it is assumed that only the Hardwood vegetation class is sufficiently deep-rooted to have access to groundwater.

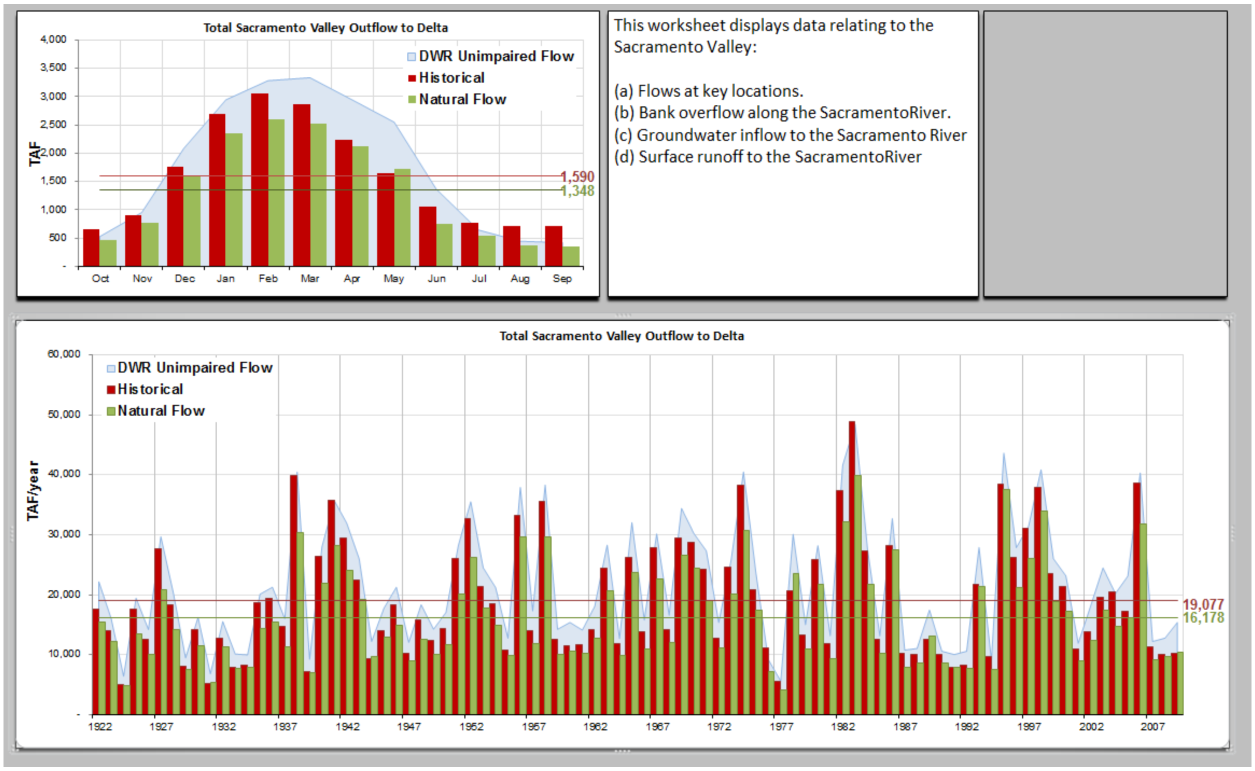
[38] Under a high water table , it is assumed that all surface vegetation can deplete groundwater to meet ET.

Worksheet 8: Result Charts Sacramento

The worksheet *Results Charts Sacramento* presents summary charts for key flows in the Sacramento Valley. The user may view charts for an initial selection of 1 flows using a dropdown box located in the upper top left of the spreadsheet. These flows are as follows:

- Sacramento Valley Inflow to the Delta

The charts compare historical and natural flows in the form of bar charts of annual timeseries and average monthly values. Zero values are shown for historical data when the data are not available. Unimpaired flows are presented where available.

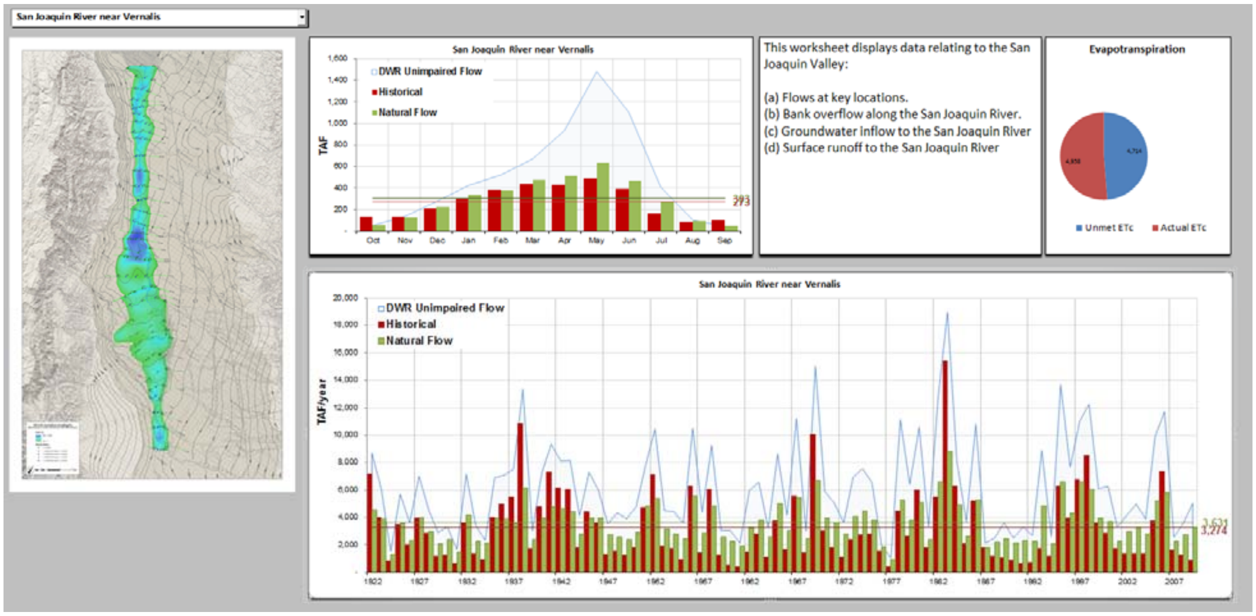


Worksheet 9: Result Charts San Joaquin

The worksheet *Result Charts San Joaquin* presents summary charts for key flows in the San Joaquin Valley. The user may view charts for an initial selection of 13 flows using a dropdown box located in the upper top left of the spreadsheet. These flows are as follows:

- San Joaquin River below Friant Dam
- San Joaquin River upstream from Merced
- San Joaquin River near Newman (includes Merced Slough and flood flows)
- San Joaquin River near Vernalis
- Tuolumne River below La Grange Dam
- Stanislaus River below Goodwin Dam
- San Joaquin River Left Bank overflow from Mendota to Merced
- San Joaquin River Right Bank overflow/spill from Mendota to Merced
- San Joaquin River Left Bank overflow/spill from Merced to Vernalis
- San Joaquin River Right Bank overflow/spill from Merced to Vernalis
- Total San Joaquin River Bank overflow/spill
- Surface Runoff inflow to the San Joaquin River
- Groundwater inflow to the San Joaquin River

The charts compare historical and natural flows in the form of bar charts of annual timeseries and average monthly values. Zero values are shown for historical data when the data are not available. Unimpaired flows are presented where available.

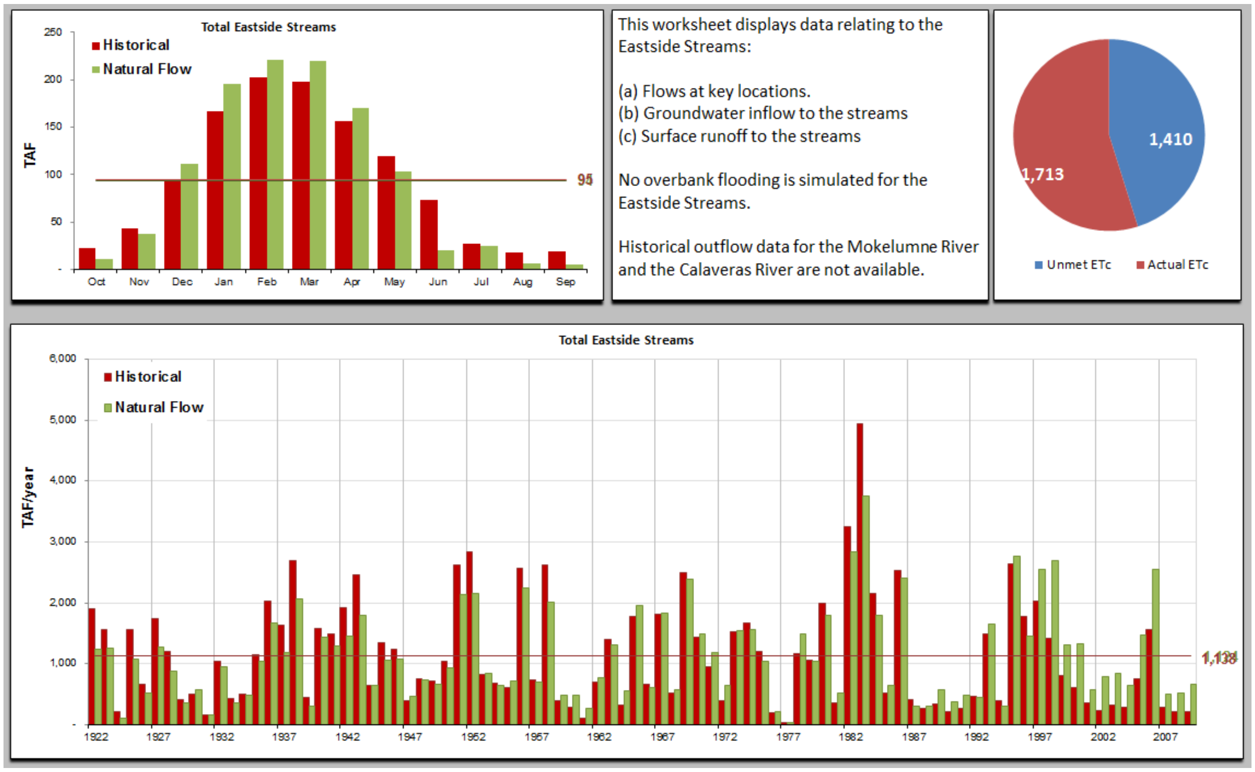


Worksheet 10: Result Charts Eastside Streams

The worksheet *Result Charts Eastside* presents summary charts for key flows in the Eastside Streams region. The user may view charts for an initial selection of 10 flows using a dropdown box located in the upper top left of the spreadsheet. These flows are as follows:

- Cosumnes River at Michigan Bar
- Mokelumne River near Mokelumne Hill
- Mokelumne River below Camanche Dam
- Mokelumne River inflow to Delta
- Calaveras River upstream from New Hogan Dam
- Calaveras River inflow to Delta
- Total Eastside Streams
- Total surface runoff to Eastside Streams
- Total groundwater inflow to Eastside Streams
- Total depletion of stream flow by riparian ET

The charts compare historical and natural flows in the form of annual timeseries and average monthly values. Zero values are shown for historical data when the data are not available.



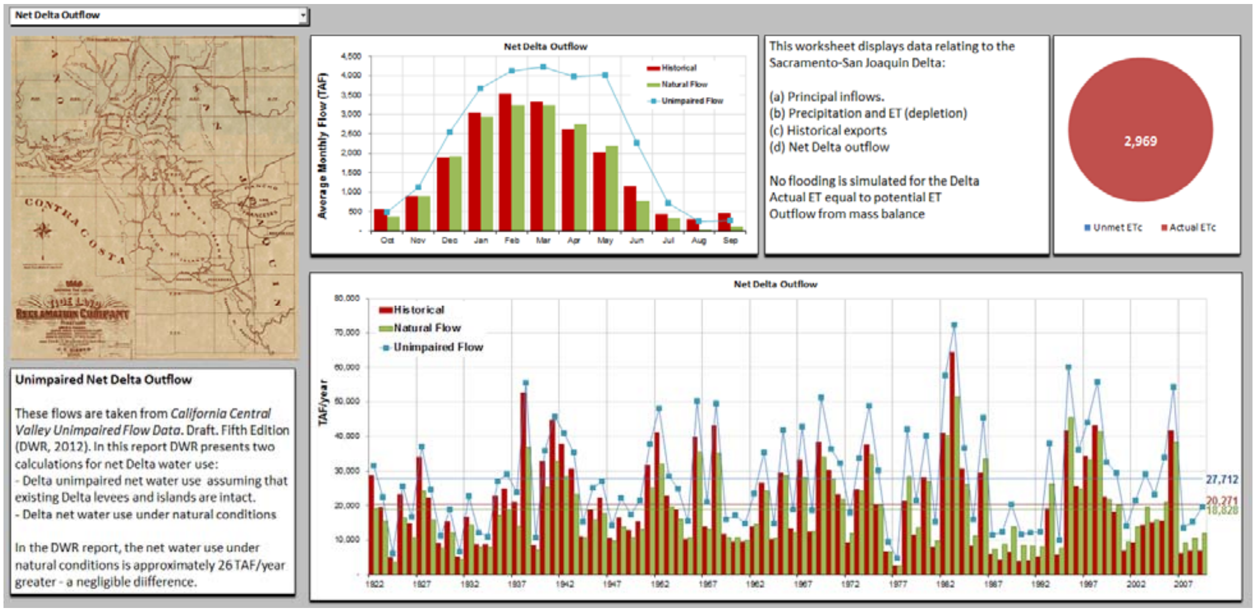
Worksheet 11: Result Charts Delta

The worksheet *Result Charts Delta* presents summary charts for key flows in the Delta. The user may view charts for an initial selection of 14 flows using a dropdown box located in the upper top left of the spreadsheet. These flows are as follows:

- Sacramento River at Sacramento/Freeport
- Yolo Bypass/Cache Slough
- Mokelumne River inflow to Delta
- Calaveras River inflow to Delta
- San Joaquin River near Vernalis
- Total Delta inflow
- Banks Pumping Plant
- Jones Pumping Plant
- Barker Slough Pumping Plant
- Contra Costa Water District diversions (sum of Rock Slough, Old River, and Middle River)
- 7-Station precipitation
- Gross Delta depletion

- Net Delta depletion
- Net Delta outflow

The charts compare historical and natural flows in the form of annual timeseries, average monthly values, and monthly and annual exceedence plots. Zero values are shown for historical data when the data are not available. Unimpaired flows are presented where available.



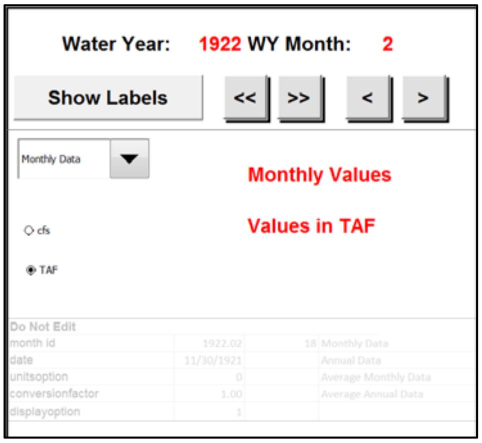
Worksheet 12: Schematic – Sacramento Valley

The worksheet *Schematic – Sacramento Valley* is the first of four node-arc diagrams that represent the Delta and its upstream drainage area. These schematics are based on the current water infrastructure, but also represent natural flow conditions. These worksheets are used to display model results.

The four worksheets use significant computer memory resources and may adversely affect model performance and the ability to view summary charts and tables. Therefore, two versions of the NatFM were created. The “lite” version of NatFM does not include these worksheets, the full version of the NatFM does.

The worksheet *Schematic – Sacramento Valley* represents the Redding Basin and the floor of the Sacramento Valley from Shasta Dam to the Sacramento River at Freeport. Historical flows are indicated using a pink fill; flows under natural conditions are indicated using a gray fill. In addition to depicting inflows from the rim watersheds and the stream/river network, elements of the schematic include the Colusa, Butte, Sutter, American, and Yolo basins, and groundwater storage.

A drop-down box in the upper-left corner of the worksheet allows the user to select between the following display options:



- Monthly flows
- Annual flows
- Long-term average monthly flows
- Long-term average annual flows

The user may also toggle between units of cubic feet per second (cfs) and TAF. However, this option is only implemented when viewing monthly timeseries data. Flow values are shown in a text boxes positioned at the center of each arc. These text boxes show the natural and historical flows at key locations throughout the schematic. Using a control button located in the upper-left of the worksheet, the user may toggle between displaying flow values and displaying the name of the arc. Under the monthly flow option and the annual flow option, the user may advance through the period of simulation, water years 1922 – 2009, using a monthly and annual timestep, respectively. For the average monthly flow option, the user may step through the 12 calendar months. In cases where no historical data are available, a value of -901 is shown.

The naming convention for the nodes consist of a six-character abbreviation for the river/channel and the associated river mile (RM). Line types and colors are used to represent a variety of node and arc attributes. For example, the U.S. Geological Survey (USGS) stream gage *Sacramento River below Wilkins Slough near Grimes* (ID 1390500) is located 120 miles upstream from the confluence of the Sacramento and San Joaquin rivers. This location is indicated by the node "SAC120."

Worksheet 13: Schematic – San Joaquin Valley

The worksheet Schematic – San Joaquin Valley presents a node-arc diagram for the floor of the San Joaquin Valley upstream from the USGS gage for the San Joaquin River near Vernalis (node SJR070). As for the Sacramento Valley schematic, historical flows are indicated using a pink fill; flows under natural conditions are indicated using a gray fill. Major inflows from the rim watersheds include flows for the San Joaquin River at Friant, Merced River at Exchequer, Tuolumne River at New Don Pedro, and Stanislaus River at New Melones.

Worksheet 14: Schematic – Eastside Streams

The worksheet *Schematic – Eastside Streams* is the third of the four schematics. The worksheet presents a node-arc diagram for the valley floor east of the Delta. This area is drained by the Cosumnes, Mokelumne, and Calaveras rivers. Flows from these watersheds are aggregated into three locations: Mokelumne River and the Calaveras Rivers at the boundary of the Delta and French Camp Slough. As for the other schematics, historical flows are indicated using a pink fill; flows under natural conditions are indicated using a gray fill. There are no observed flow records for Delta inflows from the eastside streams, and historical data are estimates derived from a depletion analysis.

Worksheet 15: Schematic – Delta

The last of the four schematics, *Schematic – Delta* presents a node-arc diagram for the Delta. The primary inflows are the Sacramento River at Freeport, Yolo Bypass at Lisbon Weir, San Joaquin River near Vernalis, Mokelumne River, and Calaveras River. As for the other schematics, historical flows are indicated using a pink fill; flows under natural conditions are indicated using a gray fill. The farthest downstream node is designated CHPPS and represents the net Delta outflow into Suisun Bay. Water use within the Delta is represented as a balance between precipitation and ET. The net depletion from these two forcings is disaggregated into seven Delta locations, similar to DWR's CalSim II model.

Worksheet 16: Input Data

All input timeseries data are stored in the worksheet *Input Data*. These data are linked to external Excel workbooks. Timeseries data are stored in over 270 columns. The data are from October 1921 through September 2009. These data are grouped by category (e.g., groundwater boundary inflow data, DayFlow data). The columns have been grouped so that the user can expand and collapse the number of columns that can be viewed. Row 16 provides the average annual flow in thousand acre-feet (TAF). The input data should not be edited directly, rather the source file should be updated and revised, if necessary. The input data are linked to the following workbooks:

- NFP_HistoricalCUAnalysis.xlsx
- NFP_IWFM_Groundwater budget.xlsx
- NFP_HistoricalValleyFloorAccretions.xlsx
- Historical flow data is not linked
- NFP_HistoricalRimInflows.xlsx
- Historical storage data is not linked
- NFP_DWR_Unimpaired_Flows.xlsx
- NFP_DayFlow.xlsx

Worksheet 17: Precipitation Subregions

The worksheet *Precipitation Subregions* contains monthly timeseries data of precipitation depth for the 21 subregions defined by C2VSim (as adjusted for the Natural Flow Project). The exception is the Delta, for which the precipitation depth is based on a 7-station weighted average and a Delta area of 679,699 acres, as defined by DWR for the CalSim 3.0 and DETAW models. These data are subsequently aggregated into four regions: Sacramento Valley, San Joaquin Valley, Eastside Streams, and Delta, and expressed as a volume. The precipitation data is linked to the following workbooks:

- NFP_C2VSim_Precipitation.xlsx
- NFP_C3_Precipitation.xlsx.

Worksheet 18: Precipitation Valley Watersheds

The worksheet *Precipitation Valley floor watersheds* contains monthly timeseries data of precipitation depth for the Water Budget Areas (WBA) defined by DWR for the CalSim 3.0 model. These data are subsequently aggregated into three regions: Sacramento Valley, San Joaquin Valley, Eastside Streams, and Delta and expressed as a volume. The precipitation data is linked to the workbook **NFP_C3_Precipitation.xlsx.**

Worksheet 19: Infiltration-Runoff

The worksheet *Infiltration-Runoff* calculates the surface runoff from precipitation using the SCS Curve Number method. Subsequently, infiltration is calculated as the difference between precipitation and runoff. Monthly values are calculated for each subregion. It is assumed that these values apply to all land use classes, other than the Aquatic class.

Worksheet 20: ETo (Reference Crop Evapotranspiration)

The worksheet *ETo* contains monthly timeseries data of reference crop evapotranspiration (ET_o) for the 16 subregions used by the NatFM from October 1921 through 2009. The ET_o data is linked to the workbook **NFP_ETc.xlsm**.

Worksheet 21: Land Use

The worksheet *Land Use* contains the land use assumptions for 16 geographic regions within the floor of the Central Valley. These regions are numbered 1 through 13. Region 5 is split into 5a and 5b; region 8 is split into 8a and 8b; region 10 is split into 10a and 10b. Originally, these regions were identical to the subregions or zones defined in C2VSim. However, the boundaries of regions 3, 4, 5, and 6 were later modified to better account for flood basins within the Sacramento Valley. Additionally, the boundary of region 9, which represents the Delta, was modified so as to agree with boundaries used by CalSim 3.0 and DETAW. The total area of the 16 regions is 7.867 million acres. The land use data is linked to the workbook **NFP_Pre1900LandUse.xlsx**.

Worksheet 22: Kc (Crop/Vegetation Coefficients)

The worksheet *Kc* contains monthly crop/vegetation coefficients (K_c) for 8 land use classes. The K_c values are divided into two types.

For 5 of the 8 land use classes, it is assumed that the vegetation is located adjacent to streams, in areas of intermittently high groundwater, and in areas prone to seasonal flooding. Actual ET is computed based on a monthly soil water balance. Once the available soil moisture is depleted, it is assumed that the vegetation wilts and ET ceases.[39] Potential ET is calculated from monthly

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[39] Actual ET for the aquatic and riparian land cover classes is assumed equal to potential ET.

timeseries of ET_o and a set of fixed 12 monthly K_c values for each land use class. These land use classes include Aquatic, Permanent Grasslands, Riparian, Wetland, and Saltbush land use.

For the other 3 land use classes (Chaparral, Hardwood, and Rainfed Grasslands), it is assumed that ET is met by precipitation stored in the root zone. In the summer and fall, once the soil moisture is depleted, ET will be reduced or cease until the soil profile is recharged from winter rains. It is assumed that these land use classes are typically located outside of the floodplain. Actual ET is dependent on the daily soil water balance. Monthly timeseries of vegetation coefficients are from work conducted by Howes et al. (2014), and are the ratio of actual ET to ET_o, computed using a daily soil water balance model. The K_c data is linked to the workbook **NFP_ETc.xlsm**. K_c values are input to a series of worksheets called *WT Subregion x (DSA xx)*.

Worksheet 23: Sacramento Stage-Discharge

The worksheet *Sacramento Stage-Discharge* presents the results of a HEC-RAS analysis of the stage-discharge relationship for the Sacramento River at 3 locations: Sacramento River at Knights Landing, Sacramento River at Fremont Weir, and Sacramento River at Natomas East Main Drain Canal. The analysis is based on channel geometry from the 2002 Sacramento and San Joaquin River Basins Comprehensive Study.

The HEC-RAS analysis is processed to provide lookup tables for water elevation for a given river flow in steps of 100 TAF. The Comprehensive Study data are based on the NGVD29 datum. The data are converted to the NAVD88 datum by subtracting 2.4 feet.

The water elevation lookup tables for the Sacramento River are used to control the outflow from the Colusa, Sutter, and American basins.

Worksheet 24: Daily Flows

The worksheet *Daily Flows* contains daily historical flows for the Sacramento River and its tributaries above Wilkins Slough. These data are used to disaggregate the monthly natural flows to daily flows for the purposes of flood routing.

Worksheet 25: Colusa Basin

The worksheet *Colusa Basin* defines the storage characteristics of the Colusa Basin in its natural state. A lookup table presents the relationship between basin elevation, wetted surface area, storage capacity, and depth. These data are used to calculate the volume of flood water stored in the basin, infiltration, and outflow.

Worksheet 26: Butte Basin

The worksheet *Butte Basin* defines the storage characteristics of the Butte Basin in its natural state. The basin is located on the left bank of the Sacramento River, north of the Sutter-Buttes. Based on recent lidar data, no significant natural storage exists. However, outflow from the basin is constricted to a narrow passage between the natural levee of the river and the Sutter-Buttes.

Worksheet 27: Sutter Basin

The worksheet *Sutter Basin* defines the storage characteristics of the Sutter Basin in its natural state. A lookup table presents the relationship between basin elevation, wetted surface area, storage capacity, and depth. These data are used to calculate the volume of flood water stored in the basin, infiltration, and outflow.

Worksheet 28: American Basin

The worksheet *American Basin* defines the storage characteristics of the American Basin in its natural state. A lookup table presents the relationship between basin elevation, wetted surface area, storage capacity, and depth. These data are used to calculate the volume of flood water stored in the basin, infiltration, and outflow.

Worksheet 29: Yolo Basin

The worksheet *Yolo Basin* defines the characteristics of the Yolo Basin in its natural state. A lookup table presents the relationship between flow through the basin and the wetted surface area. These data are used to calculate the volume of infiltration.

Worksheet 30: San Joaquin River Basin

The worksheet *San Joaquin River Basin* defines the relationship between flood flows in the San Joaquin River and the wetted/flooded surface area. This relationship is used to calculate the volume of infiltration associated with flow across the floodplain. Floodwater that infiltrates the ground surface either is stored in the root zone and used consumptively to meet vegetation ET, or percolates to the underlying groundwater aquifer.

The flow characteristics for the San Joaquin Valley were determined from a steady-state analysis using HEC-RAS. Elevation data were obtained from a historical topographic map of the San Joaquin Valley (Hall, 1887). Cross-sections through the valley were determined at 5-mile intervals. Flows of 10,000 cfs, 20,000 cfs, 30,000 cfs, 40,000 cfs, 50,000 cfs, and 100,000 cfs were considered. The corresponding flooded area for subregions 10a, 10b, 11, 12, and 13 were determined. These data are presented in cells BM7 to BS13. A logarithmic relationship was fitted to the flow-flooded area relationship for the purposes of interpolating between the flow values. This relationship is defined in a series of 5 lookup tables.

Worksheet 31: Routing Calculations

The worksheet *Routing Calculations* contains all NatFM input and output data. Monthly data from October 1921 – September 2009 are contained in rows 17-1072. Rows 1075-1162 contain the annual data. Rows 1165-1176 contain average monthly data. Row 1179 contains long-term average annual data. The routing calculations are arranged by geographic region, as follows:

- Trinity River – columns H to I
- Sacramento River and tributaries – columns K to DI

- Eastside Streams – columns DK to EF
- San Joaquin River and tributaries – columns EH to FP
- Delta – columns FR to GO

Additional columns contain the following data:

- Input data – Columns GQ to RA
- ET and groundwater simulation (summary results) – columns RC to XJ
- Dummy data for charting purposes – columns XL to YG

Each timeseries of flows is identified by name/ID contained in row 6. The prefix "U" indicates that flows are natural flows, while the prefix "H" indicates that flows are historical.

Flows through the stream/river network are calculated using simple mass balance on a daily timestep. The majority of these calculations are self-evident. However, the following sections provide greater detail for some of the more complex routing of flood flows across the floodplain and routing of flows through the Delta.

Sacramento Valley

Colusa Basin (Subregion 3)

Overbank flow to the Colusa Basin is calculated as a fixed fraction of the Sacramento River flow in excess of its channel capacity. An initial estimate of detention storage is calculated as the maximum of: (1) sum of the beginning of month storage and overbank flow; and (2) storage from the backwater from the Sacramento River downstream. The wetted area is determined from this initial estimate of basin storage. Based on this wetted area, the detention storage is revised to include any runoff from precipitation, less infiltration of floodwater into the ground (floodwater infiltrating the ground surface is either stored in the root zone or percolates to the groundwater aquifer). The revised detention storage does not account for any outflow. Subsequently, basin stage is determined from the storage-stage characteristics of the basin using the average of the beginning of month storage and the storage after accounting for flood inflows, surface runoff, and infiltration. Basin outflow is calculated based on the stage-discharge relationship. The final value of detention storage is calculated by accounting for basin outflow. Basin outflow is calculated using a daily timestep to better represent the non-linear decrease in outflow with falling stage. The estimated floodwater infiltrating the ground is calculated using a wetted surface area prior to accounting for outflow.

Butte Basin (Subregion 4)

Overbank flow to the Butte Basin is calculated as a fixed fraction of the Sacramento River flow in excess of its channel capacity. An initial estimate of detention storage is calculated as sum of the beginning of month storage and overbank flow and the wetted area determined. Based on this wetted area, the detention storage is revised to include any runoff from precipitation, less infiltration of floodwater into the ground (floodwater infiltrating the ground surface is either stored in the root zone or percolates to the groundwater aquifer). The revised detention storage does not account for any outflow. Subsequently, basin stage is determined from the storage-stage characteristics of the basin using the average of the beginning of month storage and the storage after accounting for flood inflows, surface runoff, and infiltration. Basin outflow is calculated using a daily timestep to better represent the non-linear decrease in outflow with falling stage. The estimated floodwater infiltrating the ground is calculated using a wetted surface area prior to accounting for outflow.

Sutter Basin (Subregion 5b)

Overbank flow to the Sutter Basin is calculated as a fixed fraction of the Sacramento River flow in excess of its channel capacity. Flood inflows from the Sacramento River are augmented by flood water from the Butte Basin and Feather River spills to Gilsizer Slough. An initial estimate of detention storage is calculated as the maximum of: (1) sum of the beginning of month storage and overbank flow; and (2) storage from the backwater from the Sacramento River downstream. The wetted area is determined from this initial estimate of basin storage. Based on this wetted area, the detention storage is revised to include any runoff from precipitation, less infiltration of floodwater into the ground (floodwater infiltrating the ground surface is either stored in the root zone or percolates to the groundwater aquifer). The revised detention storage does not account for any outflow. Subsequently, basin stage is determined from the storage-stage characteristics of the basin using the average of the beginning of month storage and the storage after accounting for flood inflows, surface runoff, and infiltration. Basin outflow is calculated using a daily timestep to better represent the non-linear decrease in outflow with falling stage. The estimated floodwater infiltrating the ground is calculated using a wetted surface area prior to accounting for outflow.

American Basin (Subregion 7)

Overbank flow to the American Basin is calculated as a fixed fraction of the Sacramento River flow in excess of its channel capacity. An initial estimate of detention storage is calculated as the maximum of: (1) sum of the beginning of month storage and overbank flow; and (2) storage from the backwater from the Sacramento River downstream. The wetted area is determined from this initial estimate of basin storage. Based on this wetted area, the detention storage is revised to include any runoff from precipitation, less infiltration of floodwater into the ground (floodwater infiltrating the ground surface is either stored in the root zone or percolates to the groundwater aquifer). The revised detention storage does not account for any outflow. Subsequently, basin stage is determined from the storage-stage characteristics of the basin using the average of the beginning of month storage and the storage after accounting for flood inflows, surface runoff, and infiltration. Basin outflow is calculated using a daily timestep to better represent the non-linear decrease in outflow with falling stage. The estimated floodwater infiltrating the ground is calculated using a wetted surface area prior to accounting for outflow.

Yolo Basin (Subregion 6)

Overbank flow to the Yolo Basin is calculated as a fixed fraction of the Sacramento River flow in excess of its channel capacity. No detention storage is modeled for the Yolo Basin. However, as there was no well-defined channel to transport flow through the basin, a discharge-wetted surface area was developed for the basin. This relationship is used to calculate the flooded area and resulting infiltration of floodwater into the ground. The flow through the basin is calculated as the sum of inflows from Cache and Putah creeks and flood spills from the Sacramento River at the site of the Fremont Weir (under natural flow conditions, overbank flow at the site of the Sacramento Weir is assumed to be zero). There is no inflow from the Colusa Basin through the

Knights Landing Ridge Cut. The natural channel capacity of the Yolo Basin is a user defined input. Excess water is assumed to spread over the flood plain.

San Joaquin Valley

Delta inflow from the San Joaquin Valley is equal to the flow in the San Joaquin River near Vernalis. The principle flow components of the San Joaquin River are the inflows from the rim watersheds, surface runoff, and groundwater inflows. River flows are depleted through riparian vegetation ET. Additionally, some overbank flow may not reach the Delta, but is depleted by infiltration through the ground surface.

Overbank flows for the San Joaquin River are represented at two river locations: the Mendota Pool where river flows may be augmented by flood flows from the Tulare Lake Hydrologic Region; and at Newman below the river's confluence with the Merced River. Overbank flows are assumed to be equally distributed between the left and right banks.[40] After determining the overbank flows, flood flows are routed across the floodplain. Flood water recharges the root zone, and so is indirectly depleted through soil moisture storage and ET. Additionally, once the soil profile is at field capacity,[41] flood water percolates downward to recharge five lumped-parameter groundwater basins. No detention storage is modeled in the San Joaquin Valley. However, it is recognized that some flood water may pond in small local depressions rather than flow to the Delta. This phenomenon may be simulated by artificially increasing the water holding capacity of the root zone for vegetation types located in the floodplain.

Eastside Streams

The calculation of natural flows in the Eastside Streams (Cosumnes, Mokelumne, and Calaveras) is comparatively simple. No overbank flooding is represented for these streams. Unimpaired flows from the rim watersheds are augmented by surface runoff and groundwater inflow. Flows are depleted through riparian vegetation ET. Inflows to the Delta are equal to the sum of: flows in the Mokelumne River downstream from Cosumnes River confluence, Calaveras River; and French Camp Slough.

Sacramento-San Joaquin Delta

Inflows to the Delta are the sum of inflows from three geographic regions (Sacramento Valley, San Joaquin Valley, and Eastside Streams) and minor inflow from Marsh Creek, which originates on the slopes of Mount Diablo. For calculating natural conditions, all Delta diversions and exports are assumed to be zero. The contribution of precipitation is estimated using a 7-station area-weighted average depth over the Delta area of 679,699 acres. The net Delta depletion is the consumptive use of water through soil storage, ET, and open water evaporation, less the precipitation. To facilitate comparison with CalSim II model results, the net Delta depletion is disaggregated into 7 Delta regions. The net Delta outflow is calculated as the Delta

[40] Future model refinement may distribute overbank flow according to the flow characteristics of the floodplain on the left and west banks.

[41] The NF model does not simulate the additional soil moisture stored under saturated conditions.

inflow, less Delta diversions and exports (which are assumed to be zero), less the net Delta depletion.

Boundary Flow Adjustments

The downstream boundary of the rim watersheds defines the outer limits of the valley floor watersheds. In total, the valley floor watersheds cover an area of 8.41 million acres. Located within the valley floor watersheds is the Central Valley groundwater aquifer. The NatFM fully represents the surface hydrology of lands overlying the groundwater aquifer (excluding the Tulare Lake Hydrologic Region) and the aquifer itself. However, there are lands located on the margins of the valley floor watersheds that lie upslope of the groundwater aquifer. These lands are not represented in the surface hydrology calculations within the NatFM (i.e., worksheets *ET Subregion xx*). Inflows from these lands are calculated separately in a set of three worksheets: *ET upslope SAC*, *ET Upslope SJR*, and *ET Upslope Eastside*. The flow contribution from these lands is a balance between precipitation, ET, and storage in the root zone. Any water that percolates downward from the root zone is assumed to quickly return to the stream network as interflow. The flow contributions are added to the routing calculations in columns CQ, DM, DO, and EW.

Worksheet 32: Daily Routing

The worksheet *Daily Routing* disaggregates the monthly flow in the Sacramento River at Butte City to a daily flow based on the historical daily inflow to Lake Shasta (or the flow at the dam site before construction of the dam) combined with the historical inflows from the Sacramento River tributaries. Calculation of overbank spills to Butte, Colusa, and Sutter basins is determined using daily river flows.

Worksheet 33: ET Summary

The worksheet *ET Summary* contains a summary from the set of 16 worksheets that calculate depletions for each subregion based on a root zone soil moisture budget. There are 7 columns of output for each subregion. These are as follows (where x indicates the number of the subregion):

- **UCUPR_Rx**, the consumptive use of precipitation through root zone storage and ET
- UCUGW_Rx_max, the consumptive use of groundwater under conditions of a high groundwater table.
- UCUGW_Rx_min, the consumptive use of groundwater under conditions of a low groundwater table.
- UCUNV_Rx_yyyyyy, the consumptive use of streams and rivers from riparian vegetation.
- UFFA_Rx, flooded area.
- UCUFF_Rx, the consumptive use of floodwater (flood flows) through root zone storage and ET.

- UFF_Rx_GWxmax, the floodwater available to recharge the groundwater through deep percolation.

Worksheet 34: ET Upslope SAC

The NatFM considers various geographic regions for developing a water balance for the Delta and all lands that drain into the Delta. These geographic regions have been defined for various other projects and programs and are not necessarily consistent. The NatFM divides the Sacramento River and San Joaquin River hydrologic regions into rim watersheds and valley floor watersheds. The boundaries between these two types of watersheds have been defined by DWR in work conducted for the CalSim 3.0 model. The NatFM represents the flow contribution of the rim watersheds by timeseries of inflow arcs to the streams and rivers on the floor of the Central Valley. Additionally, the NatFM considers the boundary of the Central Valley groundwater aquifer as defined by DWR's C2VSim (DWR, 2013a). Within this boundary there is significant interaction between surface water and groundwater. The NatFM includes a complete hydrology of lands overlying the groundwater aquifer (as defined by C2VSim), accounting for precipitation, ET, root zone storage, surface-runoff and deep percolation. However, within the Sacramento River Hydrologic Region there is a significant area between the rim watershed boundary (defined for CalSim 3.0) and the groundwater aquifer boundary (defined for C2VSim). The flow contribution of this area is accounted for by the worksheet *ET Upslope Sac*.

Calculations presented in worksheet *ET Upslope SAC* are similar to those described for the worksheet *ET Subregion 1 (DSA 58).* The worksheet contains a soil water balance for lands located between the rim watershed boundaries and the groundwater aquifer boundaries. It is assumed that these lands are not subject to flooding as they are located on the outer margins of the Central Valley floor. The flow contribution from these lands is calculated as the product of precipitation depth and area, less the consumptive use off precipitation, less consumptive use of surface water from riparian vegetation, and less the consumptive use of shallow groundwater for the Hardwood land class. The sections below describe the source of land use, precipitation, and ET_o data for the calculations. The flow contribution from these lands is approximately 0.7 MAF per year.

Land Use

Land use for the seven land use classes are calculated as the difference between lands located in the valley floor watersheds (as defined for CalSim 3.0) and lands located in the subregions (as defined for C2VSim). The total area is approximately 941,000 acres.[42]

Precipitation

Monthly precipitation depth is calculated as difference precipitation volume over the valley floor watersheds (as defined for CalSim 3.0) to the volume over the subregions (as defined for

[42] The C2VSim subregions are not fully contained within the CalSim 3.0 valley watersheds. Consequently, the area of some land use classes may be negative.

C2VSim), divided by the difference in land area. Average annual precipitation is approximately 29 inches per year.

Reference Crop Evapotranspiration

The ET_o is assumed equal to that of Subregion 1, as most of the unaccounted for lands are located in the Redding Basin and on the margins of the valley. ET_o values may be refined in future revisions to the NatFM. Average annual ET_o is approximately 52 inches per year.

Worksheet 35: ET Upslope SJR

The worksheet *ET Upslope SJR* serves a similar purpose to the worksheet *ET Upslope SAC*. It calculates the flow contribution of lands located on the margins of the San Joaquin Valley floor, which lie between the valley floor watersheds (defined for CalSim 3.0) and the subregions (defined for C2VSim). The flow contribution from these lands is small, less than 0.1 MAF per year. The sections below describe the source of land use, precipitation, and ET_o data for the calculations.

Land Use

Land use for the seven land use classes are calculated as the difference between lands located in the valley floor watersheds (as defined for CalSim 3.0) and lands located in the subregions (as defined for C2VSim). The total area is approximately 28,000 acres.[43]

Precipitation

Average annual precipitation volume for the valley floor watersheds (as defined for CalSim 3.0) is slightly less than that for the subregions (as defined for C2VSim), although the area of the valley floor watersheds is slightly larger. Therefore, precipitation for Subregion 10a was used as a surrogate for precipitation for the unaccounted 28,000 acres.

Reference Crop Evapotranspiration

The ET_o is assumed equal to that of Subregion 10a. ET_o values may be refined in future revisions to the NatFM. Average annual ET_o is approximately 54 inches per year.

Worksheet 36: ET Upslope Eastside

The worksheet *ET Upslope Eastside* calculates the flow contribution of lands located east of the Delta, which lie in the rim watersheds (defined for CalSim 3.0) and the subregions (defined for C2VSim). This flow contribution is subtracted from the rim watershed flows to avoid double counting. The sections below describe the source of land use, precipitation, and ET_o data for the calculations. The calculation shows that for the overlapping area ET exceeds precipitation, therefore, the rim watershed flow was increased. However, the adjustment is small, less than 0.1 MAF per year.

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[43] The C2VSim subregions are not fully contained within the CalSim 3.0 valley watersheds. Consequently, the area of some land use classes may be negative.

Land Use

Land use for the seven land use classes are calculated as the difference between lands located in the valley floor watersheds (as defined for CalSim 3.0) and lands located in the subregions (as defined for C2VSim). For lands east of the Delta, the subregions are more extensive than the valley floor watersheds. Therefore, in the NatFM, part of the flow contribution of the rim watersheds is also accounted for by the subregions. The overlapping area between the subregions and rim watersheds is approximately 239,000 acres.

Precipitation

Monthly precipitation depth is calculated as difference precipitation volume over the valley floor watersheds (as defined for CalSim 3.0) to the volume over the subregions (as defined for C2VSim), divided by the difference in land area. Average annual precipitation is approximately 20 inches per year.

Reference Crop Evapotranspiration

The ET_o is assumed equal to that of Subregion 8a. ET_o values may be refined in future revisions to the NatFM. Average annual ET_o is approximately 57 inches per year.

Worksheet 37: ET Subregion 1 (DSA 58)

Worksheet *ET Subregion 1 (DSA 58)* is one of 16 worksheets that compute ET for 7 land use types on a monthly timestep for a particular region. The sections below provide a detailed description of the calculations. All columns contain monthly timeseries data from October 1921 through September 2009. Row 7 typically contains the long-term average annual value. The calculation of ET is divided into areas that are flooded and areas that are not flooded. In the flooded areas, the root zone is recharged by the flood water.

Column D – ET_o for subregion (controlled by cell D3).

Column E – Precipitation for subregion (controlled by cell D3).

Column F – Detention storage within subregion (controlled by cell F6). For subregions where flood flows are not modeled (subregions 1, 2, 5a, 8a, 8b, 9) this column is set to zero.

Column G – Flooded area (computed for the beginning of the timestep)

Column H – Flooded depth.

Columns I-O – Non-flooded area by vegetation class. Row 8 contains the total area for each land use class. The non-flooded area is calculated as the total area less the flooded area.

Columns P-V – Flooded area by vegetation class. These data are not derived from a spatial analysis. The portions of the total area that floods are determined by assigning the total flooded area to the different land use classes in the following order: Aquatic, Riparian, Saltbush, Wetland, Chaparral, Grassland, Hardwood. For example, the wetlands are only flooded after all of the Aquatic, Riparian, and Saltbush are flooded.

Columns W-AD – Potential ET by vegetation class in inches. Product of ET_o and K_c. For the Rainfed Grassland, Chaparral, and Hardwood land use classes, the K_c values already incorporate summer senescence due to water shortage. These land use classes are assumed to lie outside the floodplain.

Columns AE-AL – Calculate the readily available soil moisture in the root zone for each land use class for areas that are not flooded. The storage is calculated as the sum of the previous end-of-month storage plus precipitation, less potential ET. Precipitation recharges the soil profile before either running-off the surface or deep percolating to the groundwater aquifer. This assumption is similar to that made in DWR's Consumptive Use model that provides the hydrology inputs to CalSim II.

However, storage is limited by the maximum value given in row 4. The previous end-of-month storage is the weighted average of areas that were not flooded in the previous month and areas that were flooded but are currently not flooded. There is no gradual reduction in ET as the soil profile becomes depleted of soil moisture. Actual ET is set equal to potential ET until the soil moisture reaches zero. Soil moisture storage is not computed for the Aquatic land use class.

Columns AM-AT – Calculate the readily available soil moisture in the root zone for each land use class for areas that are flooded. The storage is calculated as the sum of the previous end-of-month storage plus precipitation, plus the depth of flooding, less ET. However, storage is limited by the maximum value given in row 4. The previous end-of-month storage is the weighted average of areas that were flooded in the previous month and areas that were not flooded but are currently flooded. Actual ET is set equal to potential ET until the soil moisture reaches zero. Soil moisture storage is not computed for the Aquatic land use class. The Rainfed Grassland land use class is always assumed to be non-flooded.

Columns AU-BB – Calculate a storage adjustment for lands that were previously flooded, but are not flooded in the current month. This is needed to maintain mass balance.

Columns BC-BJ – Calculate a storage adjustment for lands that were previously not flooded, but are flooded in the current month. This is needed to maintain mass balance.

Columns BK-BR – Calculate the actual ET for the non-flooded areas in inches. Actual ET is less than potential ET when the soil moisture storage is zero. When the soil moisture storage is zero, actual ET is calculated as the sum of precipitation and the decrease in soil moisture storage.

Columns BS-BZ – Calculate the actual ET for the flooded areas in inches. Actual ET is less than potential ET when the soil moisture storage is zero. When the soil moisture storage is zero, actual ET is calculated as the sum of precipitation and the decrease in soil moisture storage.

Columns CA-CH – Calculate the consumptive use of precipitation by land use type for the non-flooded areas in inches. This is the precipitation that is stored in the root zone and is available to meet vegetation ET in the current or future months. It is calculated as the sum of the decrease in soil moisture storage and the potential ET, but cannot be greater than the total precipitation.

Columns CI-CP – Calculate the consumptive use of precipitation by land use type for the non-flooded areas in inches. This is the precipitation that is stored in the root zone and is available to meet vegetation ET in the current or future months. It is calculated as the sum of the decrease in soil moisture storage and the potential ET, but cannot be greater than the total precipitation.

Columns CQ-CX – Calculate the consumptive use of floodwater by land use type for flooded areas in inches. This is floodwater that is stored in the root zone and is available to meet vegetation ET in the current or future months. It is calculated as the change in soil moisture storage after accounting for recharge from precipitation and depletion from ET.

Columns CY-DF – Calculate the potential for groundwater or seepage from streams (surface water) to meet any shortfall in ET in non-flooded areas. It is calculated as the difference between potential and actual ET in inches.

Columns DG-DN – Calculate the potential for groundwater or seepage from streams (surface water) to meet any shortfall in ET in flooded areas. It is calculated as the difference between potential and actual ET in inches.

Columns DO-DW – Calculate the consumptive use of precipitation on all lands as a volume (TAF).

Columns DX-EF – Calculate the consumptive use of flood water as a volume (TAF).

Columns EG-EO – Calculate the potential consumptive use of groundwater or surface water streams as a volume (TAF).

Columns EP-EU – Calculate the total depletion of water by root zone storage or ET as a volume (TAF). This depletion is divided into depletion from a high groundwater table (Column EP), depletion from a low groundwater table (Column EQ), depletion of precipitation (Column ER), depletion of surface water (Column ES), and depletion of flood water (ET). Column potential consumptive use of groundwater or surface water streams as a volume (TAF). Precipitation that is not consumptively used becomes surface runoff or recharges the underlying aquifer. For the Aquatic and Riparian land use classes, it is assumed that potential ET not met from precipitation or floodwater is met by depletion of stream flows. For the Hardwood land use class it is assumed that potential ET not met by precipitation or floodwater is always met by groundwater. For the other land use classes, potential ET is only met under conditions of a high groundwater table. These conditions are dynamically determined in the model.

Columns EV-FC – Perform a mass balance check for each of the 7 land use classes. The combined depletion of precipitation, floodwater, groundwater, and surface water must equal the potential ET and the change in storage for each timestep.

Worksheets 38-52: ET Subregion 2 to ET Subregion 13

These 15 worksheets are identical to ET Subregion 1 (DSA 58) except for cell references D1 and G4. Cell D1 controls precipitation, ETo, and land use inputs. Cell G4 defines the area of flooding in a particular timestep.

Worksheet 53: GW Summary

The worksheet *GW Summary* contains a summary from the set of 16 worksheets that calculate groundwater storage and stream-groundwater interaction for each subregion. There are 10 columns of output for each subregion. These are as follows (where x indicates the number of the subregion):

- **PINF_Rx**, precipitation (TAF) for Subregion x
- **UCUPR_Rx**, consumptive use of precipitation (TAF) for Subregion x.
- **UP_Rx_GWx**, deep percolation of precipitation (TAF) from Subregion x to Groundwater basin x.
- **UP_Rx_yyyyyy**, surface runoff from precipitation (TAF) from Subregion x to model node yyyyyy.
- **UFF_Rx_GWx**, deep percolation from floodwater (TAF) from Subregion x to Groundwater basin x.
- **BF_GW_Rx**, lateral boundary flow (TAF) to Groundwater Basin x.
- **UCUGW_Rx**, the consumptive use of groundwater through evapotranspiration for Groundwater Basin x.
- **US_GW_Rx**, groundwater storage for basin x

- **UDS_GW_Rx**, change in storage in Groundwater Basin x.
- **UGW_Rx_yyyyyy**, groundwater inflow from Groundwater Basin x to stream node yyyyyy.

Worksheet 51: GW Subregion 1 (DSA 58)

The reaction of the groundwater basin to vertical and horizontal stresses is determined by various parameters that are defined in Column C. These parameters include the following:

- Area
- Storage at River Level
- Initial Storage
- Hydraulic Conductivity
- Specific Yield
- Horizontal Distance
- Wetted Depth
- Wetted Length
- Vertical Height of aquifer above or below equilibrium position
- Seepage Rate
- Seepage Rate
- Groundwater all at Root Zone
- Groundwater all below Root Zone

The sections below provide a detailed description of the calculation of groundwater stresses (fluxes) and storage. All columns contain monthly timeseries data from October 1921 through September 2009. All columns are in TAF unless otherwise stated below.

Column G – Infiltration from precipitation.

Column H – Consumptive use of precipitation through storage in the root zone and ET

Column I – Deep percolation of precipitation to the groundwater aquifer. This is calculated as the difference between the total precipitation and the part which is consumptively used, but limited by the “seepage rate” in cell C13.

Column J – Surface runoff. It is assumed that surface runoff occurs only when the soil profile is at or above field capacity and deep percolation is at the maximum seepage rate.

Column K – Deep percolation of floodwater. This is calculated as the depth of floodwater less floodwater that is stored in the root zone. It is limited by the seepage rate in cell

C13. The calculations account for the flooded area compared to the total area of the subregion. For Subregion 1, this column is set equal to zero, as no flooding is simulated within this subregion.

Column L – Lateral subsurface inflow to the groundwater basin from subsurface flow originating outside of the groundwater basin. These flows are either set equal to values derived from C2VSim or are set to zero.

Column M – Evaporative losses from a low groundwater table, which supports ET by the various land use classes. Under conditions of a low water table, evaporative losses are limited to the water needed to support ET from the Hardwood land use class.

Column N – Evaporative losses from a high groundwater table, which supports ET by the various land use classes. Under conditions of a high water table, evaporative losses support ET from all land use classes except Aquatic and Riparian. Aquatic ET is assumed to be a direct depletion of streams and rivers through evaporation. Riparian vegetation is assumed to deplete adjacent streams and rivers when precipitation is not available.

Column O – calculates the monthly fraction of evaporative losses to be considered so that the total evaporative loss is the minimum amount under low water table conditions plus a fraction of the additional amount that occurs when groundwater is near the ground surface. The monthly fraction varies between 0 and 1 based on the groundwater elevation. Two threshold groundwater elevations are defined. At the upper threshold (cell C15) the groundwater elevation is assumed to be sufficiently high to support 100 percent of the surface vegetation ET. At the lower threshold (cell C16) the groundwater elevation is assumed to be sufficiently low to support no additional surface vegetation ET other than for the Hardwood land use class. The NatFM interpolates between these two thresholds to determine the monthly fraction.

Column P – Evaporative loss from the groundwater table.

Column Q – Groundwater storage. This is calculated as the end-of-month storage and the sum of vertical recharge in the current month from precipitation and floodwater, less evaporative losses in the current month, less the groundwater inflow to the stream system in the current month. The initial storage (September 1921) is chosen so that there is no significant change in storage over the period of simulation.

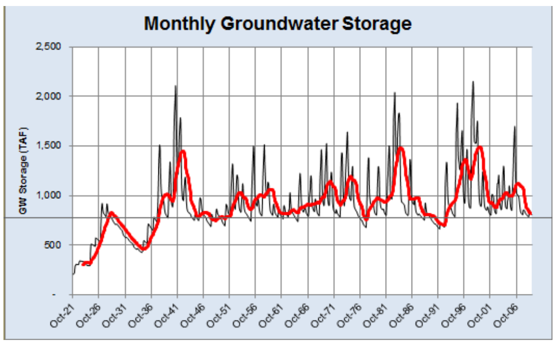
Column R – Average groundwater elevation for the subregion. The elevation is measured relative to the stream stage, which is assumed to be constant. The elevation is calculated as the end-of-month groundwater storage for the previous month divided by the specific yield and the area of the groundwater basin/subregion.

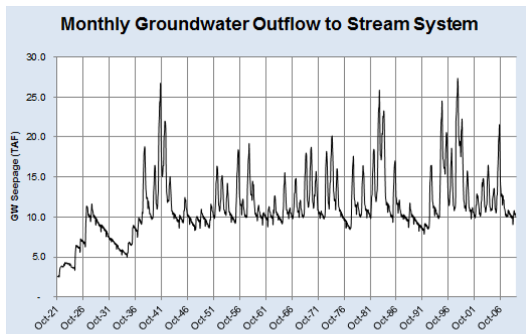
Column S – Groundwater inflow is calculated based on Darcy's Law, the wetted depth of flow and the wetted length of flow. The hydraulic gradient is determined by the groundwater elevation divided by the width of the aquifer perpendicular to the stream.

Four charts in worksheet *GW Subregion 1 (DSA 58)* present:

- Monthly timeseries of storage and the 24-month moving average.
- Average monthly storage.
- Monthly timeseries of groundwater inflow to the stream system.
- Average monthly groundwater inflow to the stream system.

These charts are used to adjust the groundwater basin parameters to obtain a reasonable performance. In particular, initialization problems may be present when the initial value of groundwater storage is set too low or too high, as evident in the charts below.





Worksheet 54-69: GW Subregion 2 to GW Subregion 13

These 15 worksheets are identical to GW Subregion 1 (DSA 58) except for cell references B1 through E1 and cell D2. These cells control groundwater parameters read from the worksheet *User Defined Input Assumptions*.

Worksheet 70: Notes – Overview

The *Notes – Overview* worksheet provides a summary of the NatFM. The spreadsheet-based model routes monthly natural flows through the streams, rivers, and channels of the Sacramento and San Joaquin valleys, and the Delta. The stream network within the valley floor is dynamically linked to the land surface hydrology and the underlying groundwater aquifer. The Central Valley groundwater aquifer is represented by a series on independent lumped-parameter groundwater basins.

Sources of water in the NatFM include:

- Surface water inflows from the mountain and foothill watersheds that surround the Central Valley (rim watersheds).
- Subsurface lateral inflows from the rim watersheds to the Central Valley groundwater aquifer.
- Precipitation falling on the floor of the Central Valley (valley floor watersheds).

- Groundwater storage.

The NatFM includes dynamic simulation of flows within the valley floor watersheds on a monthly timestep. This dynamic simulation includes the following flow components:

- Surface runoff and infiltration from precipitation.
- Over-bank flows and associated detention storage and recharge of the root zone and underlying groundwater aquifer.
- Root zone soil moisture and associated ET and deep percolation.
- Groundwater storage, stream-aquifer interaction, and groundwater lost through capillary rise and transpiration from the surface vegetation.

During high river stage, over-bank flow from the Sacramento and San Joaquin rivers and their tributaries discharged into low-lying natural basins. Subsequently, some of these flood waters drained back to the stream system. Other flood water evaporated or recharged the root zone and underlying groundwater aquifer

In the NatFM, routing of flows through the river system accounts for inflows from the rim watersheds, bank overflow during high river stage, overland flow, detention storage in the low-lying basins and gradual drainage back to the river system, surface runoff entering the rivers (either directly or indirectly via the low-lying basins), and the stream-aquifer interaction.

Worksheet 71: Notes – Schematics

The worksheet *Notes – Schematics* describes the four worksheets: *Schematic – Sacramento Valley*, *Schematic – San Joaquin Valley*, *Schematic – Eastside Streams*, and *Schematic – Delta.* These worksheets present a node-arc diagram for the Delta and upstream drainage areas for the purposes of viewing model results and comparing historical and natural flows.

Worksheet 72: Notes - Rim Inflows

The worksheet *Notes – Rim Inflows* presents a summary of the inflows from the rim watersheds to the valley floor. For each rim inflow arc (e.g., HI_SHSTA), the worksheet lists: a description of the arc, source of data, and average annual flow in TAF. Rim inflows are divided into two types. The first type of rim inflow is unimpaired flow (prefix UI_), where the historical flow has been adjusted to remove the effects of upstream storage regulation and diversions. The second type of rim inflow is historical flow (prefix HI_), for which the natural flow is assumed equal to the historical flow. Rim watersheds belonging to this second type are relatively undeveloped, with no significant storage regulation or consumptive use of water within the watershed. Within each type, rim inflows are organized by hydrologic region. The worksheet *Notes – Rim Inflows* also presents maps delineating the rim watersheds of the Sacramento River and San Joaquin River hydrologic regions.

For the Sacramento River Hydrologic Region, 60 rim watersheds are identified. The average annual inflow from these watersheds is 19.9 MAF. For the San Joaquin River Hydrologic Region, 46 rim watersheds are identified. The average annual inflow from these watersheds is

7.5 MAF. The natural inflow from the Tulare Lake Hydrologic Region is assumed to average approximately 0.2 MAF per year (DWR, 2012a).

Worksheet 73: Notes – Groundwater

The worksheet *Notes – Groundwater* describes how groundwater is represented in the NatFM. Under natural conditions, groundwater storage would increase in the winter and spring due to recharge from precipitation and decrease in the summer and fall due to groundwater discharge to the stream system.

To simulate groundwater interactions with surface waters, a set of lumped-parameter models were created. The lumped-parameter models are independent, i.e., hydraulically unconnected. Groundwater-surface water interactions are simulated using a stylized representation of the system. Groundwater is represented as a wedge that is symmetrical about the stream/river; discharge to the stream system from one side of the wedge will therefore represent half the total discharge. Groundwater flow to the river is dependent on the relative elevation of the groundwater table to the river stage. Groundwater is recharged from precipitation and flood flows over the floodplain and depleted through evapotranspiration (ET) and flow to the stream system.

Input parameters for the lumped-parameter groundwater models are as follows (cell references refer to the worksheets *GW Subregion xx (DSA yy)*:

Area: the areal extent of the aquifer in acres. Cell C4.

Storage at river level: groundwater storage in TAF at which the groundwater elevation is equal to the river stage. Cell C5.

Initial storage: groundwater storage in TAF at the start of the simulation. Cell C6.

Hydraulic conductivity: a measure of the ability of the aquifer to transmit water represented in feet per day. Cell C7.

Specific yield: the porosity of the aquifer, represented as a fractional volume (between 0 and 1). Cell C8.

Horizontal distance: a representative distance in feet for the groundwater-river geometry, taken as the length from the farthest edge of the aquifer to the river. Cell C9.

Wetted depth: the depth of the river in feet. Cell C10.

Wetted length: the horizontal length in feet of the interface between the river and groundwater, calculated as the area divided by the horizontal distance. Cell C11.

Seepage rate: the maximum infiltration rate in inches/month. Cell C13.

Groundwater at root zone: the average groundwater elevation in feet measured above the river stage at which 100 percent of the vegetation is assumed to have access to groundwater. Cell C15.

Groundwater below root zone: the average groundwater elevation in feet measured above the river stage at which 0 percent of the vegetation is assumed to have access to groundwater. Cell C16.

Worksheet 74: Notes - Historical Accretions

The worksheet *Notes – Historical Accretions* presents a summary of the historical accretions for the major river reaches, calculated as the difference in observed flows at downstream and upstream gages. These data are not used in determining the natural flows, but are presented for comparative purposes.

Worksheet 75: Notes - Input Metadata

The worksheet *Notes – Input Metadata* lists all required input data and checks that the input data has been successfully loaded from external sources (linked Excel files).

Worksheet 76: Notes - Channel Capacities

The worksheet *Notes – Channel Capacities* describes the Sacramento and San Joaquin rivers as they existed in the 19th century. The worksheet also presents a summary of a HEC-RAS analysis of channel capacities of the Sacramento River, Feather River, and San Joaquin River. The capacity is determined as the flow for which the river stage is at the elevation of the adjacent bank at the far side of the flood levee.

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Chapter 6
Supporting Spreadsheets

This section describes a set of supporting spreadsheets that contain input data for the NatFM. These spreadsheets are dynamically linked to the NatFM. Changes to input data in the supporting spreadsheets will be automatically translated to the Routing Model on opening the model. The supporting spreadsheets have the following common attributes:

- All supporting spreadsheets are named using the prefix "NFP_".
- Each file contains a ReadMe worksheet which briefly describes the file and documents all file changes.
- All input data linked to the Routing Model are contained in worksheets named NFP_Input.

NFP_ReadMe.docx

This WORD file contains a brief summary of all supporting files developed for the Routing Model.

NFP_AreaAndFlowSummary.xlsx

The workbook *NFP_AreaandFlowSummary.xlsx* contains a summary of monthly flows from the rim watersheds to the valley floor, monthly precipitation over the valley floor, and valley land use. The purpose of the workbook is to provide data for work conducted by Fox et al. (2014). The workbook is not used by the NatFM.

NFP_C2VSim_GroundwaterBudget.xlsx

The workbook *NFP_C2VSim_GroundwaterBudget.xlsx* summarizes monthly output data from C2VSim Run 374,[44] including groundwater storage, groundwater pumping, groundwater inflow to streams, and groundwater boundary inflows. The NatFM is linked to *NFP_C2VSim_GroundwaterBudget.xlsx* to identify boundary inflows for the lumped parameter groundwater models. Simulated historical groundwater storage is no longer used in the NatFM.

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[44] C2VSim Run 374 simulates historical conditions within the Central Valley from October 1921 through September

NFP_C2VSim_Precipitation.xlsx

DWR has developed an integrated surface water groundwater model of the water resources of the Central Valley. Known as the California Central Valley Simulation Model (C2VSim), the model simulates historical groundwater conditions using a monthly timestep from October 1921 through September 2009. The model defines 21 subregions that cover the floor of the Central Valley; 13 of these regions cover the Sacramento and San Joaquin valleys, including the Delta. The remaining 8 regions are located in the Tulare Lake Hydrologic Region. Subregions are aggregated from a total of 1,392 finite elements. C2VSim input data is either by element or by subregion. Precipitation data is defined for each of the C2VSim elements. Model output data is summarized by subregion.

The Routing Model uses the subregions defined by C2VSim to disaggregate the Sacramento and San Joaquin valleys into separate groundwater regions. For each of these regions, the Routing Model calculates surface runoff, infiltration, evapotranspiration (ET), and deep percolation to the underlying aquifer. Monthly precipitation data for these regions was obtained from the 2013 release of C2VSim (DWR, 2013a) and the data are contained in the file *NFP_C2VSim_Precipitation.xlsx*. *NFP_C2VSim_Precipitation.xlsx* contains precipitation data for the 21 regions, expressed in inches and acre-feet. Regions 6, 8, and 10 were divided into two sub-regions so as to better model runoff to particular streams represented in the Routing Model.

During later refinement of the Routing Model, it was found that Regions 3,4, 5, and 6 did not match the boundaries of the Colusa, Butte, Sutter, and Yolo basins. The C2VSim element data was reaggregated to better match these basins. This reaggreation of element precipitation data was conducted using an Access database. The name of the database file is *NFP_C2VSim_Precipitation.accdb*.

NFP_C2VSim_RootZoneMoistureBudget.xlsx

The workbook *NFP_C2VSim_RootZoneMoistureBudget.xlsx* contains the monthly root zone soil moisture budget for the 21 C2VSim subregions from C2VSim Run 374. The workbook is not used by the NatFM.

NFP_C3_Precipitation.xlsx

A key input to the Routing Model is the estimate of historical monthly precipitation over the floor of the Central Valley. Distributed grids of precipitation were obtained from the PRISM[45] Climate Group at Oregon State University (PRISM, 2013). The PRISM climate mapping system is a unique knowledge-based system that uses point measurements to produce continuous, gridded estimates of monthly, annual, or event-based climate data. PRISM incorporates point data, a digital elevation model, and expert knowledge of complex climatic extremes, including rain shadows, coastal effects, and temperature inversions. PRISM data sets are recognized

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[45] Parameter-Elevation Regressions on Independent Slopes Model

worldwide as the highest quality spatial climate data sets currently available and are the official climate data for the U.S. Department of Agriculture (USDA).

PRISM data were intersection with regions within the valley floor, termed Water Budget Areas (WBA). These regions were developed to support the CalSim 3.0 project and have little significance to the Natural Flow Project. However, precipitation data by WBA were aggregated to define the total precipitation over the floor of the Sacramento Valley and the floor of the San Joaquin Valley. All data analysis were performed by DWR as the PRISM data sets are proprietary. *NFP_C3_Precipitation.xlsx* contains the PRISM precipitation data by WBA.

To be consistent with DWR on-going projects, precipitation for the Delta was calculated using an area-weighted precipitation data from 7 stations (Brentwood, Galt, Lodi, Rio Vista, Stockton, Davis, Tracy-Carbona). This analysis is presented in *NFP_C3_Precipitation.xlsx* and is based on a Delta area of 679,699 acres. The longterm average annual Delta precipitation (1922 – 2009) is 15.01 inches.

NFP_ChannelCapacities.xlsx

The workbook *NFP_ChannelCapacities.xlsx* is no longer used. This workbook has been incorporated into the NatFM.

NFP_DayFlow.xlsx

DAYFLOW is a computer program developed by DWR to estimate daily tidally-average or freshwater Delta outflow. The program uses daily river inflows, water exports, precipitation, and estimates of Delta agriculture depletions to estimate the “net” flow at the confluence of the Sacramento and San Joaquin Rivers, nominally at Chipps Island (DWR, 2013b). The original DAYFLOW documentation contains the computational scheme that was used to back-calculate the 1930 – 1956 DAYFLOW output. The 1986 DAYFLOW documentation guided DAYFLOW estimates until 1996. The full DAYFLOW documentation describes the computational scheme used for the current releases of all DAYFLOW output.

The workbook *NFP_DayFlow.xlsx* contains daily DAYFLOW data from October 1, 1929 through September 30, 2012. These data also are aggregated to monthly and annual values. Additionally, *NFP_DayFlow.xlsx* calculates historical daily net Delta outflow from October 1, 1921 through September 30, 1929 using available gage data, or estimated data where historical data are unavailable.

DAYFLOW has not used a constant area for the Delta. Before October 1980, DAYFLOW used an area of 738,000 acres for the Delta accretions and depletions calculations. Beginning October 1980, the area was revised to 682,230 acres. *NFP_DayFlow.xlsx* presents net Delta outflow based on an updated Delta area of 679,699 acres based on work conducted by DWR for the CalSim 3.0 and DETAW projects. *NFP_DayFlow.xlsx* also presents net Delta outflow using a 7-station area-weighted average precipitation rather than the single station used by DAYFLOW.

NFP_DeltaPrecipitation.xlsx

The workbook *NFP_DeltaPrecipitation.xlsx* is not a source of data for the NatFM, but provides background information on Delta precipitation. The workbook compares DayFlow precipitation (QPREC) to other precipitation data sources, including PRISM gridded data, and gage data for seven stations within or adjacent to the Delta.

DayFlow uses precipitation station at Stockton Fire Station No. 4 to represent Delta-wide precipitation. DayFlow assumes that runoff from precipitation during a particular day takes place uniformly over that day and the following four days. The volume of precipitation is calculated by multiplying the depth of precipitation measured at Stockton Fire Station 4 during a day by the area of the watersheds making up the Delta. For October 1, 1955, through September 30, 1980, this area was taken to be 738,000 acres. For October 1, 1980 through September 30, 1984, this area was changed to 682,230 acres, an area about 7.6 percent smaller than the former. Documentation for this change is not available, QPREC has not been revised using a single value for the area of the Delta. Therefore, the values for QPREC reported by DayFlow reflect this discrepancy in Delta watershed area.

DayFlow data for Stockton Fire Station No. 4 does not agree with data published by CDEC, or data published by UC Davis. The reason for this is unclear.

The following conclusions were drawn from the comparison of precipitation data sources:

- The Stockton precipitation gage is representative of Delta precipitation, however, the Stockton gage data from 1922 to 1926 and from 1997 to 2010 are inconsistent with PRISM and other gage data.
- DayFlow data from 1930 to 1955 are approximately 10 percent lower than PRISM and other gage data.
- DayFlow data from 1956 to 1980 are consistent with other station data.
- DAYFLOW data from 1981 to 2010 are approximately 3 percent lower than PRISM and other gage data, and are generally less consistent.

NFP_DWR_Unimpaired_Flows.xlsx

DWR publishes estimates of historical monthly unimpaired flows for the major watersheds in the Central Valley. The Fifth Edition of the *Draft California Central Valley Unimpaired Flow Data* (DWR, 2012a) presents unimpaired flow data for 24 watersheds for water years 1922 through 2010. This report was later withdrawn by DWR because of concerns about the validity of some flow estimates.

NFP_DWR_Unimpiared_Flows.xlsx contains the DWR unimpaired flow data. The Routing Model uses DWR unimpaired flow estimates for the following locations:

- Feather River at Oroville

- American River at Fair Oaks
- Yuba River at Smartville
- Cosumnes River at Michigan Bar
- Mokelumne River near Mokelumne Hill
- James Bypass near San Joaquin
- San Joaquin River at Friant
- Merced River at Hensley Dam
- Tuolumne River at New Don Pedro Dam
- Stanislaus River at New Melones Dam

NFP_DWRUnimpairedFlows_vs_CalSim30Inflows.xlsx

The workbook *NFP_DWR_UnimpairedFlows_vs_CalSim30Inflows.xlsx* is not a source of data for the NatFM, but provides background information the flows from the rim watersheds to the valley floor. The workbook compares data DWR unimpaired flows (DWR, 2012a) to those developed by DWR as part of the CalSim 3.0 project.

In the Sacramento Valley, the major difference between CalSim 3.0 inflows and DWR unimpaired inflows is the treatment of the Redding Basin. DWR calculates the unimpaired flow at the discontinued USGS gage Sacramento River near Red Bluff. This includes significant valley floor accretions between Shasta Dam and the USGS gage. CalSim 3.0 rim inflows consider only the mountain and foothill watersheds.

In the San Joaquin Valley, the major difference between CalSim 3.0 inflows and DWR unimpaired inflows is in the treatment of inflows from minor streams. DWR UF17 is determined by multiplying the unimpaired flow at the Buchanan Dam site by a factor of 2.55. CalSim 3.0 rim inflows considers individual streams and their watersheds.

NFP_ETc.xlsm

The workbook *NFP_ETc.xlsx* is the NatFM data source for ET_o and K_{veg}. The worksheet Monthly ETo by PA contains monthly ETo values for various Planning Areas that cover the floor of the Central Valley. These values were generated by DWR using historical temperature data. ETo values by Planning Area are translated to ETo values by Subregion for use in the NatFM based on a GIS mapping of Planning Areas to Subregions. For five land use classes (Aquatic, Perennial Grasslands, Riparian, Wetlands, and Saltbush), ET values are calculated by multiplying ETo values by fixed monthly Kveg coefficients. For the remaining land use classes (Hardwood, Rainfed Grasslands, and Chaparral), ET values by Planning Area are mapped to ET values by Subregion based on a GIS mapping specific to each land use class.

NFP_GroundwaterDepths.xlsm

The workbook *NFP_GroundwaterDepths.xlsx* is not a source of data for the NatFM, but provides background information on historical groundwater conditions, as simulated by the C2VSim model. For each of the C2VSim subregions, the workbook compares depth to groundwater to groundwater storage, and presents timeseries plots of groundwater depth (layer 1), groundwater pumping, vertical recharge, and groundwater inflow to the stream system.

NFP_HistoricalCUAnalysis.xlsx

The workbook *NFP_HistoricalCUAnalysis.xlsx* contains results of a depletion analysis for various Depletion Study Areas (DSA) that cover the valley floor. The DSAs are approximately equivalent to C2VSim subregions. The depletion of precipitation and irrigation water by developed lands within the valley floor was calculated using DWR's Consumptive Use model. The depletion analysis approach was later rejected in favor of direct modeling of the hydrological system under natural conditions. However, the NatFM accesses data in this workbook to compare natural flows to historical flows.

NFP_HistoricalRimInflows.xlsx

The Sacramento River and San Joaquin River hydrologic regions are divided into rim watersheds and valley floor watersheds. The rim watersheds cover the mountain and foothill regions that surround the Central Valley. These watersheds are relatively undeveloped and changes in land use over time have not significantly affected the natural flow from these watersheds, which are characterized by complex topography, steep slopes, shallow soils, and limited aquifer systems. Precipitation percolating to groundwater quickly returns to streams as baseflow. Groundwater in these upland watersheds is not extensively used as a source of supply. Many of the rim watersheds have been extensively developed for both hydropower and water supply.

Valley floor watersheds refer to lands within the floor of the Central Valley that have been extensively developed for agriculture or have been urbanized. These lands overlay the deep Central Valley groundwater aquifer, which is an important source of water.

Historical monthly flow data for the rim watersheds are contained in the file *NFP_HistoricalRimInflows.xlsx*. For watersheds that have significantly storage regulation, flows correspond to inflows to reservoirs (i.e., unimpaired) or flows unimpaired for stream diversions. A total of 76 flows are defined. These flow data were assembled as part of DWR's CalSim 3.0 Hydrology Development Project.

NFP_HistoricalValleyFloorAccretions.xlsx

The workbook *NFP_HistoricalValleyFloorAccretions.xlsx* calculates the historical accretions between key locations on the Sacramento and San Joaquin rivers and their tributaries. Initially, the NatFM used these data as part of a depletion analysis. The depletion analysis approach was later rejected in favor of direct modeling of the hydrological system under natural conditions. However, the NatFM accesses data in this workbook to compare natural flows to historical flows.

NFP_Pre1900LandUse.xlsx

The workbook *NFP_Pre1900LandUse.xlsx* calculates the natural land use based on mapping performed by Chico State (2003) and Küchler (1977), the extent of the floodplain as delimited by Hall (1887), and soils and other data analyzed by Fox et al., (2014).

The worksheet *Final GIS Data* contains output from a GIS intersection of Chico State land use (Column Q), Küchler land use (Column T), the Hall floodplain (Column AA), C2VSim adjusted subregions (Column N), CalSim 3.0 Water Budget Areas (Column W), and Vernal Pools (Column AD). Entries in Column W described as “OUT” indicate that the lands are located outside the valley floor watersheds, and are ignored in the land use calculations. The rules for establishing the final land use are as follows:

- Within the floodplain, the default land use is from Chico State, except:
  - Lands designated by Fox as Vernal Pool are assigned to Vernal Pool.
  - Lands designated as Grassland by Chico State are assigned to Seasonal Wetland.
  - Lands designated as Wetland by Chico State are assigned to Permanent (Large Stand) Wetland.
  - Lands designated as Other Floodplain by Chico State are assigned according to Küchler.
  - Küchler California Prairie is reassigned to Seasonal Wetland.
  - Küchler Tule Marsh is reassigned to Seasonal Wetland.
- Outside the floodplain, the default land use is from Chico State, except:
  - Lands designated by Fox as Vernal Pool are assigned to Vernal Pool.
  - Lands designated as Grassland by Chico State are assigned to Rainfed Grassland.
  - Lands designated as Other Floodplain by Chico State are assigned according to Küchler.
  - Küchler California Prairie is reassigned to Rainfed Grassland.
  - Küchler Tule Marsh is reassigned to Rainfed Grassland.

The worksheet *Land Use* contains four dropdown boxes that can be used to quickly change the above mapping of land use classes.

The NatFM is linked to land use data in the worksheet *NFP_Input*. For the NatFM, an All Wetland land use class comprises both Seasonal Wetland and Permanent Wetland. Similarly, an All Grassland land use class comprises Vernal Pool, Seasonal Wetland, and Permanent Wetland.

NFP_RimInflowAdjustmentForC2VSim.xlsx

The boundary between the rim watersheds and the valley floor watersheds is not the extent of the groundwater aquifer modeled in the NatFM. Therefore, flows from the watersheds are not equivalent to inflows to the NatFM subregions. The workbook *NFP_RimInflowAdjustmentForC2VSim.xlsx* factors flows from the rim watersheds to account for these differences. Factors are based on area and precipitation depth. Currently, factors have been set to 1.00 (i.e., no adjustment) as these adjustments have been incorporated directly into the NatFM.

Chapter 7
References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56, Rome.

DPW. 1931a. Sacramento River Basin. Bulletin 26. California Department of Public Works, Sacramento, California.

———. 1931b. San Joaquin River Basin. Bulletin 29. California Department of Public Works, Sacramento, California.

DWR. 1965. Sacramento-San Joaquin Delta Area Land Use Survey Data, Office Report. Central District, California Department of Water Resources, Sacramento, California. June.

———. 1967. A Machine Program to Estimate Monthly Consumptive Use and Water Requirements, Memorandum. Hydrology and Water Operations, Statewide Planning Branch, California Department of Water Resources, Sacramento, California.

———. 1979. Consumptive Use Program Documentation, Memorandum from G.W. Barnes, Jr., to Jerry Vayder, Hydrology and Water Operations, Statewide Planning Branch, California Department of Water Resources, Sacramento, California. April 11.

———. 2012a. California Central Valley Unimpaired Flow Data. Fifth Edition. Draft. Bay-Delta Office, California Department of Water Resources, Sacramento, CA. September.

———. 2012b. The State Water Project Final Delivery Reliability Report 2011. Available at: http://baydeltaoffice.water.ca.gov/swpreliability/FINAL_2011_DRR.pdf. Accessed December 31, 2013.

_____. 2013a. Development and Calibration of the California Central Valley Groundwater-Surface Water Simulation Model. Version 3.02-CG. Bay-Delta Office, California Department of Water Resources, Sacramento, CA. June. Available at: http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/index_C2VSIM.cfm. Accessed December 31, 2013.

_____. 2013b. DAYFLOW – An Estimate of Daily Average Delta Outflow. http://www.water.ca.gov/dayflow. Accessed December 2013.

_____. 2013c. California Data Exchange Center. http://cdec.water.ca.gov/intro.html. Accessed December 2013.

_____. 2013d. California Planning Areas. http://www.waterplan.water.ca.gov/docs/maps/pa-web.pdf. Accessed December 2013.

DWR and WPRS. 1981. Joint DWR and WPRS Delta Channel Depletion Analysis. Office Report. California Department of Water Resources and Water and Power Resources Service, Sacramento, California. April 1.

Chico State. 2013. The Central Valley Historic Mapping Project. Department of Geography and Planning and Geographic Information Center, California State University, Chico. April. Available at: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/cmnt081712/sldmwa/. Accessed December 31, 2013.

Fox, P., P. Hutton, D. Howes, A. Draper, and L. Sears. 2014. Freshwater Inflow to San Francisco Bay Under Natural Conditions. Submitted to the Journal of Hydrology, March.

Gilbert, G.K. 1917. Hydraulic mining debris in the Sierra Nevada, California. Professional Paper 105. U.S. Geological Survey.

Gregory, K.J. and D.E. Walling, D.E. 1973. Drainage Basin Form and Process: A Geomorphological Approach. Edward Arnold, London, 456pp.

Grunsky, C.E. 1929. The Relief Outlets and By-Passes of the Sacramento Valley Flood-Control Project. Transactions of the American Society of Civil Engineers, v. 93, 1929, pp. 791-811.

Hall, W.H. 1880. Report of the State Engineer to the Legislature of the State of California. Session of 1880. State Engineering Department, Sacramento, California.

_____. 1886. Physical Data and Statistics of California. State Engineering Department, Sacramento, California.

_____. 1887. Topographical and Irrigation Map of the Great Central Valley of California Embracing the Sacramento, San Joaquin, Tulare and Kern Valleys and the Bordering Foothills. Available at http://www.davidrumsey.com. Accessed December 31, 2013.

Howes, D.M., P. Fox, and P. Hutton. 2014. Evapotranspiration from Natural Vegetation in the Central Valley of California: Monthly Grass Reference Based Vegetation Coefficients and the Dual Crop Coefficient Approach. Submitted to the ASCE Journal of Hydrologic Engineering.

Howes, D.J. and M. Pasquet. 2013. Grass Referenced Based Vegetation Coefficients for Estimating Evapotranspiration for a Variety of Natural Vegetation. Conference Proceedings of the U.S. Committee on Irrigation and Drainage. Denver. October.

Kadir, T. 2006. Chapter 7 – Estimates for Consumptive Water Demands using DETAW. Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh. 27th Annual Progress Report to the State Water Resources Control Board. California Department of Water Resources, Sacramento, California. October.

Küchler, A.W. 1977. The Map of Natural Vegetation of California. In Terrestrial Vegetation of California., pp. 909-938. Edited by M.G. Barbour and J. Major. John Wiley & Sons, New York.

Leopold, L.B., M.G. Wolman, and P. Miller, P. 1964. Fluvial Processes in Geomorphology. W.H. Freeman and Company, 522 pp.

Manson, M. and C.E. Grunsky. 1895. Report of the Commissioner of Public Works to the Governor of California. Sacramento, CA.

Merz, J.E. and J.D. Setka. 2004. Riverine Habitat Characterization of the Lower Mokelumne River, California. East Bay Municipal Utility District, Lodi, CA. July. Available at: http://www.ebmud.com/sites/default/files/pdfs/A-4%20Riverine%20Habitat_0.pdf. Accessed December 31, 2014.

OAC. 2014. Inventory of the William Hammond Hall Papers, 1878-1907. Online Archive of California. http://www.oac.cdlib.org/findaid/ark:/13030/tf4q2nb00m/entire_text/. Accessed December 31, 2014.

Orang, M.N., R.L. Snyder, G. Shu, Q. J. Hart, S. Sarreshteh, M. Falk, D. Beaudette, S. Hayes and S. Eching. 2013. California Simulation of Evapotranspiration of Applied Water and Agricultural Energy Use in California. Journal of Integrative Agriculture 12(8): 1371-1388.

PRISM. 2013. PRISM Climate Group, Oregon State University, Corvalis, Oregon. http://prism.oregonstate.edu. Accessed December 2013.

SCS. 1972. National Engineering Handbook, Supplement A to Section 4 - Hydrology. Soil Conservation Service, U.S. Department of Agriculture, Washington, DC, August.

Shelton, M. L. 1987. Irrigation induced change in vegetation and evapotranspiration in the Central Valley of California. Landscape Ecology 1:95-105.

Tinkham, G.H. 1880. A History of Stockton from Its Organization Up to the Present Time. Harvard University. 397pp.

Jones & Stokes. 2001. A Framework for the Future: Yolo Bypass Management Strategy. Jones & Stokes, Sacramento, CA. Prepared for Yolo Basin Foundation, Davis, CA. August.

Whipple A., R. Grossinger, D. Rankin, B. Stanford, R. Askevold. 2012. Aquatic Science Center, Sacramento-San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process. Publication 672. San Francisco Estuary Institute, Oakland, CA. August.

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