Groundwater and Stream Interaction in California's Central Valley:

Insights for Sustainable Groundwater Management

Completed June 2014
Updated and Released February 2016

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The Nature Conservancy
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Funded by:

WATER FOUNDATION

A Note to Readers

This report was undertaken to provide technical information on the state of streams and groundwater resources in the Central Valley. The findings of this report were used to support the need for what is now known as the Sustainable Groundwater Management Act (SGMA). The intent was to illustrate the physical inter-relationship between the surface and groundwater resources and the potential impacts that groundwater pumping has had and is currently having on our rivers and streams to demonstrate the need for sustainable groundwater management. Based on the scale of the data used in this study, the findings contained herein should not be used as a definitive source in determining whether a particular stream or river reach should or should not be considered as an interconnected surface water for SGMA purposes. Further study at a finer scale would be necessary for such a determination.

Suggested Citation

The Nature Conservancy. 2014. *Groundwater and Stream Interaction in California's Central Valley: Insights for Sustainable Groundwater Management.*

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Acknowledgements

This project grew out of The Nature Conservancy's recognition of the need to better illustrate the significant impacts that groundwater pumping is having on both the environment and existing water supplies, and the resulting need for groundwater management reform. Dr. Maurice Hall and Dan Wendell led the effort for The Nature Conservancy.

RMC Water and Environment led the hands-on modeling effort and report preparation. RMC's work was led by Dr. Ali Taghavi as project manager, with key support from Mr. Jim Blanke as lead hydrogeologist, and Dr. Mesut Cayar as lead modeler. As part of this study, RMC consulted with Mr. Tariq Kadir and Dr. Charles Brush of the California Department of Water Resources (DWR), leading to significant upgrades to the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), enhancements and improvements to model data files, and local improvement of model calibration.

The following individuals provided guidance and reviewed work products during the study; some of whom also served as part of the "Technical Advisory Committee" (TAC). The study benefited greatly from their input.

- John Bredehoeft, United States Geological Survey (retired)[1]
- Charles Brush, Department of Water Resources
- Trevor Joseph, Department of Water Resources[1]
- Tariq Kadir, Department of Water Resources
- Stan Leake, United States Geological Survey[1]
- Jay Lund, University of California, Davis[1]
- Dan McManus, Department of Water Resources[1]
- Bob Niblack Department of Water Resources (retired)[1]
- Anthony Saracino, Groundwater Consultant
- Marios Sophocleous, Kansas Geological Survey (retired)[1]

This report was made possible through the generous support of the Water Foundation, an initiative of the Resources Legacy Fund.

[1] Participant in the Technical Advisory Committee

List of Abbreviations

C2VSim	California Central Valley Groundwater-Surface Water Simulation Model
CVGSM	Central Valley Groundwater and Surface Water Model
CVHM	Central Valley Hydrological Model
CVP	Central Valley Project
CWEMF	California Water and Environment Modeling Forum
DAU	Detailed Analysis Unit
DSA	Depletion Study Area
DWR	California Department of Water Resources
EC BL	Existing Condition Baseline
ET	Evapotranspiration
IE	Irrigation Efficiency
IGSM	Integrated Groundwater and Surface Water Model
IWFM	Integrated Water Flow Model
KRWA	Kings River Water Authority
MAF	Million Acre-Feet
SWP	State Water Project
SWRCB	California State Water Resources Control Board
SVWMP	Sacramento Valley Water Management Plan
TAC	Technical Advisory Committee
TAF	Thousand Acre-Feet
TNC	The Nature Conservancy
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey

Section 1 Introduction and Background

Sustainable water management requires ensuring ecosystem water needs are met in balance with water needs for people. The Nature Conservancy (TNC) is working across California to demonstrate how to achieve this balance in the context of integrated water management programs. Sustainable water management must also recognize that surface water and groundwater resources are interconnected and that proper management of these resources includes understanding this interaction and managing the resources accordingly. Management of groundwater and surface water systems in an integrated manner is impeded by California water law and policy, which has separate rules and regulations for managing groundwater and surface water resources.

The Central Valley of California is the hub of the state's water supply system. An extensive network of dams and canals supplies surface water to users within the Central Valley as well as to the San Francisco Bay Area, the Central Coast, and Southern California. Analysis of information collected in this study reveals that just within the Central Valley, agricultural and urban sectors use an average of 13 million acre-feet (MAF) of surface water and over 8 MAF of groundwater per year. Approximately 2 MAF of water is exported annually to areas outside the Central Valley.

Because the availability of surface water supplies varies significantly from year to year, groundwater use also varies considerably on annual basis. In an average year, groundwater meets about 40% of the state's water demand and up to 60% or more during droughts, when groundwater provides a water supply buffer against economic and environmental harm from water scarcity (DWR, 2014). In some areas, groundwater provides 100% of the supply, even in wetter years, and then is heavily pumped during drought. In other locations, where surface water supplies are reasonably abundant, groundwater use may be relatively light during wetter years, but more heavily pumped during drier years when surface water supplies are cut back. Accordingly, the impact of groundwater use is much more evident during dry years, and especially in drought conditions. A case in point is the drought condition of 2013-15. This drought is exerting significant stress on the state's water supply. The surface water deliveries have been reduced dramatically, to near zero in many regions; therefore, agricultural and municipal water users in the Central Valley and other parts of the state that normally rely on surface water for much of their supplies, are now greatly increasing their use of groundwater to meet their needs.

"Californians are coming together to advance real solutions to our groundwater crisis. This demonstrates a turning point that makes groundwater policy improvements possible this year to ensure this critical water supply is protected in the future," said Lester Snow, executive director of CWF. "People, farms and the environment all need a more sustainable groundwater supply. This report is a starting point to ignite effective change in the way we view and manage groundwater as part of California's overall water supply portfolio."

The current drought has exacerbated California's water challenges. As a finite yet renewable resource, groundwater plays an essential role providing 40% of California's water supply during an average year and up to 60% during droughts such as this year's. When managed sustainably, groundwater can serve as a water savings account that can be dipped into during dry times. However, withdrawals from California's groundwater savings accounts have led to significant depletion of groundwater supplies, known as overdraft, creating critical problems across the state including less groundwater being available to help address drought, land subsidence, degraded water quality, reduced stream flow, and harm to fish and wildlife.

California Water Foundation, Groundwater Sustainability Report, 2014

A 2014 UC Davis report[2] indicates that expected increase in Central Valley groundwater pumping would be in the range of 20% to 25%, during the 2014 irrigation season. To the authors' knowledge, there are no reports of actual estimates of increase in groundwater use for the recent drought conditions. The long-term increase in groundwater pumping and especially recent drought related increases in pumping would translate into significantly more adverse impacts on the surface water and stream systems, as well as groundwater dependent ecosystems. In addition, this increase in groundwater pumping could potentially result in more land subsidence throughout the valley. The drought has also affected the irrigated lands under cultivation. A November 2014 DWR publication "Public Update for Drought Response" [3] reported that based on NASA satellite imagery, approximately 700,000 acres of land were estimated idled between 2011 and 2014. Majority of these acreages idled are reported to be due to the drought conditions, although, some were also due to normal agronomic practices, crop markets, and other reasons.

This report provides the results of a number of analyses and evaluations of Central Valley hydrologic conditions using the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim). The study examines important hydrologic and operational characteristics and behaviors of the California's Central Valley water system during the historical development in the Valley. In addition, the study presents results of model simulations conducted to assess potential impacts of several water management scenarios. The results of this study contribute significantly to the understanding of how management of groundwater and surface water are interrelated and will inform the development of more effective integrated water management in the Central Valley and throughout California.

The interaction between groundwater and surface water resources has been evaluated and illustrated by many researchers. As early as 1941, Theis (1941) documented the hydraulic connection between stream and aquifer systems and quantitatively described the general behavior of stream-groundwater systems. Many others, including Glover & Balmer (1954) and Hantush (1965) built on Theis' work, which demonstrated and confirmed the basic principles of hydraulic connection between stream and aquifer systems. In recent years, significant work has been conducted regarding regional impacts of groundwater pumping and operation on regional surface water systems. For example, the recent USGS study (Barlow & Leake, 2012) presents original findings of the stream-aquifer interaction in the context of sustainable groundwater management.

In an effort to quantify the interaction between the groundwater and the surface water system, DWR's C2VSim model was employed in this study. The C2VSim model was originally developed in 1990 for DWR, U. S. Bureau of Reclamation (USBR), and California State Water Resources Control Board (SWRCB) as the Central Valley Groundwater and Surface water Model (CVGSM) (James M. Montgomery Consulting Engineers, 1990a). Subsequently, the model was enhanced through numerous key applications, including the Central Valley Project Improvement Act – Programmatic Environmental Impact Statement (CVPIA-PEIS). In 2005, the CVGSM model was upgraded to the newly developed Integrated Water Flow Model (IWFM) platform, and was renamed the C2VSim model. The detailed features of the model are described and presented in Section 2 of this report. The C2VSim model is a

[2] Howitt, Medellin-Azuara, Lund, & MacEwan, 2014
[3] http://water.ca.gov/waterconditions/docs/DWR_PublicUpdateforDroughtResponse_GroundwaterBasins.pdf

leading Central Valley-wide integrated hydrologic model adopted by DWR and many other regional and state-wide agencies, as well as non-governmental organizations (NGOs) to evaluate various water management scenarios throughout the Valley.

This report is organized in six sections:

Section 1: Provides the background information and lays out the goals and objectives of this study.

Section 2: Provides information on the status of C2VSim model, refinements made during this study, and assumptions on the modeling analysis.

Section 3: Discusses simulation of the historical hydrologic conditions in the Central Valley.

Section 4: Provides the assumptions and results of the existing baseline conditions, assuming that no changes to the facilities and their operations, as well as water management actions, take place over the course of a predetermined hydrologic condition.

Section 5: Provides a description of three water management scenarios that may have major impacts on the future of surface water and groundwater interaction in Central Valley. Results of simulation of these management scenarios are presented and discussed in detail.

Section 6: Provides conclusions from this study and a list of recommendations for future work.

1.1 Goals and Objectives

The overall goal of this study is to clearly illuminate the interaction between groundwater and surface water resources, specifically, the relationship between groundwater pumping and stream flows in the Central Valley. The study is intended to support development of more proactive statewide groundwater policies and to catalyze implementation of more sustainable groundwater management to better support fish and wildlife that depend on groundwater – and the surface water resources that are supported by groundwater – while meeting the needs of agricultural and urban water users. The study assesses system behavior in both severely over drafted and reasonably stable hydrologic systems, all of which exist within the greater Central Valley groundwater basin.

Specific objectives within the overall goal include:

- Develop clear illustrations of the effects of past, current, and future groundwater pumping in the Central Valley on surface water supplies and ecosystems so that future projects and operations can more appropriately balance the range of water supply needs.
- Clarify, for the benefit of water users and decision-makers, where and how pumping has affected river flow and estimate the general magnitude of these effects to help motivate proactive groundwater management.
- Clarify the relative importance of different recharge mechanisms in different parts of the Central Valley to facilitate holistic land and water use planning.
- Contribute to enhancement of the C2VSim model, and develop new and improved tools that better meet the needs of comprehensive water planning, and appropriately consider the connection between groundwater and surface water.

- Evaluate the regional-scale impacts of potential water management activities to help shape a truly sustainable water management future for the Central Valley and for California more broadly.

Section 2 C2VSim Model

2.1 Model Background and Capabilities

C2VSim model is an integrated hydrologic model that has already been a valuable analytical tool in California's water management planning, and is being continually upgraded by DWR and partners to support water management planning and education. The C2VSim model simulates movement of water through the interconnected land surface, surface water, and groundwater flow systems in the 20,000 mi^2 area defined by the alluvial Central Valley aquifer. The C2VSim model was developed using the public domain IWFM version 3.02 (Dogrul, 2012a) (Dogrul, 2012b) (Dogrul, 2012c). IWFM couples a three-dimensional finite element simulation of saturated groundwater flow with one-dimensional land surface, stream flow, lake, unsaturated zone, and small-stream watershed simulation processes (Figure 1). The model database includes – among other data sets – the monthly rainfall, land use, crop acreage, river inflow, surface water diversion, and groundwater pumping data from October 1921 through September 2009. This database supports the model simulation for historical conditions.

The C2VSim model is based on the CVGSM model, an integrated hydrologic model that was run with the Integrated Groundwater Surface Water Model (IGSM) (James M. Montgomery Consulting Engineers, 1990b). The original CVGSM model was developed in 1990 and simulated the Central Valley hydrologic system from 1922 to 1980. The C2VSim model has undergone various updates and enhancements over time:

- 1990: Enhance IGSM & develop CVGSM (1922-1980)
- 1996: Update CVGSM (1922-1993)
- 2000-02: DWR synthesis to IGSM2
- 2005: IWFM and C2VSim Conversion and update CV2Sim (1922-2003)
- 2005-07: C2VSim integration with CalSim-III and C2VSim calibration
- 2005-07: C2VSim calibration
- 2010-11: Update C2VSim (1922-2009)
- 2011-12: Spatial refinement of the grid and model files and development of the C2VSim-FG (Fine Grid)
- 2012-15: C2VSim database is being enhanced to support SGMA analysis

DWR currently maintains two version of C2VSim model:

- C2VSim Coarse Grid (C2VSim-CG)
- C2VSim Fine Grid (C2VSim-FG)

The latest version of the C2VSim-CG model, Revision 374 (R374), was released by the DWR in June 2013, and is documented in print (Brush, Dogrul, & Kadir, 2013a; Brush, Dogrul, & Kadir, 2013b; Brush, Dogrul, & Kadir, 2013c).The C2VSim-CG model consists of a finite element grid with that uses 1,393 nodes to form 1,392 irregular elements covering an area of 19,710 mi^2, and 449 river nodes to delineate 75 river reaches.

The C2VSim-FG model consists of a finite element grid with more than 30,000 nodes and 32,000 elements with the smallest element area of approximately 0.06 square miles (Figure 2). The model area,

covering the entire Central Valley, is approximately 20,700 Acres and is divided into 21 water management areas (sub-regions) (WRIME, 2011; WRIME, 2012). C2VSim-FG model features are summarized in Table 1.

The C2VSim-FG model was used to simulate the historical hydrologic, land and water use, and surface water and groundwater flow conditions at the valley-wide and regional levels for this project. Further, a baseline model scenario to represent the existing conditions was developed for this project to simulate the impacts of hydrologic conditions under current level of development. The baseline model scenario was also used to simulate conditions under specific water management scenarios.

2.2 Hydrologic Model Platform Selection

There are several regional models available that cover parts of the Central Valley. However, there are only two existing models available that cover the entire Central Valley and can potentially be used to simulate the groundwater-surface water connection in the Central Valley: the Central Valley Hydrologic Model (CVHM) (Faunt, Belitz, & Hanson, 2009), developed by the U.S. Geological Survey (USGS) and DWR's C2VSim (2013a). Both models were peer reviewed as part of a project conducted by the California Water and Environment Modeling Forum (CWEMF), (Harter & Morel-Seytoux, 2013). The peer review process concluded that both models have capabilities to provide answers to management questions. It was also concluded that the user can compare a variety of management options by changing inputs or selecting a particular option in the model's code.

As part of model selection process for this project, the robustness and suitability of these two models were reviewed. The findings and recommendations are described in a separate Technical Memorandum (see Appendix A).

The model comparison showed several significant advantages for using the C2VSim model for this effort:

- The hydrologic period of the C2VSim-FG model (1922-2009) is longer, as shown in Figure 3, which provides information during the early groundwater development era in the Central Valley
- The C2VSim-FG grid has a finer resolution along the major streams and canals as compared with CVHM, which provides for more resolution in simulation of stream-aquifer interaction and assessment of impacts of groundwater pumping on stream flows
- CV2Sim-FG model provides more detailed water budget information for some surface processes – including land and water use system, stream and canal system, groundwater system, and soil system – that are useful for illustrating some of the issues of interest
- A user friendly Arc GIS-based Graphical User Interface (GUI) is available for C2VSim-FG and C2VSim-CG models that increases productivity and efficiency in setting up model scenarios, analyzing model results, and displaying and interpreting model results

As described in detail in Appendix A, the C2VSim model was selected as the model platform for this project.

2.3 Revisions Made to the C2VSim Model

The strengths and weaknesses of the C2VSim model in its representation of various aspects of the Central Valley physical system were assessed while conducting the analyses and simulations for this project. The C2VSim model was also compared with more detailed models that have been developed for specific local needs with respect to aquifer characterization and historical conditions simulations. Upon review of the C2VSim model results for the historical calibration period, it was concluded that model calibration can be improved in certain areas by including data and information from local data sources and/or local models covered by the C2VSim model. In addition, calibration of stream water budgets and seepage loses were compared with the Mullen & Nady (1985) study, and it was concluded that the model calibration of stream flow simulations can be improved as well. Accordingly, a set of prioritized recommendations for refinement of the C2VSim model calibration was compiled to help improve the model utility for Valley-wide and regional integrated ground and surface water resource evaluations. These recommendations were shared with - DWR staff.

The "official" version of the C2VSim model at the beginning of this project was R369. DWR staff incorporated the recommendations outlined below, in addition to other refinements to R369 and published the latest "official" version of the C2VSim model as R374. At the same time, the fine grid version of C2VSim model was updated with the course grid data C2VSimfor version R374 model with DWR's guidance. A few additional refinements, approved by DWR staff were incorporated into the both course and fine grid C2VSim models for the final version of CV2Sim model used in this project; version R379. The Beta version of C2VSim R379 was released by DWR in May 2014. Based on our correspondence with DWR staff, no changes in the Beta version are expected, as it is released in official version.

The following are the revisions that have been incorporated into the C2VSim model as part of this project.

2.3.1 Initial Conditions Update

Initial groundwater levels for October 1921 were modified to be consistent with the maps from:

- Mendenhall, Dole, & Stabler (1916)
- Bryan (1923)
- Recent unpublished DWR data

Additionally, 1921 initial conditions were modified at areas where there was a steep decline or rise at the beginning of the simulation.

2.3.2 Stream-Bed Conductance Update

Stream-bed conductance values from the C2VSim model and the following models were compared:

- CVGSM
- CVHM
- Local Models

Based on the review, the streambed conductance values for the C2VSim model were modified to better match observed groundwater flows to streams from the Mullen & Nady, (1985) study and observed groundwater levels close to streams.

2.3.3 Surface Water Supply Data Update

Surface water supply data and its distribution from various reaches in Sacramento Valley and Tulare Basin were updated based on local data sources to support an improved calibration and water budget analysis. The updates were implemented in the following areas.

- Redding Basin
- Kings River Area
- Kaweah River Area
- Tule River Area
- Kern River Flood Channel Area

2.3.4 Small Watershed Parameters Update

The change in simulated groundwater levels in these areas were showing a linear rise or decline and the observed data did not match the trend. Small watershed parameters were updated to better simulate the runoff and match the observed groundwater levels in the Sacramento Valley. This revision was implemented for areas (specifically closer to foothills) where the effects of the agricultural or urban activity are not dominant.

2.4 C2VSim Model Update Results

The simulated groundwater levels and groundwater flows to the streams for C2VSim model versions R369 and R374 were compared to the observed values to assess the impacts of the revisions to the C2VSim model.

Figure 4, Figure 5, and Figure 6 show the comparison of the observed groundwater levels and simulated groundwater levels for the C2VSim model versions R369 and R379 models for three different calibration wells within the Sacramento Valley. Figure 4 is a good example of how the updated initial conditions improved the simulated groundwater levels. Since the initial condition for R369 reflected a much higher groundwater levels than the R374 version, the simulated groundwater levels consistently declined throughout the simulation period. Figure 5 shows the improvements in the simulated groundwater levels due to the updated small watershed parameters. Simulated groundwater levels declined linearly during the simulation. Increasing the contribution of the small watersheds to the aquifer in that area stabilized the groundwater levels and better matched the C2VSim model version R379. Figure 6 shows the impacts of the updated streambed conductance on simulated groundwater levels. Updated streambed conductance value for the Yuba River improved the stream-aquifer interaction and gave a better match with the observed groundwater levels.

Figure 7, Figure 8, and Figure 9 show the comparison of the observed groundwater levels and simulated groundwater levels for the C2VSim model versions R369 and R379 models for three different calibration wells within the San Joaquin Basin. Updated initial conditions and updated streambed conductance were the only two revisions implemented in San Joaquin Basin. Figure 7, Figure 8, and Figure 9 show

how the updated streambed conductance values improved the stream-aquifer interaction and eventually the simulated groundwater levels close to the American River, the Mokelumne River, and the Fresno River, respectively.

Figure 10, Figure 11, and Figure 12 show the comparison of the observed groundwater levels and simulated groundwater levels for the C2VSim model versions R369 and R379 models for three different calibration wells within Tulare Basin. Figure 10 and Figure 11 show the improvements in the simulated groundwater levels in the Kings River area due to the updated initial conditions and surface water supply data. Figure 12 is another good example of how the updated streambed conductance improved the simulated groundwater levels. Figure 12 also demonstrates impacts of updating the data for surface water supply for the spreading operations around the Kaweah River Area. The stream flows reaching the end of the Kaweah River were being diverted and recharged along the Kaweah River resulting in the simulated groundwater levels not declining at the same rate as the observed groundwater levels during the simulation.

Data from Mullen & Nady, (1985) was used to compare the simulated and observed stream accretions and depletions. Mullen & Nady, (1985) compiled the annual stream flow data for 20 major stream systems in the Central Valley of California for water years 1961 to 1977. Their water budget tables list gaged and ungaged inflow from tributaries and canals, diversions, and gaged outflow. Theoretical outflow and gain/loss in a reach are computed. The reaches from Mullen & Nady, (1985) do not match exactly with the C2VSim model reaches, but this study was a very good source to compare the C2VSim model results with respect to the magnitude and, in some cases, for trends.

Figure 13, Figure 14, Figure 15, and Figure 16 show the comparison of the observed and simulated groundwater flows to streams for Stony Creek, the Tuolumne River, the Merced River, and the Kings River respectively. The figures show the comparison of the annual values from water years 1961 to 1977 as well as the annual average for the same time period. The improvement from C2VSim model version R369 to R379 can be attributed mostly to updated streambed conductance values, but other revisions helped improve the simulated groundwater levels, which in turn improved the simulated stream-aquifer interaction. Simulated groundwater flows to streams for Stony Creek and the Tuolumne River were improved from model version R369 to R379. The improvements are more significant for the Merced River. R369 was not able to match the trend for the Kings River. Model version R379 not only matched the trends, but also estimated the average magnitude better than model version R369.

Section 3 Historical Simulation

The Central Valley of California is the hub of the state's water supply system. An extensive network of dams and canals supplies surface water to users within the Central Valley, San Francisco Bay Area, Central Coast and Southern California. The population boom in the Central Valley started with the Gold Rush in1849 and the population has continued to grow since then. According to 2010 U.S. Census data, about 6.5 million people live in the Central Valley today and it is the fastest growing region in California (Jennings, 2010). Agriculture was introduced to the Central Valley as miners turned to farming when gold became more difficult to find. Around 6.8 million acres of land in the Central Valley are irrigated today. Urban and agricultural users within the Central Valley consume an average of 13 MAF of surface water and over 8 MAF of groundwater per year, which constitutes around 10-18 percent of U.S. pumping. Approximately 2 MAF of water is exported annually to areas outside the Central Valley. As the availability of surface water supplies varies significantly from year to year, groundwater is used as a buffer when surface water supplies are low (Brush, Dogrul, & Kadir, 2013a).

History of water development in the Central Valley follows the timeline below (Brush, 2008).

- 1849 Population boom begins with Gold Rush
- 1850 – 1900 Agriculture introduced
- 1890 – 1930 Local surface water projects implemented
    - Agriculture expands, mining canals are re-purposed
- 1910 – 1970 Groundwater use expands
    - Agricultural follows electricity and population
- 1930 – 1980 Large surface water projects implemented
    - 1937 Central Valley Project (CVP) re-authorized and construction started
        - 1942 Friant Dam completed
        - 1945 Shasta Dam completed
        - 1962 Trinity Dam completed
        - 1979 New Melones Dam completed
    - 1960 State Water Project (SWP) approved
        - 1968 Oroville Dam completed
- 1960 – 1990 Surface water distribution system completed
- 1980 - Present Conjunctive use projects implemented

As summarized above, the water development in the Central Valley hydrologic system has gone through significant changes in the last 100 years, which also resulted in significant changes in the hydrologic system of the Central Valley. Large areas of native land have been converted to irrigated agricultural and urban use due to increase in agriculture and population. Dams were built on the rivers, which resulted in changes in seasonal flow rates. An extensive network of canals followed the dams to distribute large volumes of water to farms, urban areas, and even further to other hydrologic regions. Large volumes of groundwater have been pumped, and the dependency on groundwater pumping continues to increase. This increase is tied to increasing demand and constraints on the availability of surface water supplies due to hydrologic conditions and regulatory restrictions including downstream water rights, in-stream

flow requirements, and outflow requirements for the Sacramento-San Joaquin Delta (Brush, Dogrul, & Kadir, 2013a). All of these have contributed to changes in Central Valley hydrology such as the decline in groundwater levels, change in flows between groundwater and surface water, decline in wetland areas (see Figure 17), reduction in water quality, and increase in land subsidence.

The hydrology in the Central Valley is typically classified by the hydrologic year types defined by DWR for the Sacramento Valley and San Joaquin Valley. DWR's hydrologic year types classify years as wet, above normal, below normal, dry, or critical (DWR, 2013). DWR hydrologic year types for the Sacramento Valley and San Joaquin Valley are shown in Figure 18 and Figure 19, respectively. Deep percolation of applied water and rain, recharge from water delivery conveyance and distribution system, boundary flows, and surface water availability in the Central Valley can fluctuate significantly from year to year depending on the hydrology. These fluctuations directly impact groundwater pumping, groundwater levels, and interaction of the streams and aquifer.

C2VSim-FG model historical simulation (1922-2009) results were used to assess and evaluate some of the implications of the changes in the Central Valley hydrology and hydrologic system and to explain the changes in groundwater-surface water interaction over time as groundwater levels and pumping patterns have changed. Analysis of the water budgets, stream flows, groundwater levels, and stream-aquifer interaction, with appropriate spatial and temporal scale and distribution, were used meet the project objectives.

3.1 Modeling Approach and Assumptions

The C2VSim model simulates the historical response of the Central Valley's groundwater and surface water flow systems to historical stresses. The C2VSim model inputs include monthly historical precipitation, stream inflows, surface water diversions, and land use and crop acreages for the simulation period, October 1921 through September 2009. The C2VSim model dynamically calculates crop water demands; allocates contributions from precipitation, soil moisture, and surface water diversions; and calculates the groundwater pumpage required to meet the remaining demand. Agricultural groundwater pumping is not metered in the Central Valley, and the C2VSim model provides some of the best estimates of this pumping because they are constrained spatially and temporally by estimated demand and by surface water supplies. The model can also be used to calculate the changes in aquifer storage and can be used to estimate the water flows between rivers and groundwater aquifers (Brush, Dogrul, & Kadir, 2013a; Brush, Dogrul, & Kadir, 2013b).

Hydrologic parameters (including hydraulic conductivities, storage parameters and recession coefficients) were calibrated to match observed values including groundwater heads, groundwater head differences between well pairs, surface water flows, and interaction between stream and groundwater for the period between September 1975 and October 2003 (Brush, Dogrul, & Kadir, 2013b).

The C2VSim model is divided into 21 water budget sub-regions (Figure 20). The model sub-regions are based on Depletion Study Areas (DSAs) , originally developed by DWR's Division of Planning for estimating regional water supplies and demands (Brush, Dogrul, & Kadir, 2013b). DWR further groups the sub-regions into five hydrologic regions. The three large regions – the Sacramento Valley, San Joaquin Basin, and the Tulare Basin – each comprise approximately one third of the valley. The two

small hydrologic regions – East Side Streams and Sacramento-San Joaquin Delta – are located between the Sacramento River Basin and San Joaquin River Basin. This project included the East Side Streams hydrologic region in the San Joaquin Basin (Figure 20). The historical data model input and output can be summarized to produce water budgets for each model sub-regions, hydrologic regions, or the entire model area.

3.2 Modeling Results

3.2.1 Land Use

Land use change is the main driver in shaping water use in California's Central Valley. Figure 21, Figure 23, Figure 25, and Figure 27 show the changes in irrigated agricultural and urban land use from 1922 to 2009 for the Sacramento Valley, San Joaquin Basin, Tulare Basin, and Central Valley, respectively, as represented in C2VSim model.

Sacramento Valley

The irrigated agricultural land use increased from 0.5 million acres to 1.6 million acres from 1922 to 2009 in the Sacramento Valley. Irrigated agricultural land use increased slowly until the early 1940s, increased rapidly from the early 1940s to the mid-1970s (particularly with the completion of Oroville Dam in 1968), and leveled off through the early 1980s. Land use data based on reported surveys indicates that there was a reduction of 0.2 million acres of irrigated agricultural land in the early 1980s, when agricultural land use leveled off around 1.6 million acres (Figure 21).

Crop mix in Sacramento Valley (Figure 22) has gone through significant changes, which affects the water use throughout the Valley. Rice acreage increased significantly after construction of major storage reservoirs. There is also an overall trend in reduction of annual crops, and increase in permanent crops, including orchards and citrus. Irrigation practices also changed over time, which affected the applied water use.

Urban growth in the Sacramento Valley continued slowly until the mid-1950s. The post WW II era activities resulted in a much more rapid urban growth pace until the early 1980s and continued at an even more rapid rate after the early 1980s. The urban area increased from 23,000 acres to 191,000 acres between 1922 and 1980, and had almost doubled the 1980 urban area by 2009 (Figure 21).

San Joaquin Basin

The irrigated agricultural land use grew from 0.7 million acres to 1.7 million acres from 1922 to 2009 in the San Joaquin Basin (Figure 23). The irrigated agricultural land use continuously increased and almost tripled by the early 1980s. Based on the reported land use survey data there was a decline of 0.2 million acres in the early 1980s, and agricultural land use leveled off after that time.

Crop mix in San Joaquin Valley (Figure 24) has gone through significant changes, which affects the water use throughout the Valley. It is noteworthy that pasture and alfalfa had declining trends' however; field crops and orchard acreages increased over time. Increasing orchards, including almonds and pistachios from the mid-1990s to the late 2000s changed the water use landscape of the San Joaquin Valley significantly.

Urban areas in the San Joaquin Valley increased slowly until the mid-1970s, and then continued to increase, but at a faster pace. The urban area increased from 19,000 acres to slightly more than 300,000 acres between 1922 and 2009 (Figure 23).

Tulare Basin

The reported irrigated agricultural land use declined almost 0.2 million acres from 1922 to the early 1940s in the Tulare Basin. However, the agricultural growth increased at a more rapid pace with the completion of the Friant Dam in the mid-1940s and continued to increase at the same rate through the late 1950s. The increase in irrigated agricultural land continued between the early 1960s to the early 1980s, but at a slower rate. Irrigated agricultural land use was almost 3.5 million acres in the Tulare Basin at its peak in the early 1980s (Figure 25). Irrigated agricultural land use decreased more than 0.5 million acres between the early 1980s and 2009.

Crop mix in Tulare Basin (Figure 26) also shows a significant shift from annual crops to permanent crops with field and row crops converting to permanent crops, such as citrus and orchards. Cotton acreage increased significantly after the WW II, but reduced from the mid-1990s to the late 2000s.

Urbanization in the Tulare Basin has a trend similar to that of the San Joaquin Basin. Urban areas increased slowly until the early 1970s and then continued to increase, but at a more rapid rate. Urban land use increased from 38,000 acres in 1922 to 125,000 acres in 1970 and finally to slightly more than 500,000 acres in 2009 (Figure 25).

Central Valley

Irrigated agriculture became the dominant land use in the late 1950s and has since been the dominant land use in the Central Valley. Previously, most of the Valley floor was non-irrigated grassland and woodland. Large increases in population have resulted in a shift in land use in the Central Valley. Conversion of lands in the Central Valley started with the conversion from native vegetation to irrigated agricultural and urban uses and continued in that way until the early 1980s. Since the early 1980s conversion from native vegetation to urban land use has continued at a slower rate. Around the same time, conversion from irrigated agricultural to urban land use started and this conversion has continued, but at a higher rate, over time. Agricultural land use declined from 6.9 million acres to 6.1 million acres between the early 1980s and 2009. The reduction in agricultural land use was primarily on pasture, alfalfa, and cotton lands (Figure 28). Urban land use increased from 0.5 million acres to 1.2 million acres during the same period (Figure 27).

3.2.2 Surface Water Supply

Sacramento Valley

Due to the availability of abundant water in the Sacramento Valley, surface water supplies have historically been very reliable. However, the contribution of surface water to the total water supply of the Sacramento Valley declined steadily from 80 percent in the 1920s to 65 percent in the 2000s with significantly less contribution in dry years, such as 56 percent during the 1976-77 drought and 60 percent during the 1987-92 drought (Figure 29).

Figure 21 shows that agricultural water supply increased steadily until the early 1980s and then leveled off. This trend for agricultural surface water supply resembles the trend for irrigated agricultural land use. The annual agricultural surface water supplies increased from 1.7 MAF in 1922 to almost 2 MAF in the early 1940s and then doubled by the early 1980s. There were some exceptions to this trend. The agricultural surface water supply declined significantly in the 1976-77 and the 1987-92 droughts, to as low as 3 MAF/year.

Figure 21 shows that the urban surface water supply has increased through time in a very similar trend to the urban land use. The annual urban surface water supply increased from 0.04 MAF in the early 1920s to 0.65 MAF in the mid-1950s and to almost 0.4 MAF in 2009. Again, droughts such as those in (1976-77 and in 1987-92) reduced the urban surface water supplies significantly and resulted in deviations in the generally increasing trend.

San Joaquin Basin

Like the Sacramento Valley, the contribution of surface water to the total water supply of the San Joaquin Basin declined steadily from 78% in the early 1920s to 50% in the late 2000s with significantly less contribution in dry years such as 30% during the 1976-77 drought and 45% during the 1987-92 drought (Figure 30).

Agricultural water supply from the San Joaquin River increased steadily through the early 1980s with the exceptions of drought years such as 1924, 1931, 1961, and 1977 (Figure 23). There was around 3.8 MAF/year of agricultural surface water available in the early 1980s with the exception of 1977, for which the available surface water supply was 1.7 MAF/year. The agricultural surface water supply leveled off until the beginning of the 1987-92 drought and then fell sharply to 2.4 MAF/year. The agricultural water supply could never again reach its pre-drought volume; it leveled off around 2.8 MAF/year.

The urban surface water supply for the San Joaquin Basin has increased through time as with the Sacramento Valley urban surface water supply (Figure 23). The trend of change in urban surface water supply is similar to the trend of urban land use increase with the exceptions of fluctuations in drought years. The annual urban surface water supply increased from 0.025 MAF to slightly more than 0.155 MAF between 1922 and 2009.

Tulare Basin

Unlike the Sacramento Valley and San Joaquin Basin, the contribution of surface water to the total water supply of the Tulare Basin increased steadily from 1922 to 2009. The contribution of surface water was around 25% in the 1920s. The contribution increased to 67% in 2006 but then decreased to 35% from 2007 to 2009 (Figure 31). The effects of the droughts on surface water availability were more drastic in the Tulare Basin. The 1976-77 drought caused the contribution of surface water to decrease to 15% and the 1987-92 drought drove it to less than 30%.

Agricultural surface water supply has steadily increased in the Tulare Basin. The rate of the increase was higher after the mid-1940s (completion of Friant and Shasta Dams). The expansion of the delivery systems to the Tulare basin through time (in the early 1960s and the late 1970s) helped the steady increase of agricultural surface water supply until the early 1990s. Environmental and fiscal concerns slowed down the expansion and at the same time, the rate of increase after the early 1990s (Faunt,

Belitz, & Hanson, 2009). The 1924, 1931, 1976-77, and 1987-92 droughts caused notable fluctuations in the agricultural surface water availability. There was around 1 MAF/year of agricultural surface water supply in early 1920s. The volume went up to a little bit more than 5 MAF/year before the 1976-77 drought and the drought reduced the volume to almost 1.5 MAF/year. The volume increased to 6MAF/year before the 1987-92 drought and then decreased to 2.3 MAF/year during the drought. The agricultural surface water supply increased after the drought and fluctuated between 7.3 MAF/year and 3.2 MAF/year until 2009 (Figure 25).

Annual urban surface water supply for the Tulare Basin leveled off at less than 0.01 MAF until the late 1940s. The urban surface water supply increased dramatically after the completion of the Friant and Shasta Dams, up to 0.1 MAF/year by the late 1950s. The expansion in delivery systems in the early 1960s increased the volume to 0.175 MAF/year on average. The deliveries leveled off through 2009 with fluctuations in dry years (Figure 25).

Central Valley

The contribution of surface water to the total water supply of the Central Valley was stable (around 54%) from 1922 to 2009 with fluctuations due to water year types (Figure 32). The contribution of surface water dropped to 30% during 1977 (one of the driest years in the Central Valley). On the other hand, the contribution was as high as 70% in wet years such as 1983.

The annual agricultural surface water supply increased steadily from approximately 4.6 MAF in the 1920s to almost 14 MAF in the early 1980s (Figure 27). There were fluctuations in the dry years but none of them were as notable as the drought in 1977, when agricultural surface water supply dropped to 6.2 MAF/year. The expansion of the SWP and the CVP between the mid-1940s and the early 1980s helped storing and moving surface water within Central Valley and reduced the impacts of the droughts on surface water deliveries. However, the slowdown in the expansion of delivery systems stopped the increase in agricultural surface water deliveries in the mid-1980s. The annual agricultural surface water deliveries declined as low as 7.7 MAF during the 1987-92 drought. The deliveries increased after the drought and fluctuated between 10 MAF/year and 14 MAF/year until 2009; rising in wet periods and falling in dry periods.

The portion of the surface water supply that is used for urban use constituted only 2% of the total supply in the 1920s. The portion went up to 5% by the 2000s. Annual urban surface water supply for the Central Valley increased at a low rate from 0.09 MAF to 0.1 MAF from the early 1920s to the late 1940s. The urban surface water supply increased dramatically after the completion of the Friant and Shasta Dams up to 0.26 MAF/year by late 1950s. The urban surface water supply continued to increase through 2009 (0.6 MAF/year by 2009) with fluctuations in dry years (Figure 27).

3.2.3 Groundwater Pumping

Groundwater serves as the main source of water for some agricultural areas and for many cities, and also serves as a supplemental water source in dry periods for many agricultural and urban users that generally rely on surface water. The C2VSim model calculates the sub-regional groundwater pumping in each month to meet agricultural and urban demands that cannot be met with surface water supplies

(Brush, Dogrul, & Kadir, 2013a). The historic groundwater production for the Central Valley, as represented in C2VSim model, is summarized below.

Sacramento Valley

The contribution of groundwater pumping for the total water supply of the Sacramento Valley increased steadily from 18% in the 1920s to 35% in the 2000s with significantly higher contributions in dry years such as 44% during the 1976-77 drought and 40% during the 1987-92 drought to make up the reduction in surface water supplies (Figure 29).

Simulated annual groundwater production steadily increased in the Sacramento Valley from the 1920s to the 2000s. Figure 34 shows total groundwater production in the Sacramento Valley. The 10-year moving average is shown to reduce the noise of annual variation and better highlight the long-term trends in groundwater production. Annual simulated groundwater pumping increased from 0.45 MAF to 2.2 MAF from the early 1930s to the late 2000s. Figure 33 shows the annual simulated groundwater production for the Sacramento Valley. The figure shows that the groundwater production spiked during the droughts such as the 1976-77 and 1987-92 and dipped in wet years such as 1983 and 1986.

Figure 21 shows that the historical agricultural groundwater pumping follows a trend similar to that of the irrigated agricultural land use with fluctuation depending on the hydrologic year type. The simulated annual agricultural groundwater pumping was stable around 0.4 MAF from the early 1920s to the early 1940s. The steep rise in irrigated agricultural land development in the early 1940s resulted in a steep rise in agricultural groundwater production as well. The simulated agricultural groundwater production was around 1.5 MAF/year before the 1976-77 drought and increased all the way to 2.3 MAF/year during the drought. The simulated groundwater pumping declined back to 1.5 MAF/year after the 1977-1978 drought and continued to increase through 2009 with water year type fluctuations. The simulated groundwater pumping was more than 2 MAF/year in the late 2000s.

The historic urban groundwater pumping also followed the trend of the historic urban land use development (Figure 21). The simulated annual urban groundwater pumping increased steadily from the 1920s to 2000s with a slower rate between the early 1920s and the early 1950s. The simulated urban groundwater pumping increased from 0.02 MAF/year in the early 1920s to more than 0.35 MAF/year in the late 2000s.

San Joaquin Basin

The contribution of groundwater pumping to the total water supply of the San Joaquin Basin increased steadily from 22% in the early 1920s to 50% in the late 2000s with significantly higher contributions in dry years such as 70% during the 1976-77 drought and 55% during the 1987-92 drought (Figure 30).

Figure 33 and Figure 34 show that groundwater production in the San Joaquin Basin steadily increased from the 1920s to the 2000s. The 10-year moving average of simulated groundwater pumping increased from almost 1 MAF/year in the early 1930s to 2.5 MAF in the late 2000s (Figure 34). Figure 33 shows that the historic groundwater production in the San Joaquin Basin fluctuated depending on the hydrology, decreasing during the wet periods and increasing during the dry periods.

The simulated agricultural groundwater pumping in the San Joaquin River increased rapidly, from 0.75 MAF/year in the 1920s to 2 MAF/year in the mid-1970s following the historic trend of irrigated agricultural land use development (Figure 23). The agricultural groundwater production increased to more than 3.5 MAF/year during the 1976-77 drought and then decreased to about 1 MAF/year during the wet years of 1983 and 1986. The 1987-92 drought increased the simulated agricultural groundwater pumping to slightly more than 2.5 MAF/year. The agricultural groundwater production declined to 2 MAF/year after the 1987-92 drought and leveled off until 2009.

The simulated urban groundwater pumping grew exponentially, following the rapid expansion of the urban land use, from 0.025 MAF/year in the 1920s to 0.45 MAF/year in the 2000s with small fluctuations from year to year (Figure 23).

Tulare Basin

Figure 31 shows that the contribution of groundwater pumping for the total water supply of the Tulare Basin was around 75% in the 1920s. The contribution steadily declined to 33% in 2006 and increased to 65% from 2007 to 2009 (Figure 31). The effects of the droughts on groundwater pumping are more significant in the Tulare Basin than the Sacramento Valley and the San Joaquin Basin. The 1976-77 drought increased the contribution of groundwater pumping up to 85% and the 1987-92 drought increased it to more than 70%.

Figure 34 shows the 10-year average simulated groundwater pumping for the Tulare Basin decreased from 3.5 MAF/year in 1922 to 2.6 MAF/year in the early 1940s due to reduction in agricultural land use, over the same time period. Even though the completion of the Friant and Shasta Dams increased the availability of surface water in the Tulare Basin in the mid-1940s, the simulated groundwater pumping started increasing in the early 1940s and continued to increase rapidly until the late 1960s. At its peak, the 10-year moving average was more than 7 MAF/year in 1969. The simulated groundwater pumping started decreasing in the early 1970s due to the expansion of surface water delivery systems to the Tulare Basin. The decline continued until the beginning of the 1987-92 drought, and then it started rising again until the end of the drought. A new decline started after the drought and continued until the early 2000s (the 10-year moving average was as low as 4.9 MAF/year), when the 10-year moving average started increasing slightly again. Figure 33 shows the historic effects of the hydrology on the trend described above on an annual basis.

The historical agricultural groundwater pumping generally follows the pattern described above. On the other hand, the historic urban groundwater pumping trend closely follows the historic trend of urban land use development. The annual simulated urban groundwater pumping increased steadily from 0.06 MAF in 1922 to almost 0.2 MAF in the early 1970s. The increase was more rapid after the early1970s and the annual simulated urban groundwater pumping became more than 0.7 MAF by 2009.

Central Valley

The contribution of groundwater pumping for the total water supply of the Central Valley was steady (around 46%) from 1922 to 2009 with annual fluctuations due to the year type (Figure 32); rising in the dry years and declining in the wet years. The contribution of groundwater pumping increased to 70%

during 1977 (one of the driest years in the Central Valley). On the other hand, the contribution was as low as 30% in wet years such 1983.

Figure 34 shows the 10-year moving average of simulated groundwater pumping in the Central Valley. The figure shows that the Central Valley follows the trend of the Tulare Basin since the Tulare Basin was the dominant contributor to Central Valley groundwater production. Figure 33 shows the historic annual groundwater pumping in the Central Valley and effects of the water year type fluctuations on the long-term trend. The Central Valley was pumping almost 16 MAF/year during the 1976-77 drought; the highest level during the historic simulation period. On the other hand, the pumping in the Central Valley was as low as 7 MAF/year during a wet year such 1983.

The agricultural groundwater pumping in the Central Valley was mostly dominated by irrigated agricultural land use development before the beginning of the CVP and SWP in the mid-1940s. Figure 27 shows that the simulated agricultural groundwater production declined from 5 MAF/year to 4 MAF/year due to reduction in irrigated agricultural land use in the same time period. The greatest increase in the agricultural groundwater pumping occurred between the early 1940s and early 1960s – it tripled from 4 MAF to almost 12 MAF– despite the increased surface water supplies after completion of the Friant and Shasta Dams. The expansion of surface water delivery systems between the early 1960s and early 1970s reduced the reliance on groundwater pumping. The annual simulated agricultural groundwater production fluctuated between approximately 6 MAF and 12 MAF before rising almost to 15 MAF during the 1976-77 drought. It declined significantly and leveled off after the 1976-77 drought and has not risen above 11 MAF/year since then. This is due to several management practices adopted after the drought, including changes in cropping practices, and expansion of conjunctive use and surface water exchanges (Brush, Dogrul, & Kadir, 2013a).

Figure 25 shows that simulated urban groundwater pumping steadily increased in the Central Valley from the 1920s to the 2000s. The portion of the groundwater pumping that is used for urban use constituted only 3 percent of the total groundwater pumping in the 1920s. The portion went up steadily to 15% by the 2000s. Annual simulated urban groundwater pumping for the Central Valley increased from 0.1 MAF to more than 0.4 MAF from the early 1920s to the early 1970s. The urban groundwater pumping continued to increase but more dramatically after the after that and reached almost 1.6 MAF/year by 2009 despite the stabilization in agricultural groundwater pumping (Figure 27).

Figure 35 shows the 10-year moving average percent distribution of groundwater pumping between the three major hydrologic regions in the Central Valley. Although the figure shows that the Tulare Basin always had the higher percentage of the total groundwater production in the Central Valley, the percentage declined continuously from the 1920s to the early 2000s due to the groundwater production growth in San Joaquin Basin and the Sacramento Valley before the 1976-77 drought and also due to the reduction and stabilization of Tulare Basin groundwater pumping after the early 1970s as explained above. The Sacramento Valley constituted less than10% of the total Central Valley groundwater pumping in the 1920s while the San Joaquin Basin and Tulare Basin constituted 21% and 70%, respectively. The contribution of the Sacramento Valley and San Joaquin Basin increased to 22% and 25% in the 2000s, respectively. The Tulare Basin contributions decreased to 53% Figure 35 shows that

the groundwater pumping distribution leveled off in the 2000s as the groundwater production started increasing in the Tulare Basin again.

3.2.4 Groundwater Budget and Change in Groundwater Storage

The aquifers underlying the Central Valley receive water through deep percolation from the land surface, seepage from rivers and lakes, conveyance and delivery system recharge and subsurface inflow from surrounding small watersheds. Outflows from the groundwater system are primarily through groundwater pumping, outflows to rivers and lakes, and outflows to on-farm tile drains (Brush, Dogrul, & Kadir, 2013a). The groundwater budget for the C2VSim model reports the beginning and ending groundwater storages as well as inflows and outflows to/from the groundwater as summarized below (Dogrul, 2012b).

- **Deep Percolation**: Precipitation and excess irrigation water percolating through the unsaturated zone and entering the groundwater
- **Gain from Stream**: Water losses from streams that enter the aquifer system
- **Recharge**: Recharge from conveyance and delivery canal system and recharge to the aquifer from injection wells (artificial recharge)
- **Boundary Flows**: Net inflow into the aquifer through the boundaries including flows from the small watersheds
- **Pumping**: Total pumping from the groundwater
- **Other Flow**: Water lost from lakes that enter the aquifer system, flow released out of groundwater storage due to subsidence, and flows from the groundwater into tile drains; these flows are generally are not significant compared to the other flows and they are grouped and reported together for this report

The historic groundwater budget and change in groundwater storage for the Central Valley, as represented in C2VSim model, is summarized in this section.

Changes in land use, agricultural practices, surface water deliveries, and urban pumping in the Central Valley have significantly affected the balance of flows into and out of the groundwater systems and resulted in significant losses from aquifer storage. Figure 36 shows the cumulative change in storage for the three major hydrologic regions in the Central Valley. Groundwater storage in the Sacramento Valley increased through the mid-1940s, but started decreasing after that. The initial rise in the Sacramento River Basin was most likely due to increasing diversion of relatively abundant surface water supplies for irrigation combined with the relatively low rates of groundwater pumping in the first half of the 20th century. As the groundwater usage increased through mid-1940s the aquifer started losing water and the cumulative groundwater storage declined slowly over time. Figure 36 shows a different trend for the San Joaquin and Tulare Basins, where cumulative groundwater storage has decreased over the time period.

Sacramento Valley

Figure 37 shows the historic annual groundwater budget and cumulative storage change in storage for the Sacramento Valley. Conveyance system Recharge, deep percolation, and boundary flows (subsurface inflow from surrounding small watersheds and subsurface flows from south of the Sacramento Valley)

have increased over time. All these components showed fluctuations due to the hydrology over time; rises in wet years (with increased precipitation and surface water availability) and falls in dry years. The historic trends for the different components of the groundwater budget are summarized below.

- The simulated annual water recharge for the Sacramento Valley increased from 0.02 MAF in the 1920s to 0.4 MAF in the 2000s. Again, this was most likely due to the increase in surface water supplies through time that are used for agricultural irrigation, which effectively diverted water from rivers and onto the Valley floor, providing additional recharge.
- The simulated annual deep percolation for the Sacramento Valley increased from 0.6 MAF in the 1920s to almost 0.8 MAF in the 2000s mostly due to conversion of native land to irrigated agricultural land in the Sacramento Valley. Agricultural land generally has a higher infiltration rate than the native vegetation because of tilling (Scanlon, Reedy, Stonestrom, Prudic, & Dennehy, 2005).
- The simulated annual boundary flows for the Sacramento Valley increased from 0.5 MAF in the 1920s to 0.8 MAF in the 2000s. The historical trend of boundary lows shows annual variations due to changes in hydrology.
- Groundwater pumping in the Sacramento Valley increased over time as discussed in the previous section.
- The streams in the Sacramento Valley gained water from the aquifer system over most of the historical period. The aquifer underneath the Sacramento Valley discharged, on average, about 0.75 MAF/year water to streams in the 1920s. The aquifer continued to discharge increasing amounts of water to streams until the mid-1940s, coinciding with the construction of Shasta Dam. Streams in the Sacramento Valley were gaining as much as 1.4 MAF/year by the mid-1940s. After the construction of the Shasta Dam, the Sacramento River flows became regulated. Around the same time, groundwater pumping in the Sacramento Valley increased and groundwater levels experienced a declining trend. As a result, the stream depletion due to groundwater pumping began sometime around the end of the 1987-92 drought and streams appear to have become net losers of water for the first time. After the drought, stream depletion and accretion fluctuated, mainly as a result of stream stage, groundwater levels, and hydrologic conditions.
- The amount of water flowing into and out of the groundwater storage has fluctuated significantly from year to year with groundwater levels declining in dry years and recovering in wet years. Sacramento Valley groundwater storage was able to recover from the droughts and even increased between the droughts before the mid-1940s. However, with increasing groundwater pumping over time the aquifer apparently could not be replenished completely between the droughts and the cumulative storage change had a declining trend. The impacts of the droughts on Sacramento Valley groundwater storage became more significant over time. The aquifer underneath the Sacramento Valley almost recovered from the 1976-77 drought compared to pre-drought levels due mainly to the 1982-84 wet period, but it did not have as much of a recovery after the 1987-92 drought.
- The cumulative loss in groundwater storage for the Sacramento Valley over the 1922-2009 hydrologic period and historical land and water use conditions is approximately 3.8 MAF.

When an aquifer is pumped, the water withdrawn is either taken out of storage, which means groundwater levels decline, or water is taken from other sources; including natural recharge, deep percolation, flows from boundaries of the groundwater basin, and seepage from streams. Figure 38 shows where the water that is pumped from the Sacramento Valley groundwater basin comes from in terms of the percent contribution from the various sources. The 10-year moving average is shown to reduce the noise of annual variation and better highlight the long-term trends of how water pumped from the groundwater basin is resupplied. In the early 1930s, conveyance system recharge, deep percolation, and boundary flow contributed more than 90% of the water withdrawn by pumping (40 to 45% was from deep percolation, 10 to 15% from conveyance system recharge, and 30 to 35% from boundary flow). The fraction of pumping supplied by reduction in groundwater storage (draining the aquifer and lowering groundwater levels) increased slowly over time with fluctuations during wet and dry periods until groundwater levels dropped steeply during the 1976-77 drought. During the 1982-84 wet period, increased contributions from deep percolation and boundary inflow recovered levels somewhat. The 1987-92 drought caused another significant increase in the fraction of pumped water supplied from reductions in groundwater storage (and a corresponding drop in water levels), and toward the end of that drought, more than 20% of the groundwater withdrawn is estimated to have come from reductions in aquifers storage, reflected by lower water levels. After the 1987-92 drought, the rate of groundwater level declines slowed, but by this point – somewhere in the vicinity of the early 1990 – some of the pumping supply began coming from seepage from streams. This change signals the point at which the rivers and streams of the Sacramento Valley switched from net gaining to net losing streams – giving up more flow to the Valley groundwater basin than they receive. At the end of the simulation period (late 2000s), the model estimates that 33 percent of the pumped water came from deep percolation, 17% from conveyance system recharge, 34% from boundary flows, 15% from reductions in groundwater storage, and 2% from the rivers and streams flowing across the Valley.

San Joaquin Basin

Figure 39 shows the historic annual groundwater budget and cumulative change in storage for the San Joaquin Basin. The historic trends for the different components of the groundwater budget are summarized below.

- The historical trend for the simulated annual recharge for the San Joaquin Basin is very similar to that of the historical surface water supply. The simulated annual recharge in the San Joaquin Basin increased from 0.4 MAF in the 1920s to 0.8 MAF in the early 1980s and then it decreased and leveled off around 0.6 MAF until 2009.
- The simulate deep percolation for the San Joaquin Basin increased steadily from 0.6 MAF in the early 1920s to 0.8 MAF in the late 2000s. Simulated boundary flows to the San Joaquin Basin increased steadily from 0.06 MAF/year in the 1920s to 0.3 MAF/year in the 2000s.
- All of these components summarized above show fluctuations depending on hydrology; with rises in the trend during wet years and declines during dry years. The rises and declines became more drastic after the 1970s.
- The historic increasing trend of the groundwater pumping for the San Joaquin Basin was discussed in the previous section.

- The aquifer underneath the San Joaquin Basin discharged, on average, about 0.3 MAF/year water to streams in the 1920s. The discharge declined as the groundwater pumping in the San Joaquin Basin started increasing and groundwater levels started declining. As a result, the stream depletion due to groundwater pumping began sometime around the early 1950s and streams appear to have become net losers of water for the first time. Streams were continuously net losers after the 1987-92 drought.
- The San Joaquin Basin has been in overdraft since the 1920s. The cumulative groundwater storage for the San Joaquin Basin consistently declined with increasing groundwater pumping in the basin. Except for the 1982-86 wet period, none of the wet periods were able to replenish the groundwater storage reductions due to the previous drought(s). The 1982-86 period was able to replenish the storage change due to the 1976-77 drought because the groundwater pumping was considerably less during that time interval due to implementation of new agricultural practices.
- The cumulative groundwater storage for the San Joaquin Basin was down approximately 25 MAF by 2009, as compared to with 1922 conditions.

Figure 40 shows the sources of pumped water in the San Joaquin Basin in terms of the percent contribution from the various sources. The 10-year moving average shows a smoother trend without the noise of annual variation and better highlights the long-term trends of how water pumped from the groundwater basin is replenished. In the early 1930s, deep percolation, conveyance system recharge, and boundary flows contributed 38%, 28%, and 4% of the water withdrawn by pumping, respectively. The fraction of pumping supplied by reduction in groundwater storage (draining the aquifer and lowering groundwater levels) was around 30% on average from the early 1920s to the late 2000s with fluctuations during wet and dry periods. During the wet periods, increased contributions from deep percolation and boundary flows recovered levels somewhat. Around 10 to15% of the groundwater withdrawn is estimated to have come from reductions in aquifers storage, reflected by lower water levels) during those periods. Somewhere in the vicinity of the early 1950s, some of the pumping supply began coming from seepage from streams. This change signals the point at which the rivers and streams of the San Joaquin Basin switched from net gaining to net losing streams – giving up more flow to the groundwater basin than they receive. At the end of the simulation period (late 2000s), the model estimates that 31 percent of the pumped water came from deep percolation, 23 percent from conveyance system recharge, 11 percent from boundary flow, 23 percent from reductions in groundwater storage, and 2% from the rivers and streams flowing across the San Joaquin Basin

Tulare Basin

Figure 41 shows the historic annual groundwater budget and cumulative change in storage for the Tulare Basin. The historic trends for the different components of the groundwater budget are summarized below:

- The historical trend for the simulated annual recharge for the Tulare Basin is very similar to that of the historical surface water supply. The simulated annual recharge in Tulare Basin increased from 0.35 MAF in the early 1920s to almost 2 MAF in the early 1980s, and then declined to 1.2 MAF and leveled off until 2009.

- The annual recharge fluctuated significantly during the wet and dry years. It increased to 2.5 MAF/year during the 1982-1984 wet period and dropped to 0.5 MAF/year during the droughts of 1976-77 and 1987-92.
- The simulated deep percolation consistently increased (with fluctuations depending on the hydrology from year to year) from 0.65 MAF/year in the early 1920s to 2 MAF in the late 2000s. The simulated boundary flows to the Tulare Basin was generally stable between 0.1 MAF/year and 0.35 MAF/year after the early 1940s.
- Other sources, such as gain from the lake and subsidence, are plotted as a part of "other" in Figure 41. Other sources peaked at around 2 MAF /year in the early 1960s as the subsidence significantly increased due to increased pumping and significant declines in groundwater levels. As the pumping stabilized and started declining slightly by the mid-1970s, the volume of other components declined to 0.5 MAF/year and leveled off until 2009.
- The streams and groundwater system in the Tulare Basin appear to have already been disconnected as early as 1922. As a result the streams were losing water to the groundwater system over the entire period evaluated. Streams were losing around 0.25 MAF/year in the early 1920s. They started losing more as the groundwater pumping started increasing in the Central Valley around the mid-1940s. The streams continued to lose more until the early 1960s and then leveled off in the late 1970s because of the expansion of surface water capacity and less reliance on groundwater pumping. The streams were losing around 0.6 MAF/year during that interval. With the introduction of new agricultural practices and conjunctive water use water transfer programs in the early 1990s, the groundwater pumping in the Tulare Basin started declining which in return reduced the losses from streams to 0.5 MAF/year on average through 2009. The losses from the Tulare Basin streams fluctuated from year to year depending on the surface water supply, groundwater pumping and groundwater levels.
- Figure 41 suggests that the groundwater overdraft has been persistent in the Tulare Basin since the mid-1940s. The reduction in cumulative groundwater storage slowed down after the mid-1970s for the same reasons streams began to lose less. The wet periods after the mid-1970s became more effective through time and replenished more of the storage loss from the previous drought(s) due to reductions in groundwater pumping.
- The simulated cumulative groundwater storage for the Tulare Basin at 2009 was down approximately 125 MAF by 2009, as compared to with 1922 conditions.

Figure 42 shows where the water that is pumped from the Tulare Basin comes from in terms of the percent contribution from the various sources. The 10-year moving average is shown to reduce the noise of annual variation and better highlight the long-term trends of how water pumped from the groundwater basin is resupplied. In the early 1930s, deep percolation, conveyance system recharge, boundary flows, reduction in groundwater storage, gain from stream and other sources contributed 20%, 10%, 2%, 48%, 8%, and 12% of the water withdrawn by pumping, respectively. The fraction of pumping supplied by reduction in groundwater storage (draining the aquifer and lowering groundwater levels) declined slightly from the early 1920s to the late 2000s with fluctuations during wet and dry periods. During the wet periods, increased contributions from deep percolation and boundary flows recovered levels somewhat. Around 15% of the groundwater withdrawn is estimated to have come from

reductions in aquifers storage, reflected by lower water levels) during those periods. At the end of the simulation period (late 2000s), the model estimates that 32% of the pumped water came from deep percolation, 16% from conveyance system recharge, 3% from boundary flow, 32% from reductions in groundwater storage, 7% from the rivers and streams flowing across the Tulare Basin, and 7% from other sources.

Central Valley

Figure 43 shows the historic annual groundwater budget and cumulative change in storage for the Central Valley. The historic trends for the different components of the groundwater budget are summarized below.

- The historical trend for the simulated annual recharge for the Central Valley is very similar to that of the historical surface water supply.
- Deep percolation in the Central Valley steadily increased through time.
- The boundary flows were generally leveled off through time.
  The components summarized above are highly dependent on hydrology of the Central Valley and they showed fluctuations from year to year depending on the annual hydrology.
- Other sources include gain from the lakes and subsidence. Gain from the lakes in general has a stable historical trend with fluctuations due to hydrology. The subsidence has been historically more of a serious problem in the Tulare Basin than the San Joaquin Basin and the Sacramento Valley. Consequently, the trend of the subsidence in the Central Valley is mostly dominated by the trend of subsidence in the Tulare Basin.
- Streams were gaining water from Central Valley aquifers from the 1920s to mid-1960s. However, significant increases in groundwater pumping from the mid-1940s to the mid-1960s resulted in declines in groundwater levels and the discharge from the aquifer to the streams declined. Eventually, the stream depletion due to groundwater pumping began, and sometime around the early 1960s streams appear to have become net losers of water for the first time. Streams were continuously net losers after the 1987-92 drought.
- Figure 43 suggests that groundwater overdraft has been persistent in the Tulare Basin since the mid-1940s. The cumulative groundwater storage had its most drastic decline between the mid-1940s and end of the 1976-77 drought. The expansion of surface water supplies in the wet years, changes in agricultural practices, and implementation of conjunctive use and water transfer programs starting from the early 1960s helped stabilize the groundwater pumping and slowed down the steep decline of groundwater storage in the Central Valley.
- The cumulative groundwater storage for the Central Valley was down approximately 155 MAF by 2009, as compared to with 1922 conditions.

Figure 44 shows where the water that is pumped from the Central Valley groundwater basin comes from in terms of the percent contribution from the various sources. The 10-year moving average is shown to reduce the noise of annual variation and better highlight the long-term trends of how water pumped from the groundwater basin is resupplied. In the early 1930s, deep percolation, conveyance system recharge, boundary flows, reduction in groundwater storage, and other sources contributed 32%, 17%, 11%, 33%, and 7% of the water withdrawn by pumping, respectively. The fraction of pumping

supplied by reduction in groundwater storage (draining the aquifer and lowering groundwater levels) was around 32% on average from the early 1920s to the late 2000s with fluctuations during wet and dry periods. During the wet periods, increased contributions from deep percolation and boundary inflow recovered levels somewhat. Around 10 to 15 percent of the groundwater withdrawn is estimated to have come from reductions in aquifer storage, reflected by lower water levels during those periods. Somewhere in the vicinity of the early 1960s, some of the groundwater pumping supply began coming from seepage from streams. This change signals the point at which the rivers and streams of the San Joaquin Basin switched from net gaining to net losing streams – giving up more flow to the groundwater basin than they receive. At the end of the simulation period (late 2000s), the model estimates that 33% of the pumped water came from deep percolation, 20% from conveyance system recharge, 12% from boundary flow, 25% from reductions in groundwater storage, 5% from the rivers and streams flowing across the Central Valley, and 5% from other sources.

3.2.5 Groundwater Levels

The C2VSim model simulates the aquifer system of the Central Valley using three model layers. Model layer one represents the unconfined portion of the aquifer, and model layers two and three represent the confined portions. Layer three generally represents the portion of the aquifer that is not pumped. The vertical distribution of groundwater pumping in the Central valley varies spatially, but on average 30 percent of the total Central Valley groundwater pumping is from layer one and the remaining 70 percent is from layer two. A detailed description of the model layers can be found in Brush, Dogrul, & Kadir (2013a) and Brush, Dogrul, & Kadir (2013b).

Groundwater pumping is the most significant factor that affects groundwater storage and groundwater-surface water interaction in the Central Valley. Figure 45 and Figure 46 show the simulated historical (from 1925 to 2009) groundwater level changes in the Central Valley for layer one and layer two, respectively. As shown in the figure, years of agricultural and urban groundwater pumping have produced regional cones of depression across the Central Valley.

Sacramento Valley

As indicated in Figure 45 and Figure 46 the groundwater levels in Sacramento Valley did not change significantly from 1925 to 2009 as groundwater pumping in Sacramento Valley has not been as significant as in the San Joaquin Basin and the Tulare Basin due to greater surface water supply. Groundwater levels for both layer one and layer two declined between 25 to 50 feet in the south of the Valley. These areas are mostly urbanized between Cache Creek and Putah Creek and north of the America River. There regional cones of depression in the north American River sub-basins are simulated reasonably well, and show a regional decline of more than 75 feet.

San Joaquin Basin

Groundwater levels in layer one of the San Joaquin Basin declined mostly in the north-east and south-east portion of the Basin and around the major cities (Figure 45). The drawdowns were mostly less than 75 feet. Some areas around the Calaveras River and the north of Fresno River had drawdowns between 75 and 150 feet. The drawdowns in layer two are more extensive than the layer one (Figure 46). There was at least 25 feet of drawdown all around layer one of the San Joaquin Basin except east of the

Modesto-Turlock area. Parts of layer two under the Corcoran Clay experienced higher drawdowns (75 to 100 feet). Two cones of depressions developed around the Modesto-Turlock area and the Los Banos area with groundwater level drawdowns of 150 feet or higher.

Tulare Basin

Historically, the Tulare Basin had the highest groundwater production in the Central Valley. This fact is reflected both in Figure 45 and Figure 46. Groundwater levels in layer one of the Tulare Basin declined everywhere except Tulare Lake, Buena Vista Lake, and the surrounding of the Tule River (Figure 45). Groundwater levels in some areas between the Kings River and San Joaquin River declined as much as 250 feet. The cone of depression in layer one between Tulare Lake and Buena Vista Lake had a groundwater level drawdown of more than 400 feet. South-east tip of the Tulare Basin and north-west and south-west of Kettlemen Hills experienced drawdowns as high as 150 to 250 feet. Groundwater level drawdowns were spatially more extensive in layer two than layer one (Figure 46). The depths of the cones depressions, although in much the same locations as layer one, are not as deep as those in layer one. The deepest cone of depression is between Tulare Lake and Buena Vista Lake with a depth of 250 to 400 feet. On the other hand, the extent of the 75 to 150 feet drawdown zone and 150 to 250 feet drawdown zone in layer two are wider than those of layer one.

Figure 45 and Figure 46 are good illustrations of areas within the Central Valley where extensive groundwater pumping caused drastic changes in groundwater storage and where the loss in groundwater storage could not be recovered by other sources of water. These figures, specifically Figure 45, are also good illustrations of how the streams in the Central Valley interact with the aquifer with the declines in groundwater levels. Figure 45 shows how the groundwater level drawdowns around the major streams are lower compared to their surroundings because of the flows from the streams to the groundwater system as the groundwater levels go down.

3.2.6 Groundwater Flows to Streams

Streams and the groundwater system in the Central Valley are intimately linked. Their interaction is very sensitive to changes in groundwater levels, stream flows, and the pattern of the streams flows. Under pre-development conditions, significant volumes of water seeped into the aquifer from river channels near the valley margins, and significant volumes discharged from groundwater to rivers near the valley trough. During the summer months when rim inflows were low, groundwater discharges near the valley trough provided steady in-stream flows and moderated water temperatures (Brush, Dogrul, & Kadir, 2013a).

The historic hydrologic development of the Central Valley caused dramatic changes in exchanges between streams and aquifers. Stream flow patterns all around the Central Valley have changed due to the SWP and the CVP. Operation of these projects increased the summer flows and reduced the winter flows in the streams, and they also increased the diversions from streams. Increased groundwater pumping all around the valley increased the depth to the groundwater and changed the dynamics of the stream-aquifer interaction.

Figure 47, Figure 48, and Figure 49 show the gaining and losing streams reaches in the Central Valley for the 1920s (average of 1922-1929), 1960s (average of 1960-1969), and the 2000s (average of 2000-2009),

respectively. The changes over time from the 1920s, and 1960s to the 2000s are summarized below for each hydrologic region.

- Many of the tributaries in the Sacramento Valley were net losers by the 1920s. On the other hand, major streams like the Sacramento River, Feather River, and American River were net gaining streams. Agricultural development occurred between 1920s and 1960s resulted in some changes in the nature of stream-aquifer interaction during this period. By the 1960s, the American River, Putah Creek, Yuba River, and Butte Creek became net losers in addition to the tributaries in the Sacramento Valley. Significant amount of development occurred after the major storage and conveyance facilities were on-line, after 1960s. As a result, both surface water and groundwater use increased. By the 2000s, portions of the Sacramento River between the Sutter Buttes and Feather River became net losers.
- Most of the streams in the San Joaquin Valley were gaining in the 1920s with the exceptions of Calaveras River, Cosumnes River, and a portion of the San Joaquin River between the Merced River and Deadman's Creek. Bear Creek and portion of the San Joaquin River between the Stanislaus River and the Calaveras River became net losers by 1960s. All streams from the Merced River to Fresno River on the east side of the San Joaquin River became net losers by 2000s.
- All the streams in the Tulare Basin were net losers of water by 1920s.

Figure 50 shows the simulated historic and 10-year moving average of net groundwater flows to the streams of the three major hydrologic regions in the Central Valley on the same graph. The details of the groundwater flows to the streams were discussed in the previous section. Figure 50 is a good illustration of how stream aquifer interaction started changing drastically with the implementation of the large water projects in the Central Valley. The groundwater flows to the streams were consistent until the mid-1940s (completion of Friant and Shasta Dams). The expansion of the CVP and SWP continued and more streams became regulated after the mid-1940s. At the same time, the Central Valley's dependence on groundwater started increasing rapidly. As a result, the groundwater flows to streams all around the Central Valley had sharp declines until the end of the 1976-77 drought. The groundwater flows to streams started increasing with the help of the 1982-1986 wet period and increased water conservation consciousness after the drought. However, the 1987-92 drought reduced groundwater flows to the streams sharply. The decline due to the 1987-92 drought was worse than any other decline in the history. The groundwater flows to the streams stabilized after the drought again due to the efforts to stop groundwater decline through implementation of new agricultural practices, conjunctive use, and water transfer programs and also due to increased environmental consciousness. By 2009 both the San Joaquin and Tulare Basin streams were net losers to groundwater and Sacramento Valley streams were on the verge of becoming net losers to groundwater.

Spatial and temporal groundwater flows to the Sacramento River were investigated as a part of this project. The Sacramento River was split into five reaches. The reaches were named Reach A, Reach B, Reach C, Reach D, and Reach E from north to south as shown in Figure 51.

The simulated annual groundwater flows to these stream reaches, as shown in Figure 52, are summarized below.

- The two south reaches, Reaches D and E, were net losers to the aquifer in the 1920s and they continued to lose to the aquifer through time with a consistently increasing trend. The losses of Reaches D and E did not fluctuate as much as Reach B or C depending on the year type.
- Reach E was losing around 0.025 MAF/year to the aquifer in the early 1920s and 0.1 MAF/year in the late 2000s.
- The net simulated stream flow to aquifer from Reach D to the aquifer increased from 0.075 MAF/year in the early 1920s to 0.12 MAF/year in the late 2009s.
- The groundwater flows to Reach C were around 0.15 MAF/year in the early 1920s, and the flows increased more than 0.3 MAF in the mid-1940s. With the completion of the Shasta Dam and increasing trend in groundwater pumping, the groundwater flows to the Reach C started declining. The rate of the drop became steeper with the completion of the Oroville Dam in the mid-1960s. The decline continued until the mid-1990s. The direction of the flow even changed after the 1987-92 drought and Reach C became a losing stream for a few years. The groundwater flows to the stream started increasing slightly by the late 1990s and the stream was gaining around 0.03 MAF/year around the late 2000s.
- Reach C is the most sensitive reach to the changes in the hydrology among all of the Sacramento River reaches.
- Reach A and Reach B followed a similar trend. The net groundwater flows to these reaches increased until the mid-1940s and started declining after that. The decline continued all the way to the 2000s. The trend showed fluctuations from year to year depending on the hydrology.
- The net groundwater flow to both Reaches A and B was around 0.22 MAF/year in the early 1920s. The net groundwater flow to Reach B was around 0.3 MAF/year at its peak in the mid-1940s and it was 0.26 MAF/year for Reach A. The net groundwater flows to Reaches A and B declined to 0.2 MAF/year and 0.15 MAF/year by the late 2000s, respectively.

Section 4 Baseline for Management Scenario Simulations

Beyond evaluating existing historical conditions, a calibrated model is well-suited for simulating hypothetical management scenarios and conditions. In that respect, an Existing Condition Baseline (EC BL) simulation was developed to use as a reference for the scenarios described in the following chapter.

The EC BL simulation was also used to show how stream aquifer interaction may change over time in the future. The baseline applies constant land use conditions over the same hydrology, so analysis of water budgets, stream flows, groundwater levels, and stream-aquifer interaction – with appropriate spatial and temporal scale and distribution –from the EC BL were used to assess future impacts assuming current hydrologic conditions continue. The baseline was also used to show the impacts of hydrologic variability, as shown in Table 2, on groundwater pumping, groundwater levels and groundwater flows to streams.

4.1 Modeling Approach and Assumptions

The 1973 to 2009 hydrology was selected as baseline hydrologic period, because historical surface water delivery data starting in 1973 is the most stable set of data, and most storage and conveyance facilities have been in place since 1973. The EC BL maintains current levels of land use, water use, and water supplies. The model input files for the EC BL were developed using the assumptions listed below.

- Historical hydrology and surface water deliveries from 1973 to 2009 (37 years) were used to represent future hydrological conditions for the EC BL. The 1973 to 2009 period contained both wet and dry periods and appropriate hydrologic variability to represent a wide-range of conditions.
- The 37-year hydrology will be repeated twice for a 74 year baseline simulation run.
- 2005 land use and crop acreages from the historic C2VSim model run were used as suggested by DWR.
- Agricultural water demand was calculated within the model based on 2005 land use and crop acreage and subject to 1973-2009 hydrology.
- 2009 urban water demand estimates from the historical C2VSim model were used.
- Pumping was calculated internally within the model to meet the remaining demand after the surface water supplies.
- End of September 2009 values from the historic C2VSim model run were used for initial groundwater levels, soil moisture, unsaturated soil moisture, and small watersheds.

4.2 Modeling Results

4.2.1 Groundwater Budget and Change in Groundwater Storage

The EC BL groundwater budget and change in groundwater storage for the Central Valley, as represented in C2VSim model, is summarized in this section. The inflow and outflow components of the C2VSim groundwater budget are as summarized in Section 3.2.4.

The historic and EC BL cumulative groundwater storage change plots for the three major hydrologic regions in the Central Valley are shown in Figure 53. The figure shows that the San Joaquin and Tulare Basins continue to be in overdraft condition under the EC BL. Cumulative groundwater storage for the Sacramento Valley was declining after the mid-1940s during the historic simulation and the decline continues in the EC BL. The EC BL cumulative groundwater storage for all three hydrologic regions follows the trend from the last 20 years of the historic simulation. The wet years would stop the cumulative groundwater storage decline, but they cannot replenish all the water lost during the dry years.

Sacramento Valley

Figure 54 shows the historic and EC BL groundwater budget and cumulative storage change for the Sacramento Valley. The historic and EC BL trends for the different components of the groundwater budget are summarized below.

- Due to the fixed land use for the EC BL, the trends for recharge, deep percolation, boundary flows, and groundwater pumping for the EC BL level off at their late 2000s averages from the historic run.
- The simulated deep percolation, conveyance system recharge, boundary flows, and groundwater pumping level off around 0.8 MAF/year, 0.4 MAF/year, 0.8 MAF/year, and 2.5 MAF/year, respectively.
- Deep percolation, conveyance system recharge and boundary flows can go up or down 0.1 to 0.2 MAF/year during a wet or a dry year. On the other hand, the simulated groundwater pumping can fluctuate more significantly. The simulated groundwater pumping can go above 3.5 MAF/year on a dry year and can go as low as 1.8 MAF during a wet year.
- The streams in the EC BL are not net losers for most of the EC BL simulation. The direction of the flow is generally from streams to the aquifer except in especially dry years of the EC BL during which time the rivers have little water to lose. This situation occurs in simulation years 5 and 42 that correspond to the 1977 dry year and simulation years 15 and 52 that correspond to the 1987 dry year. The simulated average flow from streams to aquifers increases from 0.2 MAF/year at the beginning of the simulation to 0.35 MAF/year at the end of the simulation. The simulated net flow from the streams to the aquifer can be as high as 1.1 to 1.2 MAF/year during the wet years.
- The decline in the cumulative groundwater storage for the Sacramento Valley in the first half of the EC BL simulation is more drastic than the decline in the second half due to the increasing flows from the streams to the aquifer throughout the simulation. The aquifer can recover the losses from the drought that corresponds to the 1976-77 drought in both halves of the simulation, but it cannot recover the drought that corresponds to the 1987-92 drought. While the aquifer losses 5 MAF of storage in the first half the simulation, it only losses 1.9 MAF in the second half due to almost 3.1 MAF of additional gains from the streams in the second half.

When an aquifer is pumped, the water withdrawn is either taken out of storage, which means groundwater levels decline, or the aquifer is replenished by other sources, including deep percolation, recharge from canals and conveyance system, inflow from boundaries of the groundwater basin, and

seepage from streams. Figure 55 shows where the water that is pumped from the Sacramento Valley groundwater basin comes from in terms of the percent contribution from the various sources for the historic and EC BL simulations. The 10-year moving average is shown to reduce the noise of annual variation and better highlight the long-term trends of how water pumped from the groundwater basin is resupplied. The figure shows that the fraction of all the sources decreases towards the end of the simulation as the contribution from the streams increases. The fraction of pumping supplied from reduction in groundwater storage has the most significant decline. Around 20% of the groundwater withdrawn is estimated to have come from reductions in aquifers storage during the dry years and the same contribution can be as low as 5% during the wet years. During the wet periods, the contribution from streams, deep percolation, and boundary flows is higher and contribution from conveyance system recharge is lower compared to their long-term averages. On the other hand, the contribution from conveyance system recharge increases while the contribution from streams, deep percolation, and boundary flows is decreasing during the wet years. At the end of the EC BL simulation period, the model estimates that 31 percent of the pumped water came from deep percolation, 16% from conveyance system recharge, 33% from boundary flow, 10% from reductions in groundwater storage, and 10% from the rivers and streams flowing across the Sacramento Valley.

San Joaquin Basin

Figure 56 shows the historic and EC BL groundwater budget and cumulative storage change for the San Joaquin Basin. The historic and EC BL trends for the different components of the groundwater budget are summarized below.

- The simulated deep percolation, conveyance system recharge, boundary flows and groundwater pumping are leveled off through the EC BL simulation, with an average of 0.9 MAF/year, 0.65 MAF/year, 0.3 MAF/year and 2.3 MAF/year, respectively.
- Deep percolation, conveyance system recharge, and boundary flows can go up or down by 0.1 to 0.2 MAF/year during a wet or a dry year. On the other hand, the simulated groundwater pumping can fluctuate more significantly. The simulated groundwater pumping can go up to 4 MAF/year in a dry year and go as low as 1.6 MAF during a wet year.
- Another component that contributes to the San Joaquin Basin groundwater budget is subsidence. Subsidence is labeled under “other” in Figure 56.
- The San Joaquin Basin streams in the EC BL are net losers from the beginning of the EC BL simulation. The direction of flow is generally from the streams to the aquifer, except for extra dry years of the EC BL like simulation years 4 and 41 that correspond to the 1976 dry year and simulation year 15 that corresponds to the 1987 dry year. The simulated average stream depletions increases from 0.3 MAF/year at the beginning of the simulation to 0.45 MAF/year at the end of the simulation. The simulated net stream losses to the aquifer can be as high as 1.1-1.2 MAF/year during the wet years.
- Figure 56 shows that the decline in cumulative groundwater storage for the San Joaquin Basin in the first half of the EC BL simulation is more than the decline in the second half of the simulation due to increased flows from the streams to the aquifer throughout the simulation. The aquifer can recover the losses from the drought that corresponds to the 1976-77 drought in both halves

of the simulation but it cannot recover the drought that corresponds to the 1987-92 drought. While the aquifer lost 5.5 MAF of storage in the first half the simulation, it only loses 3.4 MAF in the second half due to almost 2.1 MAF of additional gains from the streams in the second half.

Figure 57 shows where the water that is pumped from the San Joaquin Basin comes from in terms of the percent contribution from the various sources for the historic and EC BL simulations. The 10-year moving average is shown to reduce the noise of annual variation and better highlight the long-term trends of how water pumped from the groundwater basin is resupplied. The figure shows that the fraction of all the sources decreases towards the end of the simulation as the contribution from the streams increases. The fraction of pumping supplied from reduction in groundwater storage has the most significant decline. Around 30% of the groundwater withdrawn is estimated to have come from reductions in aquifers storage during the dry years and the same contribution can be as low as 10% during the wet years. During the wet periods, the contribution from streams, deep percolation, and boundary flows is higher and contribution from recharge is lower compared to their long-term averages. On the other hand, the contribution from recharge increases while the contribution from streams, deep percolation, and boundary flows is decreasing during the wet years. At the end of the EC BL simulation period, the model estimates that 3% of the pumped water came from deep percolation, 22% from conveyance system recharge, 12% from boundary flow, 21% from reductions in groundwater storage, 13% from the rivers and streams flowing across the Sacramento Valley, and only 1% from the other sources.

Tulare Basin

Figure 58 shows the historic and EC BL groundwater budget and cumulative storage change for the Tulare Basin. The historic and EC BL trends for the different components of the groundwater budget are summarized below.

- The simulated deep percolation, conveyance system recharge, boundary flows and groundwater pumping are leveled off through the EC BL simulation with an average of 2.1 MAF/year, 1.3 MAF/year, 0.25 MAF/year and 5.3 MAF/year, respectively.
- While deep percolation and conveyance system recharge can go up or down 0.4 to 0.6 MAF/year during a wet or a dry year, boundary flows can fluctuate between 0.05 and 0.075 MAF/year. The simulated groundwater pumping can fluctuate more significantly during the wet and dry periods. The simulated groundwater pumping can go above 8 MAF/year in a dry year and can go as low as 3.5 MAF during a wet year.
- The other components that contribute to the Tulare Basin groundwater budget are subsidence and gain from lakes. These two components are labeled under “other” in Figure 58. Together, they are leveled at around 0.4 MAF/year, with a maximum of almost 1 MAF/year during dry years and minimum of 0.1 MAF/year during the wet years.
- The Tulare Basin streams in the EC BL are net losers through the EC BL simulation period. The simulated average flow from streams to aquifers increases from 0.6 MAF/year at the beginning of the simulation to 0.67 MAF/year at the end of the simulation. The simulated net flow from the streams to aquifer can be as high as 1.2 MAF/year and as low as 0.25 MAF/year.

- The cumulative groundwater storage for the Tulare Basin consistently declines through the EC BL simulation. The aquifer can recover the losses from the drought that corresponds to the 1976-77 drought in both halves of the simulation but it cannot recover the drought that corresponds to the 1987-92 drought. While the aquifer losses 30.6 MAF of storage in the first half the simulation, it only losses 29.2 MAF due to almost 1.4 MAF additional gains from the streams in the second half.

Figure 59 shows where the water that is pumped from the Tulare Basin comes from in terms of the percent contribution from the various sources for the historic and EC BL simulations. The 10-year moving average is shown to reduce the noise of annual variation and better highlight the long-term trends of how water pumped from the groundwater basin is resupplied. The figure shows that the fraction of all the sources is fairly consistent throughout the EC BL simulation. Around 35% of the groundwater withdrawn is estimated to have come from reductions in aquifers storage during the dry years and the same contribution can be as low as 10%during the wet years. During the wet periods, the contribution from streams, deep percolation, and boundary flows is higher and contribution from recharge is lower compared to their long-term averages. On the other hand, the contribution from recharge increases while the contribution from streams, deep percolation, and boundary flows is decreasing during the wet years. At the end of the EC BL simulation period, the model estimates that 33% of the pumped water came from deep percolation, 15%from conveyance system recharge, 3% from boundary flow, 33% from reductions in groundwater storage, 9% from the rivers and streams flowing across the Sacramento Valley, and 7% from the other sources.

Central Valley

Figure 60 shows the historic and EC BL groundwater budget and cumulative storage change for the Central Valley. The historic and EC BL trends for the different components of the groundwater budget are summarized below.

- The simulated deep percolation, conveyance system recharge, boundary flows and groundwater pumping are leveled off throughout the EC BL simulation with an average of 3.8 MAF/year, 2.35 MAF/year, 1.35 MAF/year and 10.3 MAF/year, respectively.
- While deep percolation and conveyance system recharge can go up or down 0.6 to 0.8 MAF/year during a wet or a dry year, boundary flows can fluctuate between 0.2 and 0.3 MAF/year. The simulated groundwater pumping can fluctuate more significantly during the wet and dry periods. The simulated groundwater pumping can go up to 15.5 MAF/year on a dry year and can go as low as 6.9 MAF during a wet year.
- The other components that contribute to the Central Valley groundwater budget are subsidence and gain from lakes. These two components are labeled under “other” in Figure 60. Together, they are leveled around 0.4 MAF/year, with a maximum of almost 1.1 MAF/year during dry years and minimum of 0.1 MAF/year during the wet years.
- The Central Valley streams in the EC BL are net losers through the EC BL simulation period. The simulated average flow from streams to aquifers increases from 1.2 MAF/year at the beginning

of the simulation to 1.5 MAF/year at the end of the simulation. The simulated net flow from the streams to aquifer can be as high as 3.6 MAF/year and as low as 0.12 MAF/year.

- The declines in the cumulative groundwater storage for the Central Valley in the first half of the EC BL simulation is more than the decline in the second half of the simulation due to the increased flows from the streams to the aquifer throughout simulation. The aquifer can recover the losses and from the 1976-77 drought in both halves of the simulation but it cannot recover back from the 1987-92 drought. While the aquifer losses 41.2 MAF of storage in the first half the simulation, it only losses 34.5 MAF due to almost 6.7 MAF additional gains from the streams.

Figure 61 shows where the water that is pumped from the Central Valley comes from in terms of the percent contribution from the various sources for the historic and EC BL simulations. The 10-year moving average is shown to reduce the noise of annual variation and better highlight the long-term trends of how water pumped from the groundwater basin is resupplied. The figure shows that the fraction of all the sources decreases slightly towards the end of the simulation as the contribution from the streams increases. The fraction of pumping supplied from reduction in groundwater storage has the most significant decline. Around 35 percent of the groundwater withdrawn is estimated to have come from reductions in aquifers storage during the dry years and the same contribution can be as low as 10% during the wet years. During the wet periods, the contribution from streams, deep percolation, and boundary flows is higher and contribution from recharge is lower compared to their long-term averages. On the other hand, the contribution from recharge increases while the contribution from streams, deep percolation, and boundary flows is decreasing during the wet years. At the end of the EC BL simulation period, the model estimates that 32% of the pumped water came from deep percolation, 17% from conveyance system recharge, 12% from boundary flow, 25% from reductions in groundwater storage, 10%from the rivers and streams flowing across the Sacramento Valley, and 4% from the other sources.

4.2.2 Groundwater Levels

The changes in the simulated groundwater levels (difference between the end and beginning of the simulation) for EC BL simulation for layers one and two are shown in Figure 62 and Figure 63, respectively. The changes in the simulated groundwater levels for layer one (Figure 62) are summarized below.

- Most of the change in the simulated groundwater levels in layer 1 in the Central Valley is between the -25 and 25 feet interval.
- The groundwater level drawdown for layer one in the Eastside Streams Region (area located to the east of the Delta that includes the Mokelumne and Cosumnes Rivers) and the area between the American River and Yuba River is between 25 and 75 feet. The groundwater levels for a small area on the north side of the American River drops below 75 feet in layer one.
- There is a 25 to 75 foot cone of depression around the Los Banos area for layer one.
- The drawdown in the area between the Kings River and the San Joaquin River continues under the EC BL. The dropdown in layer one is mostly between 25 and 75 feet with a small patch of area that is more than 75 feet.

- The drawdown for layer one on the west side of the Kettlmen Hills and south east side of the Tulare Basin can go as high as 75 to 150 feet.

The changes in the simulated groundwater levels for layer two (Figure 63) are summarized below.

- The magnitude and extent of the simulated changes in the groundwater levels for layer two follows the footprint of the layer one changes.
- The extent of the 25 to 75 feet drawdown area around the Los Banos area is larger for layer two. It extends further south and east compared to layer one.
- The drawdown area for layer two between the Kings River and the San Joaquin River extends further in the east, south, and west directions with respect to layer one and it is connected with the drawdown area of the Kettlemen Hills area.
- The decline in groundwater levels in layer two is capped with 150 feet all around the Central Valley.

4.2.3 Groundwater Flows to Streams

The groundwater flows to the streams in the Central Valley were averaged for the last 10 years of the EC BL simulation and reaches displayed as losing or gaining depending on the sign of the averages (Figure 64). When Figure 64 is compared to Figure 49, which shows the losing and gaining streams in the Central Valley for the 2000s, there is a slight difference. Based on the model results, it appears that only Cottonwood Creek in the north of the Sacramento Valley and Dry Creek in the Eastside Streams Region have changed trends from gaining to losing streams.

Figure 65 shows the simulated 10-year moving average net groundwater flows to the streams of the three major hydrologic regions in the Central Valley for the historic and EC BL simulation on the same graph. The results are summarized below.

- The Sacramento Valley streams were on the verge of becoming losing streams at the end of the historic simulation and they are net losers throughout the EC BL.
- The San Joaquin Valley and the Tulare Basin streams were already net losers at the end of historic simulation and they continue to be losing streams in the EC BL simulation.
- The 10 year moving average flows from the streams to the aquifer for all the hydrologic regions increase throughout the EC BL simulation but the rate of increase is not as steep as the historic rate of increase. Also, the rate of increase is slower in the second half of the EC BL simulation than in the first half.
- The 10 year moving average flows from the streams to the aquifer during the period that corresponds to the 1976-77 drought increase and then decrease almost back to their pre-drought values for the streams in all of the hydrologic regions except the Sacramento Valley. However, the same behavior does not repeat during the period that corresponds to the 1987-92 drought; none of the hydrologic regions bounce back.

Figure 66 shows the simulated historic and EC BL annual groundwater flows to the Sacramento River reaches shown in Figure 51. The simulated annual groundwater flows to these stream reaches, are summarized below.

- Reaches D and E continue to lose to the aquifer during the EC BL simulation as they did in the historic simulation. The rate of increase for the losses from the Reaches D and E are fairly consistent with their historic rates and they do not fluctuate as much as the rates of losses from Reaches B and C due to hydrology.
- The simulated flows from Reach D to the aquifer increases from 0.12 MAF/year at the beginning of the EC BL to 0.155 MAF/year at the end of the EC BL simulation. The losses from Reach E to the aquifer increases from 0.1 MAF/year to 0.115 MAF/year from the beginning to the end of the EC BL simulation.
- The declining trend in the groundwater flows to the Reach C in the historic simulation stops in the EC BL simulation.
- Groundwater flows to Reach C level off right around 0 during the EC BL simulation; the reach can be gaining or losing trough the simulation depending on the hydrology. Reach C becomes a losing stream during long drought periods such as periods representing 1987-92 drought. The reach can lose as much as 0.15 MAF/year to aquifer during those times. However, the losses from the reach can decline quickly after the drought and the reach can become gaining again.
- Groundwater flows to Reaches A and B for the EC BL continue their trend from the last 15-20 years of the historic simulation. The groundwater flows to these reaches declines with a consistent small rate throughout the EC BL simulation with fluctuation depending on the hydrology. Reach B fluctuates more than the Reach A, but not as much as Reach C.
- The simulated groundwater flows to the Reach A was around 0.2 MAF/year at the end of the historic simulation. It decline to 0.185 MAF/year by the end of the EC BL simulation. The simulated groundwater flows to Reach B for the EC BL decline from 0.15 MAF/year at the beginning of the simulation to 0.135 MAF/year at the end of the simulation.

Section 5 Water Management Scenarios

In addition to using the existing model to illustrate and better understand hydrologic conditions and behavior in the Central Valley in the past and under future "no action" (baseline) conditions, several potential future management scenarios were developed and simulated. The intent of these simulations was to provide insight for water resource planning efforts and to inform policy recommendations. Three such scenarios were developed and simulated as a part of this project:

- Groundwater Substitution Scenario
- Increased Agricultural Water Demand Scenario
- Increased Irrigation Efficiency Scenario

5.1 Scenario 1: Groundwater Substitution

Groundwater substitution transfers--where surface water users forgo the use of their surface water for transfer to other users and instead pump local groundwater to meet their water demands – have been viewed as a valuable tool for meeting future water needs in California since the early 1990s. It has been recognized that groundwater pumping for groundwater substitution transfers has effects on stream flow in the vicinity of the pumping – thereby affecting other surface water supplies in the region of the transfer.

In the future, it is foreseeable that more widespread use of such transfers might be employed to improve the reliability of water supplies. The Groundwater Substitution Scenario was developed to quantitatively estimate the impacts of groundwater pumping associated with short-term or long-term groundwater substitution on:

- Groundwater conditions
- Stream flows
- Other components of the regional water balance

The scenario was developed to assess the overall impacts of a conceptual large-scale groundwater substitution project, not any particular or specific set of projects.

5.1.1 Modeling Approach and Assumptions

This scenario assumes transferring surface water to water users south of Sacramento-San Joaquin Delta by meeting the surface water supply requirements to the Sacramento-San Joaquin Delta in non-wet years, as identified by the Sacramento River Index (Figure 67). The following assumptions were used for developing this scenario.

- Surface water contractors who participate in the groundwater substitution program in the Sacramento Valley will replace their surface water supplies from the Sacramento River and its tributaries with groundwater pumping for the months of June through October (the transfer period) in non-wet years.
- The surface water allocations left in the streams will be used for short-term transfers to south of Sacramento-San Joaquin Delta.

- 186 thousand acre-feet (TAF) of additional groundwater will be pumped during non-wet years.

Figure 68 shows the hypothetical location of groundwater pumping for the Groundwater Substitution Scenario. The schedule of groundwater pumping that is proposed for this scenario is shown in Figure 69. The figure shows that the proposed pumping fluctuates between the pumping years. This is because the water year runs from October to September and the scenario pumping runs from June through October. Also, the pumping could not be evenly distributed between June and October because there is not enough demand for September and October in some of the operation years.

As a part of this project, a sub-scenario of the full Groundwater Substitution Scenario was developed. The second scenario was set up to operate the Groundwater Substitution Scenario for only the first year of pumping (Figure 70). The scenario does not pump any additional groundwater for the rest of Groundwater Substitution program and lets the system recover from the impacts of one year of pumping. This scenario was developed to isolate the impact of one year pumping to better illustrate the effects of groundwater pumping on stream depletion. For the rest of this project, this sub-scenario will be called Scenario 1a – Short Project Pumping Cycle and the scenario with a full cycle of pumping will be called Scenario 1b - Full Project Pumping Cycle.

5.1.2 Results

Scenario 1a – Short Project Pumping Cycle

Impacts on the Groundwater Levels

Two observation wells within the hypothetical pumping areas are selected to evaluate the impacts of Scenario 1a on the groundwater levels, as shown in Figure 71. One is close to the Sacramento River and one is away from any major streams. Figure 72 shows the changes in groundwater levels for Scenario 1a relative to EC BL for an observation well away from any major streams for layers one and two. After one year of pumping, the groundwater level for both layers one and two decline 2.5 feet. It takes around 25 years for the groundwater levels to fully recover after one year of additional scenario pumping. Figure 73 shows the changes in groundwater level for Scenario 1a relative to EC BL for an observation well close to the Sacramento River for layers one and two. Layer two groundwater levels for this observation well decline between 2 and 2.5 feet after one year of additional scenario pumping. Like the previous observation well, it takes around 25 years for the groundwater levels to recover in layer two. On the other hand, the groundwater levels for layer one declines only 0.25 feet after one year of additional pumping and it takes less than 10 years for the groundwater levels to recover due to additional flows from the streams to the aquifer.

Impacts on the Groundwater Storage and Stream-Aquifer Interaction

Figure 74 shows the cumulative change in groundwater budget for Scenario 1a relative to EC BL. This figure shows the sources of water that compensate for the additional groundwater pumping due to Scenario 1a. Additional pumping, in the amount of 186 thousand acre-feet (TAF), in the first year of the scenario run comes almost exclusively from the groundwater storage right after the pumping. However, additional depletions from the streams start compensating the lost groundwater storage over time. The contribution from the streams increases exponentially at the beginning and then then slows down over time. Twenty five years after the beginning of the simulation almost 90% of the additional pumping in

the first year of the simulation comes from stream depletions and the rest from change in groundwater storage. By the end of the simulation, the contribution from the streams is more than 95%. However, the impacts of such stream depletion is most significant during the times when the Delta is in "surplus" condition. Therefore, as shown in Figure 75, the stream depletion impacts during Delta in-balance conditions is much less – approximately 35% of the additional pumping – although there is still a considerable amount of water supply impact.

Scenario 1b - Full Project Pumping Cycle Impacts on the Groundwater Levels

Impacts on Groundwater Levels

Figure 76 and Figure 77 show the simulated changes in groundwater levels for Scenario 1b relative to EC BL for layers one and two at the end of the simulation, respectively. Groundwater level differences in layer one are generally more significant than layer two because the percent of pumping from layer one in the Sacramento Valley is more than layer two. Simulated groundwater levels can decline 15 feet or more in layer one in some areas covered by the hypothetical pumping areas in the north of the valley and south-east of the Sutter Buttes. On the other hand, the simulated groundwater level drawdowns in layer two do not exceed 10 feet. Another notable difference between Figure 76 and Figure 77 is that the simulated groundwater drawdowns around the areas that are close to the major streams in layer one are significantly less than the areas in layer two. The groundwater levels close to streams in layer one recover faster because of the increased flows from the streams to the aquifer after pumping events for the Groundwater Substitution Scenario.

Figure 78 shows the simulated change in groundwater levels between Scenario 1b and EC BL for layers one and two at the end simulation year 22, which corresponds to the second long pumping cycle due to the Groundwater Substitution Scenario. There is a five-year wet period from simulation year 23 to 28. This is the longest non-pumping period for Scenario 1b (this time period corresponds to the 1995-2000 wet period) in the history. The simulated change in groundwater levels for Scenario 1b relative to EC BL for layers one and two for simulation are shown in Figure 79. Due to higher groundwater pumping rates in layer one in the Sacramento Valley, the drawdowns in layer one at the end of simulation year 22 are higher than layer two except in the areas close to the major streams due to the contribution of streams to the aquifer. The simulated change in groundwater levels in layer one and layer two at the end of simulation year 28 looks very similar. This explains that the simulated groundwater levels in layer one recover more quickly than layer two for the same time interval. Figure 79 also shows a wider (0 to 2.5 feet) band around he major streams for layer one compared to layer two.

The temporal change in simulated groundwater levels for layers one and two for Scenario 1b relative to EC BL for the two observation wells mentioned for Scenario 1a (Figure 71) is shown in Figure 80 and Figure 81. The blue stripes in these figures represent the years with additional pumping for the Groundwater Substitution Program. Figure 80 shows the simulated change in groundwater level for layers one and two for Scenario 1b relative to EC BL for the observation well away from and major streams. The figure shows that both layer one and layer two follow the same trend; decline during the pumping years and some degree of recovery during the non-pumping years. Both layer one and layer two changes in groundwater levels seem to reach equilibrium around simulation year 22. After the equilibrium the decline in simulated groundwater level for layer one is 1.5 to 2 feet higher than the layer

two. The simulated change in groundwater level for layers one and two for Scenario 1b relative to EC BL for the observation well close to the Sacramento River is shown in Figure 81. The figure clearly shows that there are drastic differences between the simulated changes in groundwater level for layers one and layer two. The hydrograph for layer one declines until simulation year 10 and then reaches equilibrium around -0.5 feet. On the other hand the hydrograph for layer two declines until simulation year 22 and then reaches equilibrium around -7 feet. Both of the hydrographs decline during the pumping years and recover somewhat during the non-pumping years.

Impacts to the Groundwater Storage and Stream-Aquifer Interaction

Figure 82 shows the annual simulated difference in the groundwater budget for Scenario 1b relative to EC BL. The groundwater system loses water because of additional pumping and less recharge from the diversion canals which is a result of reductions in surface water diversions during the Groundwater Substitution Program. The figure shows that the losses from the groundwater system are compensated for by reductions in aquifer storage and additional flows from the streams to the aquifer (i.e., stream depletion). According to Figure 82, compensation from the streams to the aquifer increases from the first year of the pumping cycle while compensation from groundwater storage decreases. As the pumping cycle ends the streams continue to contribute to the aquifer and the aquifer storage starts to increase. The contribution from the streams during the non-pumping periods decreases from the beginning of the non-pumping period and continues to decrease through the end of the period. The change in flows from the streams to the aquifer can go as high as 170 TAF/year during the project pumping periods and can go as low as 23 TAF/year during the non-pumping periods. The aquifer storage can decline as much as 160 TAF/year during the pumping periods while it can increase up to 19 TAF/year during non-pumping periods.

A cumulative graph of stream depletion and change in groundwater storage is shown in Figure 83. The figure clearly shows that the majority of the groundwater pumping for the Groundwater Substitution Program comes from stream depletion. By the end of the simulation, the Groundwater Substitution Program pumps around 9.3 MAF of water. Around 86% of this pumping is compensated for through stream depletion and the rest by loss of groundwater storage.

Figure 84 shows the overall change in stream and groundwater budget for Scenario 1b relative to EC BL. The Groundwater Substitution Program pumps a long term average of approximately 125 TAF/year of water to replace surface water diversions. The long term average recharge from the diversion canals to the aquifer declines around 25 TAF/year due to reduced surface water diversions. These declines are compensated for by 120 TAF/year additional flows from the streams to the aquifer and 20 TAF/year loss of groundwater storage. Also, the aquifer losses 1 MAF of groundwater from storage to achieve the new equilibrium.

Impacts to the Stream Flows

Figure 84 also shows the long term average changes in the stream budget for Scenario 1b relative to EC BL. The surface water diversions decrease 140 TAF/year which leaves the same amount of water as additional surface water supply to the stream. On the other hand, streams are losing an additional 120 TAF/year to aquifer due to declining groundwater levels. As a result, the downstream flows to the Sacramento-San Joaquin Delta increase only 20 TAF/year. Figure 85 shows the long-term average

(whole simulation period) monthly comparison of forgone diversions versus stream flows reductions due to additional losses to aquifer. Reductions in stream flows are distributed differently across the months as compared to diversions. Stream flow reduction between June and October (transfer months) is 68 TAF/year as opposed to 120 TAF/year for the whole year. In that respect, downstream flows during transfer period increases 72 TAF/year while it decreases 52 TAF/year during the rest of the year.

Figure 86 shows the monthly comparison of forgone diversions versus stream flows reductions due to additional losses to aquifer for the scenario pumping (transfer) years. The annual average additional diversions left in the streams during pumping years is 208 TAF/year. The annual average additional losses from the streams are 134 TAF/year. Consequently, the downstream flows for the whole year increase 74 TAF/year. Stream flow reduction between June and October (transfer months) is 80 TAF/year as opposed to 134 TAF/year for the whole year. In that respect, downstream flows during transfer periods increases 128 TAF/year while it decreases 54 TAF/year during the rest of the year. However, the important impacts of such stream depletions are during the times when the Delta is in surplus condition (Figure 87).

5.2 Scenario 2: Increased Agricultural Demand

Although the Central Valley water supply is currently over-allocated during portions of most years, current state policy allows new groundwater pumping to be implemented in many situations without consideration of the impacts of the additional pumping on other groundwater users and on surface water flows. In order to better understand potential impacts associated with this practice, a scenario was developed whereby an area of new irrigated agriculture was assumed to be brought into production. This scenario was simulated to evaluate how such an expansion of agriculture affects:

- Overall water balance through time
- Surrounding groundwater levels
- Stream-aquifer interaction
- Stream flows

5.2.1 Modeling Approach and Assumptions

The following assumptions were used to develop the Increased Agricultural Demand Scenario.

- An area of approximately 10,000 acres within Tehama County was brought under irrigation for this scenario. The selected area lies to the south of Corning, north of Stoney Creek, and west of the Sacramento River (Figure 88).
- Orchards were assigned as the crop type for the area that was brought under irrigation because orchards are the most dominant new crop type in the area.
- Minimum soil moisture requirement, evapotranspiration (ET) and crop efficiency for the orchards from the EC BL were also used for the orchards in the new area developed for irrigated agriculture.
- The additional agricultural water demand was calculated by the C2VSim model using the assigned crop acreages, precipitation, ET, minimum soil moisture content, and crop efficiency.
- The increase in agricultural water demand was met by groundwater pumping.

- The additional groundwater pumping was disrupted between layers 1 and 2. Layer 1 was assigned 70% of total pumping and layer 2 was assigned 30%. These ratios are the ratios used for the EC BL in the surrounding area.
- The surface water supply was kept the same as EC BL.

5.2.2 Results

Impacts on the Groundwater Levels

The expansion of the irrigated agricultural land use for the project creates an additional 30 TAF/year groundwater pumping; this is to supply roughly 3 feet/acre of water for the new irrigated area. To evaluate the impacts of the additional pumping on the surrounding groundwater levels, simulated change in groundwater level hydrographs for the Scenario 2 relative to EC BL were developed for five observation wells as shown in Figure 89; one in the middle of the area developed for irrigated agricultural use (Central), one in the west right next to the Sacramento River, one to the north of Thomes Creek (West), one in the east close to the foothills (East), and one to the south of Stoney Creek (South).

Figure 90 shows the corresponding change in the groundwater level hydrographs for the observation wells. The change in groundwater levels for the central observation well is substantially higher than the other observation well. The figure shows that the groundwater system reaches equilibrium after about 25 years of irrigation pumping. At that point the groundwater levels decline almost 30 feet for the central observation well and the decline is less than five feet for all the other observation wells. It takes much longer for the west observation well to reach equilibrium since there are no major streams close by to replenish the aquifer in that area. Water level declines are less in the north and south observation wells compared to the east observation well because there is a stream between those observation wells and the pumping wells. One interesting observation for Figure 90 is that the hydrographs for the north and south observation wells decline more than the general trend during the simulation period that corresponds to the 1976 -1977 and the 1987-92 droughts due to the reduced flows from Stoney Creek and Thomes Creek to the aquifer. This shows the much smaller tributaries and their interaction with the aquifer are sensitive to the hydrology.

Figure 91 shows the spatial distribution of the simulated change in groundwater levels for Scenario 2 relative to EC BL at the end of simulation year 25 and at the end of simulation period. The contour maps are fairly similar because of the equilibrium of the groundwater system after simulation year 25. The simulated groundwater level declines more than 30 feet within the area developed for irrigated agricultural use and the drawdown is less at further distances and declines below five feet as it gets to closer to streams due to increased flows from the streams to aquifers. The biggest difference between the contour maps for simulation year 25 and for the end of the simulation is that the drawdown contours move further east in the latter one.

Impacts to the Groundwater Storage and Stream-Aquifer Interaction

Figure 92 shows the annual simulated difference in the groundwater budget for Scenario 2 relative to EC BL. The average additional groundwater pumping for the area developed for irrigated agricultural land use is about 30 TAF/year, as mentioned before. The additional pumping fluctuates due to hydrology,

and increases as much as 36 TAF in wet years and declines as low as 23 TAF/year in dry years. The amount of deep percolation in the project area increases by 5 TAF /year due to higher amounts of water applied to the soil after the conversion from native land use to irrigated agricultural land use. As a result, 5 TAF out of 30 TAF of additional pumping is already going back the aquifer every year. The flows from the streams to the aquifer in the project area increase 19 TAF/year while the aquifer storage loses an additional 6 TAF/year. These values and their directions are displayed in the overall stream and groundwater budget schematic provided in Figure 93.

Figure 92 shows that the project pumping at the beginning of the simulation shows up in the aquifer predominantly as changes in groundwater storage (lower groundwater levels). As the groundwater levels continue to decline, stream depletion increases while changes in groundwater storage decrease. As equilibrium is reached, at about simulation year 25, the contribution from the aquifer storage reduces significantly. The change in aquifer storage even increases during the wet years. Over the 20 years or so prior to attainment of the new equilibrium, roughly on third of project pumping is compensated for by changes in aquifer storage, and the remainder by stream depletion. The aquifer loses 80 TAF of storage to achieve new equilibrium. On the other hand, only 5% project pumping is compensated for by aquifer storage from simulation year 20 to the end of the simulation with stream depletion accounting for most of the of the reduction in recharge. After equilibrium, stream depletion compensates for most of the additional groundwater pumping. Until equilibrium, 48% of project pumping is compensated by changes in aquifer storage, 36% by gain from the streams, and 16% by deep percolation. The aquifer losses 360 TAF of groundwater from the storage to achieve a new equilibrium (Figure 93). On the other hand, only six percent project pumping is compensated by change in aquifer storage from simulation year 25 to the end of the simulation. In the same time interval, stream depletion and deep percolation compensate 77% and 17% of the additional project pumping, respectively.

Impacts on the Stream Flows

The changes in stream seepage between Scenario 3 and EC BL for surrounding stream reaches (Figure 94) were developed to investigate temporal and spatial impacts of the Increased Agricultural Demand Scenario on stream flows. Stream seepage for each reach is divided by the length of that stream reach to normalize values for comparison purposes.

Figure 95 shows simulated changes in stream seepage for Scenario 2 relative to EC BL for the Sacramento River reaches from north to south. The change in stream seepage for all the reaches increases rapidly until simulation year 25. After the simulation year 25, some of the reaches level off and some of them continue to increase but at a considerably slower rate. The fluctuation in the hydrographs increases going from north to south reaches. In general, the change in seepage from the streams increases during wet years and decreases during the dry years. Reach 73 has the biggest change in stream seepage average, followed by Reaches 75 and 71. The changes in stream seepage get smaller further towards the north or south of the project area. The average simulated change in stream seepage per mile for the Sacramento River reaches from north to south are:

- Sacramento River - Reach 65 : 0 TAF/mile/year
- Sacramento River - Reach 66 : 7 TAF/mile/year

- Sacramento River - Reach 68 : 38 TAF/mile/year
- Sacramento River - Reach 71 : 103 TAF/mile/year
- Sacramento River - Reach 73 : 163 TAF/mile/year
- Sacramento River - Reach 75 : 138 TAF/mile/year
- Sacramento River - Reach 76 : 51 TAF/mile/year
- Sacramento River - Reach 78 : 47 TAF/mile/year

Figure 96 shows simulated changes in stream seepage for Scenario 2 relative to EC BL for the tributaries to Sacramento River. The change in stream seepage for all the reaches increases rapidly until simulation year 25. After simulation year 25, some of the reaches level off and some of them continue to increase but at a considerably slower rate. The hydrographs of Stoney Creek - Reach 81 and Thomes Creek fluctuate significantly from year to year due to hydrology. Like Sacramento River reaches, the change in seepage for these two creeks increases during wet years and decreases during the dry years. On the other hand, Stoney Creek - Reach 79 shows very small fluctuations from year to year. Stoney Creek - Reach 81, Stoney Creek - Reach 79, and Thomes Creek have the biggest changes in average stream seepages, followed by Elder Creek. The average simulated change in stream seepage per mile for the tributaries to the Sacramento River reaches from north to south are:

- Antelope Creek - Reach 67 : 3 TAF/mile/year
- Elder Creek - Reach 69 : 55 TAF/mile/year
- Mill Creek - Reach 70 : 1 TAF/mile/year
- Thomes Creek - Reach 72 : 173 TAF/mile/year
- Deer Creek Group - Reach 74 : 13 TAF/mile/year
- Stoney Creek - Reach 79 : 205 TAF/mile/year
- Stoney Creek - Reach 80 - Reach 80 : 21 TAF/mile/year
- Stoney Creek - Reach 81 - Reach 81 : 248 TAF/mile/year

5.3 Scenario 3: Increased Irrigation Efficiency

Increases in irrigation efficiency (IE) are often discussed as a means of water conservation in the agricultural sector. Over the past few decades, developments in irrigation technology and global crop markets have facilitated an environment for large increases of IE. This has been particularly evident across the Central Valley with the installation of drip and micro-spray irrigation systems, principally on permanent crops such as orchards and vineyards. As water prices continue to rise and water availability continues to fall, the demand for high efficiency irrigation management and technology will follow. An understanding of regional benefits and impacts of irrigation efficiency to the hydrologic system is important for statewide water management.

While IE improvements reduce the applied water and can provide accompanying benefits such as reduced pumping or conveyance costs, reduced direct diversions from streams, and other operational and production advantages impacts to the groundwater system and effects on the overall regional water balance are more complex. Improvements in IE to areas irrigated with groundwater will generally have little long-term impact on groundwater conditions, as the decreased pumping is balanced by decreased deep percolation. In areas served by surface water, IE increases result in decreased recharge to

groundwater, with resultant declines in water levels if surrounding pumping levels remain the same. If groundwater levels are lowered, the lower levels have the indirect effect of reducing stream flows, negating some of the benefits that may have been sought by the improved IE.

This scenario was developed to explore the relationship between irrigation efficiency and the regional hydrologic system.

5.3.1 Modeling Approach and Assumptions

In order to assess impacts of increased irrigation efficiency, an analysis of the model sub-regions was preformed to identify an appropriate area for such scenario. The primary variables contributing to potential IE improvements are water source, crop type, and distribution. Taking these into consideration, Subregion 2 was selected for the analysis because it is primarily serviced by surface water, contains the large percentage of orchards and vineyards, and contains little rice which tends to haves unique IE characteristics.

The following assumptions were used to develop the Increased Agricultural Demand Scenario.

- Improved irrigation efficiency is implemented on roughly 100,000 acres irrigated land in Subregion 2 as shown in Figure 97.
- As the rising cost of water and limited availability are generally the driving factors in new system installation, this scenario includes improvements to irrigation efficiency only to those parcels operating with surface water.
- Furthermore, while permanent crops and drip systems have received a majority of the notoriety, proper irrigation management and scheduling have been shown to increase IE by equal measure (Howell, 2003). Subsequently, increases to IE for all crop types within this subregion were increased by 10 percentage points up to a maximum of 87%, the maximum IE used in C2VSim model for some parts of the Tulare Basin.
- Minimum soil moisture requirement and crop ET does not change from EC BL to Scenario 3. As a result, the consumptive use by the crops is the same for both EC BL and Scenario 3. (Note that in some cases, crop yield, and therefore crop ET, have been known to increase with improved irrigation timing and deliveries that often accompany improved irrigation efficiencies. For simplicity of illustration, crop yields for improved efficiency areas were assumed to stay the same as yields without efficiency improvements.)
- As a result of improved irrigation efficiency, the surface water diversions will be reduced and forgone surface water diversions can be transferred to downstream water users or retained in storage reservoirs for other uses. Again, for simplicity of illustration, the fate of water not diverted is not addressed in this simulation. Only the impacts on the regional water balance where the irrigation efficiency improvements are implemented (simulated) are evaluated.

5.3.2 Results

Impacts on the Groundwater Levels

As a result of increasing increased irrigation efficiency on surface water irrigated areas for this scenario, less water is diverted and applied for irrigation. As a result of less surface water diversion, the recharge

from the diversion canals to the aquifer reduces. Similarly, the reduction in applied water to irrigated agricultural land reduces the deep percolation to the aquifer. Consequently, this scenario reduces recharge to the aquifer by about 10.5 TAF/year on average. To evaluate the spatial and temporal impacts of reduction in groundwater recharge, simulated change in groundwater level hydrographs for Scenario 3 relative to EC BL were developed for four observation wells. The locations of these wells are shown in Figure 98; two away from the streams (OW 1 and OW 2), one next to the Sacramento River (OW3), and one next to Big Chico Creek, which is a tributary to Sacramento River (OW4).

The simulated change in groundwater level hydrographs for Scenario 3 relative to EC B for the four observation wells are shown in Figure 99. OW 1 has the highest groundwater level drawdown. The drawdown is around three feet after a new equilibrium (around simulation year 20 when the rate of the decline reduces significantly) is reached in the groundwater system. OW 2 and OW3 have the second and third highest drawdowns. The drawdown after equilibrium is reached is around 2.5 feet and 2.3 feet for OW 2 and OW4, respectively. OW1 has significantly less drawdown (less than 0.5 feet) compared to the other observation wells as a result of the masking effect of the Sacramento River. Figure 99 shows that the impacts of the Scenario 3 on the groundwater levels are significantly less around the major streams compared to the smaller tributaries.

Figure 100 shows the contour maps for the simulated change in groundwater levels for Scenario 3 relative to EC BL at the end of simulation year 20 and end of the simulation period. The maps for simulation year 20 and end of simulation period look relatively similar. The extent of the drawdowns are the same, but the simulated groundwater levels declined 0.5 feet more at the core of the drawdown area at the end of the simulation compared to year 20. The hydrographs from Figure 99 also show that the drawdowns, specifically away from the streams, continue to increase slightly from simulation year 20 through the end of the simulation. But, the rate of increase is small enough to assume simulation year 20 as the equilibrium year.

Impacts to the Groundwater Storage and Stream-Aquifer Interaction

Figure 101 shows the annual simulated changes in the groundwater budget for Scenario 2 relative to EC BL. The deep percolation to the aquifer for the Scenario 3 declines around 9.7 TAF/year compared to EC BL. The reduction in deep percolation fluctuates with year type; as high as 13 TAF/year during the wet years and as low as 6.3 TAF/year during the dry years. The reduced surface water diversions for Scenario 3 result in reductions in conveyance system recharge to the aquifer. The reduction is 0.8 TAF/year on average and fluctuates between 0.6 TAF/year and 1.2 TAF/year depending on the hydrology. Consequently, the total reduction in recharge to groundwater as result of reduction in deep percolation and conveyance system recharge is around 10.5 TAF/year. The aquifer storage and additional gains from the streams compensate for the reduction in recharge. The additional gain from streams increases around 9 TAF/year and aquifer losses 1.5 TAF/year from the storage. These long-term average values and their directions are displayed in the overall stream and groundwater budget schematic provided in Figure 102.

Figure 101 shows that the reduction in the recharge at the beginning of the simulation shows up in the aquifer predominantly as changes in groundwater storage (lower groundwater levels). As the groundwater levels continue to decline, stream depletion increases while changes in groundwater

storage decrease. As equilibrium is reached, at about simulation year 20, the contribution from the aquifer storage reduces significantly. The change in aquifer storage even increases during the wet years. Over the 20 years or so prior to attainment of the new equilibrium, roughly on third of project pumping is compensated for by changes in aquifer storage, and the remainder by stream depletion. The aquifer loses 80 TAF of storage to achieve new equilibrium. On the other hand, only 5% project pumping is compensated for by aquifer storage from simulation year 20 to the end of the simulation with stream depletion accounting for most of the of the reduction in recharge.

Impacts on the Stream Flows

Figure 102 also shows the average changes in the stream budget for Scenario 3 relative to EC BL. The surface water diversions decrease 14 TAF/year and leave the same amount of water as additional surface water supply to the streams. Application of less water due to increased irrigation efficiency does not only reduce the diversions 14 TAF/year but also reduce the return flows to streams, 2.5 TAF/year. As a result, the downstream flows to the Sacramento-San Joaquin Delta increases only 2.5 TAF/year due to 2.5 TAF/year reductions in return flows and 9 TAF/year of additional stream seepage. Figure 103 shows the long-term average (whole simulation period) monthly comparison of forgone diversions versus stream flows reductions due to additional losses to aquifer and reductions in return flows. Reductions in stream flows are distributed differently across the months as compared to diversions. Stream flow reduction between April and October (irrigation season) is 8.3 TAF/year as opposed to 11.5 TAF/year for the whole year. In that respect, downstream flows during irrigation season increases 5.7 TAF/year while it decreases 3.2 TAF/year during the rest of the year.

The changes in stream seepage between Scenario 3 and EC BL for surrounding stream reaches (Figure 104) were developed to investigate temporal and spatial impacts of the Increased Irrigation Efficiency Scenario on stream flows. Stream seepage for each reach is divided by the length of that stream reach to normalize values for comparison purposes.

Figure 105 shows the simulated changes in stream seepage for Scenario 3 relative to EC BL for the Sacramento River reaches from north to south. The change in stream seepage for all the reaches increases rapidly until simulation year 20. After the simulation year 20, some of the reaches level off and some of them continue to increase but at a considerably slower rate. The fluctuation in the hydrographs increases going from north to south reaches. In general, the change in seepage from the streams increases during wet years and decreases during the dry years. The reaches in the south, 76 and 78, have the largest average change in seepage. The average simulated change in stream seepage per mile for the Sacramento River reaches from north to south are:

- Sacramento River - Reach 65 : 13 TAF/mile/year
- Sacramento River - Reach 66 : 33 TAF/mile/year
- Sacramento River - Reach 68 : 97 TAF/mile/year
- Sacramento River - Reach 71 : 78 TAF/mile/year
- Sacramento River - Reach 73 : 93 TAF/mile/year
- Sacramento River - Reach 75 : 92 TAF/mile/year
- Sacramento River - Reach 76 : 141 TAF/mile/year

- Sacramento River - Reach 78 : 103 TAF/mile/year

Figure 106 shows simulated changes in stream seepage for Scenario 3 relative to the EC BL for tributaries to Sacramento River. Stream seepage for the tributaries is significantly less than for the Sacramento River. Stoney Creek – Reach 81 has the biggest average change in seepage. Mill Creek and Stoney Creek –Reaches 79 and 80 are not affected at all. Stoney Creek - Reach 81 fluctuates significantly more than the other tributaries and Sacramento River reaches from year to year due to hydrology. The average simulated change in stream seepage per mile for the tributaries to the Sacramento River reaches from north to south are:

- Antelope Creek - Reach 67 : 22 TAF/mile/year
- Elder Creek - Reach 69 : 12 TAF/mile/year
- Mill Creek - Reach 70 : 1 TAF/mile/year
- Thomes Creek - Reach 72 : 19 TAF/mile/year
- Deer Creek Group - Reach 74 : 14 TAF/mile/year
- Stoney Creek - Reach 79 : 0 TAF/mile/year
- Stoney Creek - Reach 80 - Reach 80 : 0 TAF/mile/year
- Stoney Creek - Reach 81 - Reach 81 : 36 TAF/mile/year

Section 6 Conclusions

The goal of this study was to clearly illuminate the interaction between groundwater and surface water resources by using specific relationships between groundwater pumping and stream flows in the Central Valley as an example. Important conclusions regarding these relationships are summarized below.

1. Groundwater and surface water resources in California's Central Valley are intimately interconnected, with groundwater pumping ultimately leading to depletion of stream flows. Although effects on nearby streams may be fairly immediate, groundwater pumping can have impacts many miles away, leading to stream depletion impacts that are not fully expressed for years or even decades.
2. Understanding the timing ("lag time") and location of groundwater pumping impacts on surface water systems is important for proper management of these interconnected resources. The timing and location of impacts is best assessed through the use of properly calibrated, integrated surface water-groundwater models. In the case of the Central Valley, these effects take place over years to decades, depending on the distance between the well and the stream, and the depth from which the well draws water.
3. Because even small changes in groundwater levels can lead to potentially significant stream depletion, and given lag times that may take decades, simply monitoring and subsequently reacting to changes in observed water level data is not sufficient for proper integrated water resource management. Use of models is critical in understanding the timing and spatial extent of pumping effects on surface water systems and managing these impacts accordingly.
4. The Sacramento Valley has large surface water courses and rivers, and groundwater pumping has significantly increased in the past 80 years; therefore, this area provides excellent examples of groundwater-surface water interactions. Whereas in the early part of the 20th century the Sacramento River and its tributaries were net gaining streams, some are now net losers of water due to increases in groundwater pumping. This trend has troubling implications during dry years when reduced stream flows have especially severe consequences for ecosystems and surface water rights holders. This condition is projected to get worse in the future as stream depletion effects from existing wells become more apparent.
5. In the San Joaquin Basin, the transition from net-gaining to net-losing streams occurred during the mid-1960s. However, there is still significant hydraulic connection along many stream reaches such that increased groundwater pumping would cause even greater stream depletion. Although this may be viewed as positive from the perspective of groundwater supply, it has negative impacts on ecosystems and surface water rights holders.
6. Surface water systems in the Tulare basin have been net losers of water for much of the 20th century due to early groundwater development. In fact, except during occasional periods of high flows on the Kings River, practically all stream flows that are not diverted for surface supplies end up as groundwater recharge. Some of the river reaches, such as the upper reaches of Kings River, exhibit gaining behavior during winter and spring seasons of wet years. However, this trend is changing as well, especially as drought conditions exacerbate the stress on the groundwater system.

7. Modeling results show that groundwater storage in the Central Valley has declined by about 150 MAF since the early 1920s. Assuming constant 2009 land use conditions, simulations suggest that groundwater in storage will potentially decline by approximately an additional 75 MAF over the next 74 years. It is expected that additional groundwater development, which has occurred since 2009, will lead to additional declines in groundwater storage.
8. Average annual stream depletion throughout the Central Valley has been approximately 700 TAF/year over the past 20 years. Assuming 2009 land use conditions, model simulations suggest that streams throughout the Central Valley will experience an average annual depletion of approximately 1.3 MAF/year over the next 74 years. This is much more than what was experienced historically, and will likely result in significant additional impacts to ecosystems and surface water rights holders, including the amount of water available for export from the Delta and flow conditions within the Delta itself.
9. Modeling results clearly indicate that groundwater substitution and transfer projects impact flow in streams. Although pumped groundwater initially comes from storage, it eventually is balanced by an equivalent amount of stream depletion. Results from this study indicate that stream depletion from groundwater pumping may take years to decades to fully develop. While groundwater transfer may be deemed a useful drought mitigation measure, it needs to be designed and implemented with full recognition of long-term impacts.
10. Increased agricultural development in the Central Valley dependent on groundwater pumping will ultimately result in stream depletion similar in amount to the consumptive use of applied water. The nature, rate and location of these impacts are a function of distance to the river, and the depth, timing, and rate of groundwater pumping. Stream depletion impacts from this groundwater pumping may take years to decades to fully develop.
11. Results from this study (along with numerous scientific studies by others) indicate that increased irrigation efficiency can result in a reduction in deep percolation of excess applied water to underlying groundwater (i.e., a reduction in groundwater recharge). Therefore, in cases where improved efficiency is implemented in agricultural areas that depend on surface water, reduced applied water from surface water deliveries can result in less deep percolation and, therefore, declining groundwater levels. Declining groundwater levels translate to greater stream depletion. Increases in irrigation efficiency do not necessarily lead to net water savings.

Tables

Table 1 - C2VSim Model Features

GW Nodes	30,179
Elements	32,537
Min Element Area (Sq. Miles)	0.006
Max Element Area (Sq. Miles)	2.767
Ave Element Area (Sq. Miles)	0.636
Total Model Area (Sq. Miles)	20,742
Stream Nodes	4,529
Stream Reaches	105
Stratigraphic Layers	3
Sub-regions	21
Small Watersheds	210
Calibration Wells	1,385
Calibration Stream Flow Gages	26
Hydrologic Period	1922-2009
Calibration Period	1973-2003
Time Step	Monthly

Table 2 - Simulation Year and Water Year Type Mapping for the EC BL and Scenarios

Simulation Year	Historic Year	Sacramento Valley Water Year Type	San Joaquin Valley Water Year Type
1	1973	Above Normal	Above Normal
2	1974	Wet	Wet
3	1975	Wet	Wet
4	1976	Critical	Critical
5	1977	Critical	Critical
6	1978	Above Normal	Wet
7	1979	Below Normal	Above Normal
8	1980	Above Normal	Wet
9	1981	Dry	Dry
10	1982	Wet	Wet
11	1983	Wet	Wet
12	1984	Wet	Above Normal
13	1985	Dry	Dry
14	1986	Wet	Wet
15	1987	Dry	Critical
16	1988	Critical	Critical
17	1989	Dry	Critical
18	1990	Critical	Critical
19	1991	Critical	Critical
20	1992	Critical	Critical
21	1993	Above Normal	Wet
22	1994	Critical	Critical
23	1995	Wet	Wet
24	1996	Wet	Wet
25	1997	Wet	Wet
26	1998	Wet	Wet
27	1999	Wet	Above Normal
28	2000	Above Normal	Above Normal
29	2001	Dry	Dry
30	2002	Dry	Dry
31	2003	Above Normal	Below Normal
32	2004	Below Normal	Dry
33	2005	Above Normal	Wet
34	2006	Wet	Wet
35	2007	Dry	Critical
36	2008	Critical	Critical
37	2009	Dry	Below Normal

Simulation Year	Historic Year	Sacramento Valley Water Year Type	San Joaquin Valley Water Year Type
38	1973	Above Normal	Above Normal
39	1974	Wet	Wet
40	1975	Wet	Wet
41	1976	Critical	Critical
42	1977	Critical	Critical
43	1978	Above Normal	Wet
44	1979	Below Normal	Above Normal
45	1980	Above Normal	Wet
46	1981	Dry	Dry
47	1982	Wet	Wet
48	1983	Wet	Wet
49	1984	Wet	Above Normal
50	1985	Dry	Dry
51	1986	Wet	Wet
52	1987	Dry	Critical
53	1988	Critical	Critical
54	1989	Dry	Critical
55	1990	Critical	Critical
56	1991	Critical	Critical
57	1992	Critical	Critical
58	1993	Above Normal	Wet
59	1994	Critical	Critical
60	1995	Wet	Wet
61	1996	Wet	Wet
62	1997	Wet	Wet
63	1998	Wet	Wet
64	1999	Wet	Above Normal
65	2000	Above Normal	Above Normal
66	2001	Dry	Dry
67	2002	Dry	Dry
68	2003	Above Normal	Below Normal
69	2004	Below Normal	Dry
70	2005	Above Normal	Wet
71	2006	Wet	Wet
72	2007	Dry	Critical
73	2008	Critical	Critical
74	2009	Dry	Below Normal

Figures

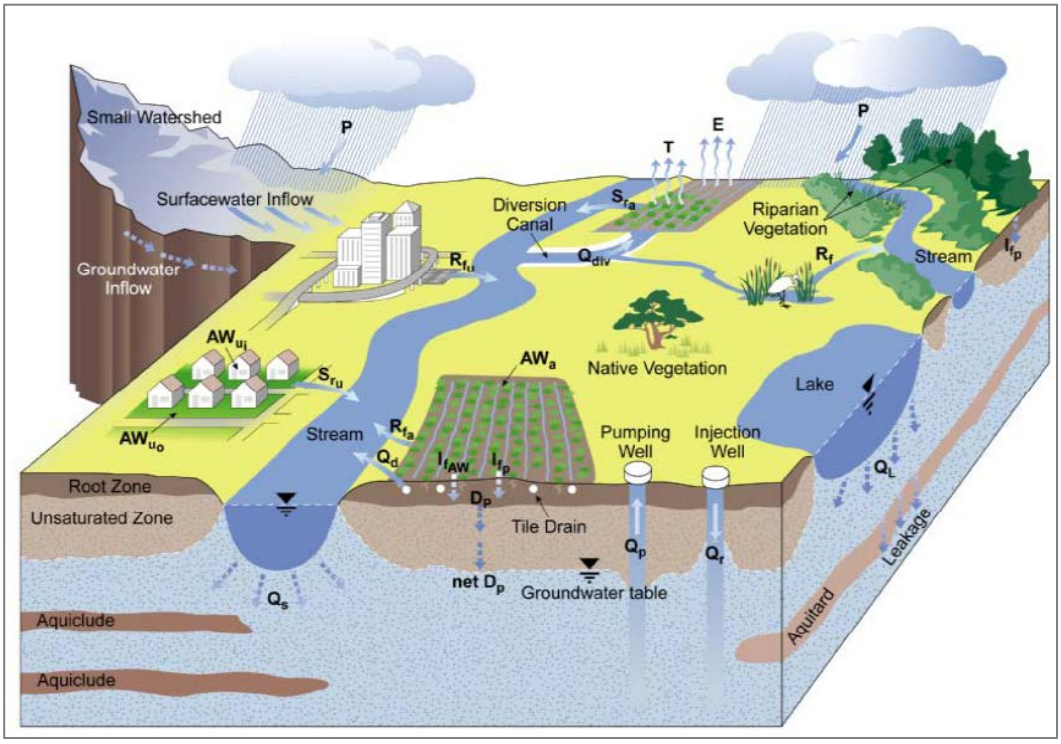


Figure 1 - C2VSim Model Origins (IWFM)

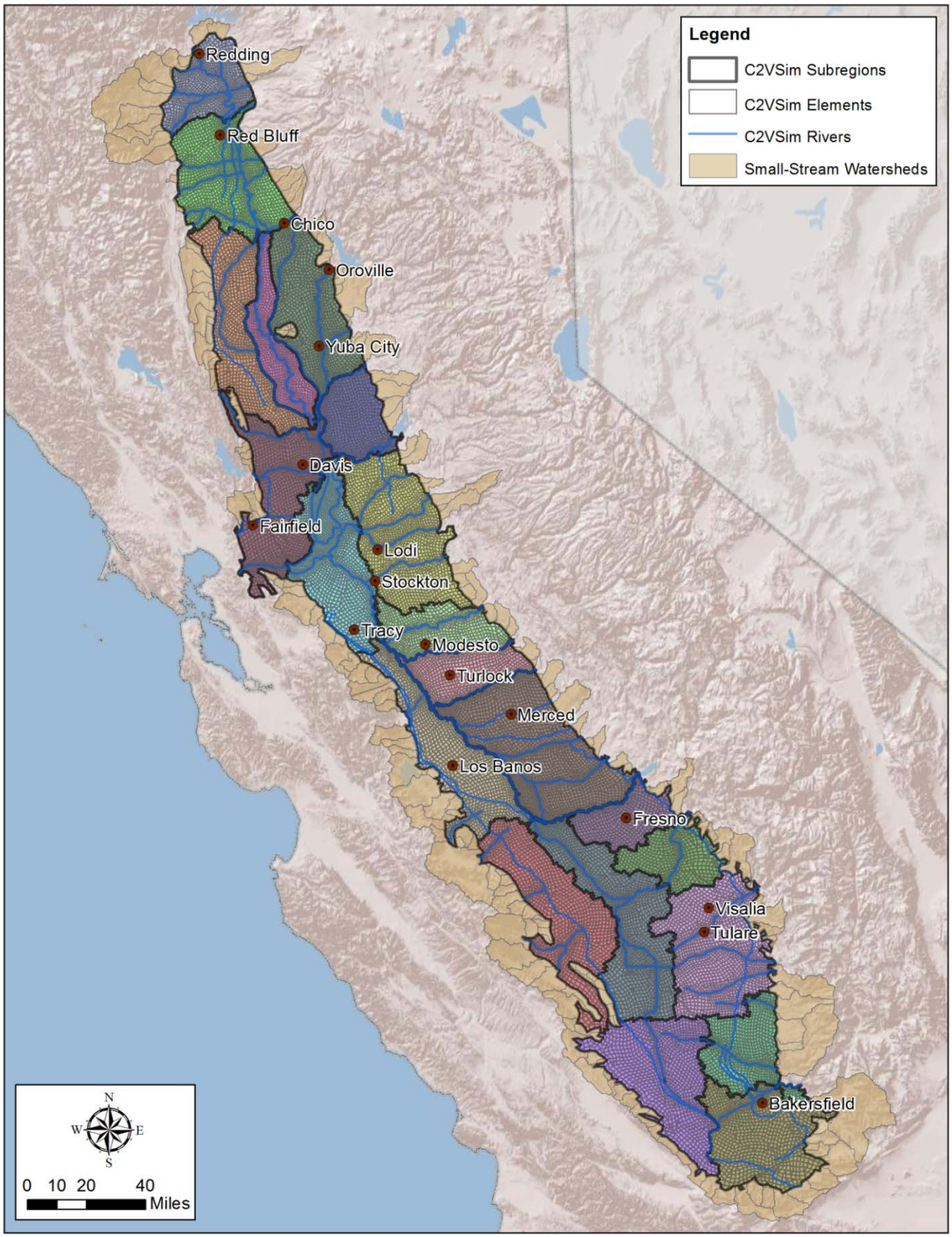


Figure 2 - C2VSim model Grid

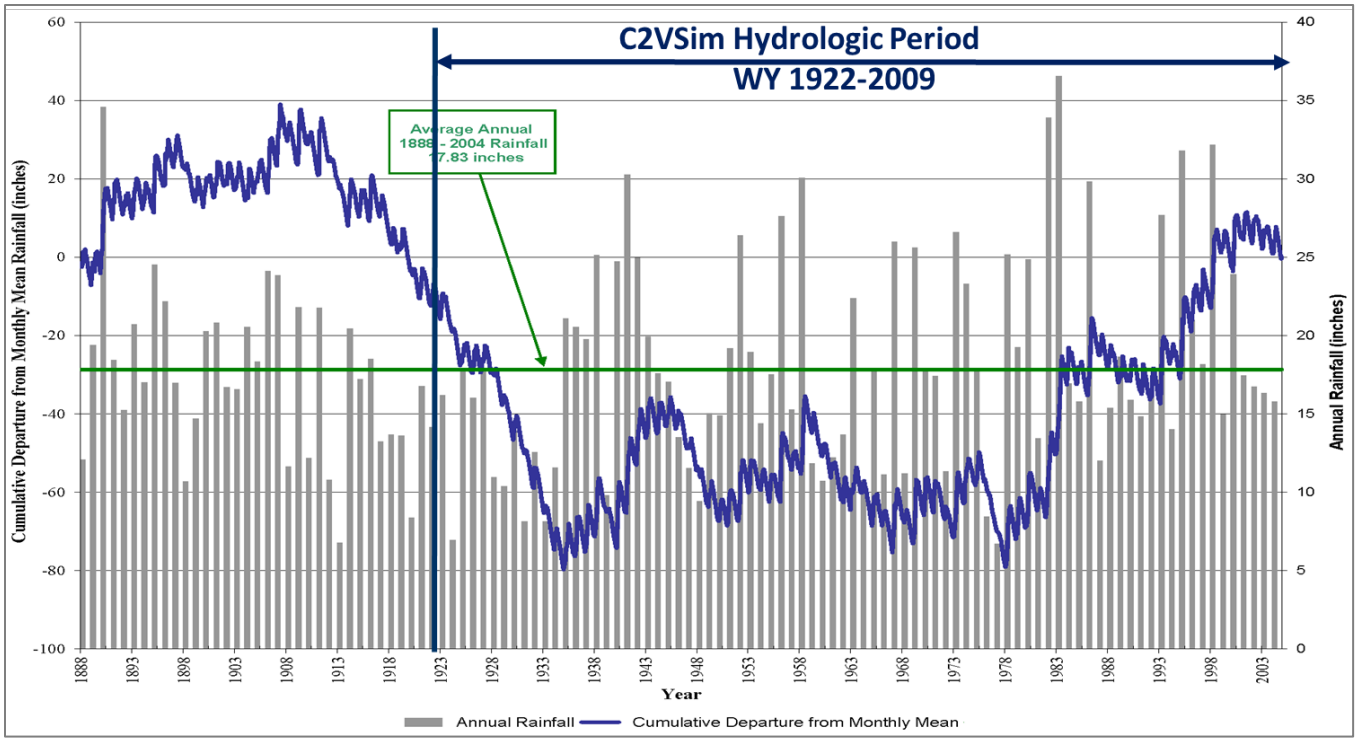


Figure 3 - C2VSim model Hydrologic Period

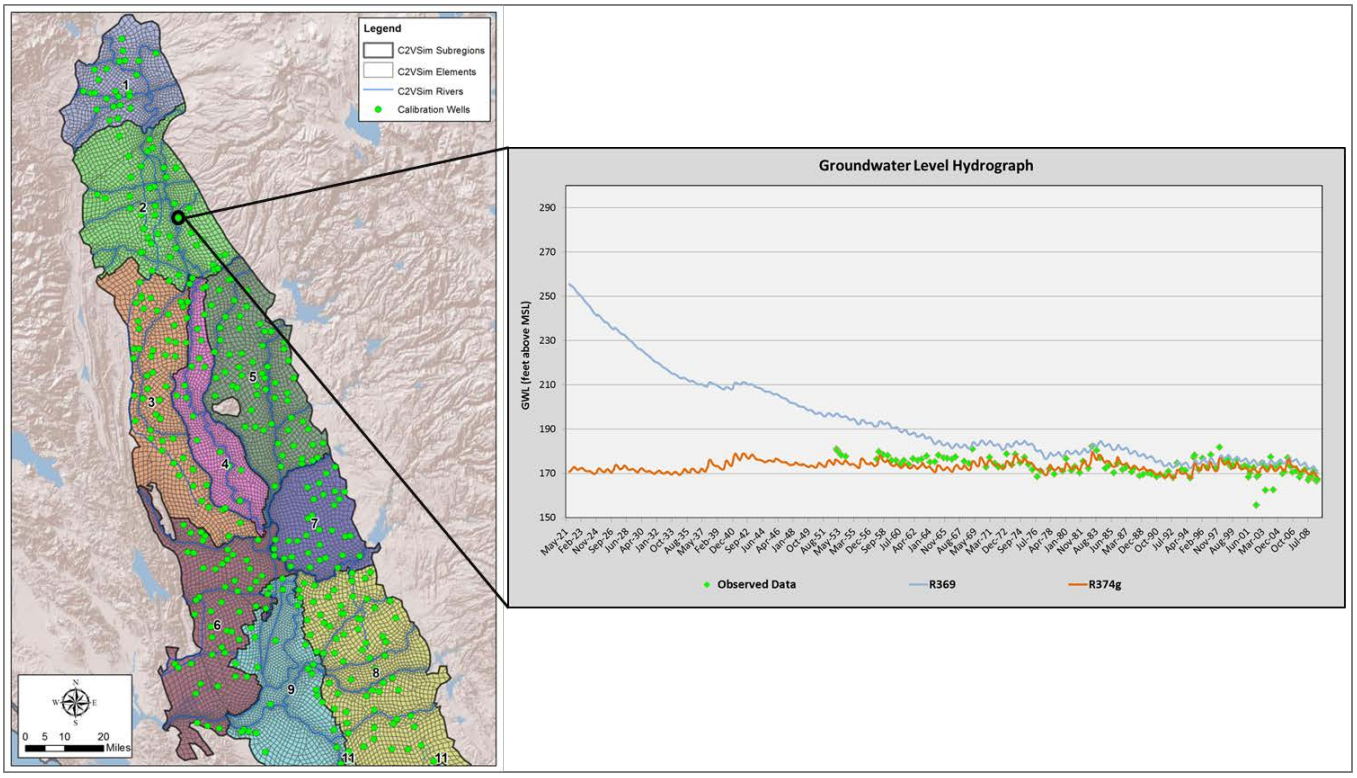


Figure 4 - Comparison of Observed and Simulated Groundwater Levels - Sacramento Valley

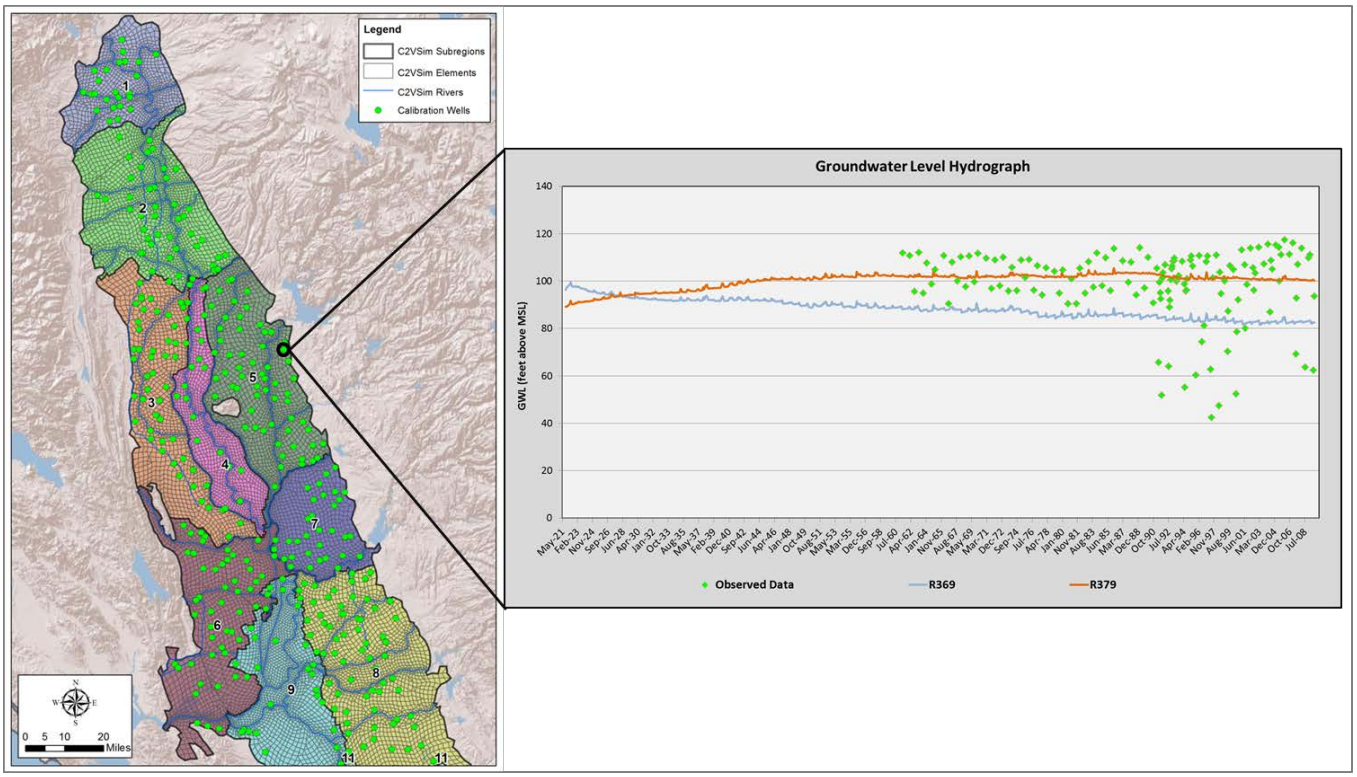


Figure 5 - Comparison of Observed and Simulated Groundwater Levels - Sacramento Valley

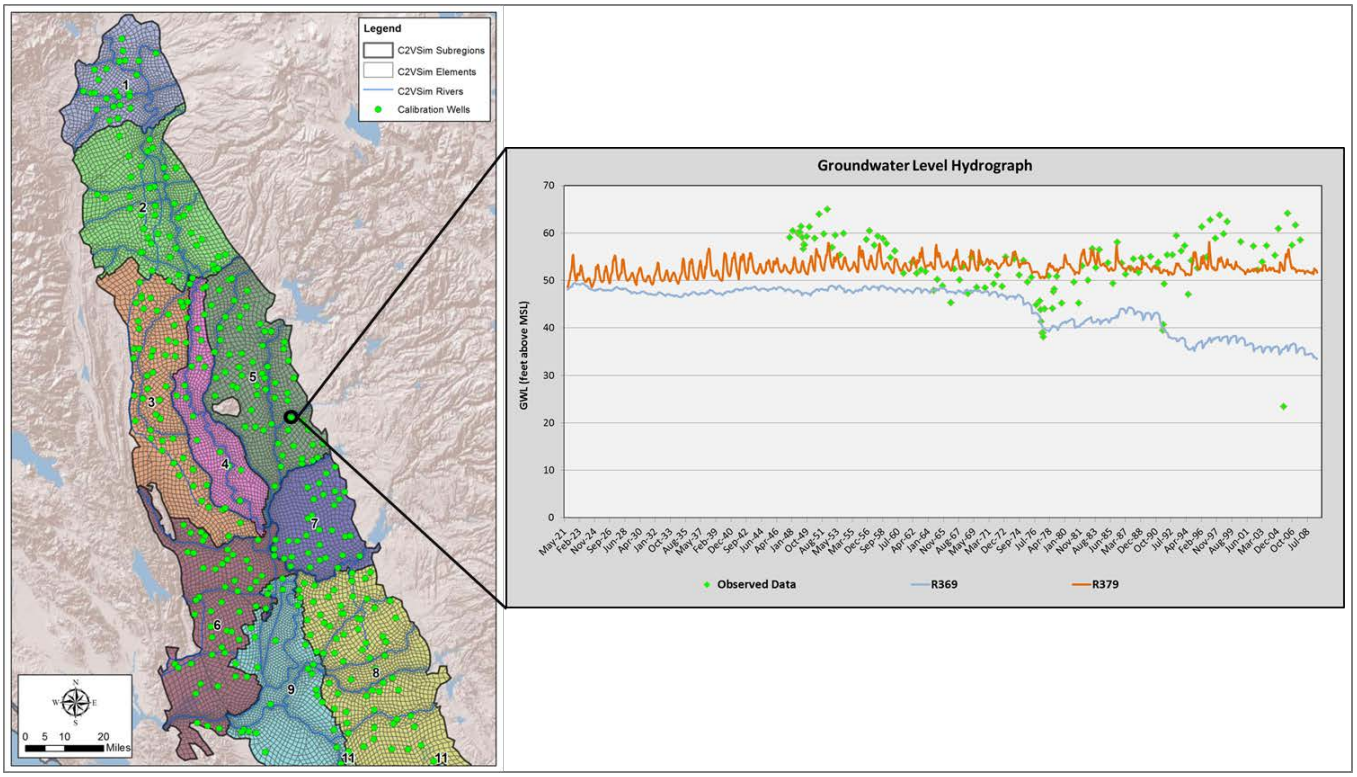


Figure 6 - Comparison of Observed and Simulated Groundwater Levels - Sacramento Valley

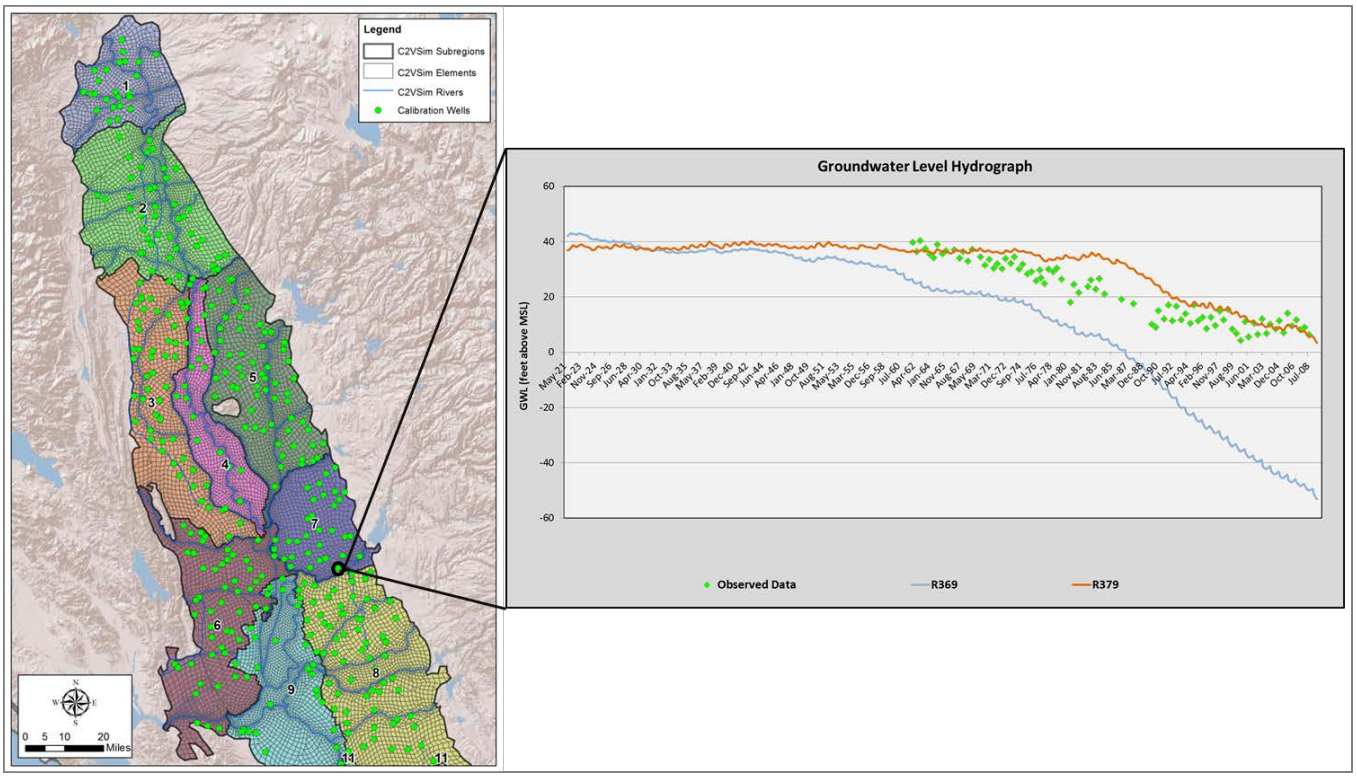


Figure 7 - Comparison of Observed and Simulated Groundwater Levels - San Joaquin Basin

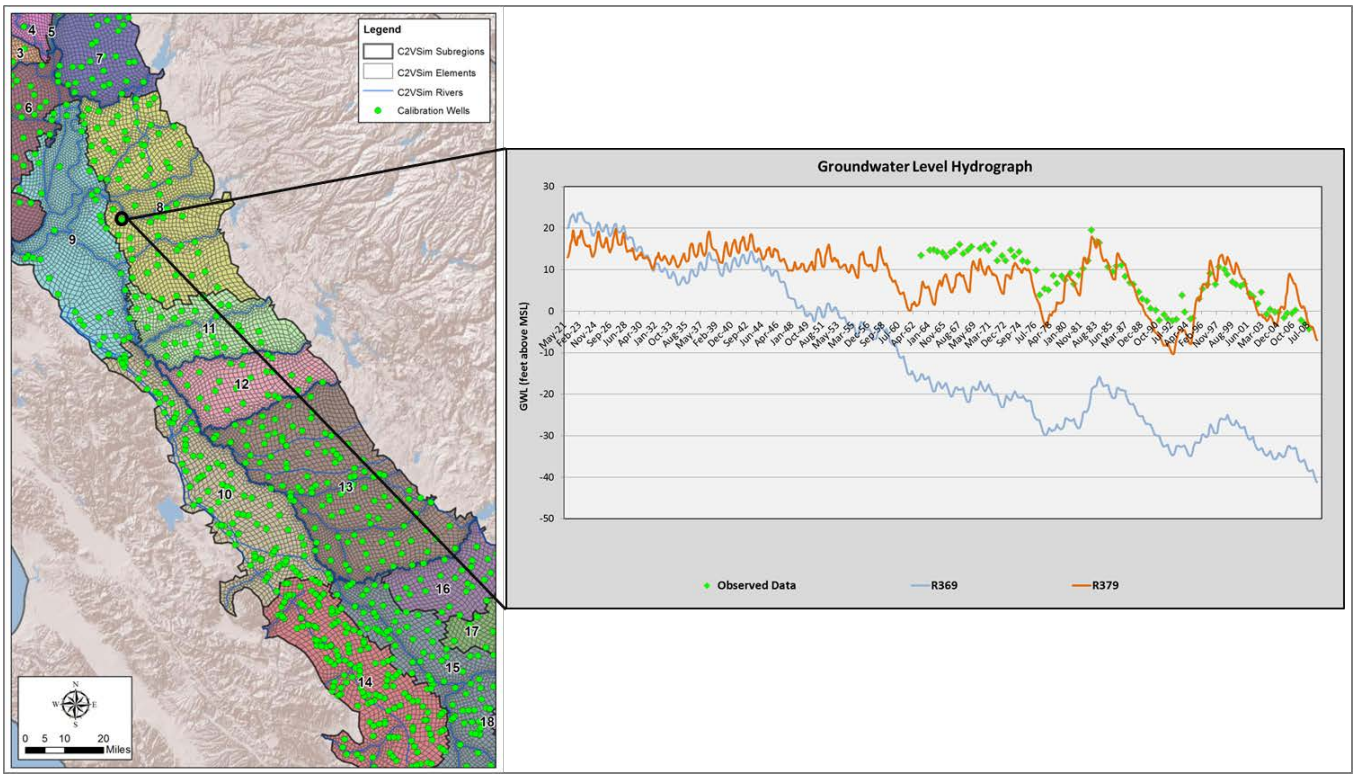


Figure 8 - Comparison of Observed and Simulated Groundwater Levels - San Joaquin Basin

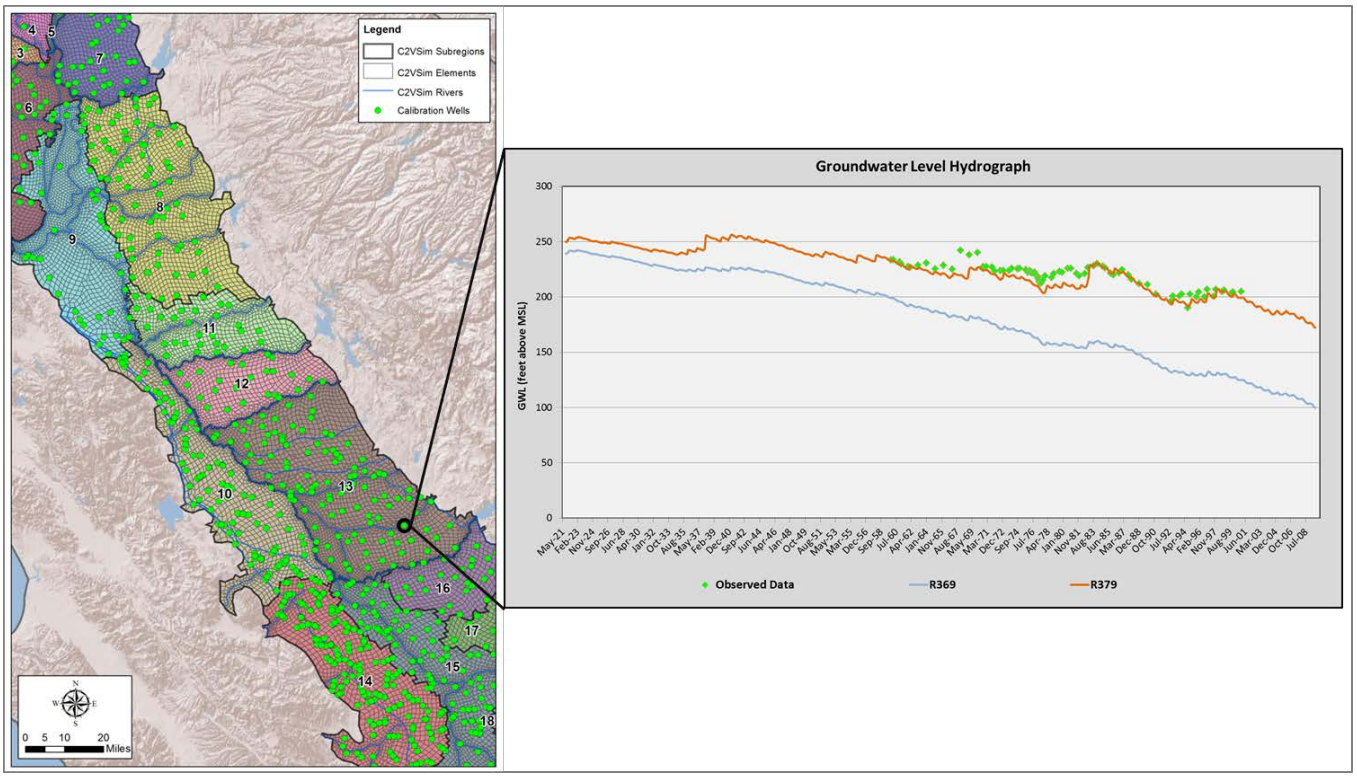


Figure 9 - Comparison of Observed and Simulated Groundwater Levels - San Joaquin Basin

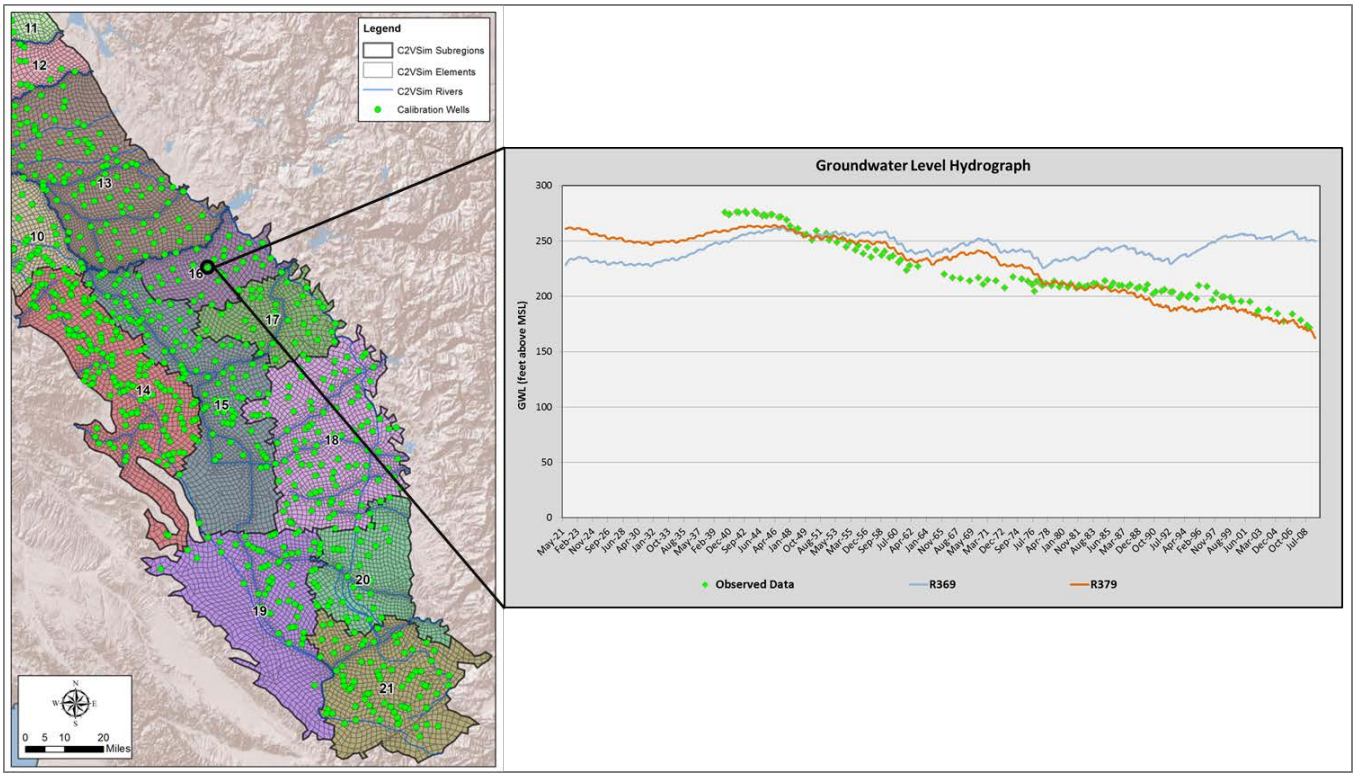


Figure 10 - Comparison of Observed and Simulated Groundwater Levels - Tulare Basin

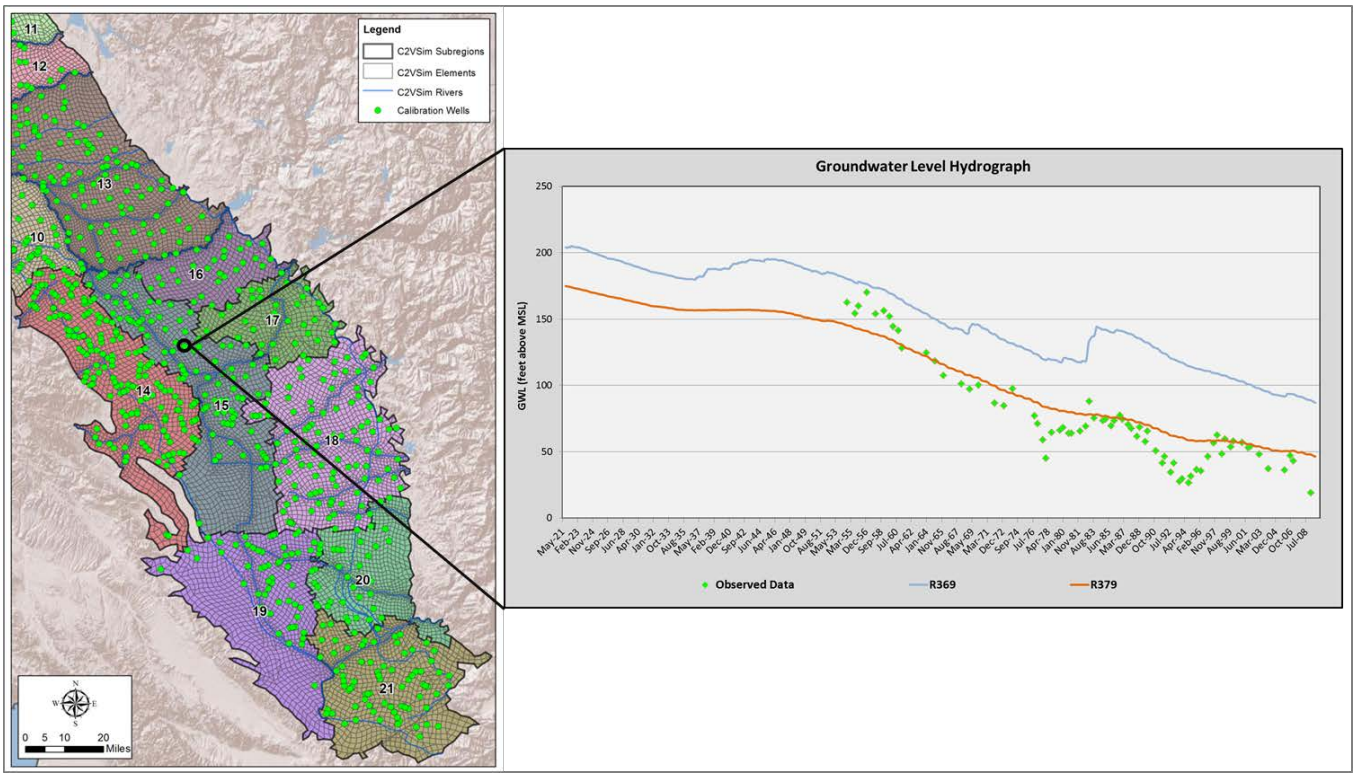


Figure 11 - Comparison of Observed and Simulated Groundwater Levels - Tulare Basin

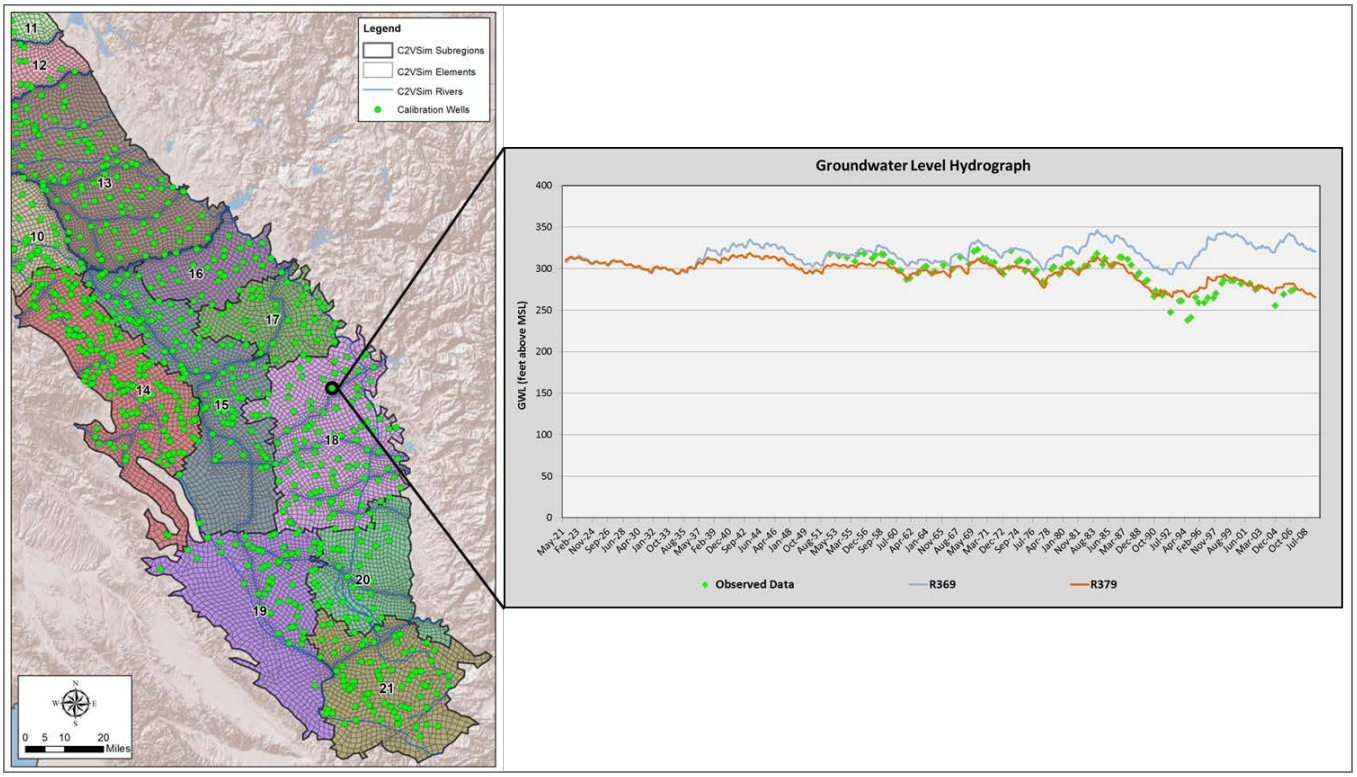


Figure 12 - Comparison of Observed and Simulated Groundwater Levels - Tulare Basin

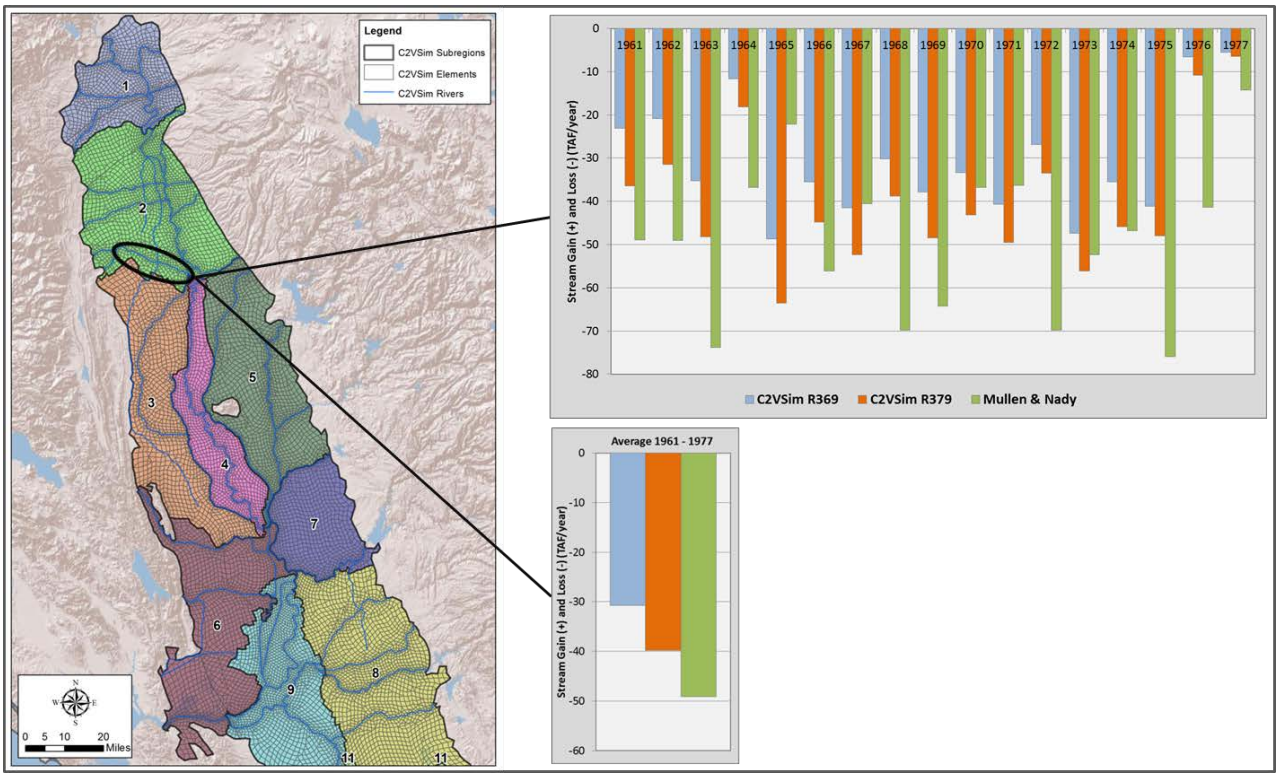


Figure 13 - Comparison of Observed and Simulated Groundwater Flows to Streams - Stony Creek

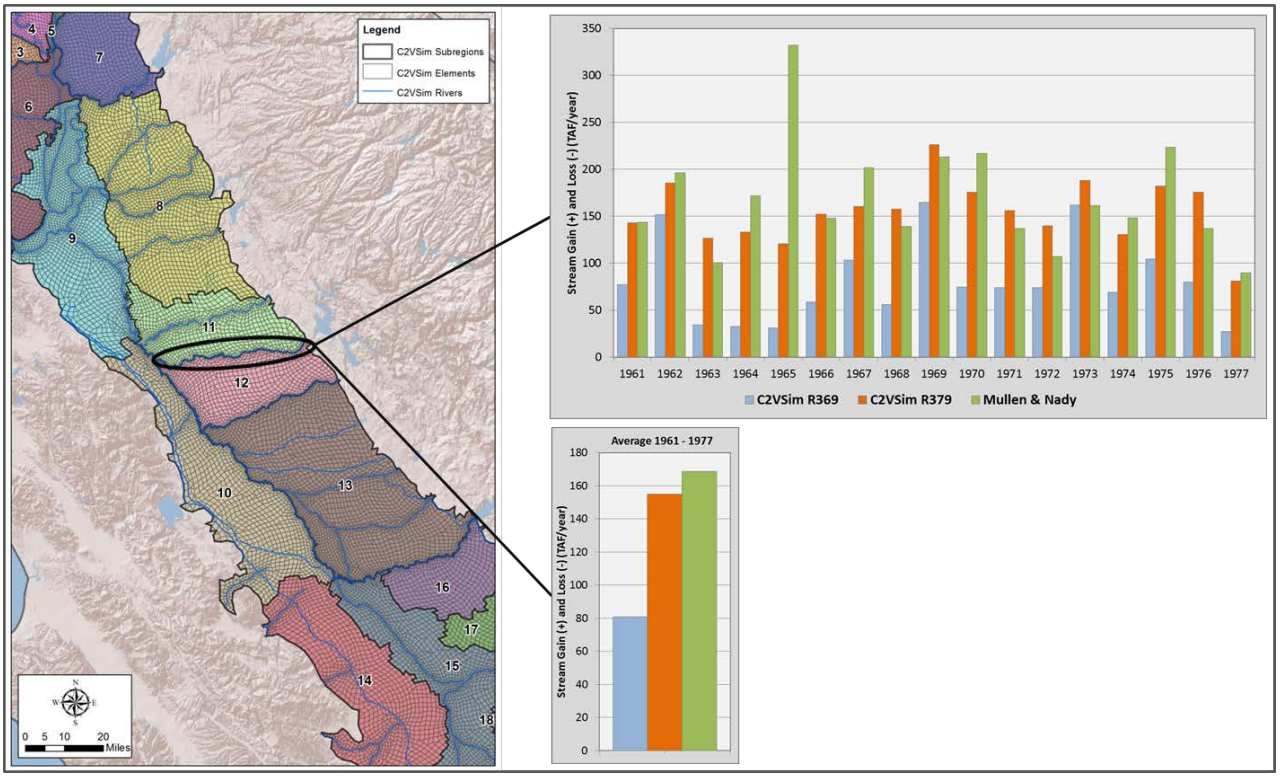


Figure 14 - Comparison of Observed and Simulated Groundwater Flows to Streams - Tuolumne River

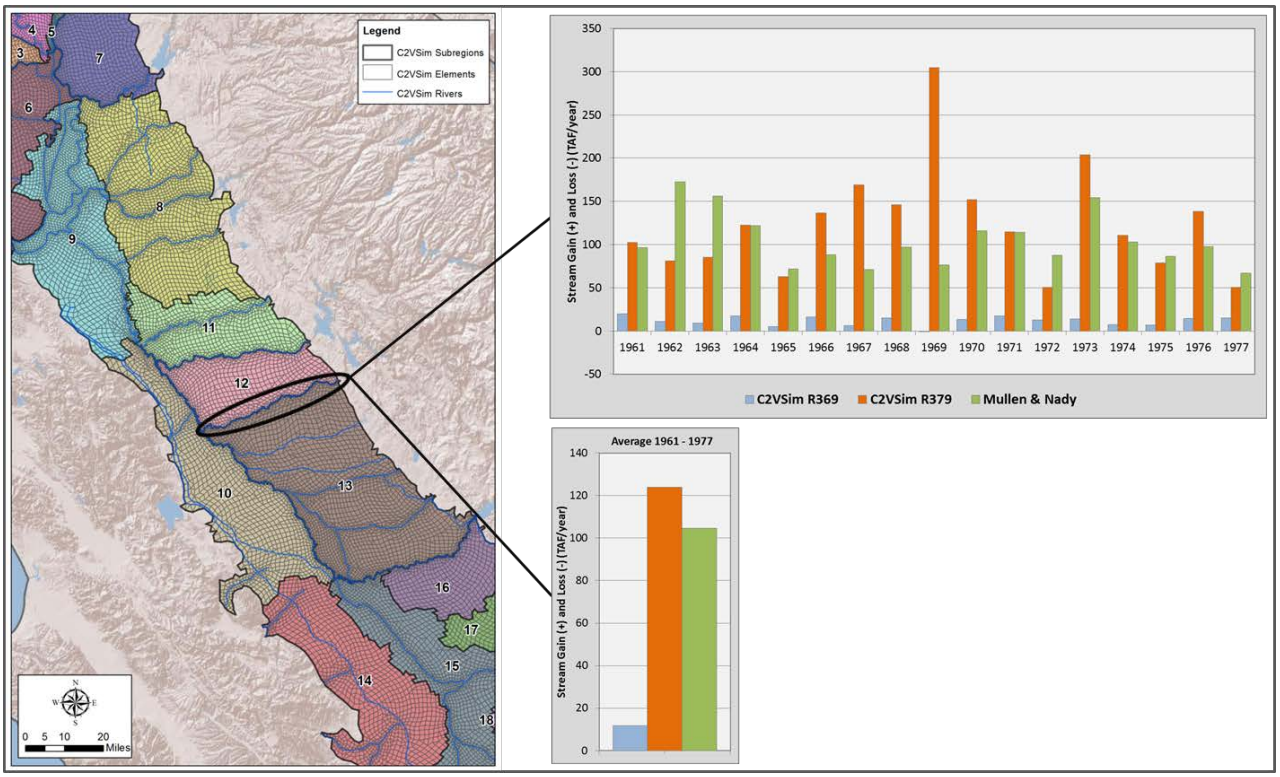


Figure 15 - Comparison of Observed and Simulated Groundwater Flows to Streams - Merced River

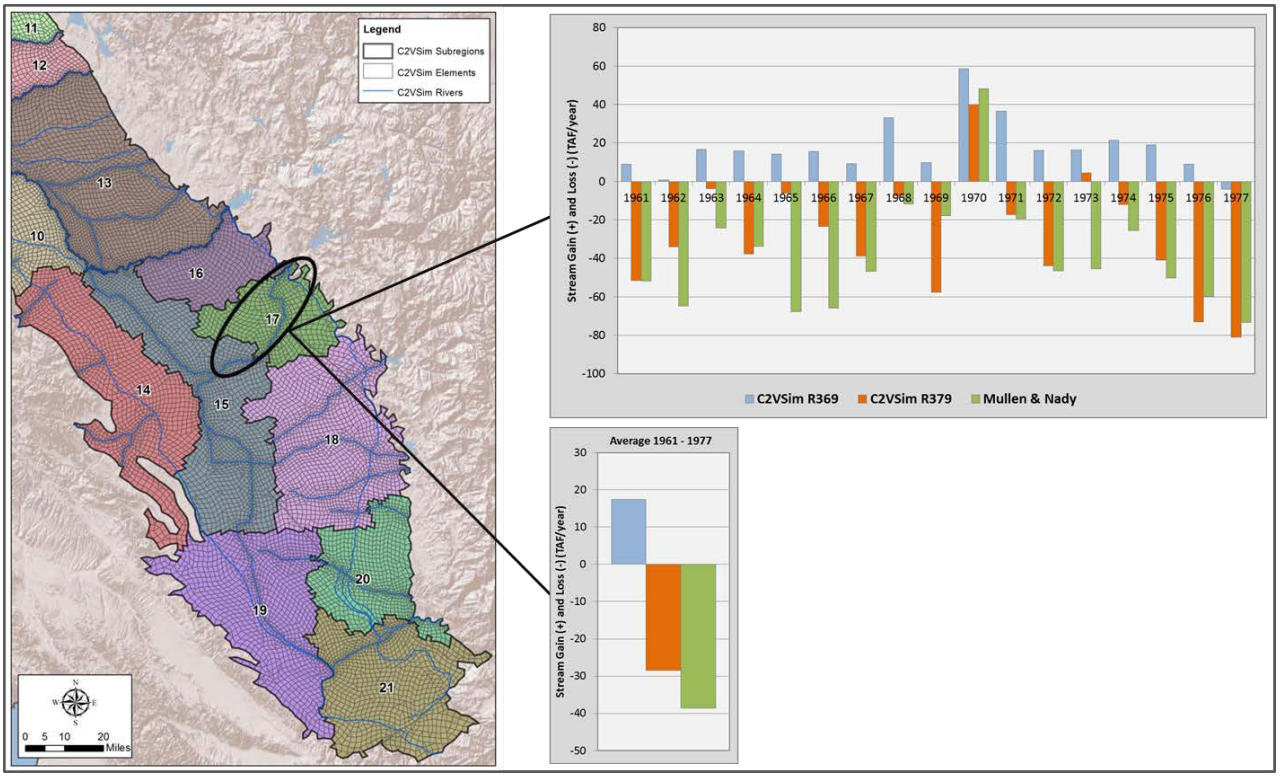


Figure 16 - Comparison of Observed and Simulated Groundwater Flows to Streams - Kings River

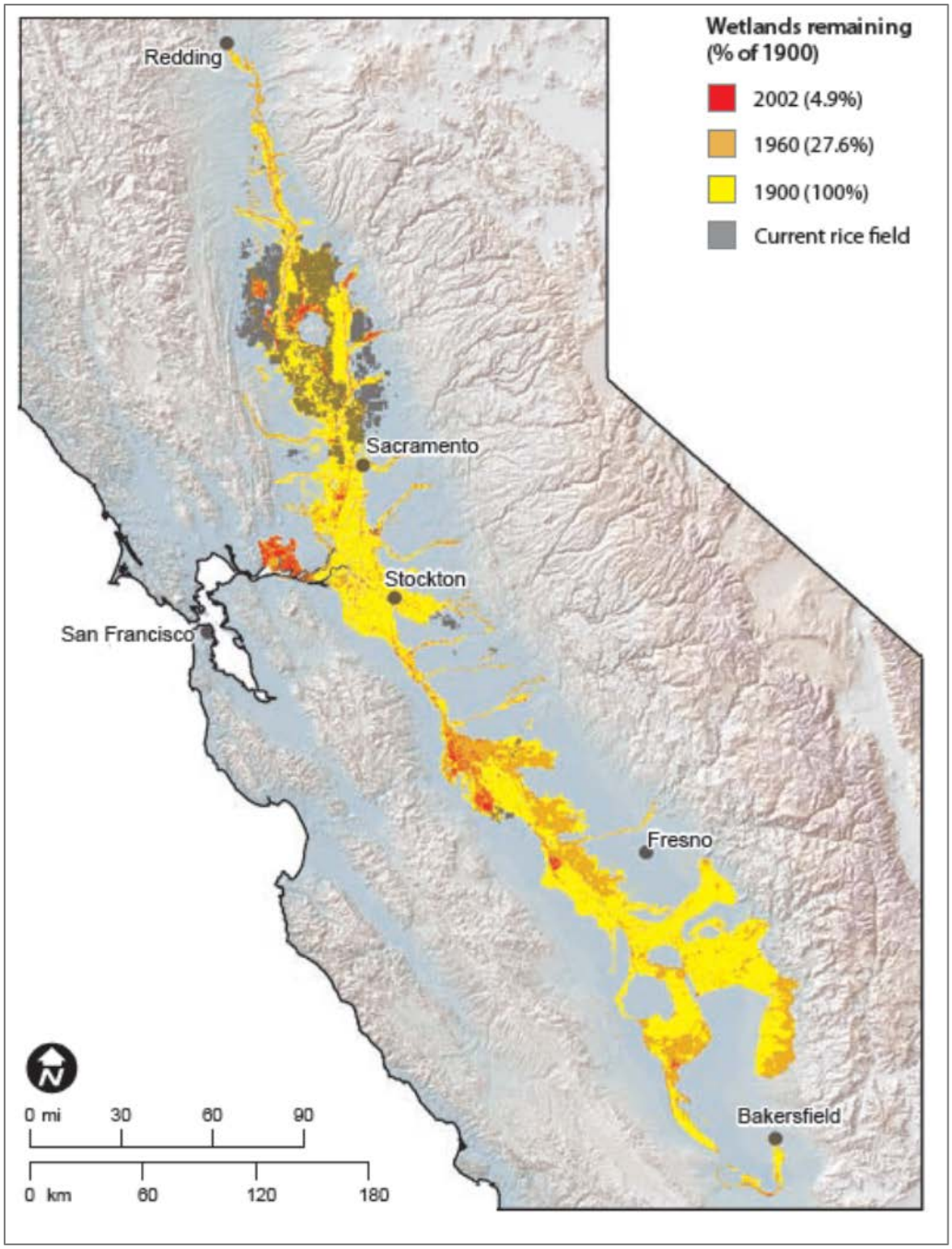


Figure 17 - The Central Valley's Lost Wetlands - Source: (Hannak, et al., 2011)

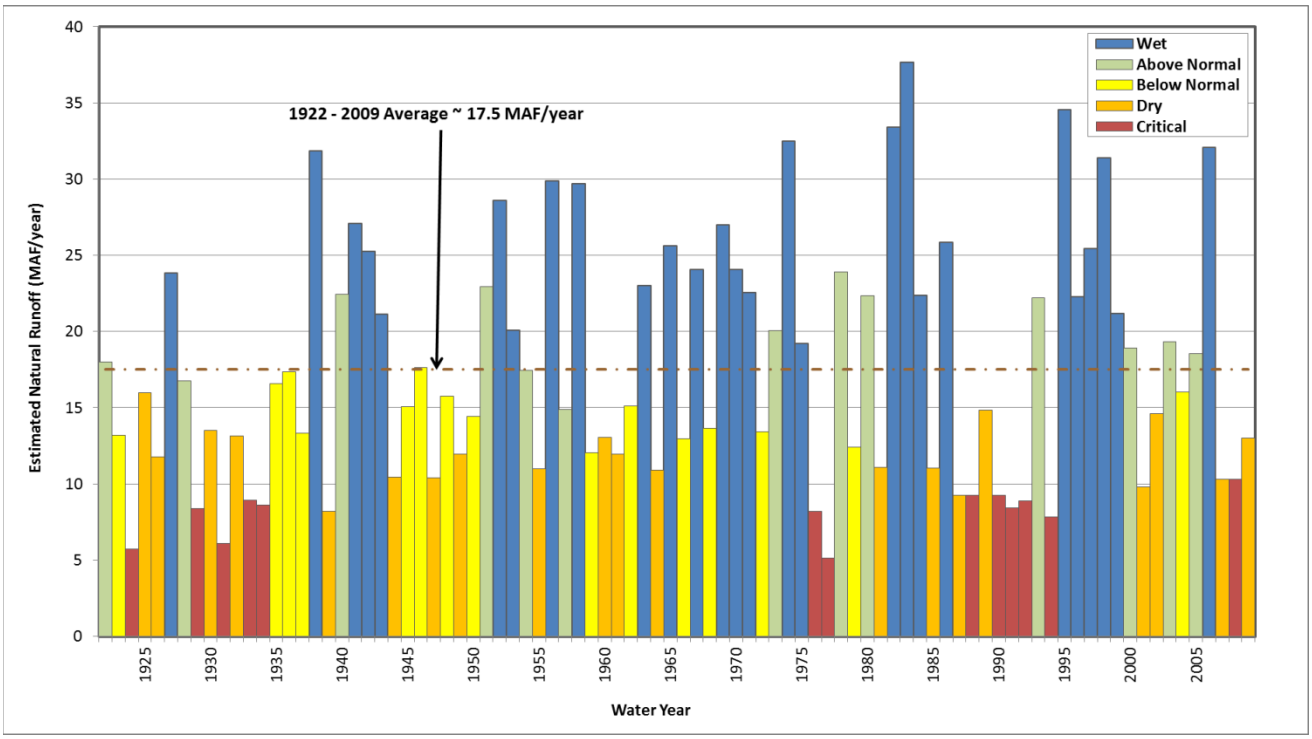


Figure 18 - Sacramento River Unimpaired Runoff and Sacramento Valley Water Year Hydrologic Classification from 1922 to 2009

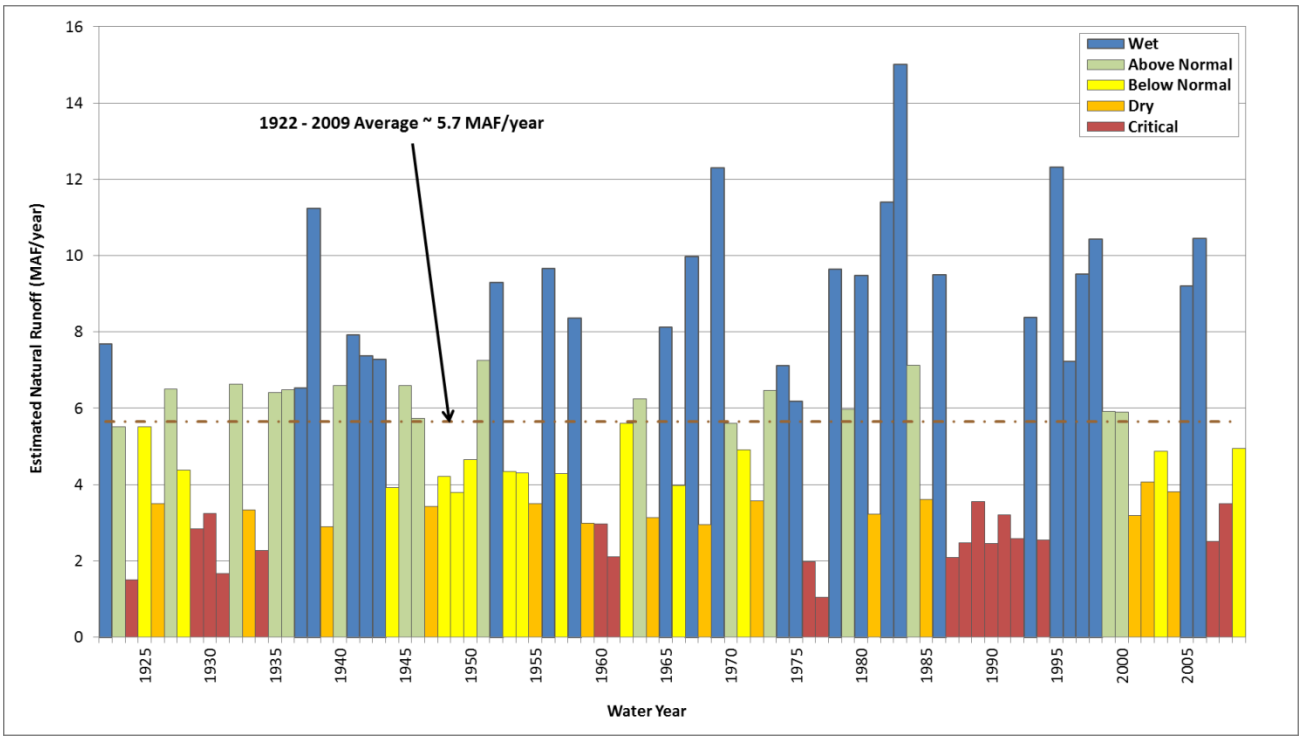


Figure 19 - San Joaquin River Unimpaired Runoff and San Joaquin Valley Water Year Hydrologic Classification from 1922 to 2009

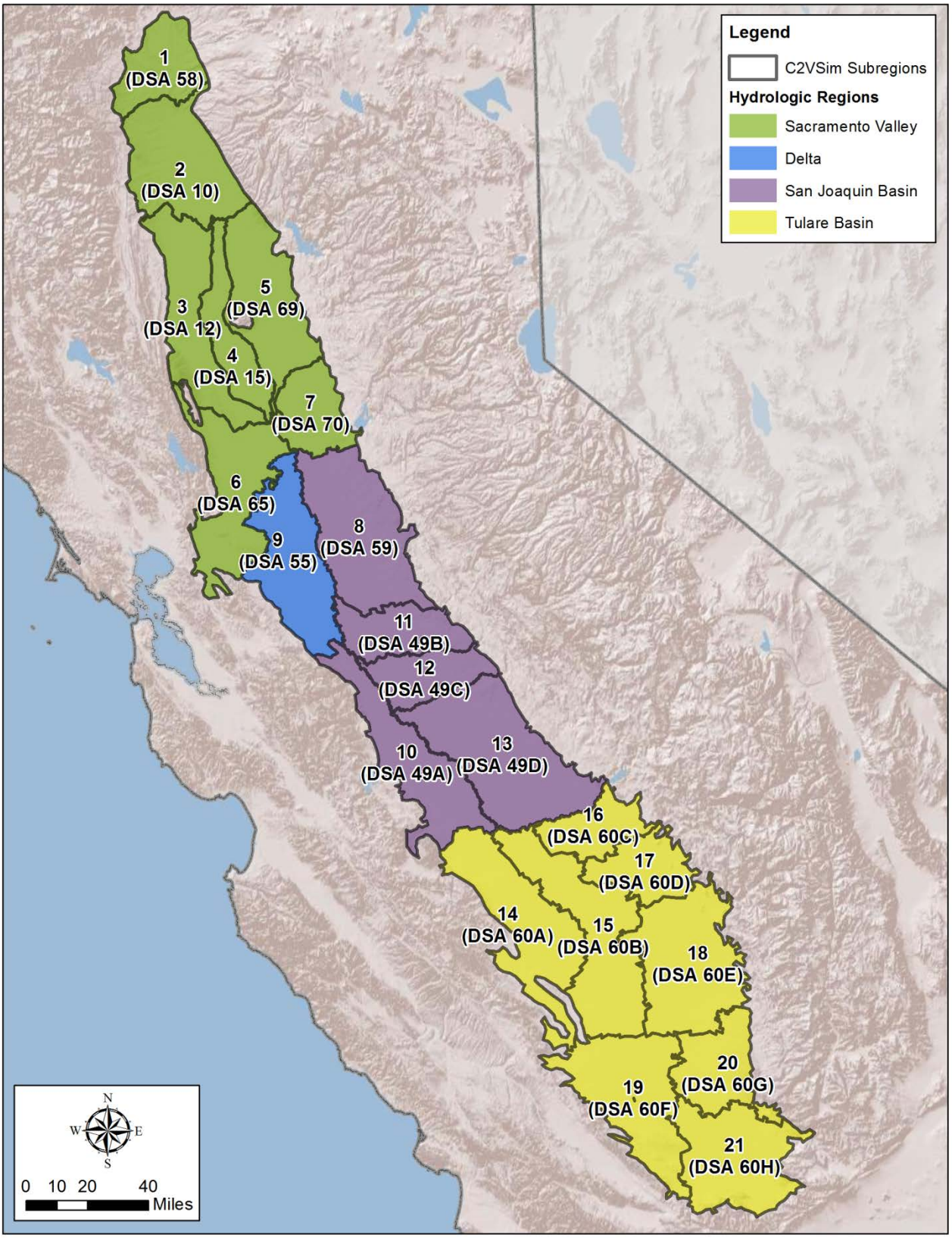


Figure 20 - Hydrologic Regions of the Central Valley

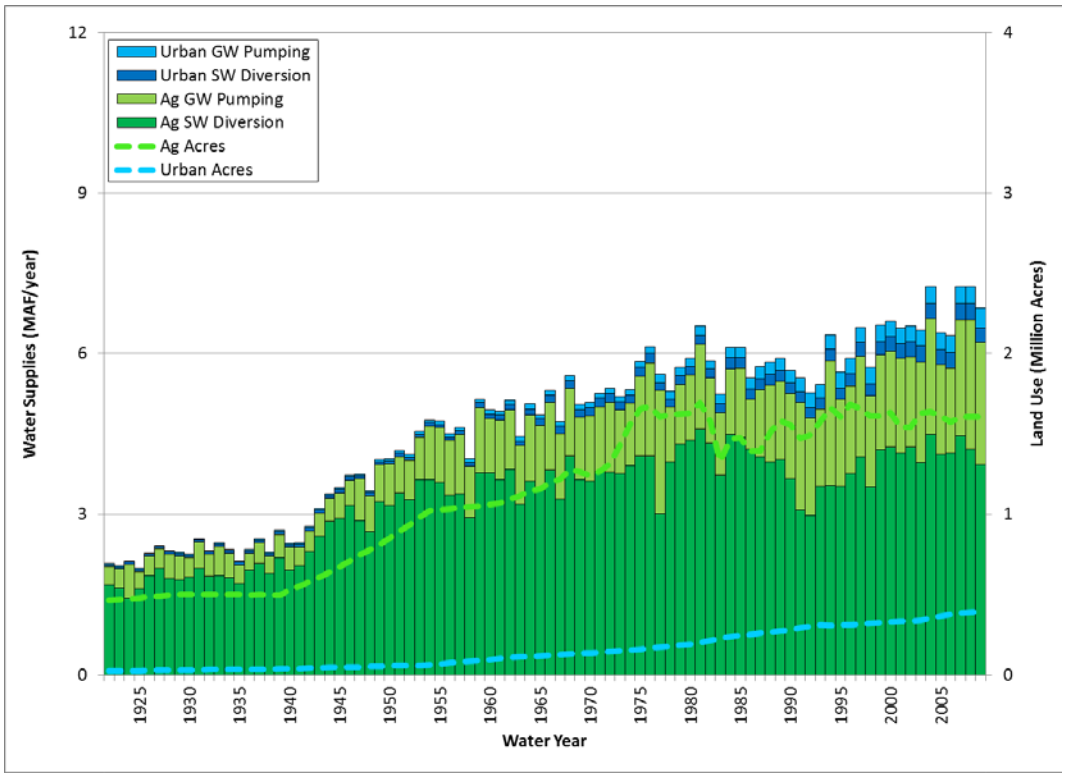


Figure 21 - Historic Land Use vs. Water Supplies in the Sacramento Valley

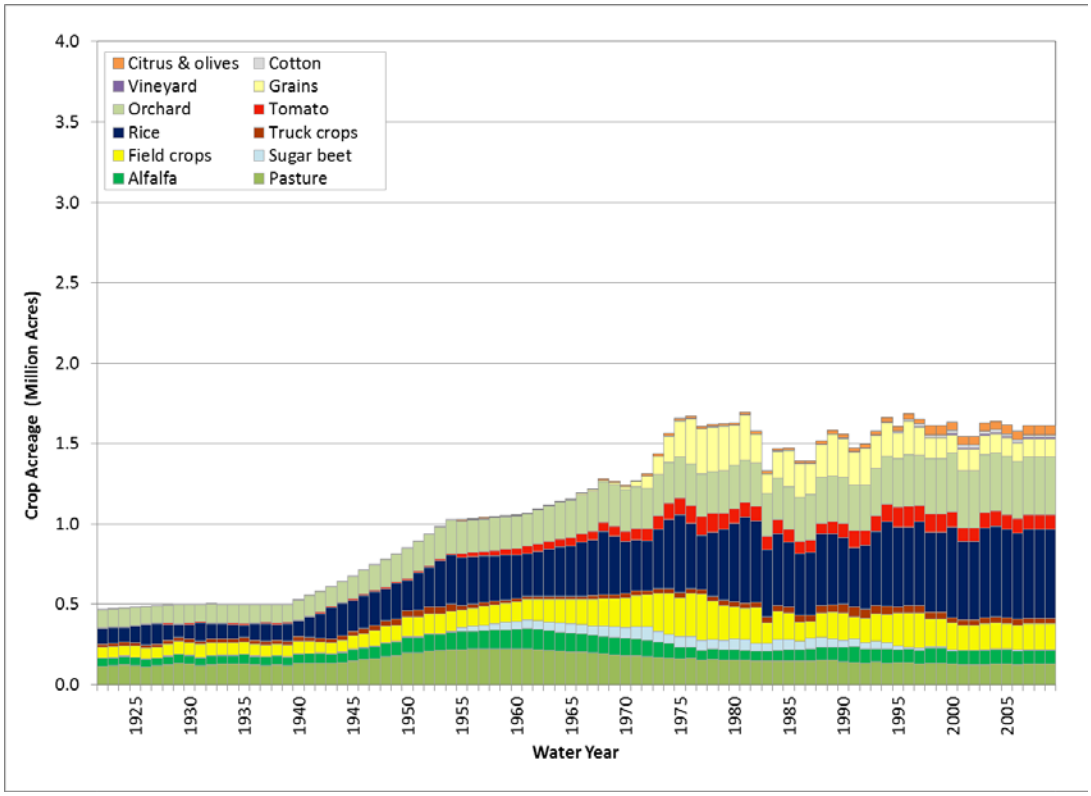


Figure 22 - Historic Cropping Patterns for the Sacramento Valley

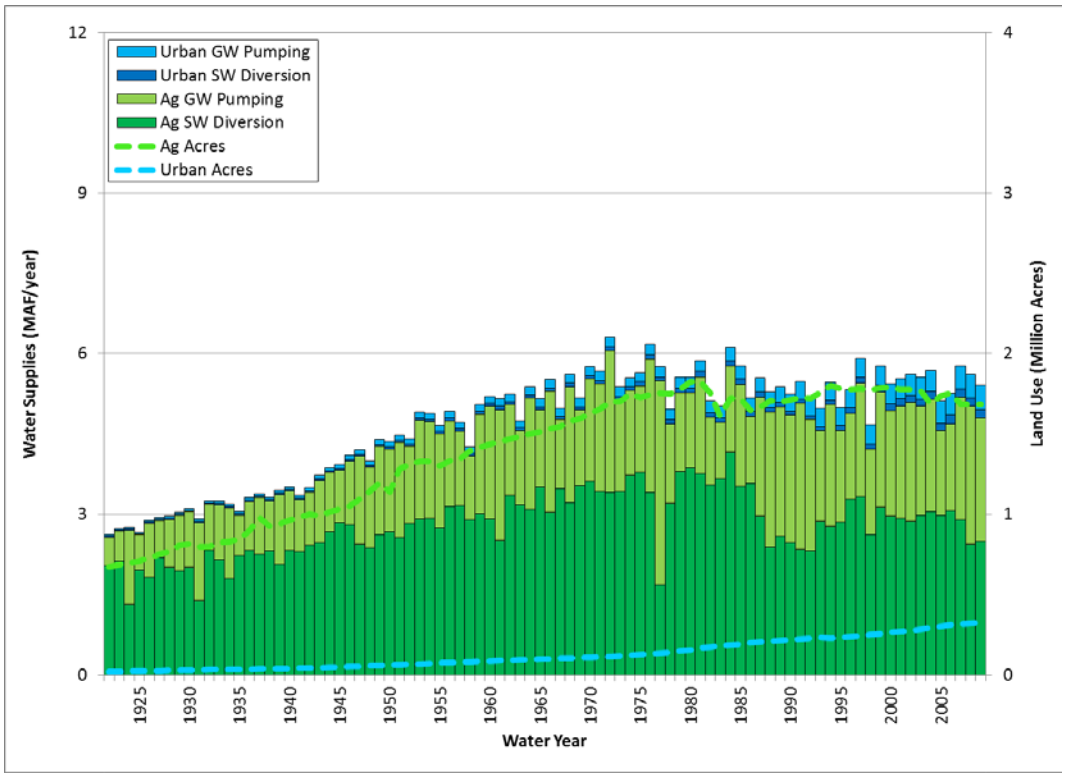


Figure 23 - Historic Land Use vs. Water Supplies in the San Joaquin Basin

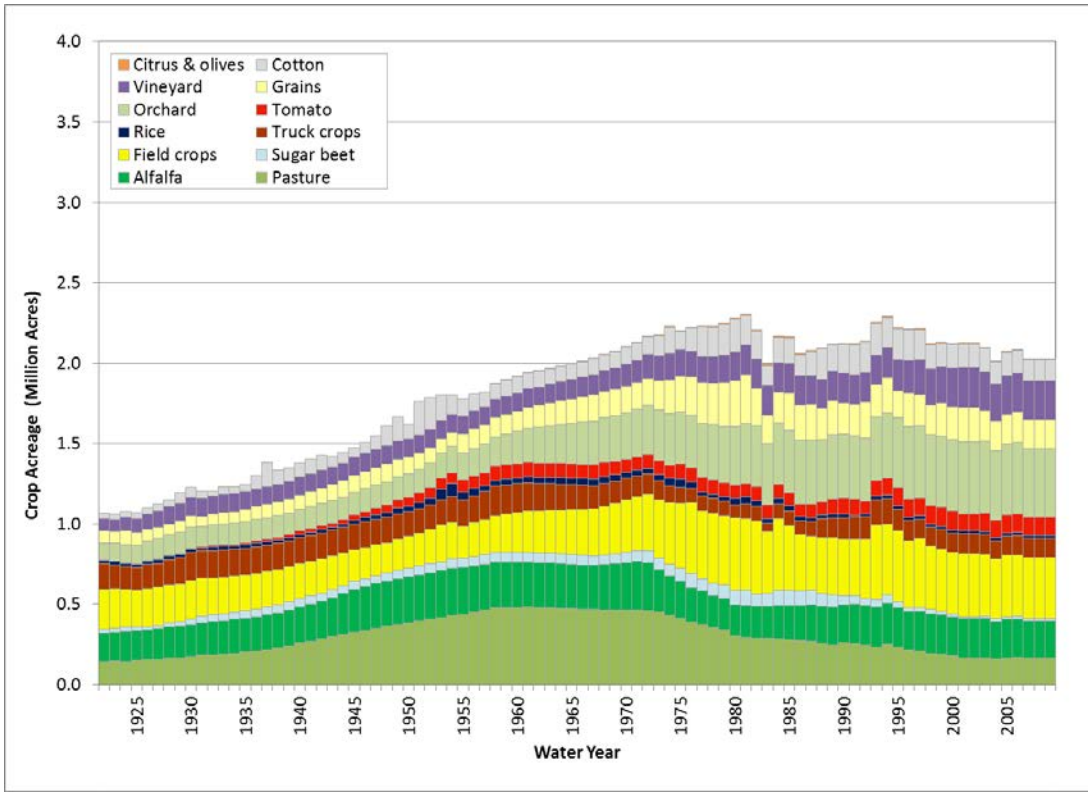


Figure 24 - Historic Cropping Patterns for the San Joaquin Basin

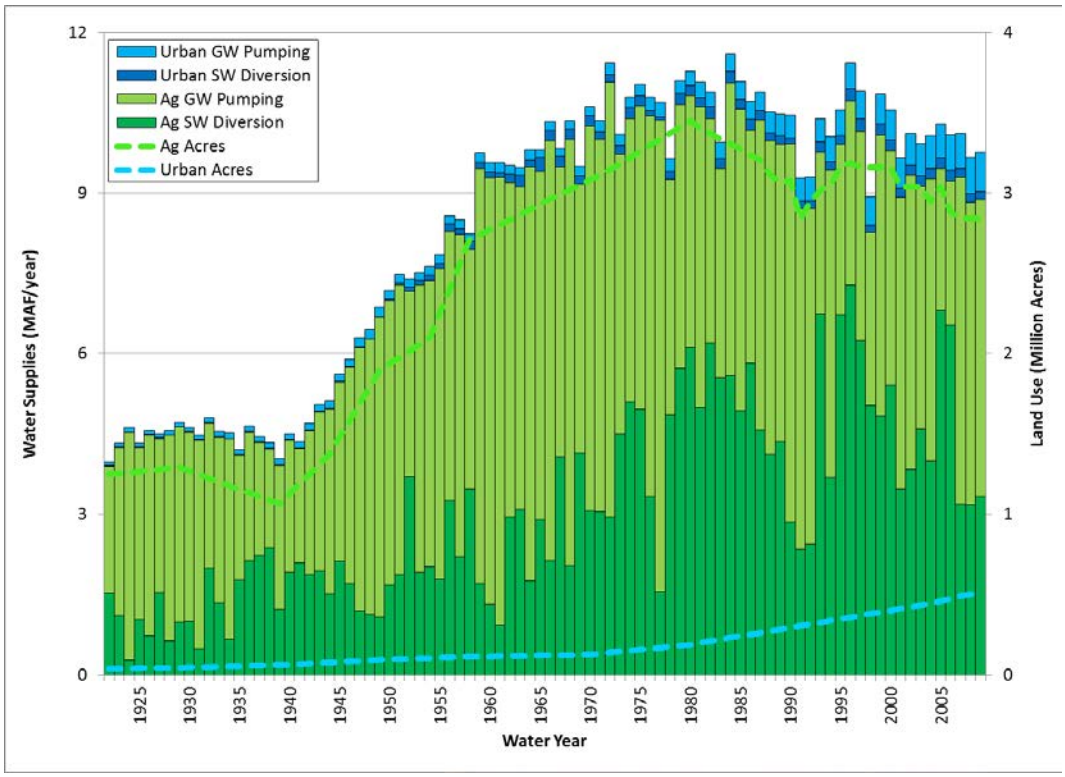


Figure 25 - Historic Land Use vs. Water Supplies in the Tulare Basin

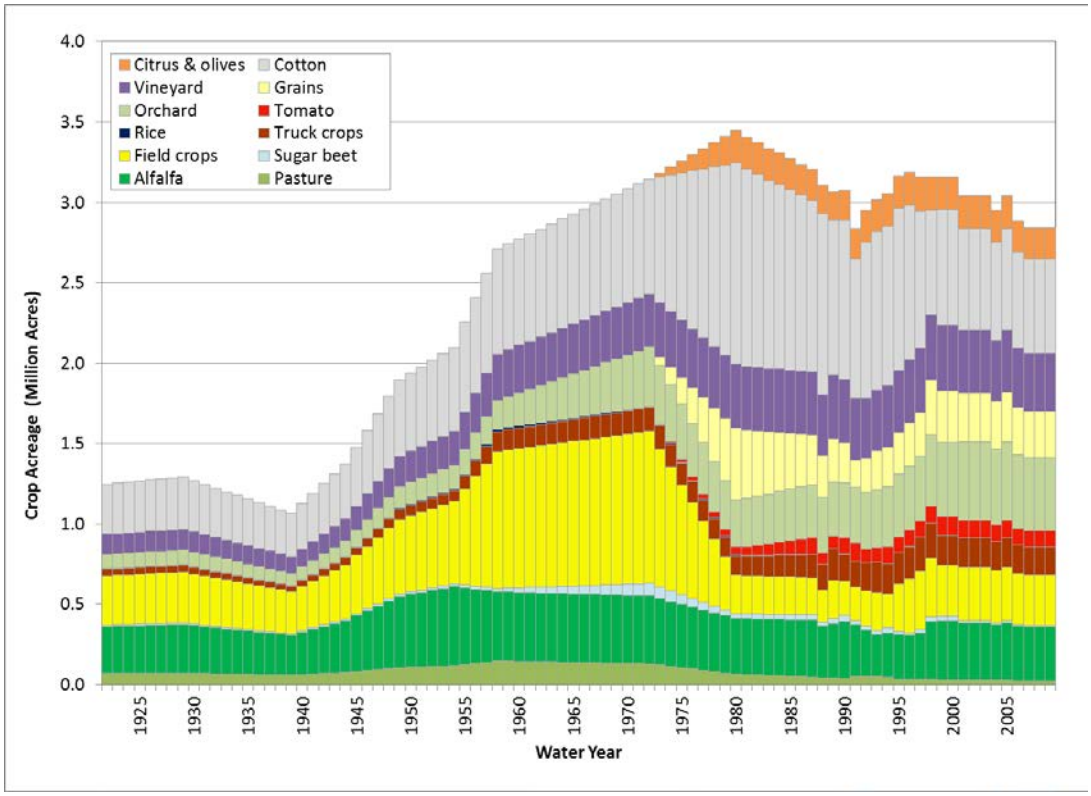


Figure 26 - Historic Cropping Patterns for the Tulare Basin

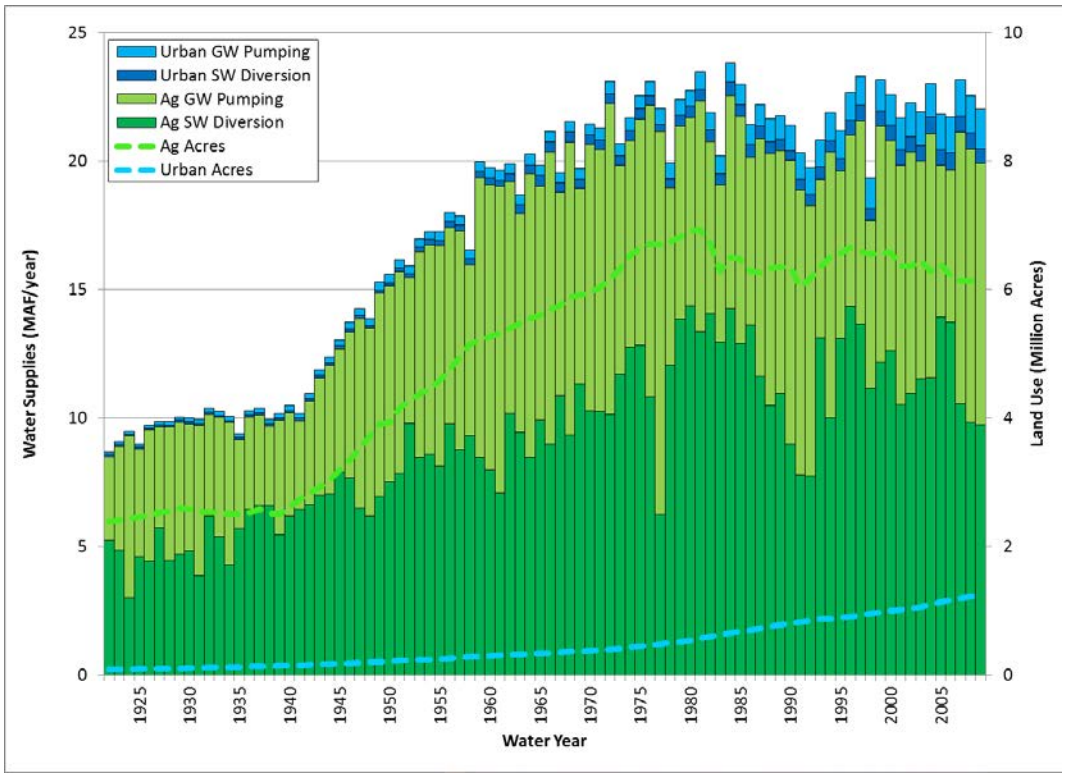


Figure 27 - Historic Land Use vs. Water Supplies in the Central Valley

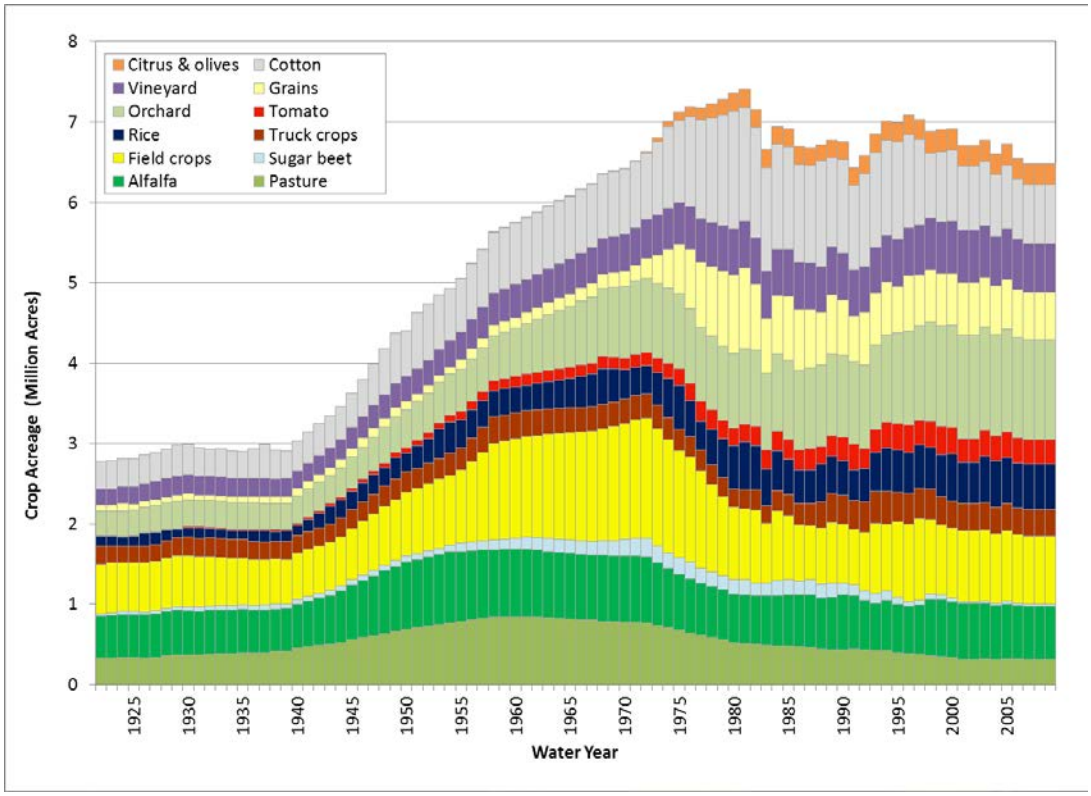


Figure 28 - Historic Cropping Patterns for the Central Valley

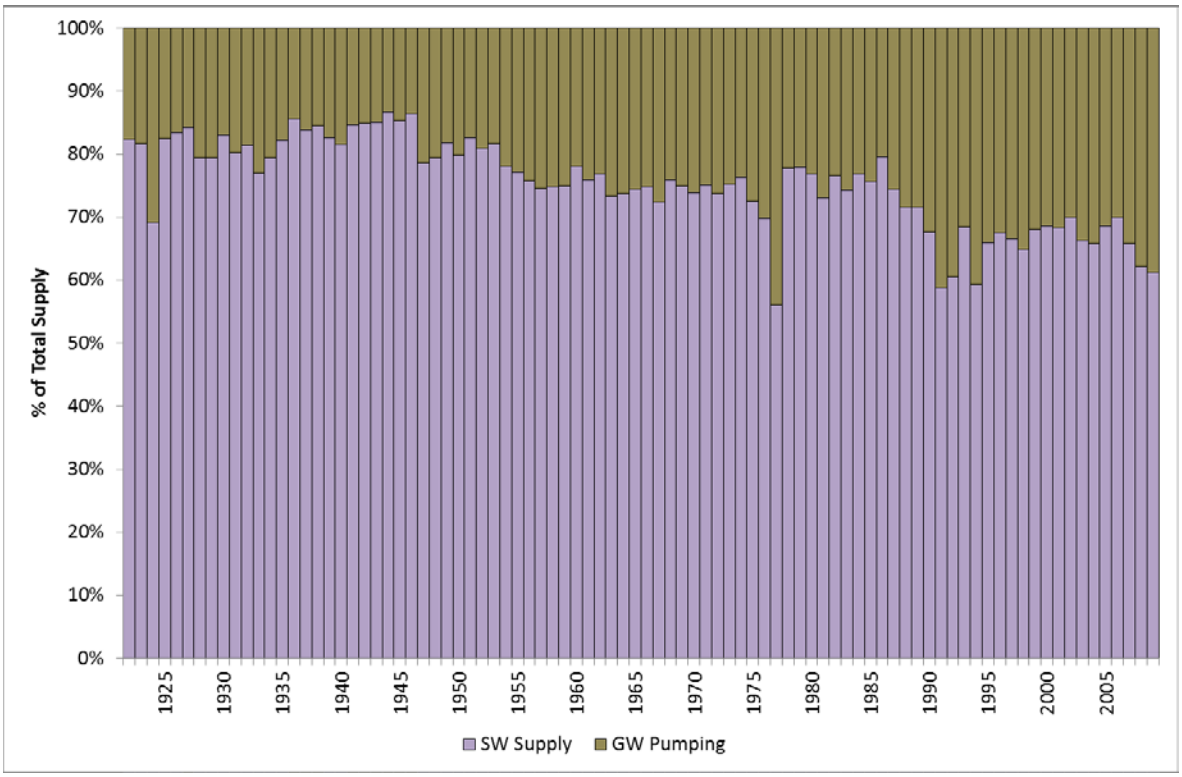


Figure 29 - Percent of Total Water Supply in the Sacramento Valley

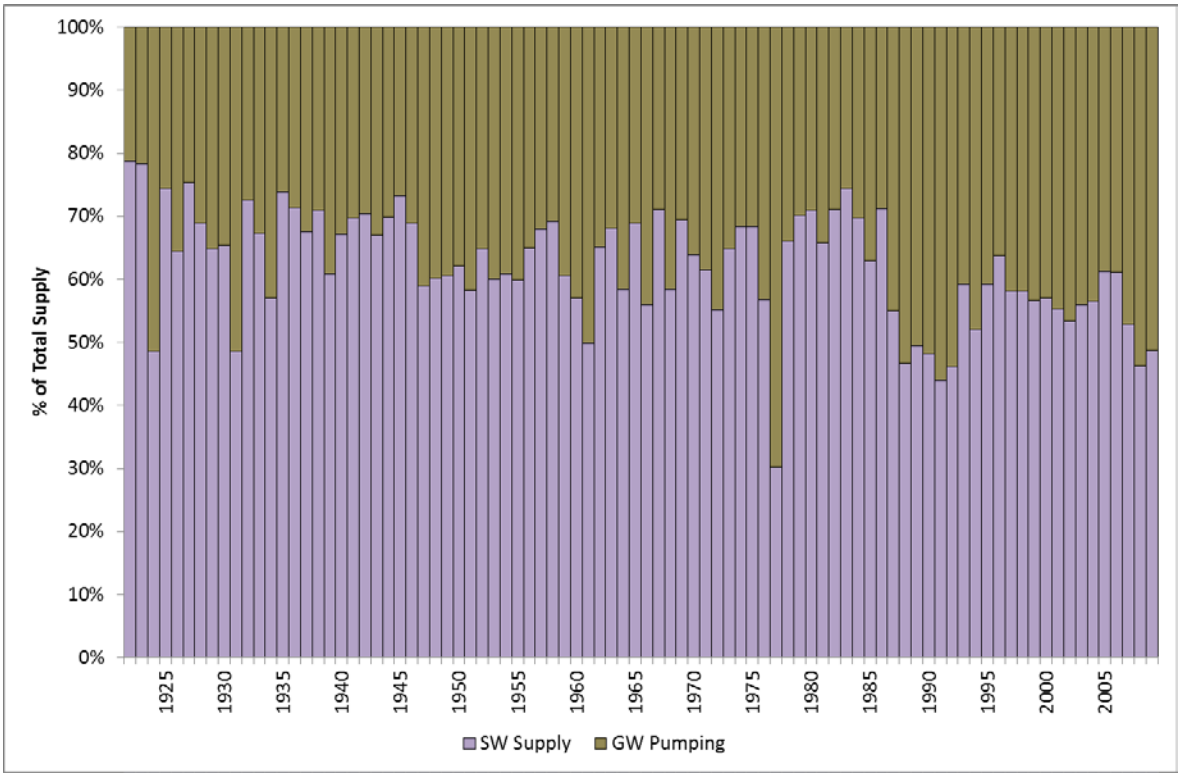


Figure 30 - Percent of Total Water Supply in the San Joaquin Basin

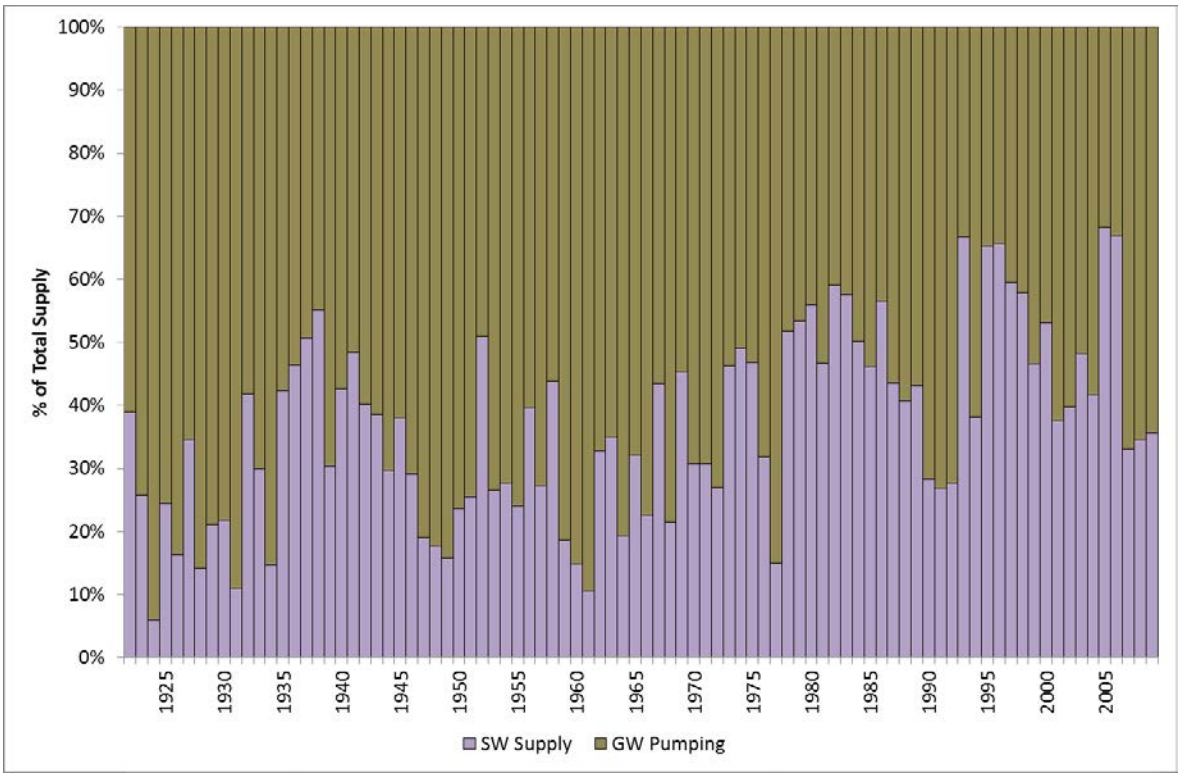


Figure 31 - Percent of Total Water Supply in the Tulare Basin

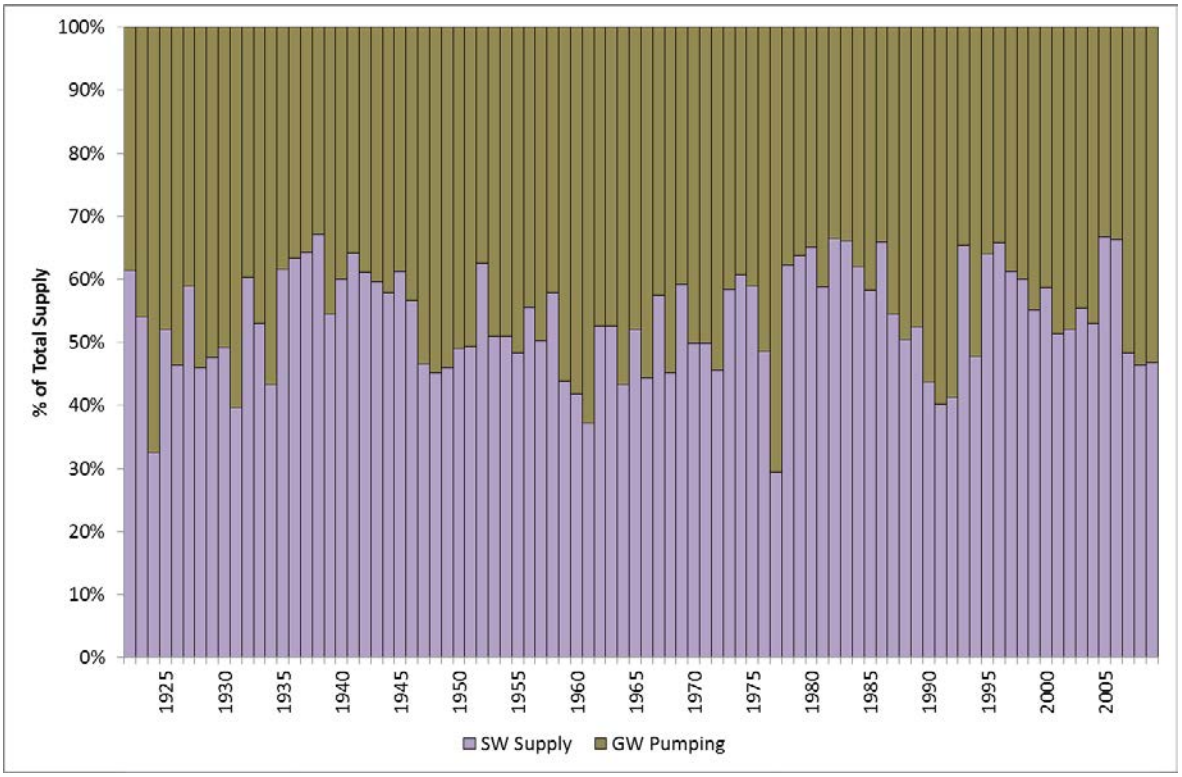


Figure 32 - Percent of Total Water Supply in the Central Valley

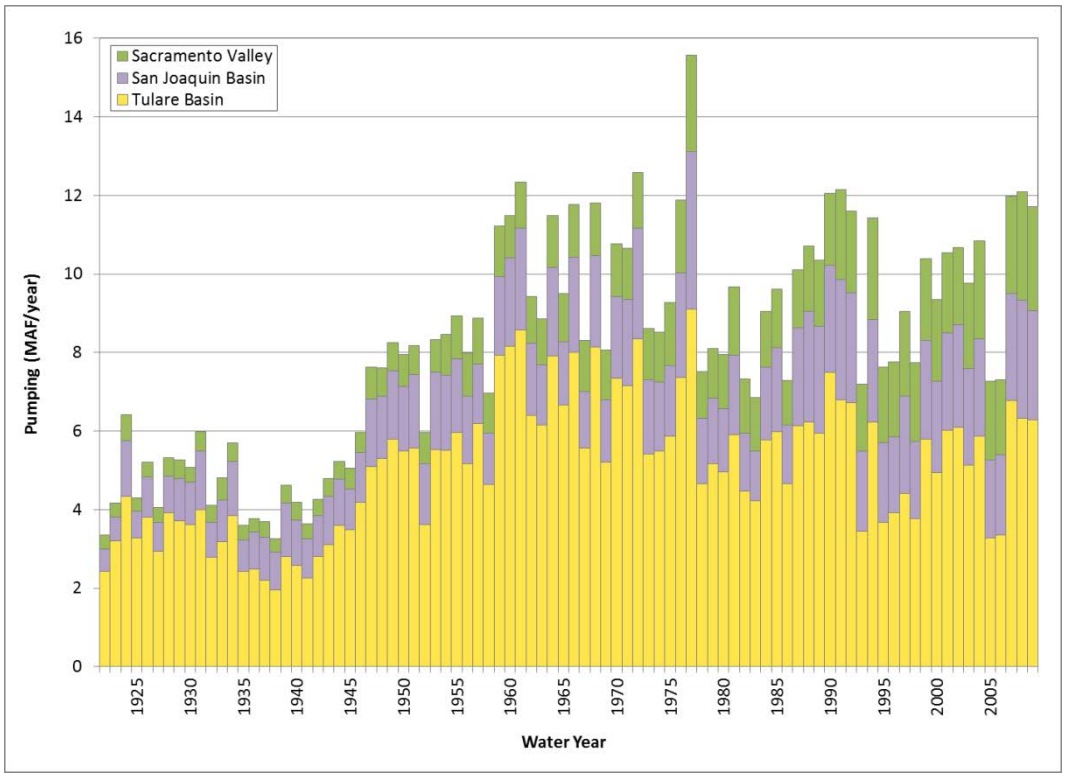


Figure 33 - Total Groundwater Production in the Central Valley

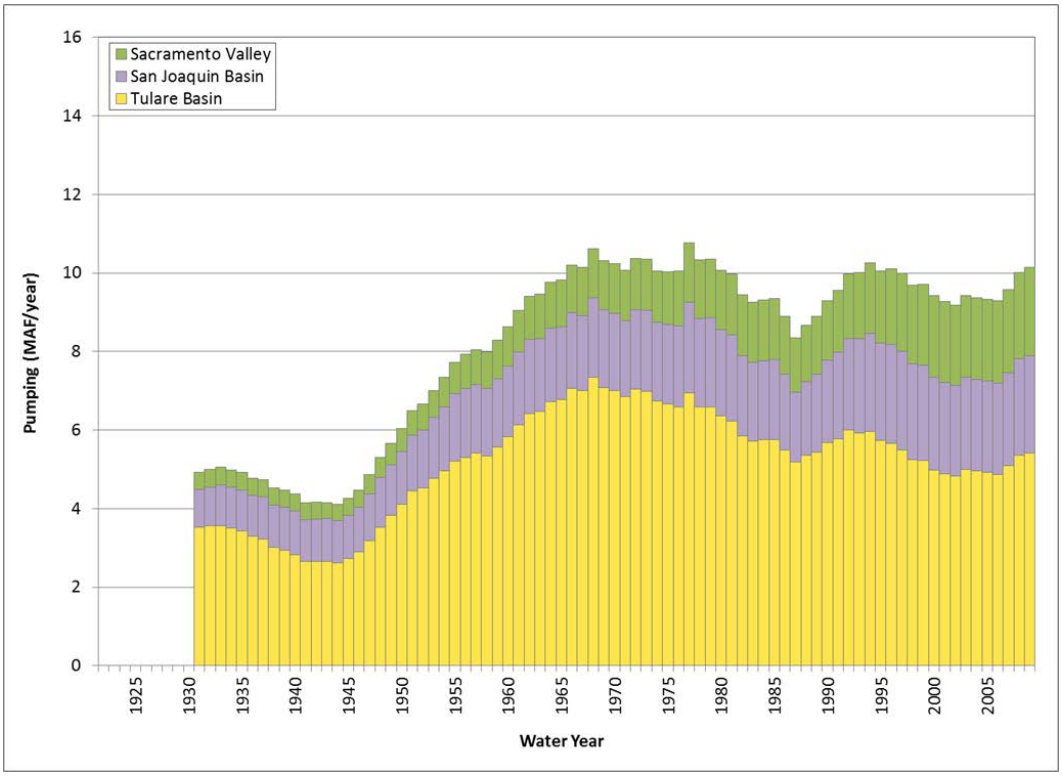


Figure 34 - Total Groundwater Production in the Central Valley (10 Year Moving Average)

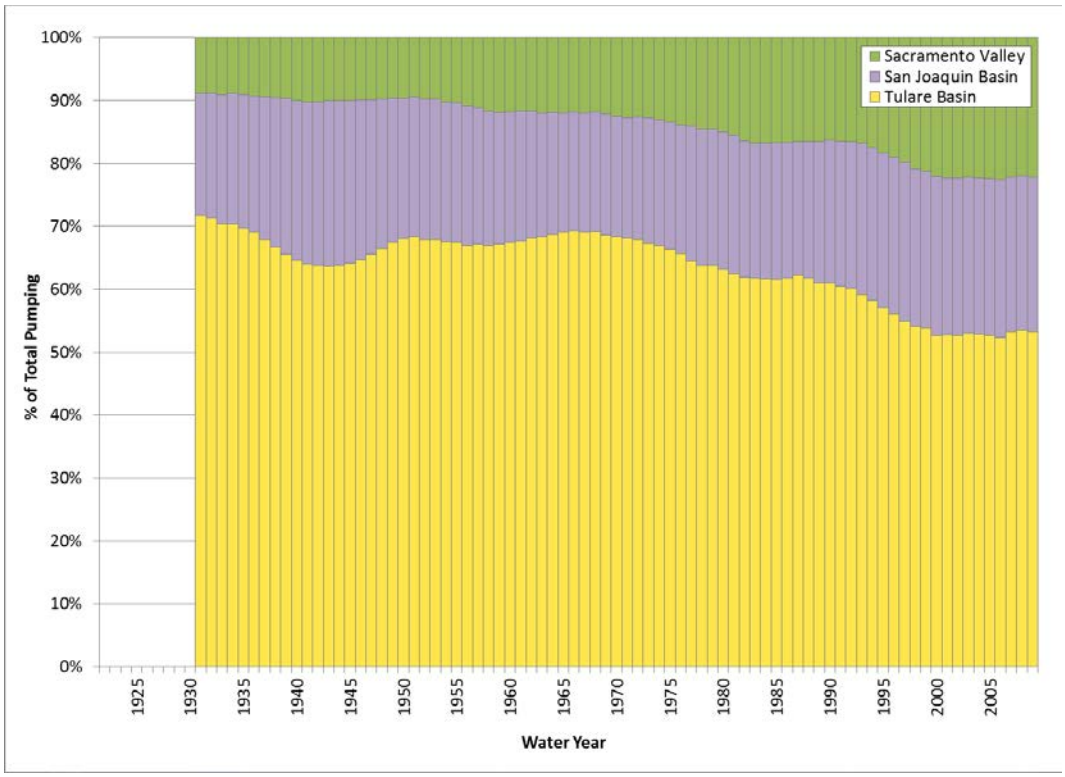


Figure 35 - Percent of Total Groundwater Production in the Central Valley – 10 Year Moving Average

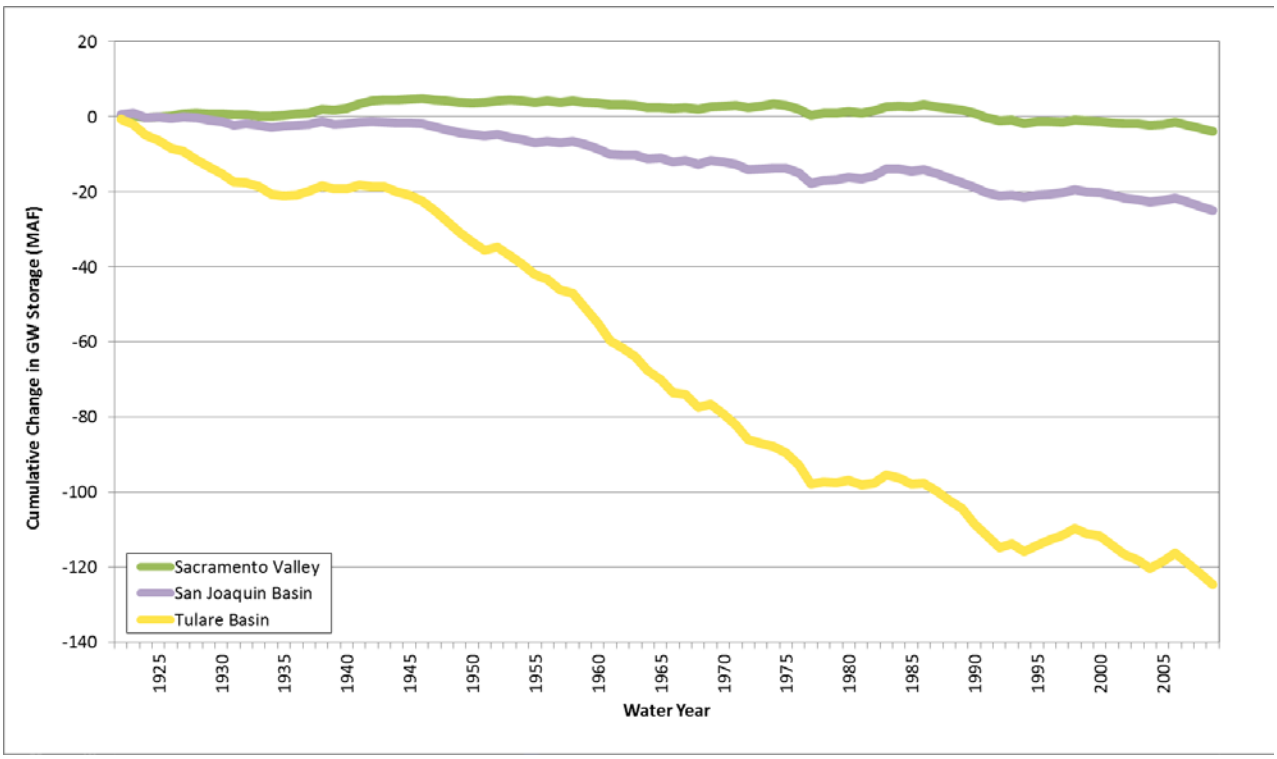


Figure 36 - Cumulative Change in Groundwater Storage by Hydrologic Region

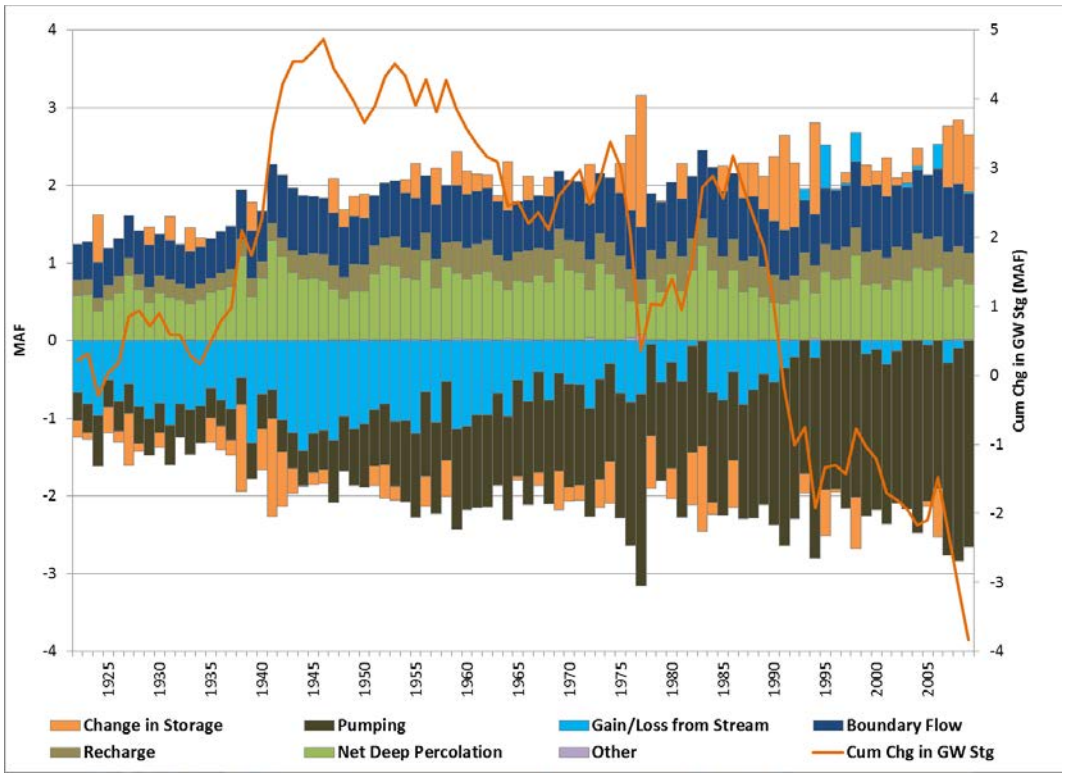


Figure 37 - Historic Groundwater Budget - Sacramento Valley

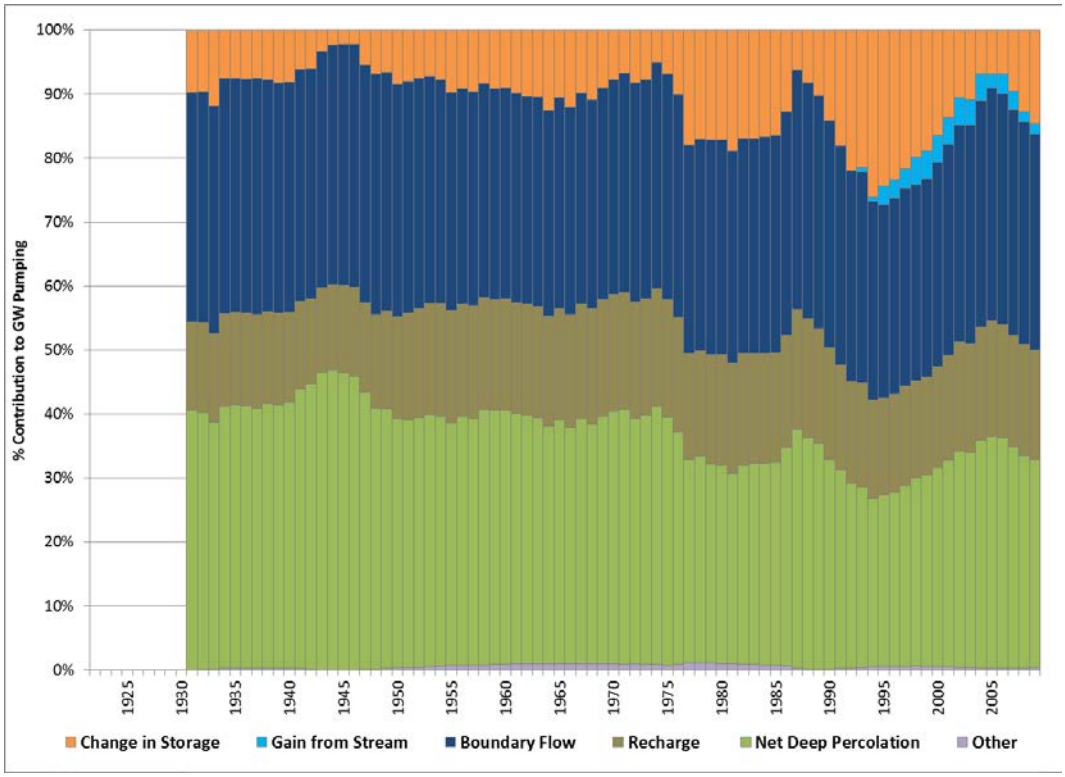


Figure 38 - Percent Contribution of Various Sources of Water to GW Pumping - Sacramento Valley (10 Year Moving Average)

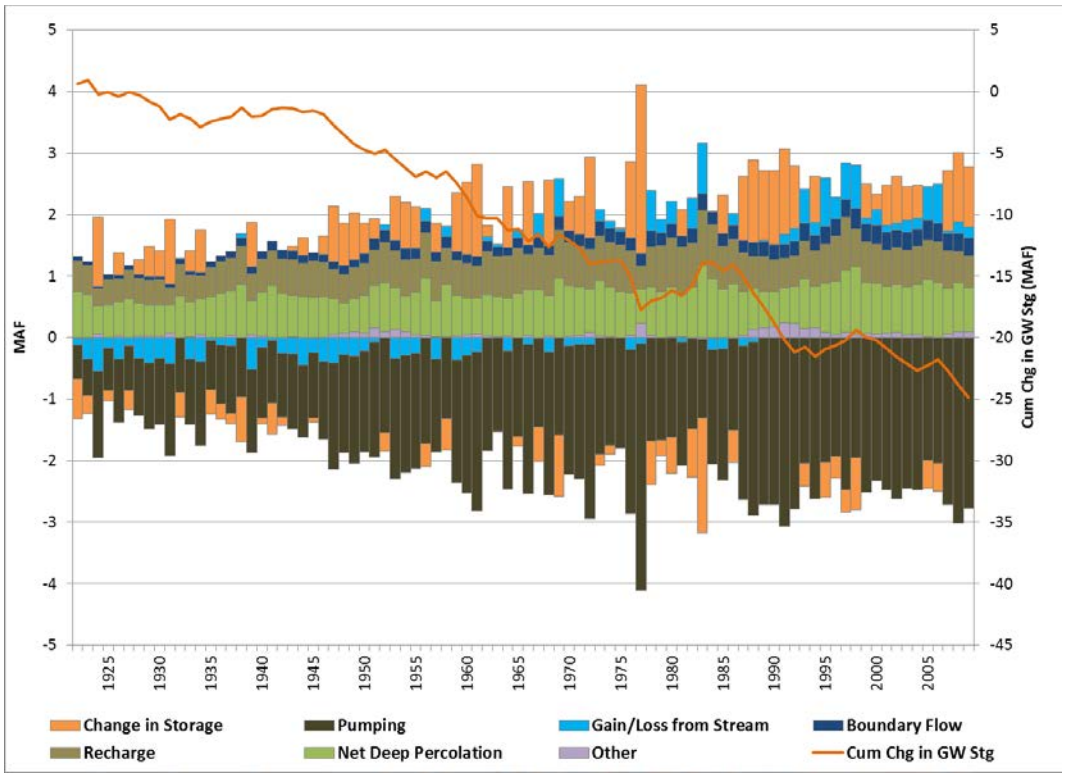


Figure 39 - Historic Groundwater Budget - San Joaquin Basin (Note different scale as compared to Figure 37)

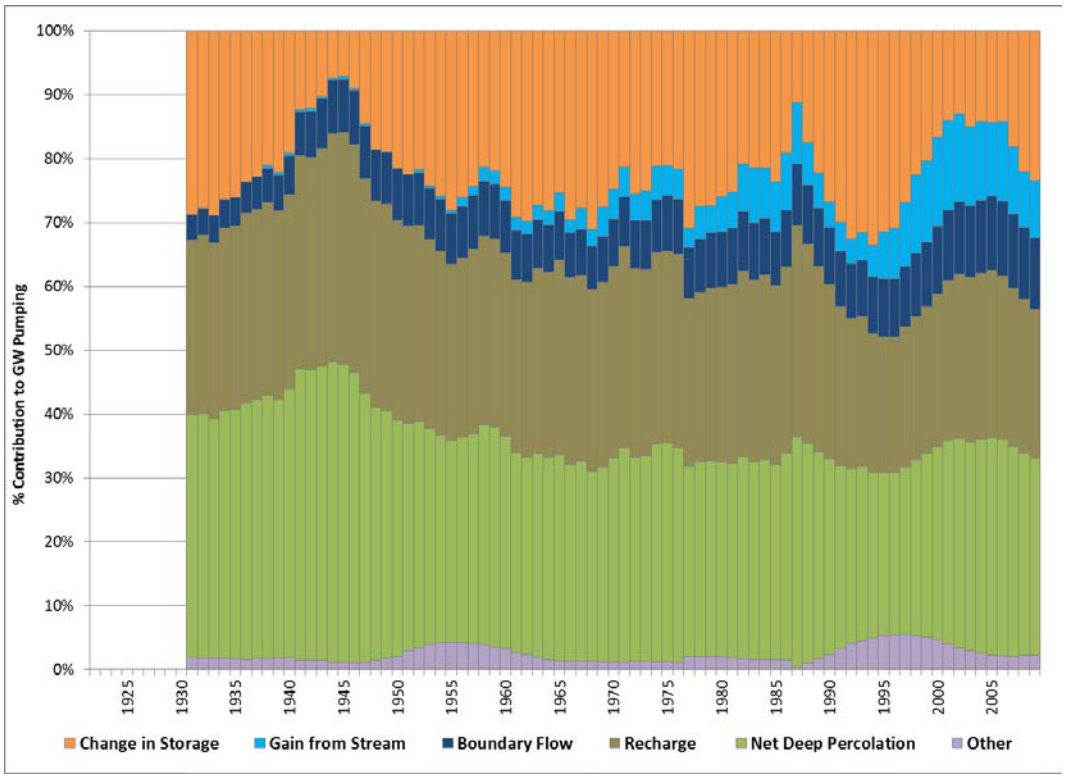


Figure 40 - Percent Contribution of Various Sources of Water to GW Pumping - San Joaquin Basin (10 Year Moving Average)

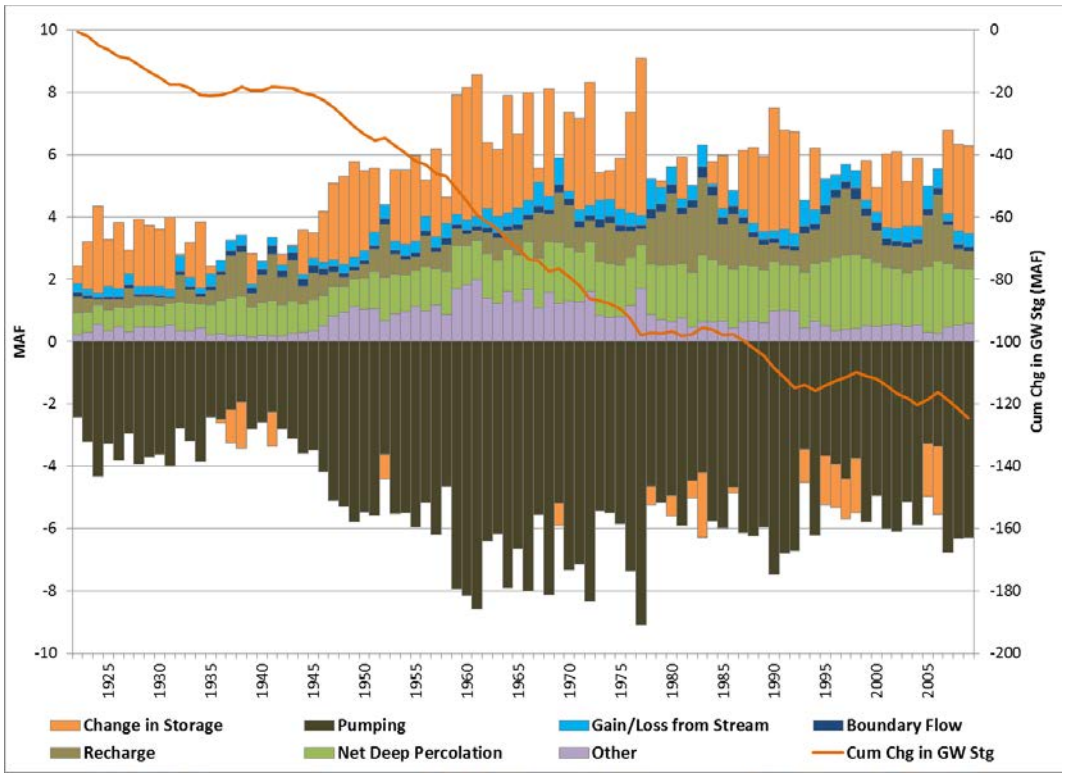


Figure 41 - Historic Groundwater Budget - Tulare Basin (Note different scale as compared to Figure 37 and Figure 39)

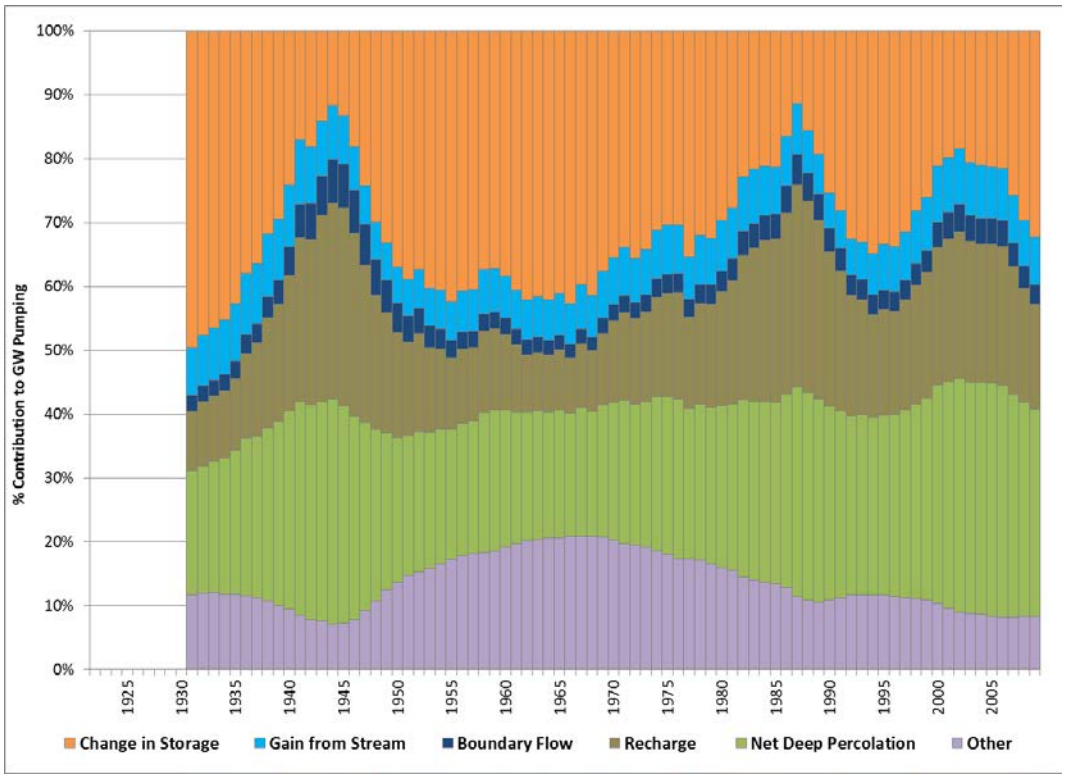


Figure 42 - Percent Contribution of Various Sources of Water to GW Pumping - Tulare Basin (10 Year Moving Average)

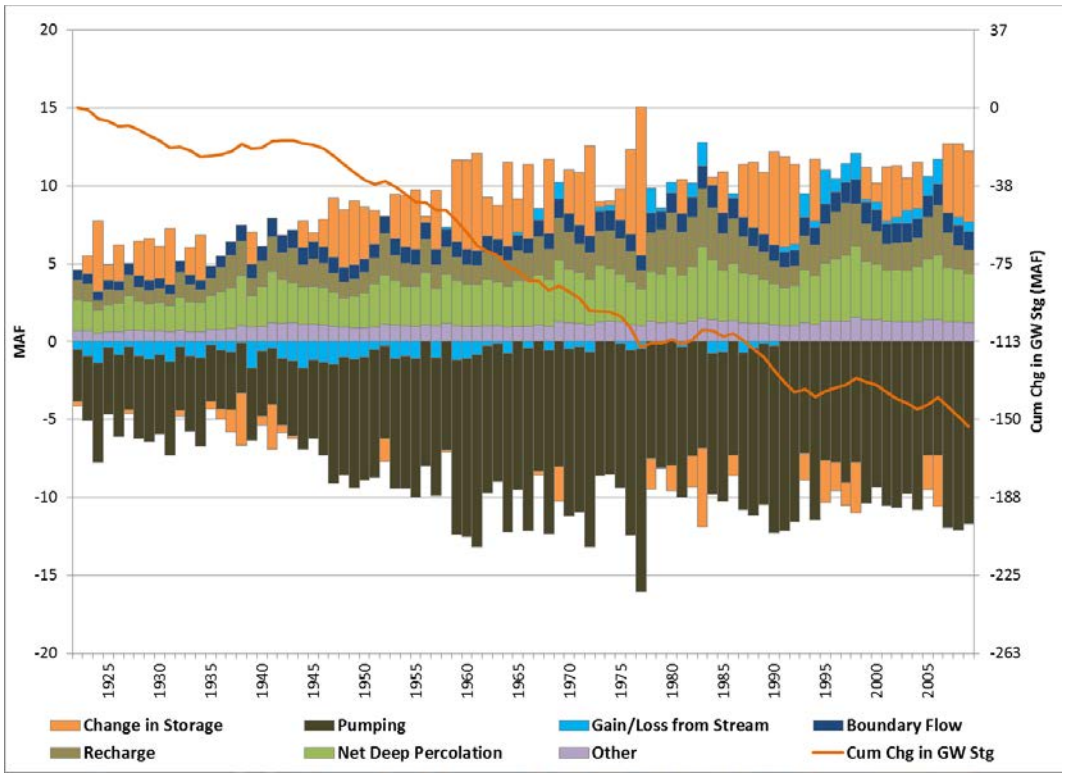


Figure 43 - Historic Groundwater Budget - Central Valley

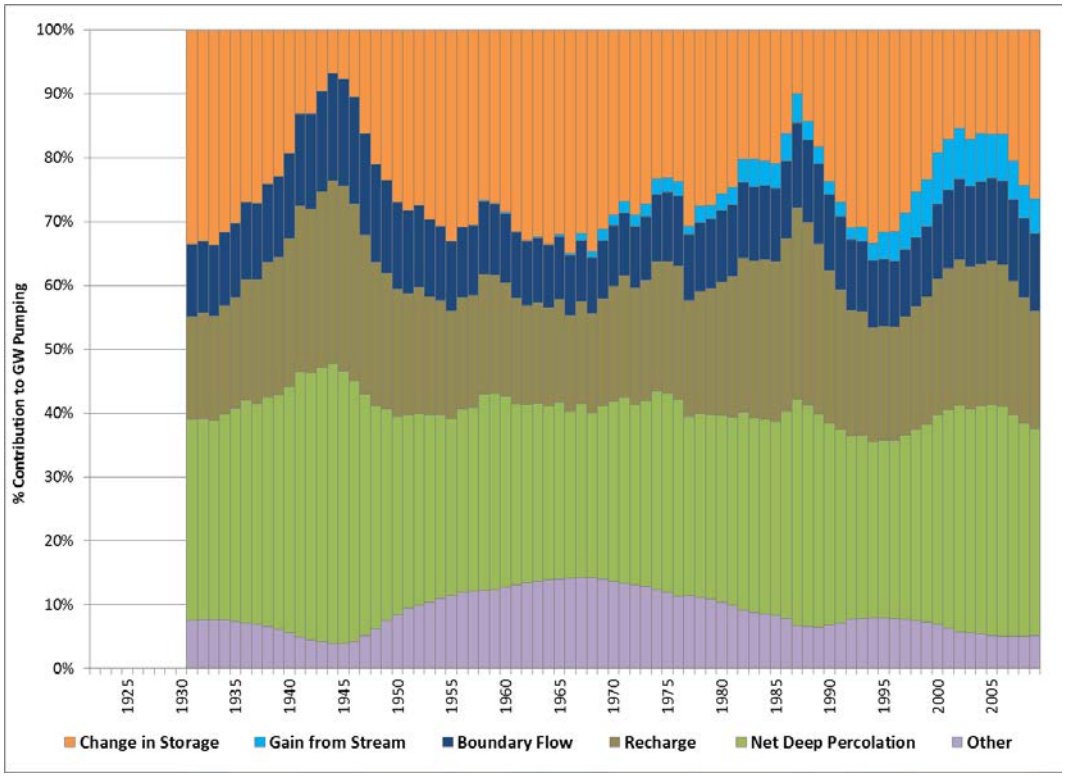


Figure 44 - Percent Contribution of Various Sources of Water to GW Pumping - Central Valley (10 Year Moving Average)

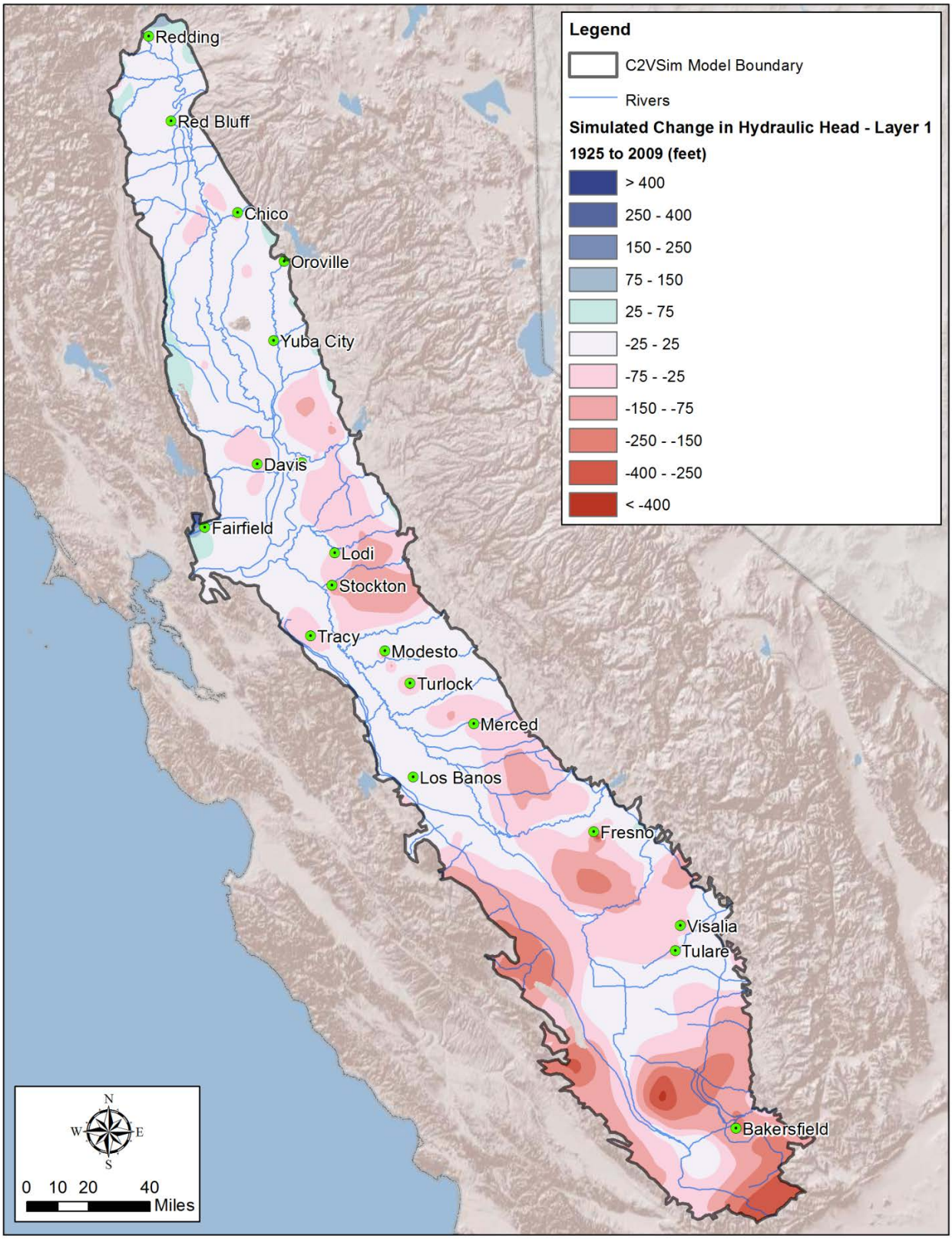


Figure 45 - Groundwater Level Differences 1925 to 2009 - Aquifer layer 1 (Upper-most Aquifer Layer)

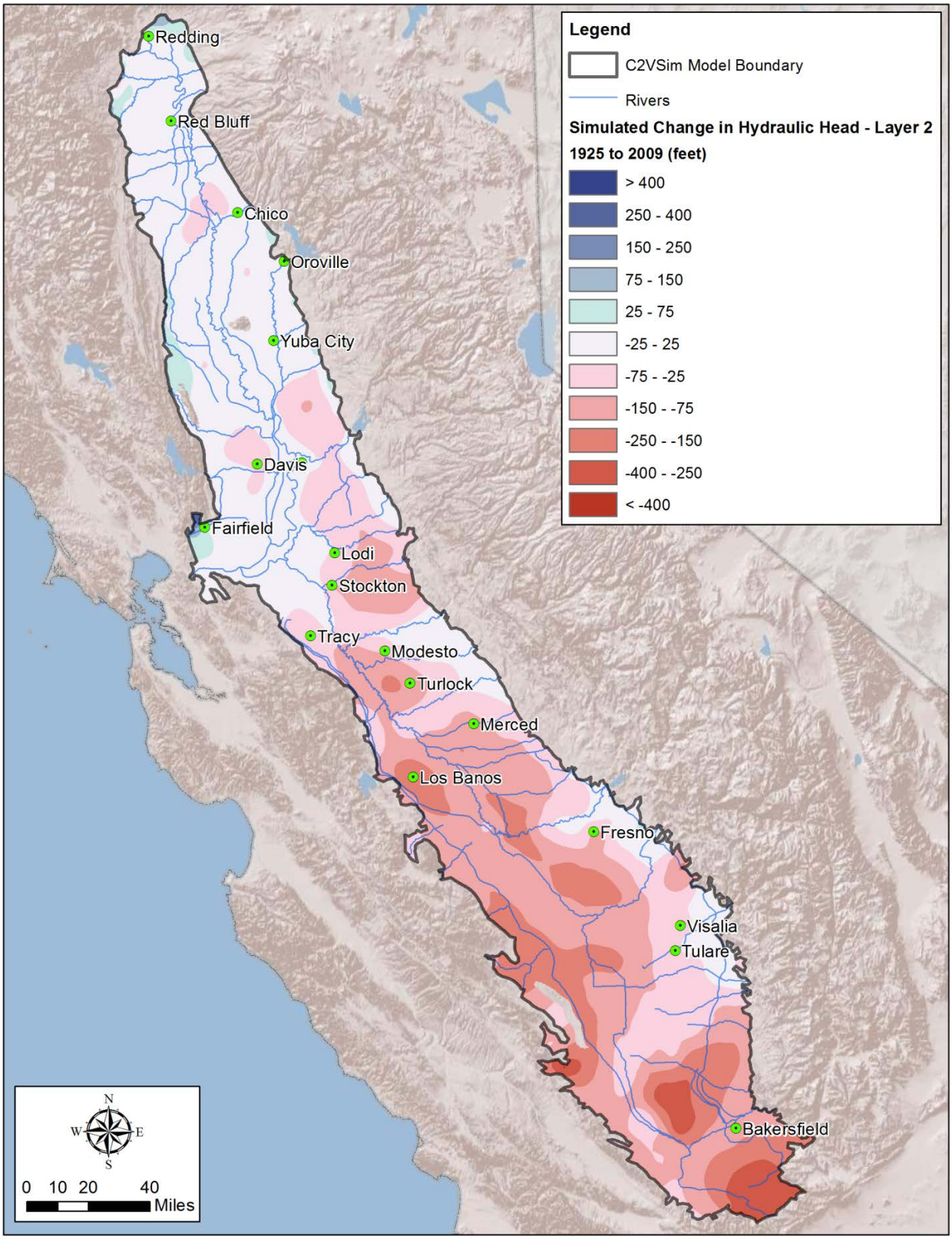


Figure 46 - Groundwater Level Differences 1925 to 2009 - Aquifer Layer2

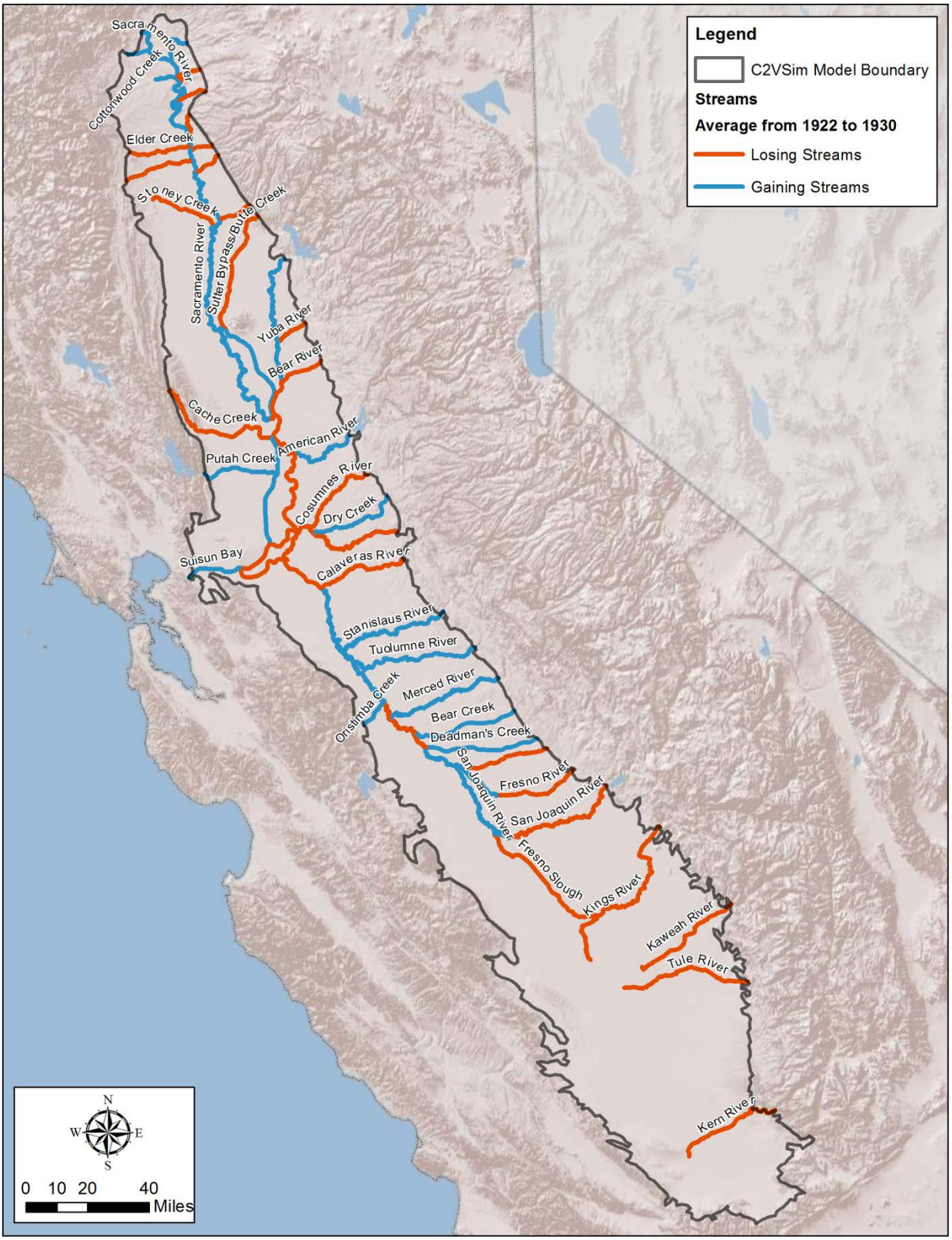


Figure 47 - Average Stream Gain Loss - 1920's

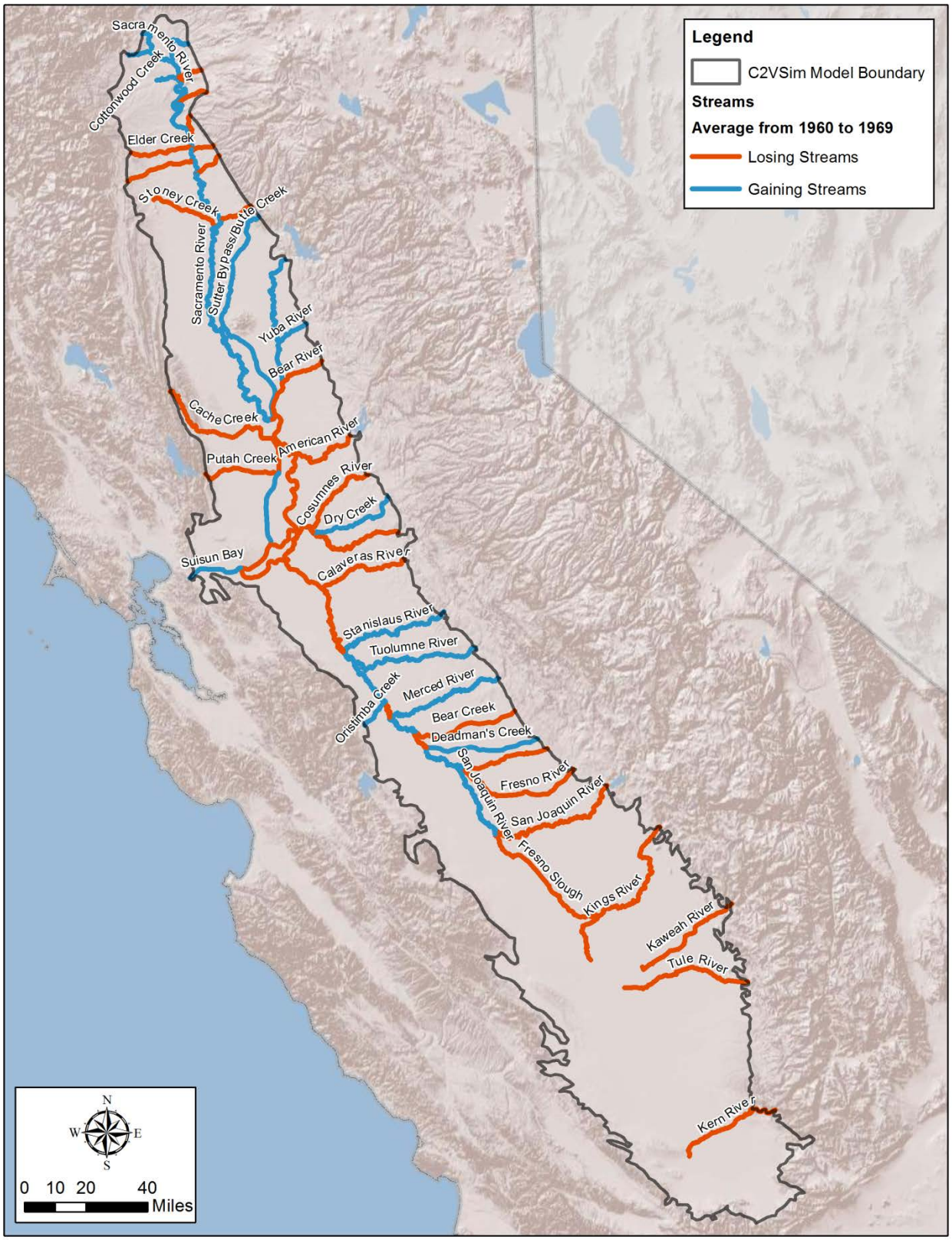


Figure 48 - Average Stream Gain Loss - 1960's

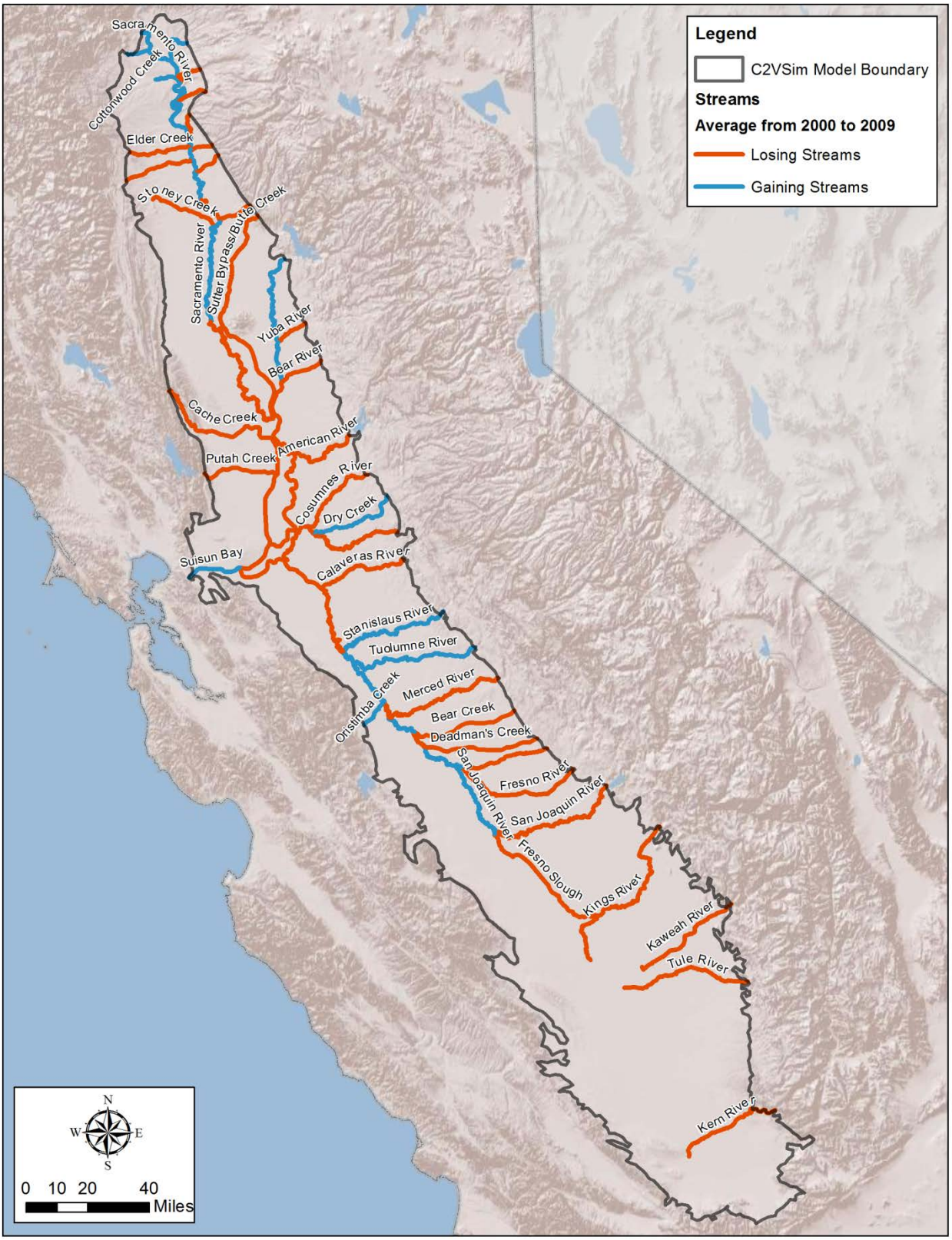


Figure 49 - Average Stream Gain Loss - 2000's

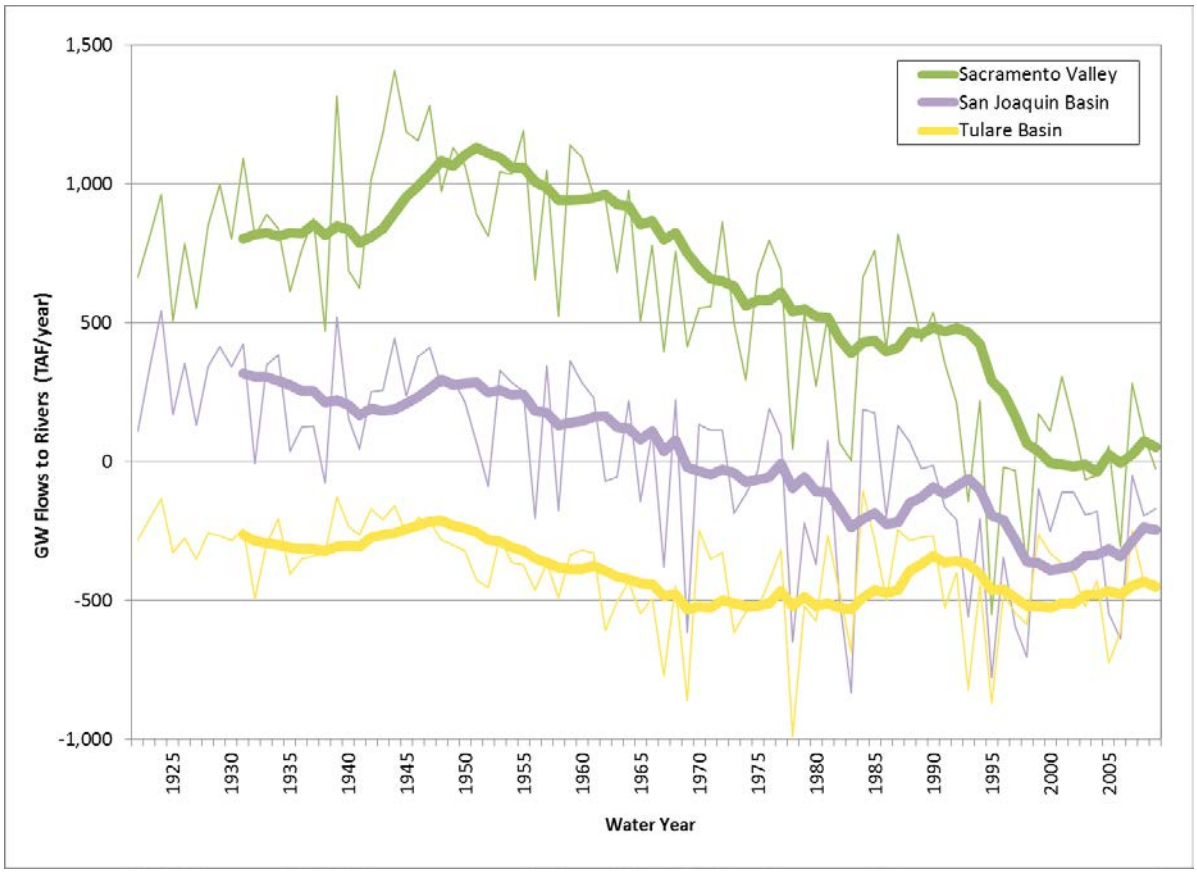


Figure 50 - Net Historic Groundwater Discharge to Rivers with 10 Year Moving Average

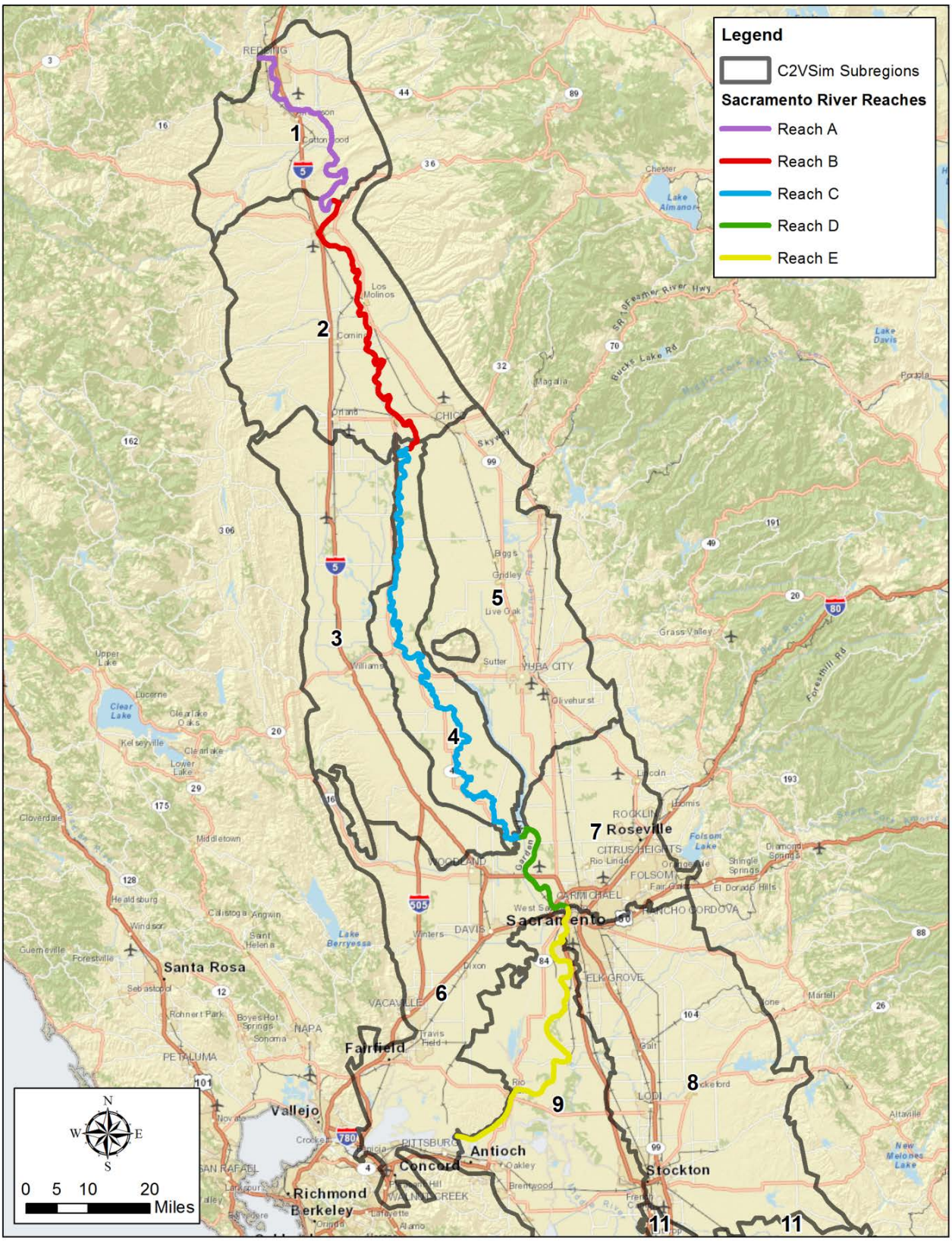


Figure 51 - Sacramento River Reaches

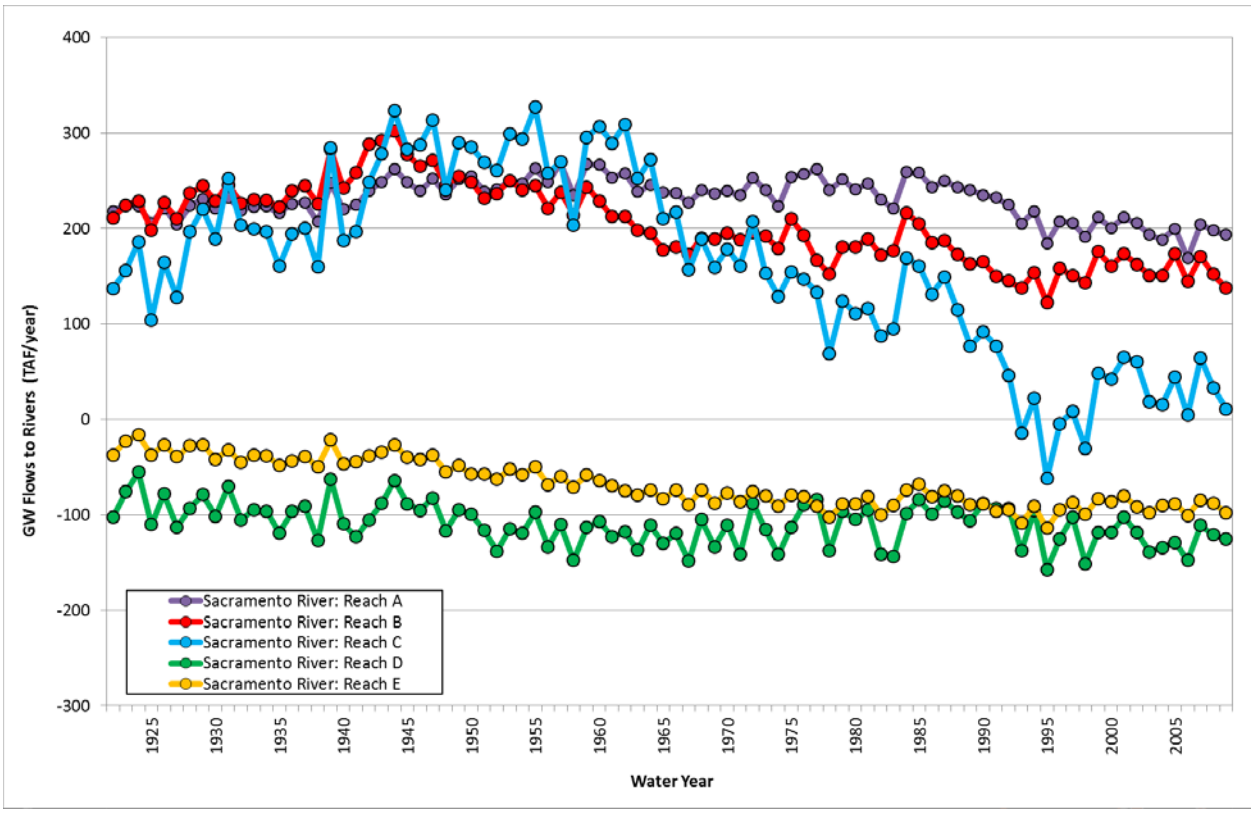


Figure 52 - Historic Groundwater Flows to the Sacramento River

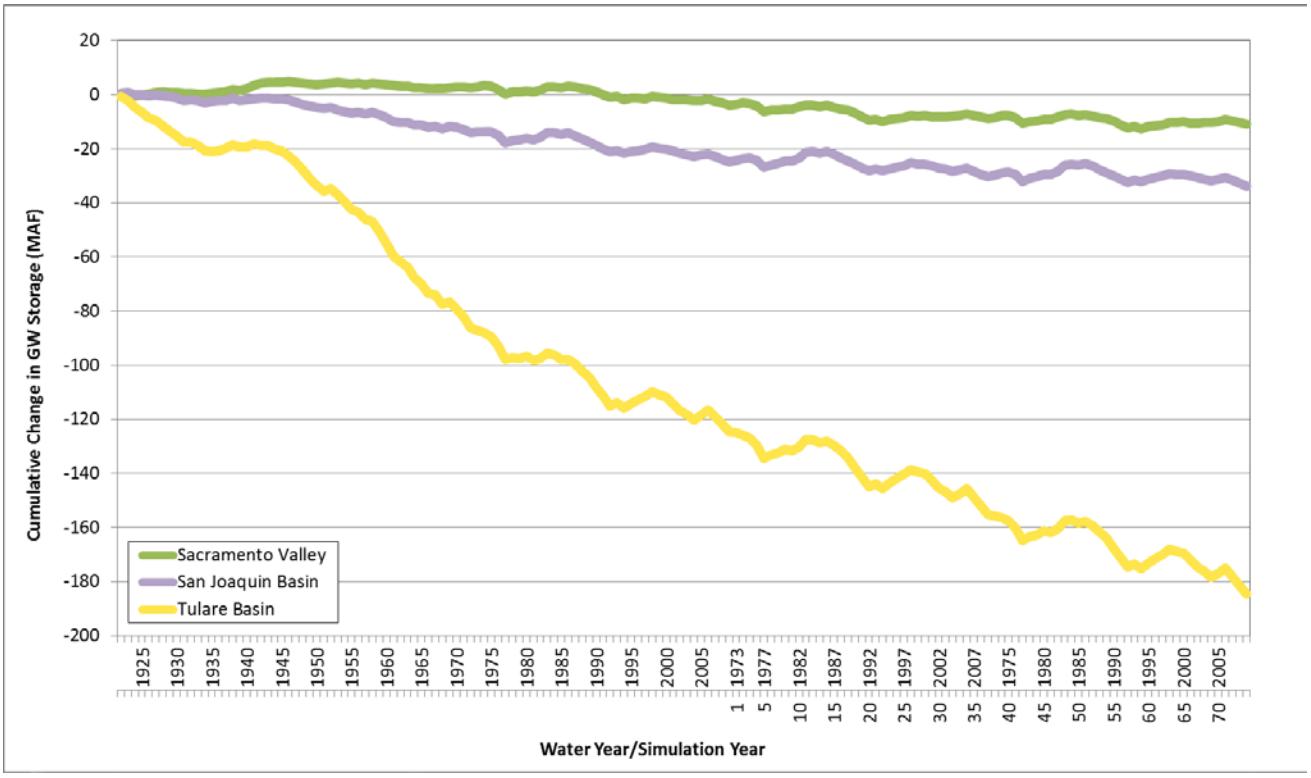


Figure 53 - Cumulative Change in Groundwater Storage by Hydrologic Region - (Historic + Baseline)

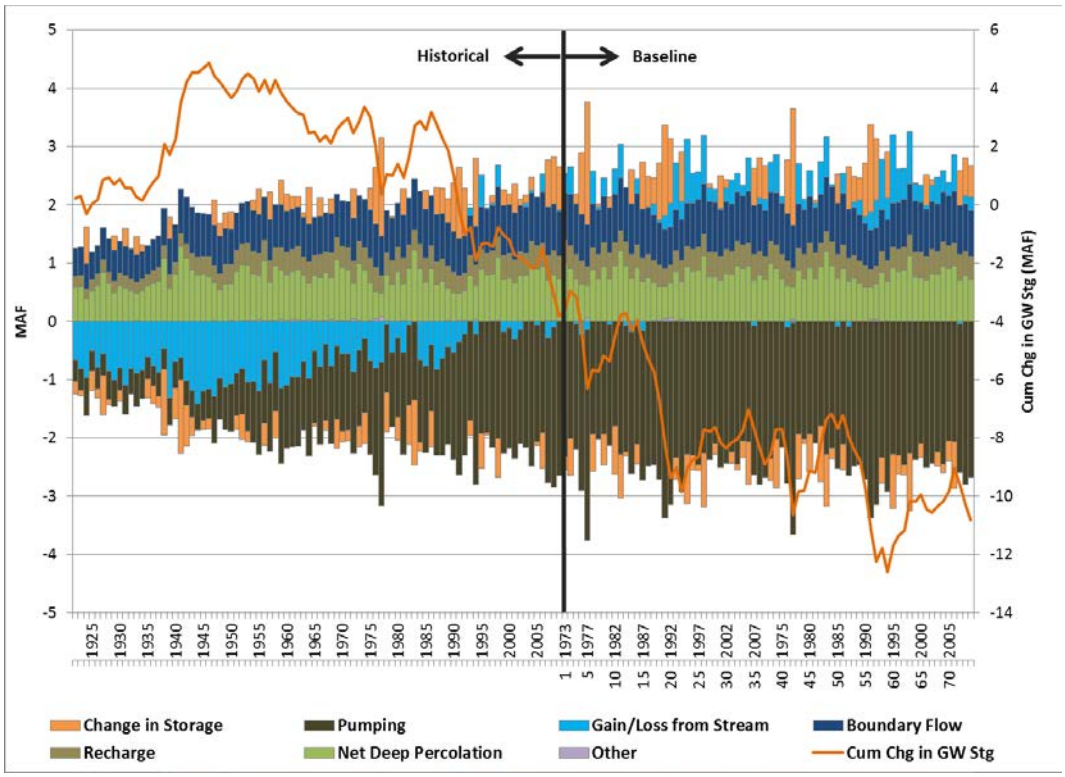


Figure 54 - Historic and Baseline Groundwater Budget - Sacramento Valley

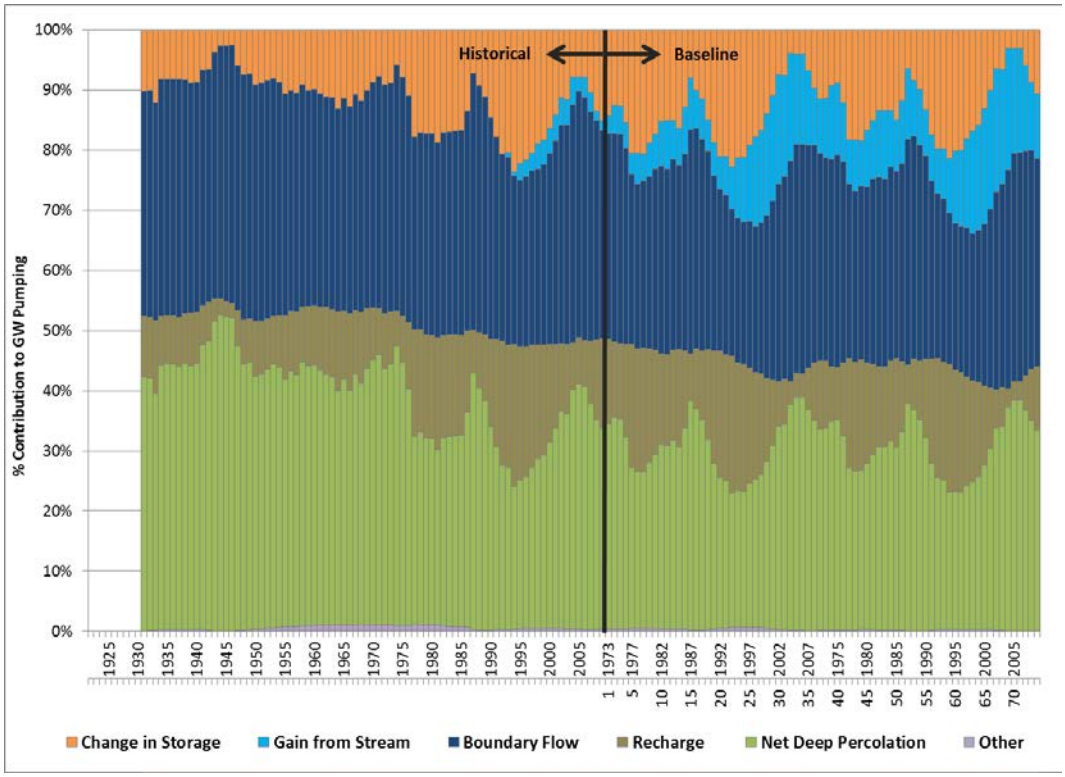


Figure 55 - Historic and Baseline Percent Contribution of Various Sources of Water to GW Pumping - Sacramento Valley (10 Year Moving Average)

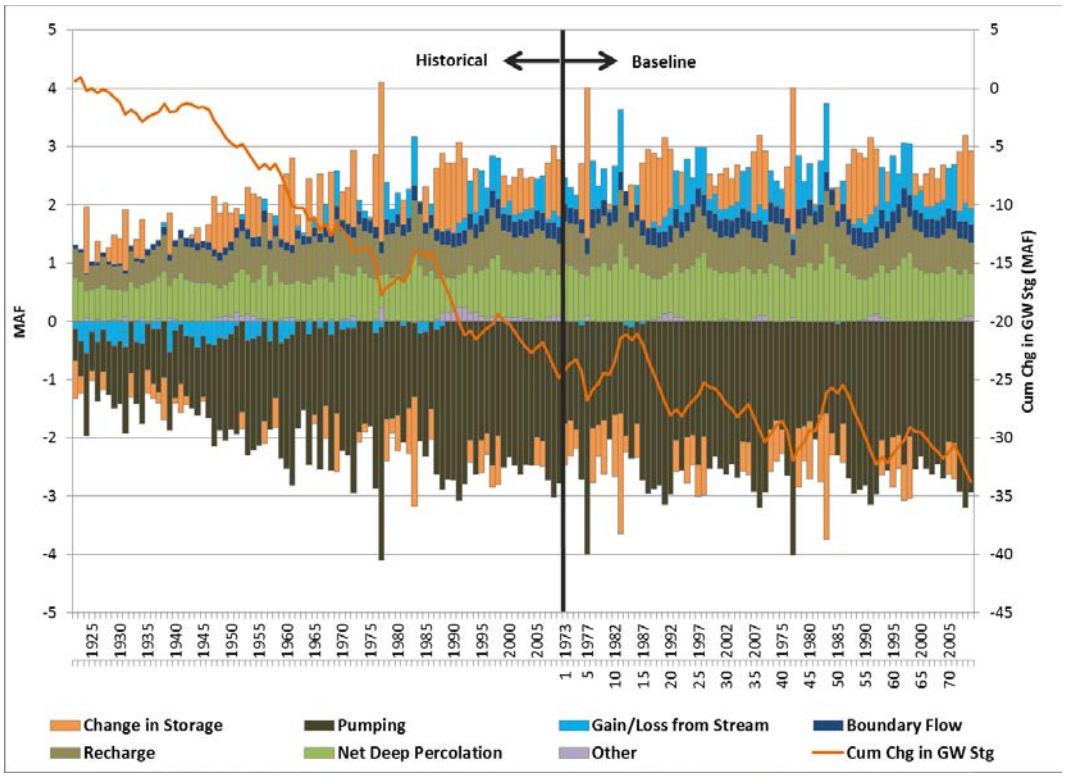


Figure 56 - Historic and Baseline Groundwater Budget - San Joaquin Basin (Note different scale as compared to Figure 54)

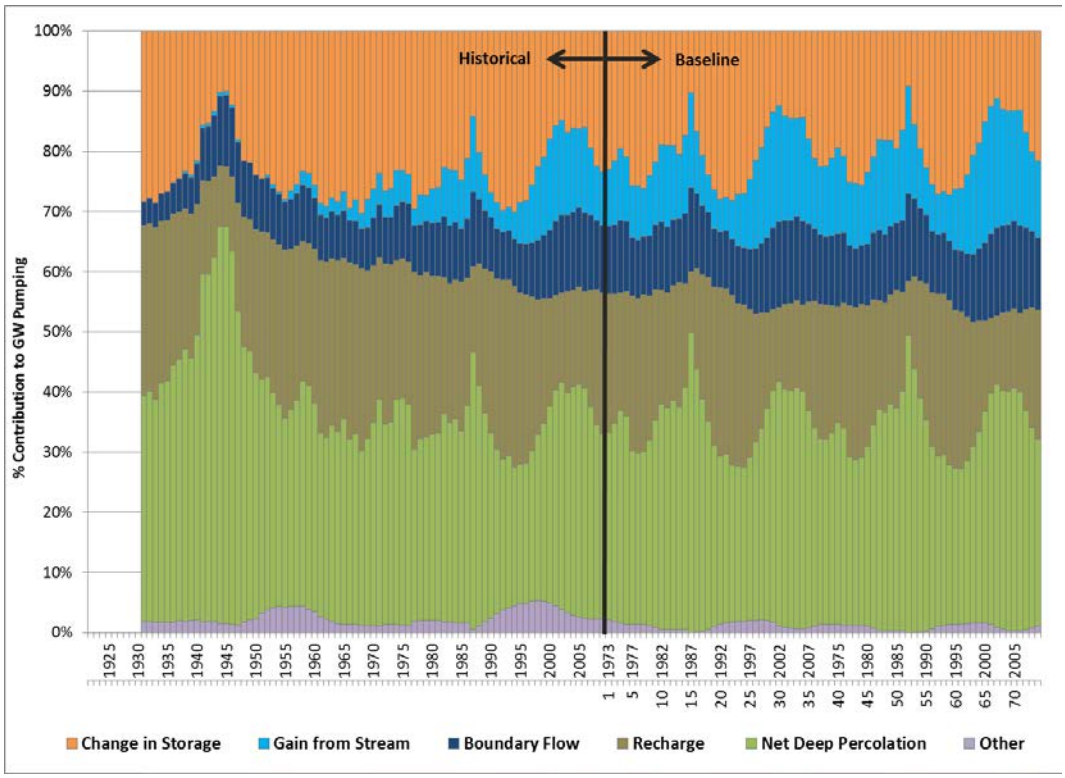


Figure 57 - Historic and Baseline Percent Contribution of Various Sources of Water to GW Pumping - San Joaquin Basin (10 Year Moving Average)

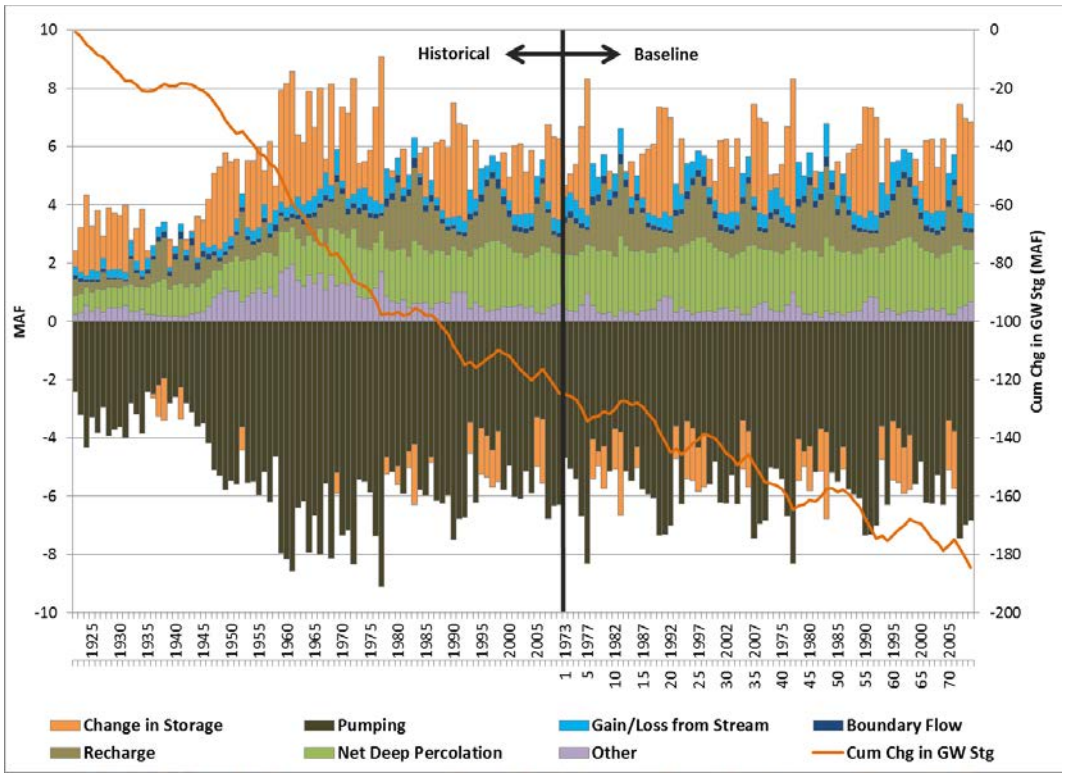


Figure 58 - Historic and Baseline Groundwater Budget - Tulare Basin (Note different scale as compared to Figure 54 and Figure 56)

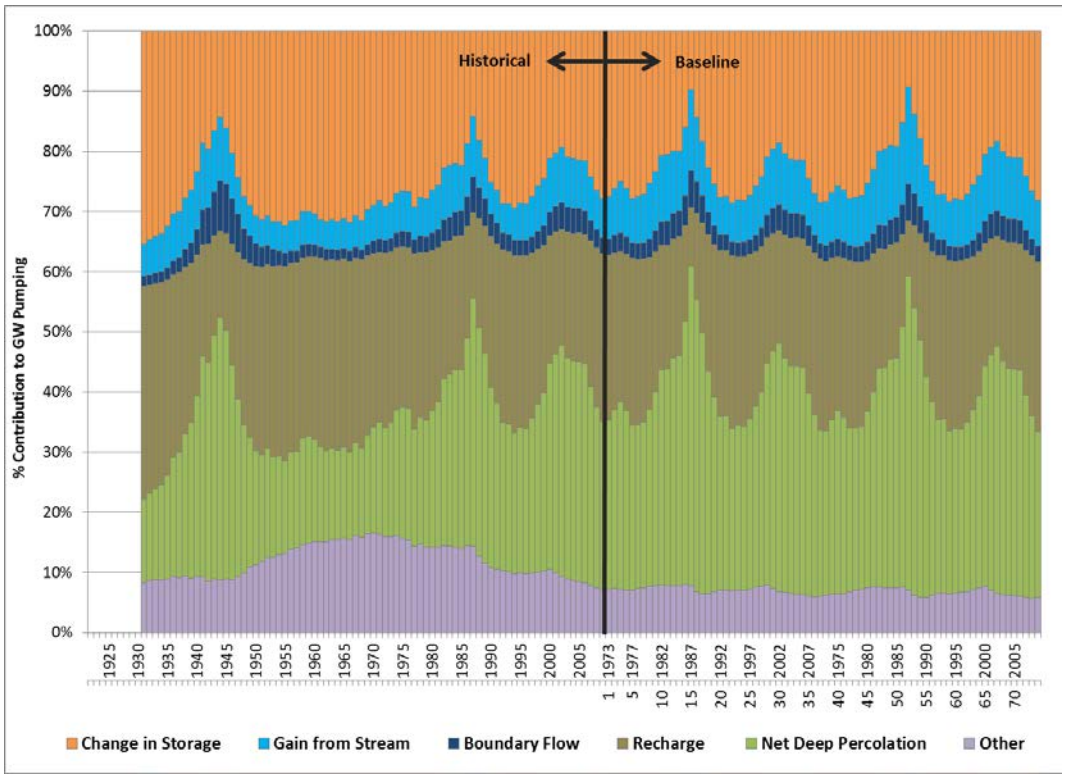


Figure 59 - Historic and Baseline Percent Contribution of Various Sources of Water to GW Pumping - Tulare Basin (10 Year Moving Average)

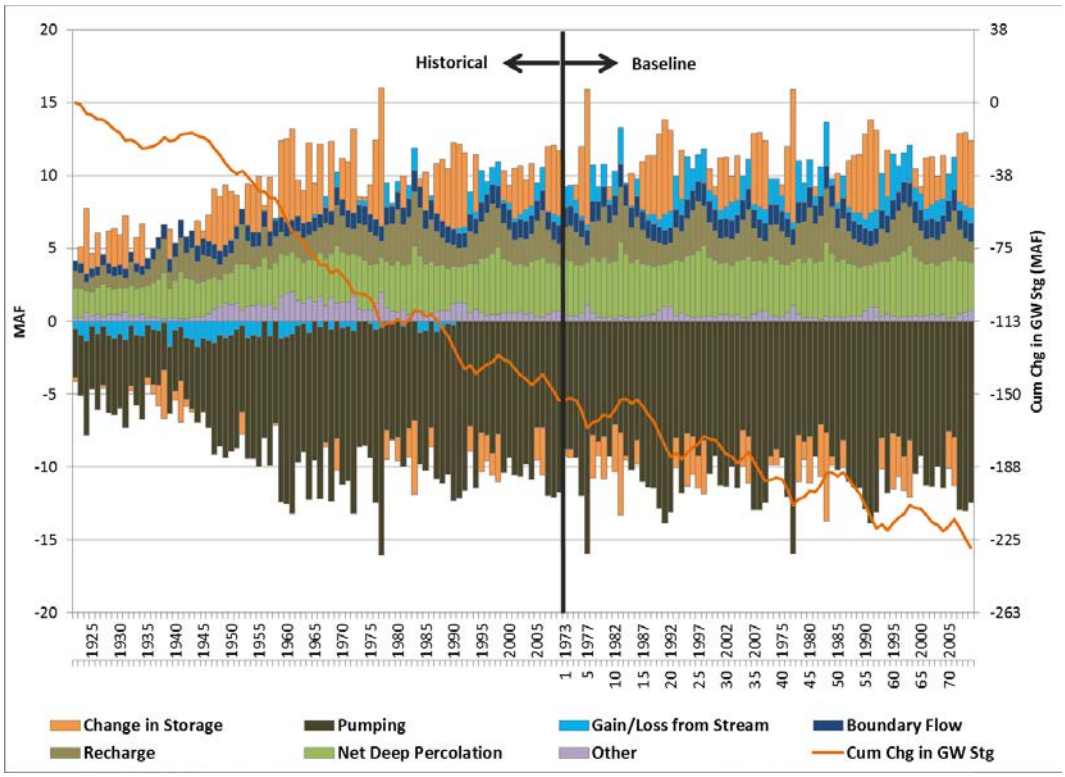


Figure 60 - Historic and Baseline Groundwater Budget - Central Valley

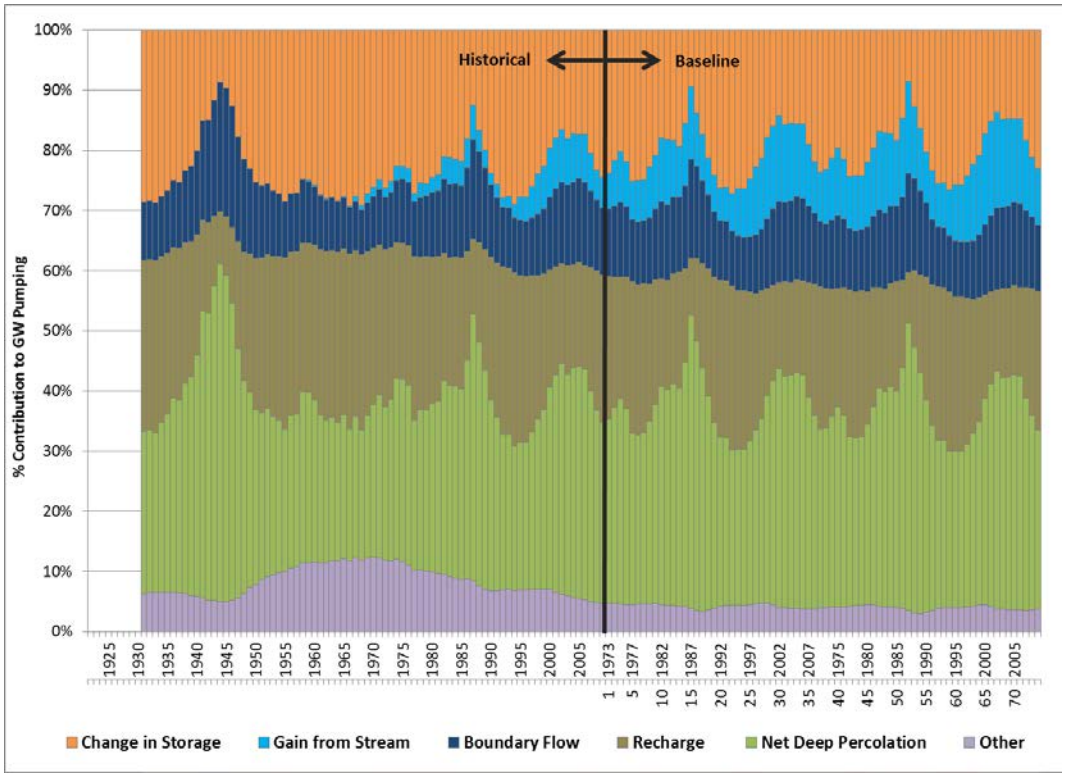


Figure 61 - Historic and Baseline Percent Contribution of Various Sources of Water to GW Pumping - Central Valley (10 Year Moving Average)

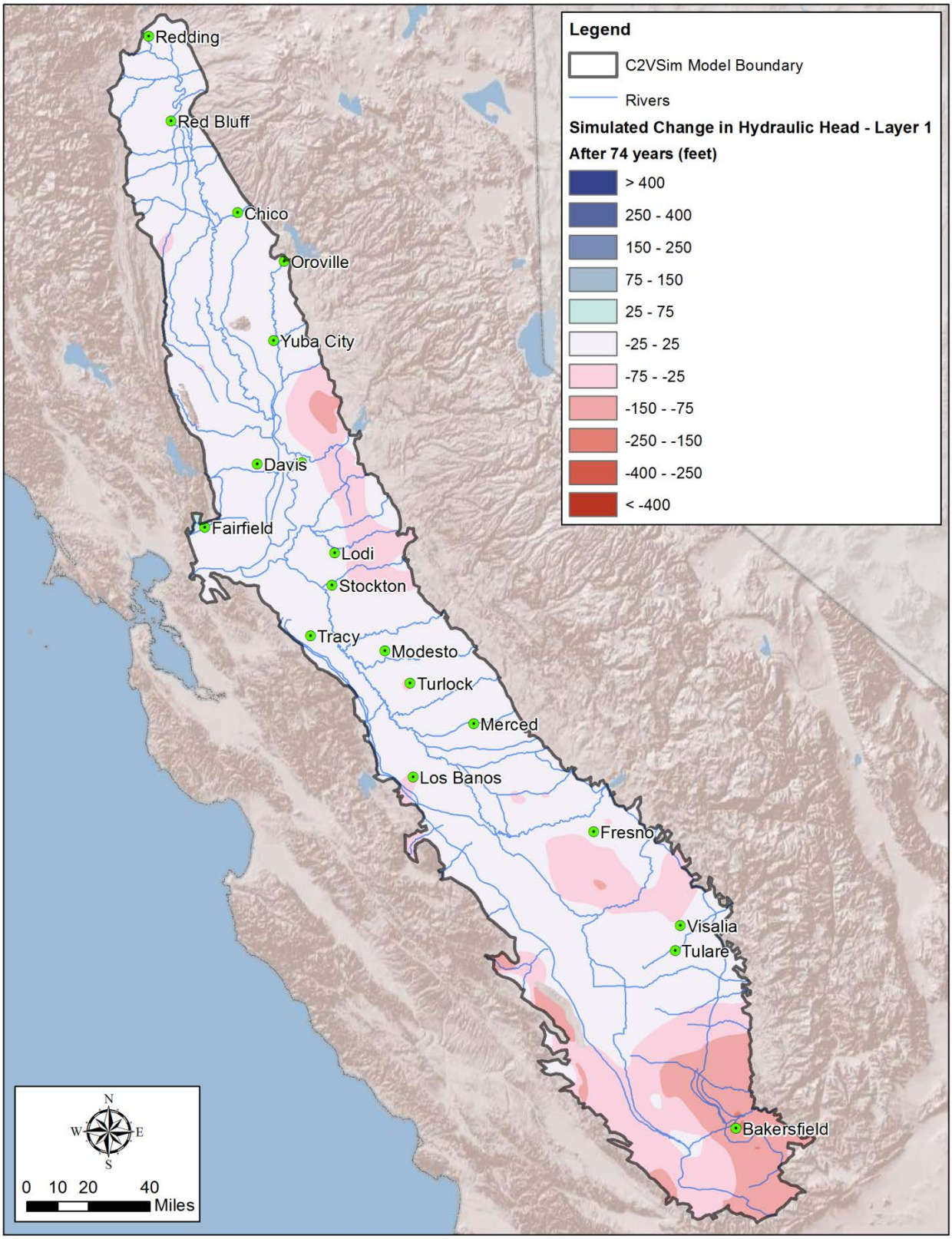


Figure 62 - Groundwater Level Differences if Current Management and Operational Conditions Continue for 74 Years Beginning in 2010 - Aquifer Layer 1 (Upper-most Aquifer Layer)

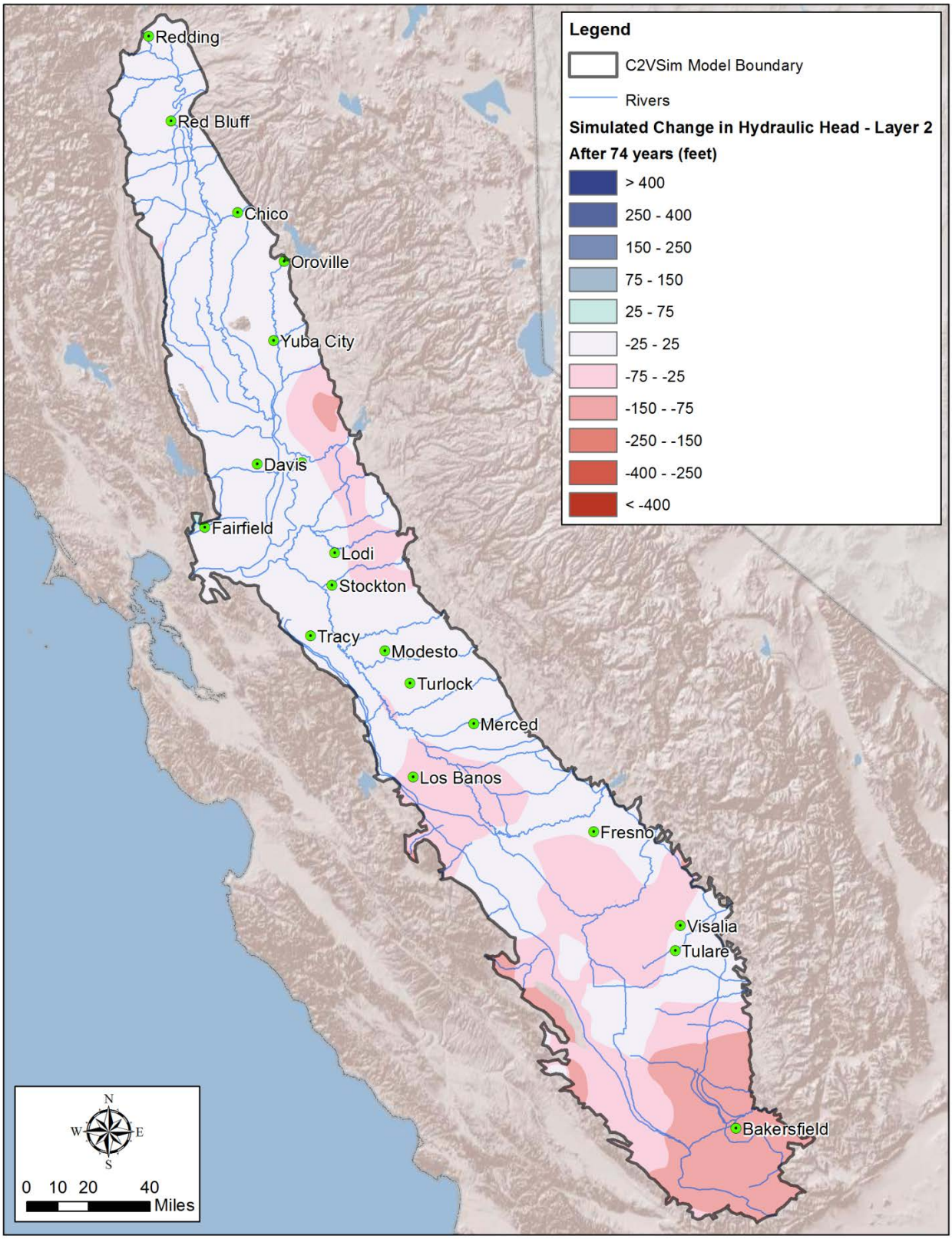


Figure 63 - Groundwater Level Differences if Current Management and Operational Conditions Continue for 74 Years Beginning in 2010 - Aquifer Layer2

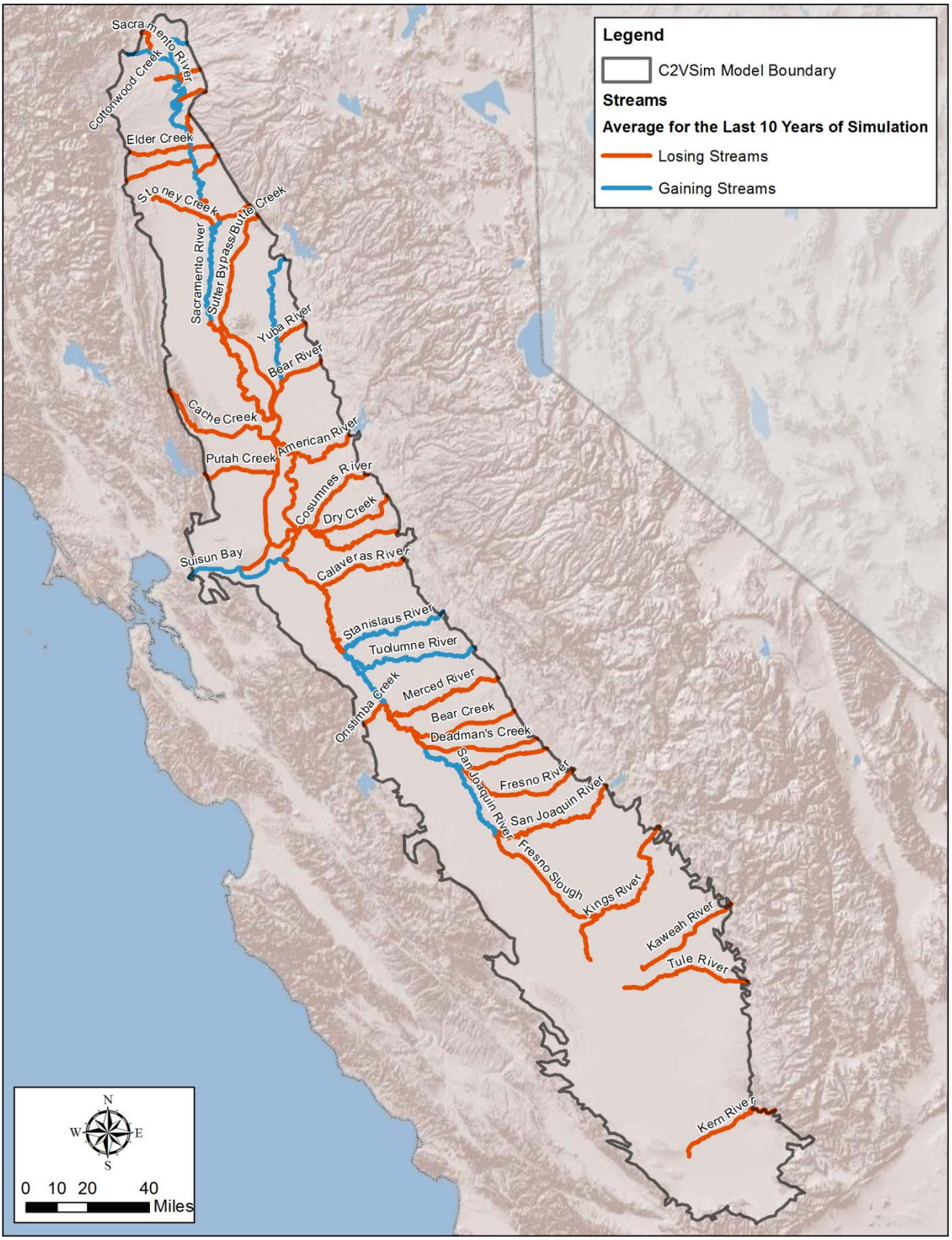


Figure 64 - Average Stream Gain Loss if Current Management and Operational Conditions Continue for 74 Years Beginning in 2010 – Last 10 Years of the Baseline Simulation

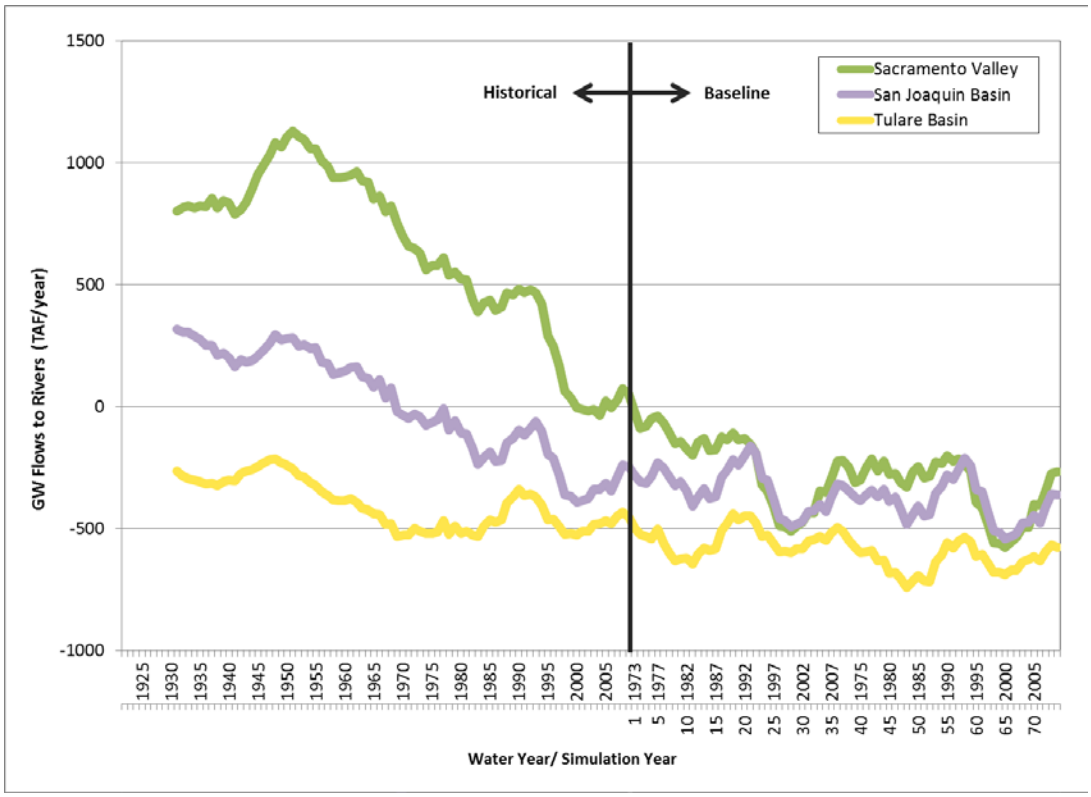


Figure 65 - Net Groundwater Discharge to Rivers if Current Management and Operational Conditions Continue for 74 Years Beginning in 2010 - 10 Year Moving Average

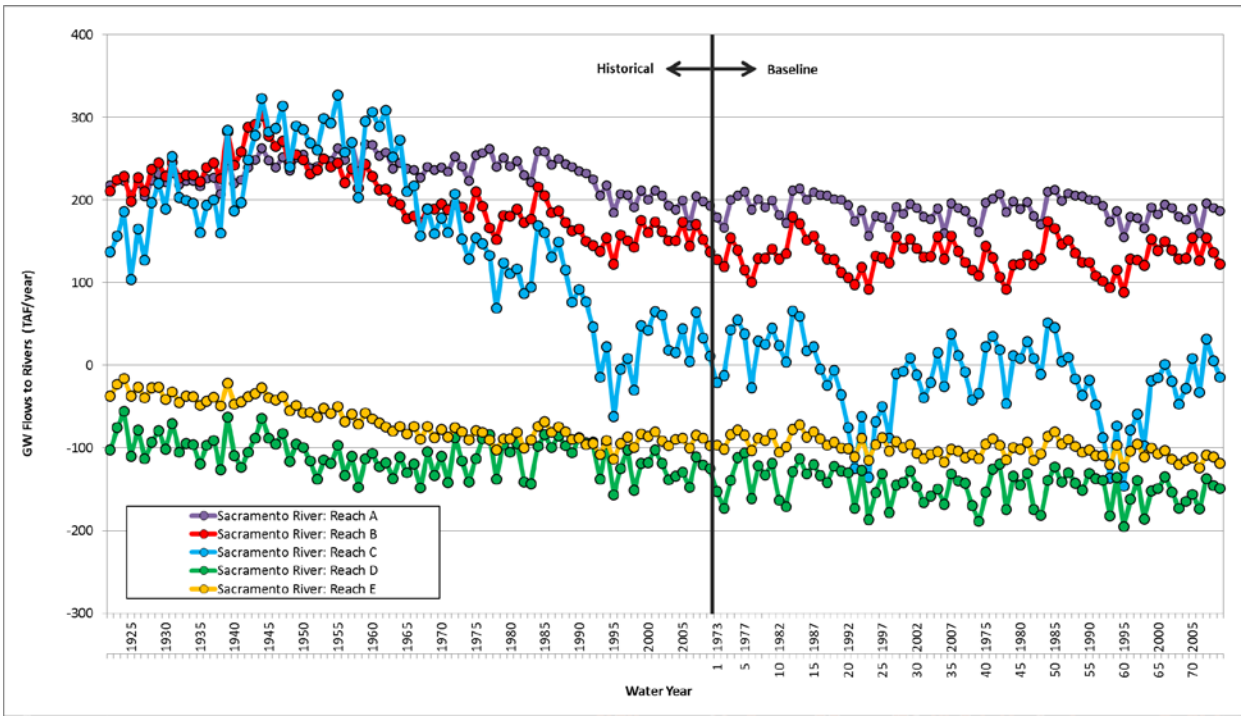


Figure 66 - Groundwater Flows to the Sacramento River if Current Management and Operational Conditions Continue for 74 Years Beginning in 2010

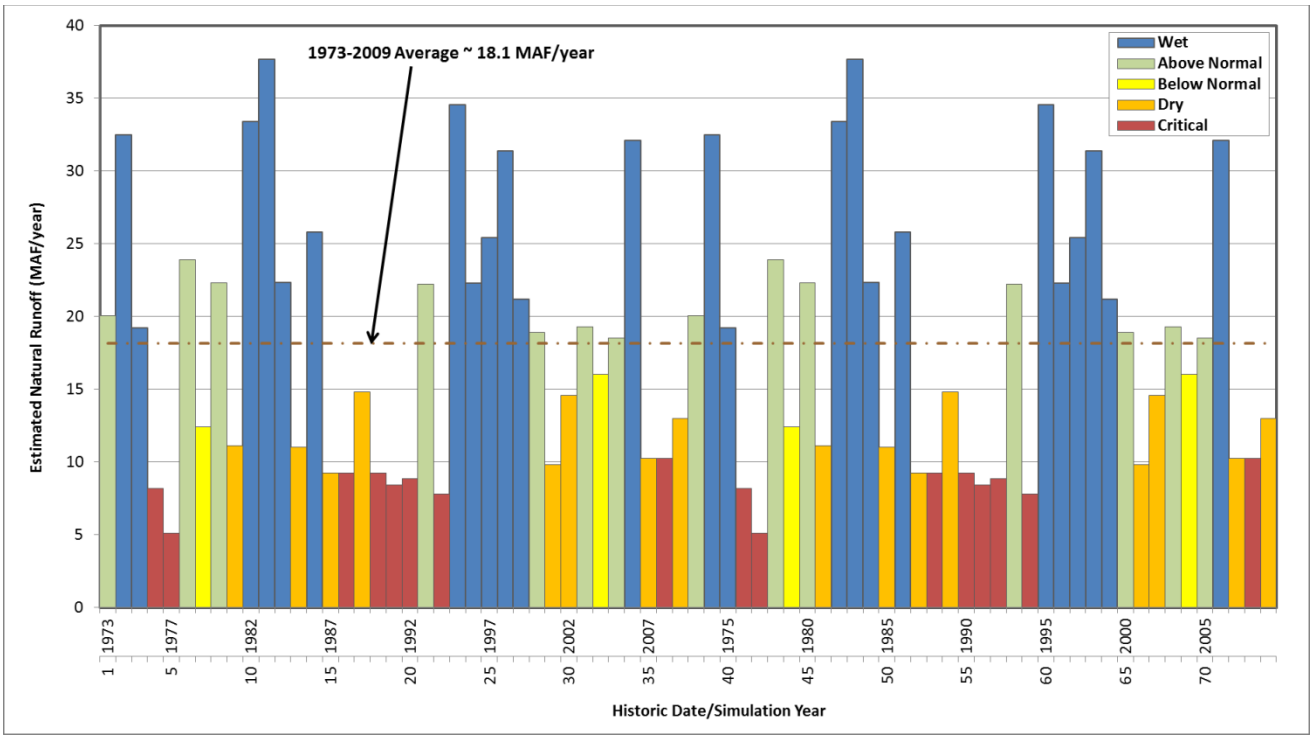


Figure 67 - Sacramento River Unimpaired Runoff and Sacramento Valley Water Year Hydrologic Classification for the EC BL and Scenarios

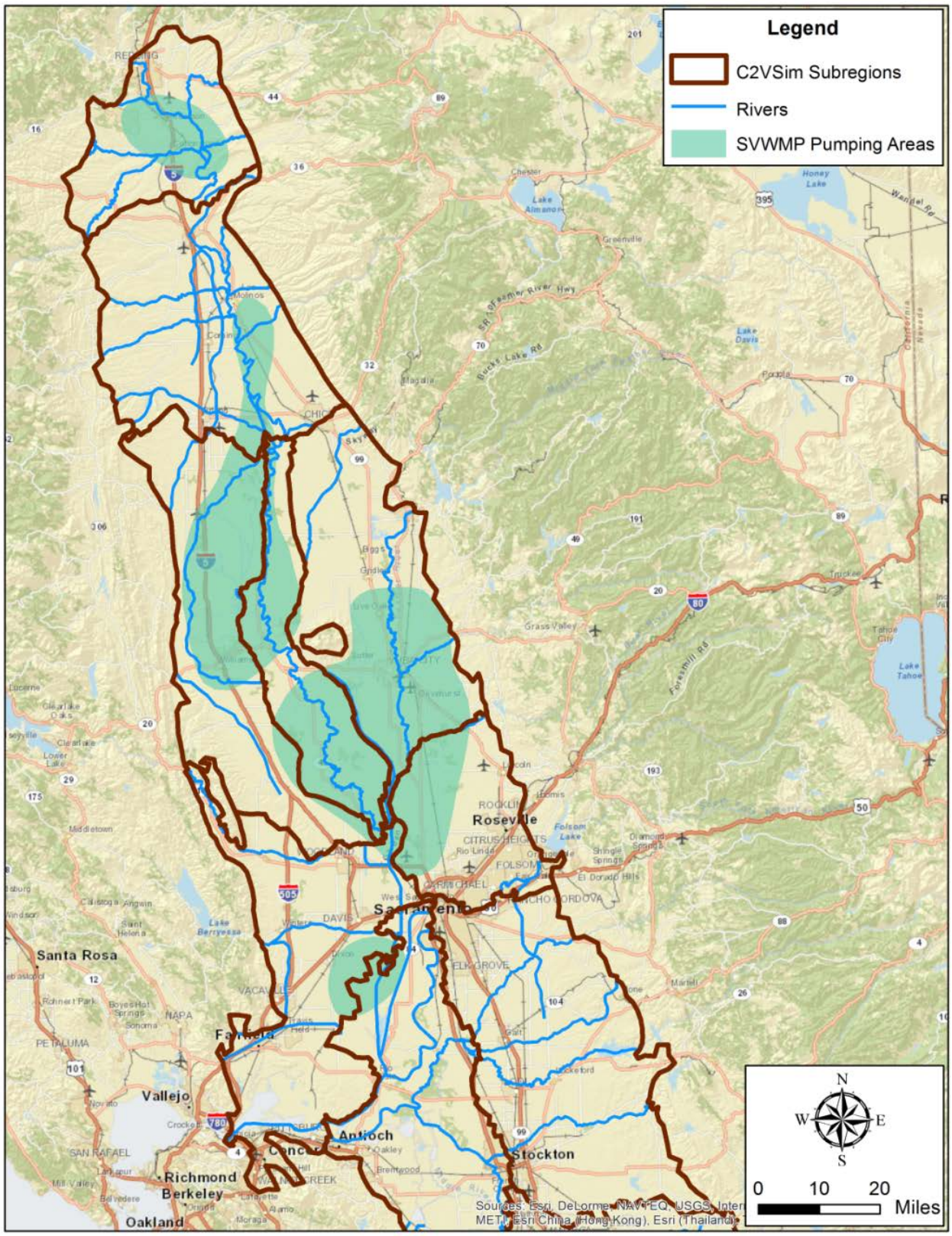


Figure 68 - Hypothetical Locations of Groundwater Pumping for the Groundwater Substitution Scenario

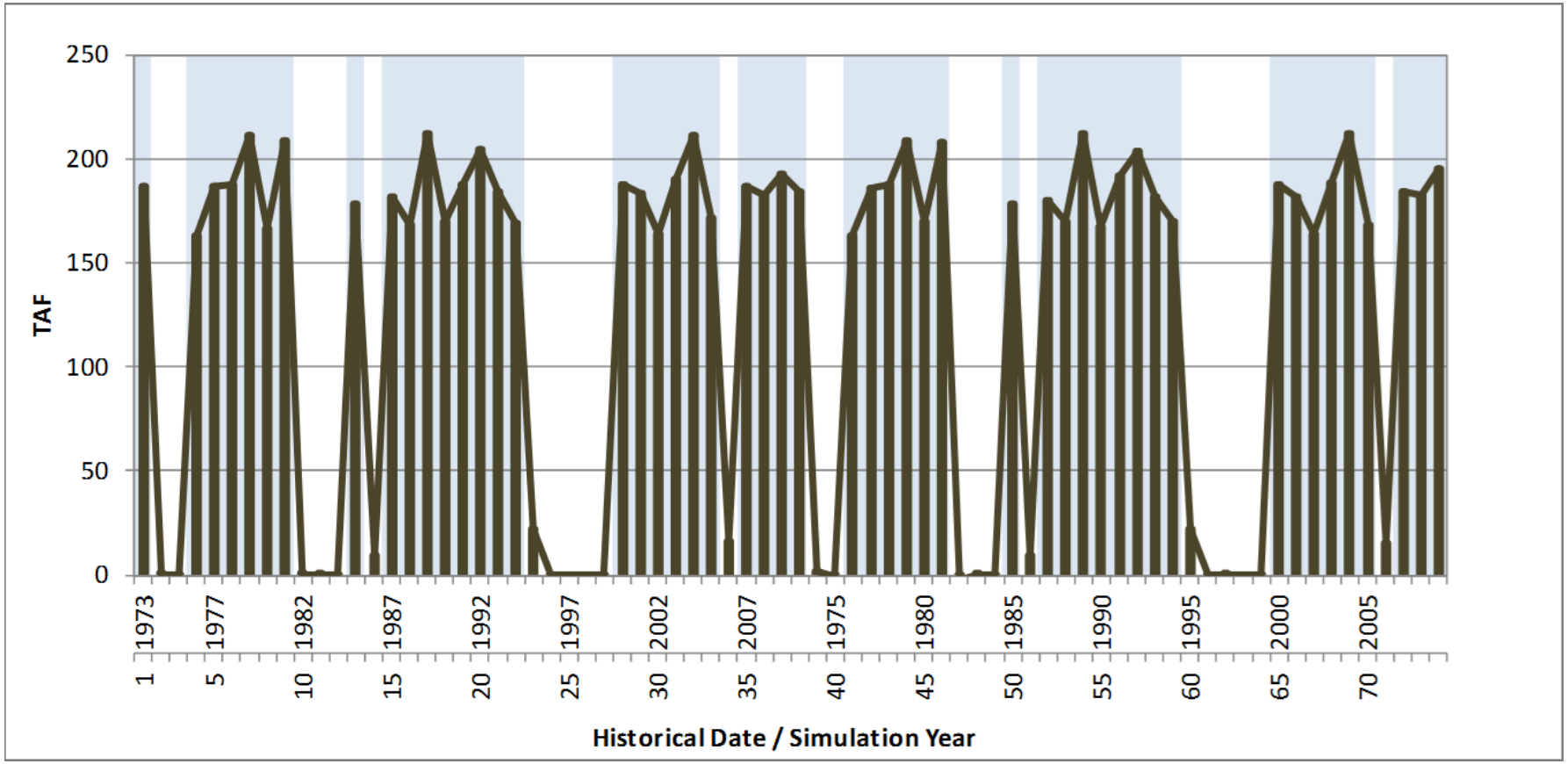


Figure 69 - Groundwater Substitution Program Transfer/Pumping Schedule

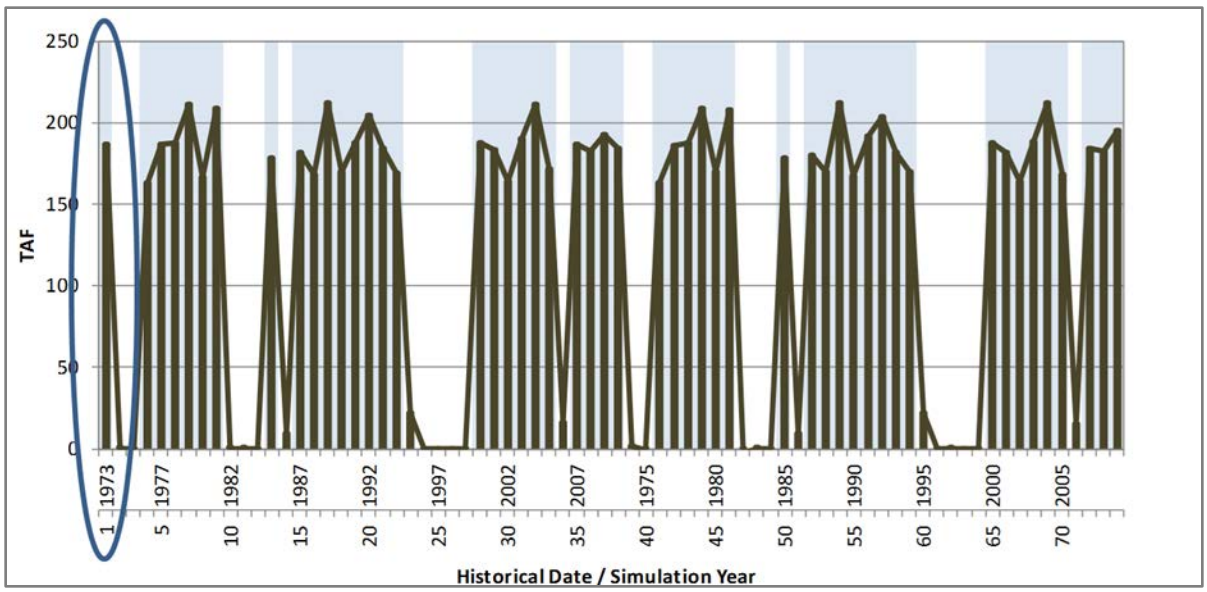


Figure 70 - Scenario 1a - Short Project Transfer/Pumping Schedule

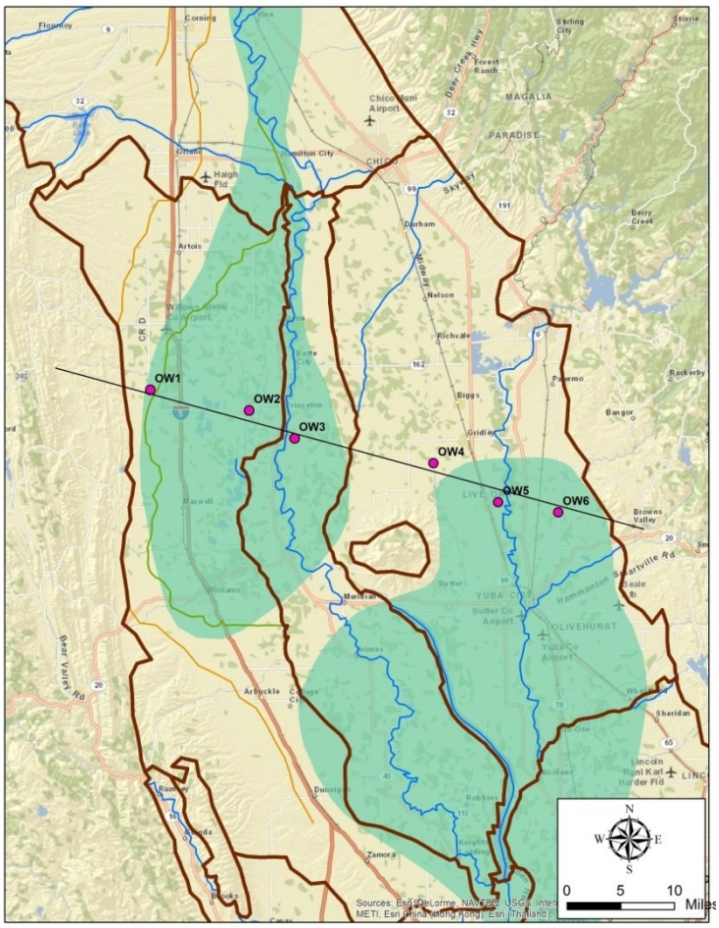


Figure 71 - Location of Groundwater Level Difference Hydrographs for Scenario 1 (Groundwater Substitution)

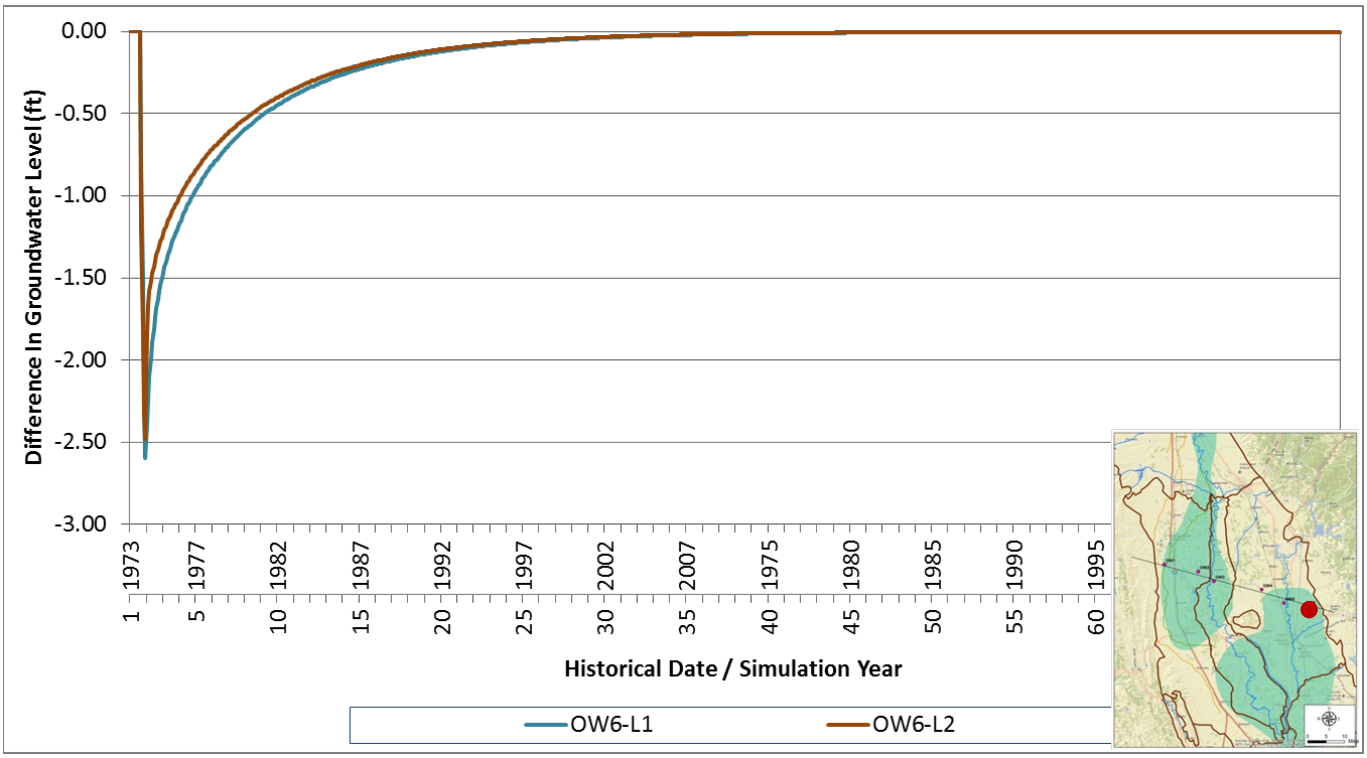


Figure 72 - Change in Groundwater Levels for Scenario 1a (Short Groundwater Substitution) Compared to Baseline away from the Sacramento River

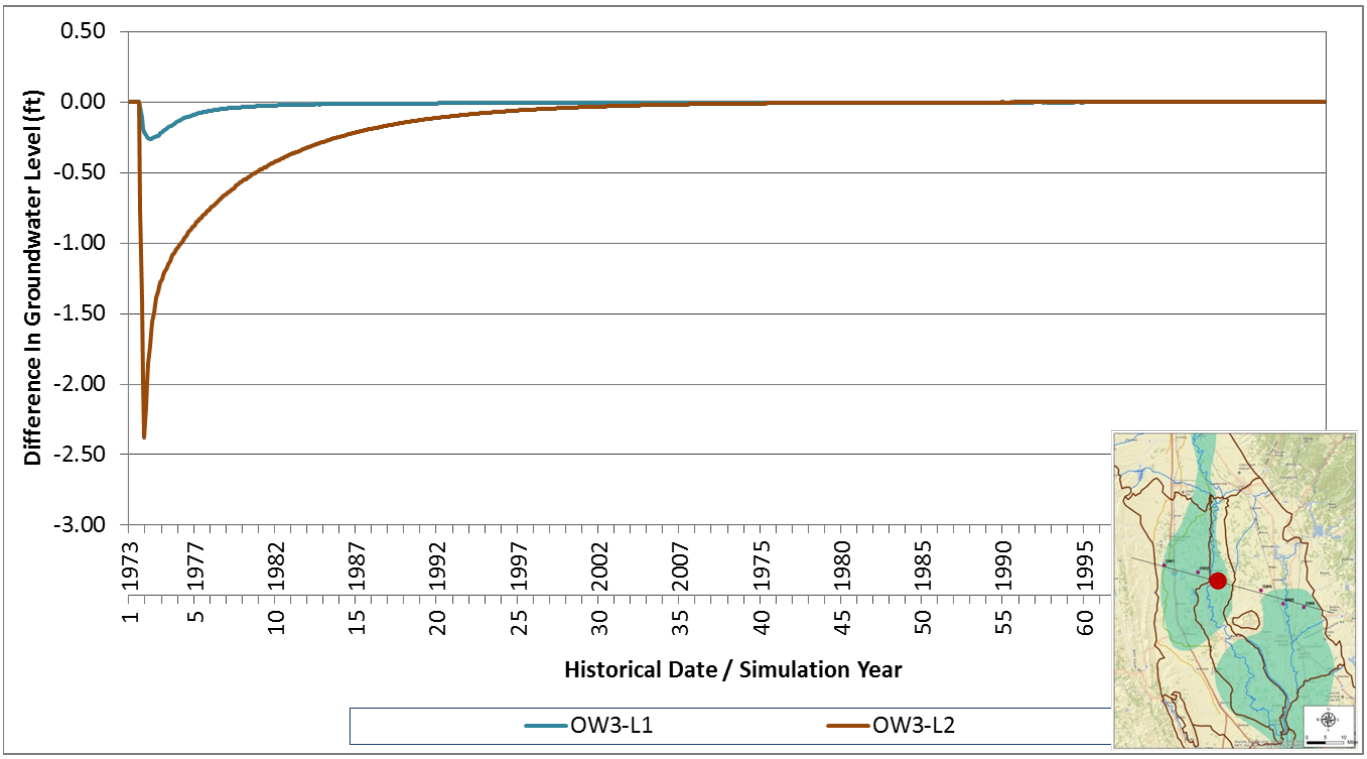


Figure 73 - Change in Groundwater Levels for Scenario 1a (Short Groundwater Substitution) Compared to Baseline close to the Sacramento River

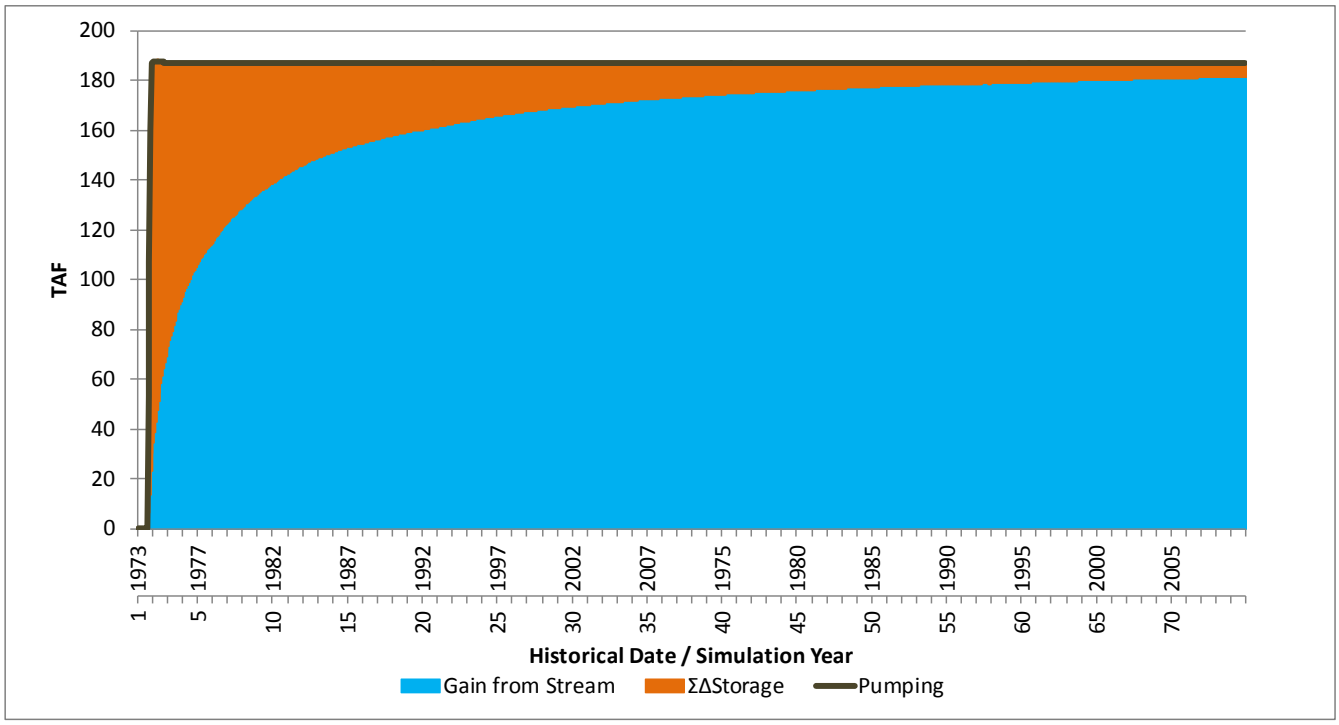


Figure 74 - Cumulative Change in Groundwater Budget for Scenario 1a (Short Groundwater Substitution) Compared to Baseline

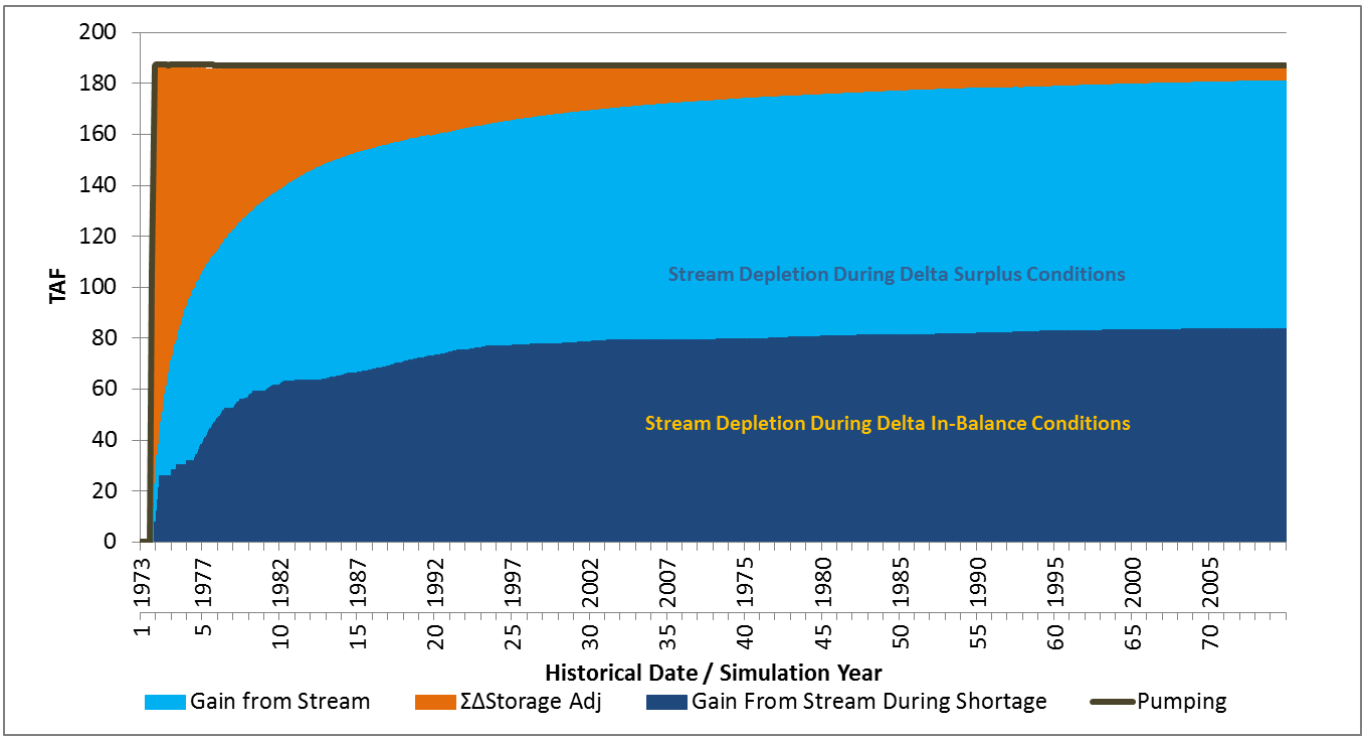


Figure 75 - Stream Depletion during Delta Surplus and In-Balance Conditions for Scenario 1a (Short Groundwater Substitution) Compared to Baseline

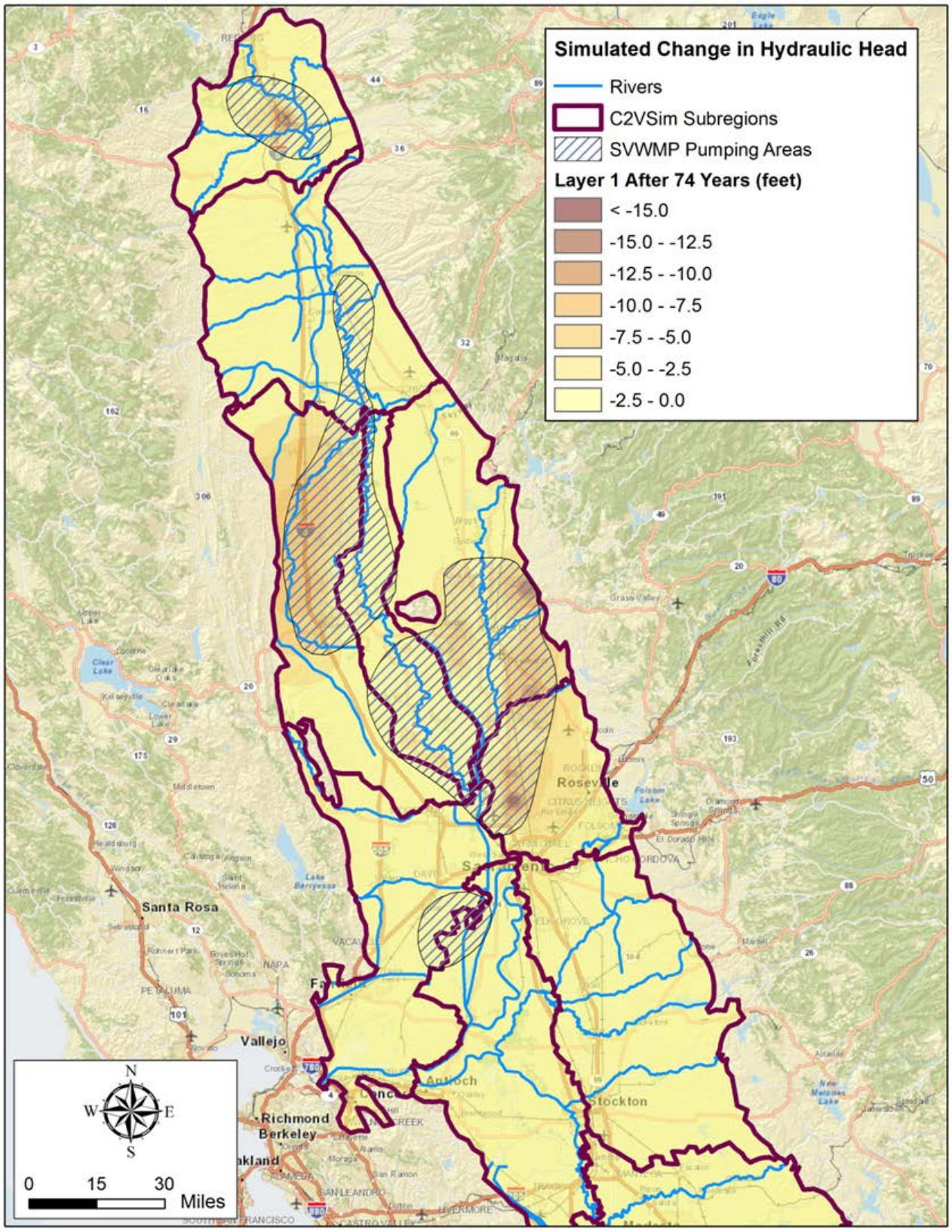


Figure 76 - Change in Groundwater Levels for Scenario 1b (Full Groundwater Substitution) Compared to Baseline at the End of Simulation - Aquifer Layer 1 (Upper-most Aquifer Layer)

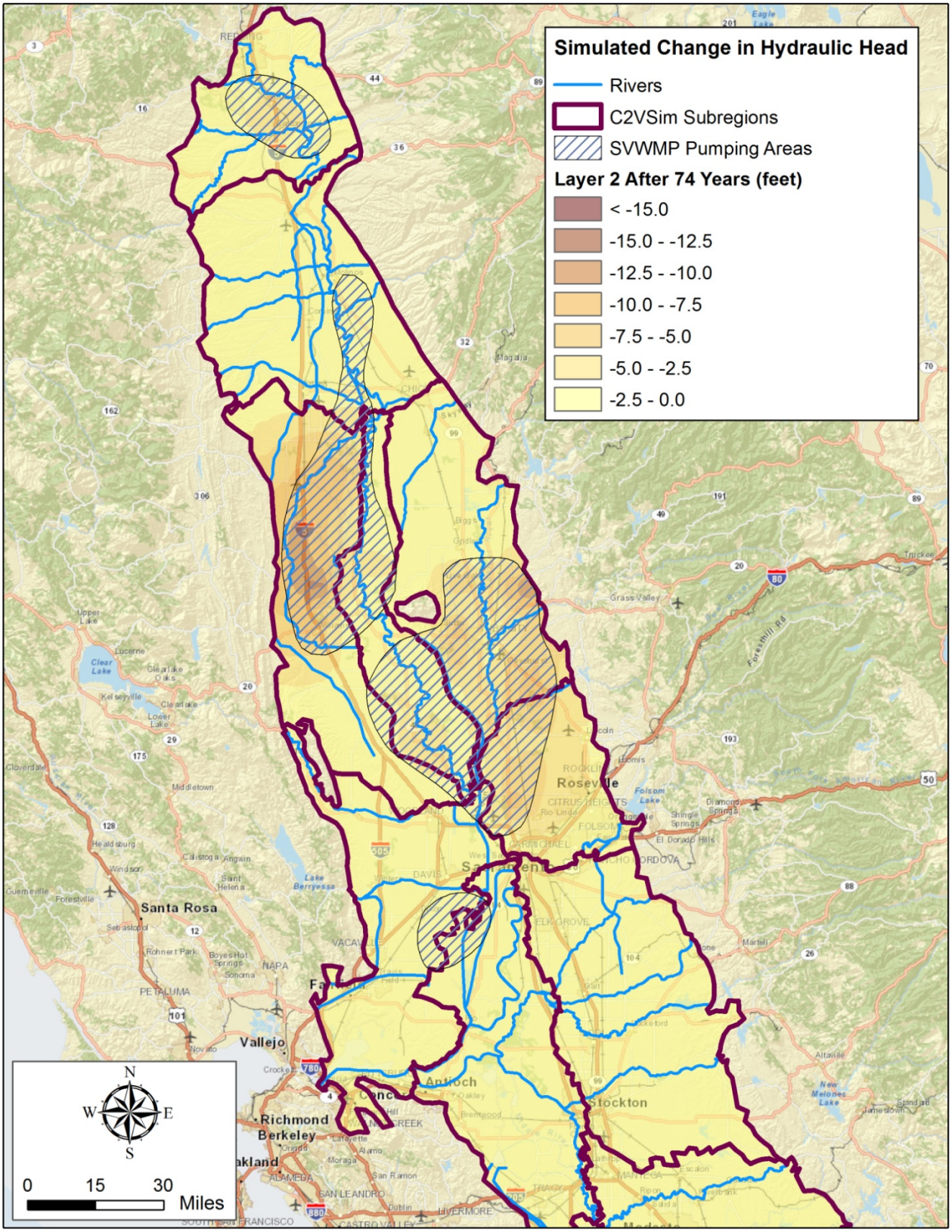


Figure 77 - Change in Groundwater Levels for Scenario 1b (Full Groundwater Substitution) Compared to Baseline at the End of Simulation - Aquifer Layer 2

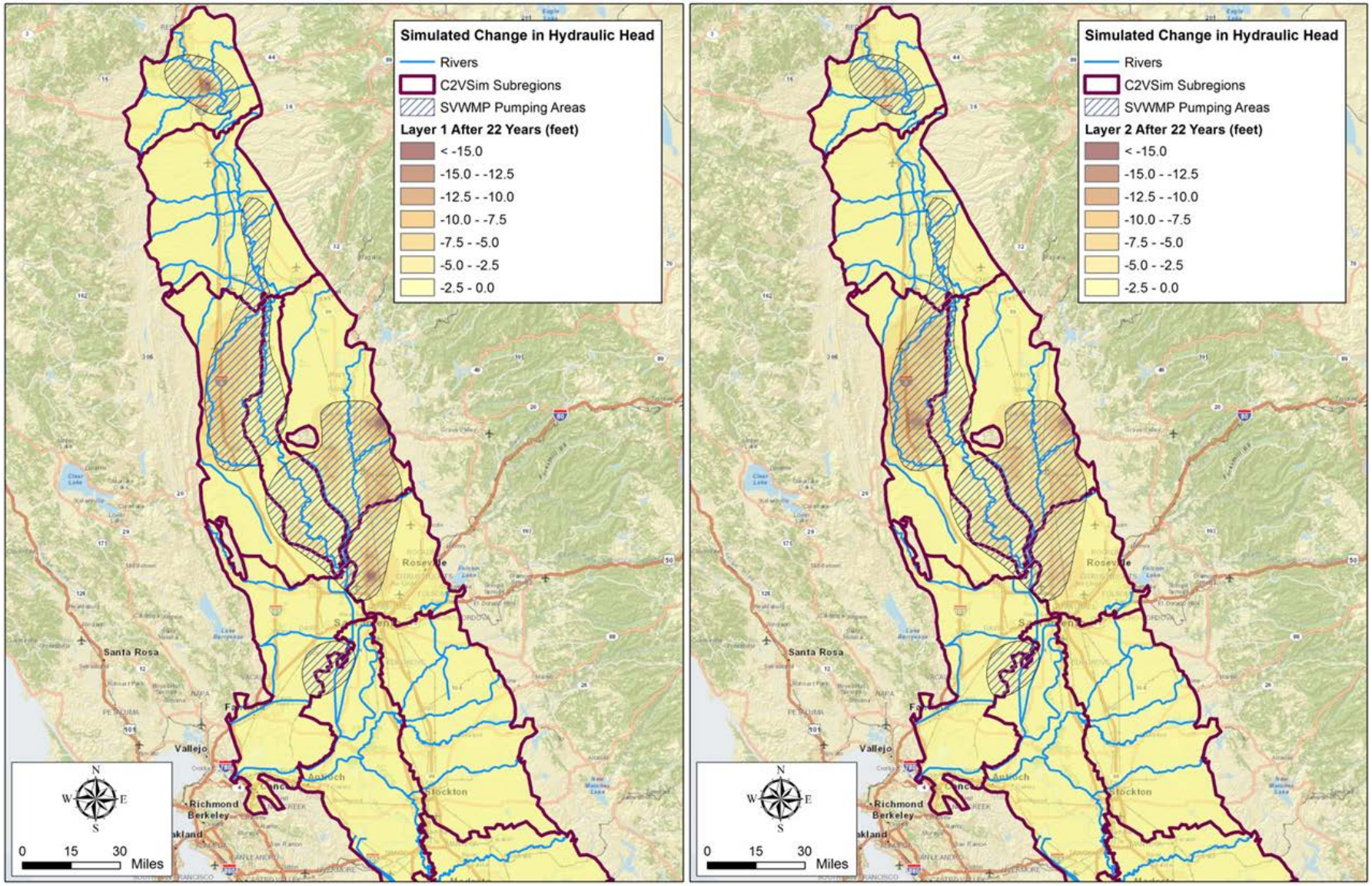


Figure 78 - Change in Groundwater Levels for Scenario 1b (Full Groundwater Substitution) Compared to Baseline after Simulation Year 22 - End of First Long Term Pumping Cycle

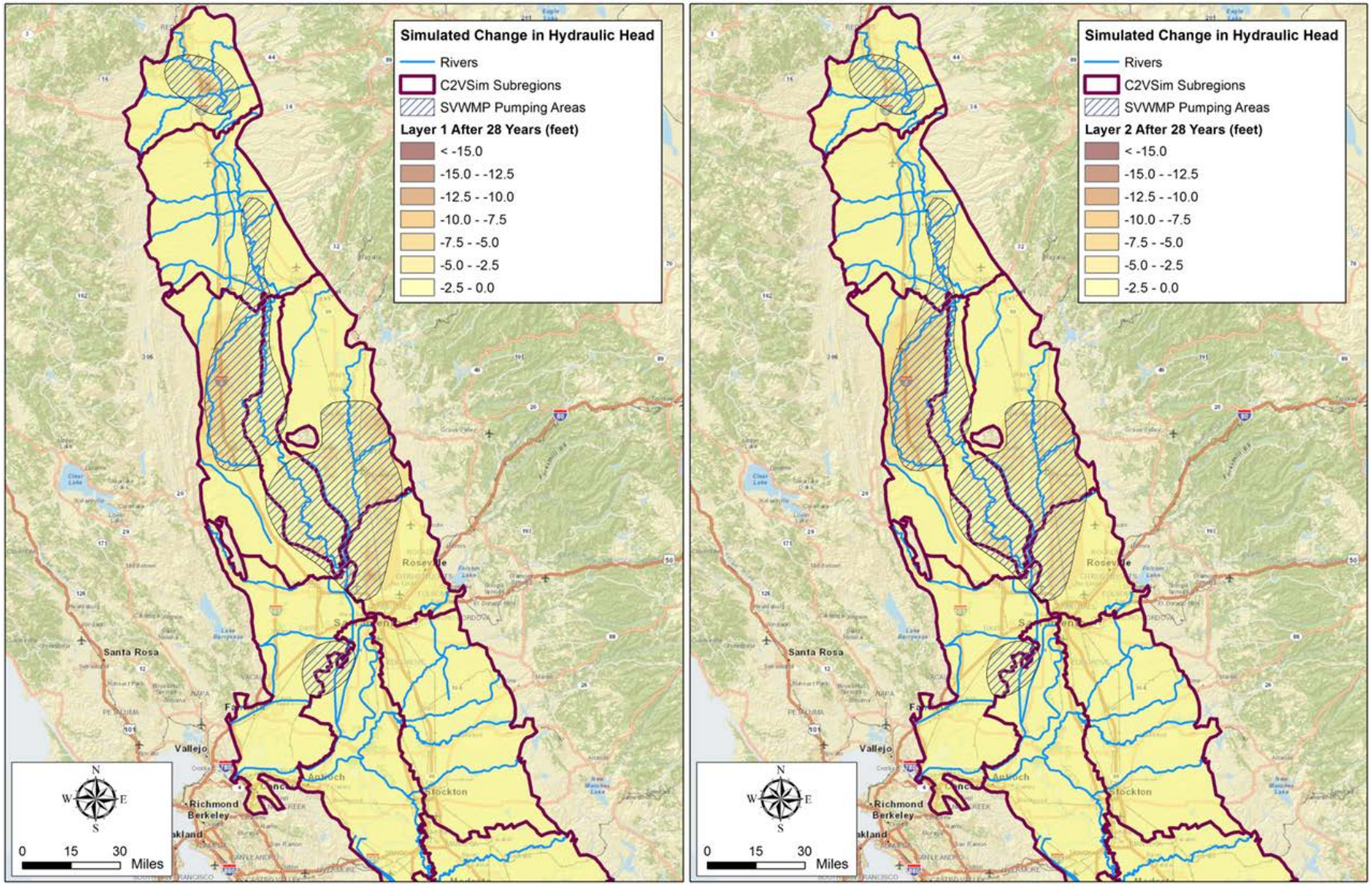


Figure 79 - Change in Groundwater Levels for Scenario 1b (Full Groundwater Substitution) Compared to Baseline after Simulation Year 28 - Beginning of Second Long Term Pumping Cycle

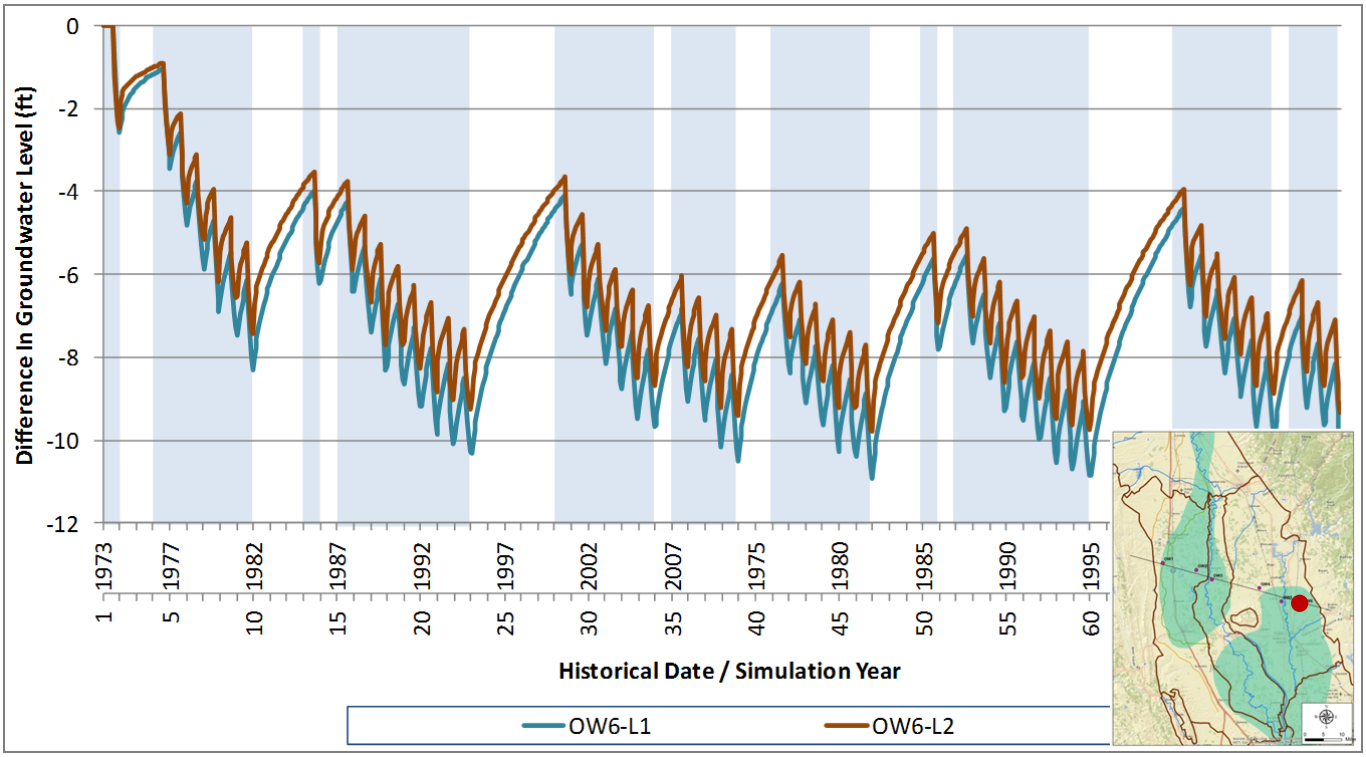


Figure 80 - Change in Groundwater Levels for Scenario 1b (Full Groundwater Substitution) Compared to Baseline away from the Sacramento River

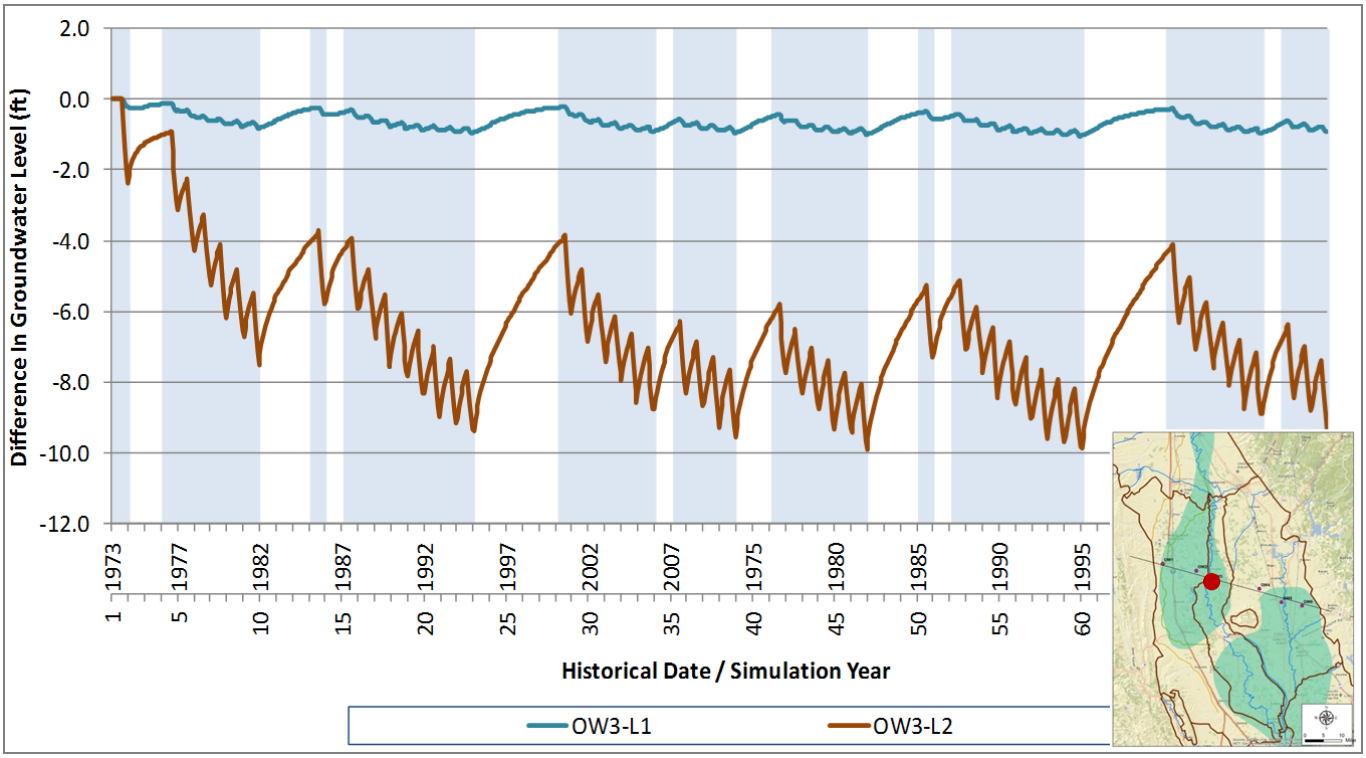


Figure 81 - Change in Groundwater Levels for Scenario 1b (Full Groundwater Substitution) Compared to Baseline close to the Sacramento River

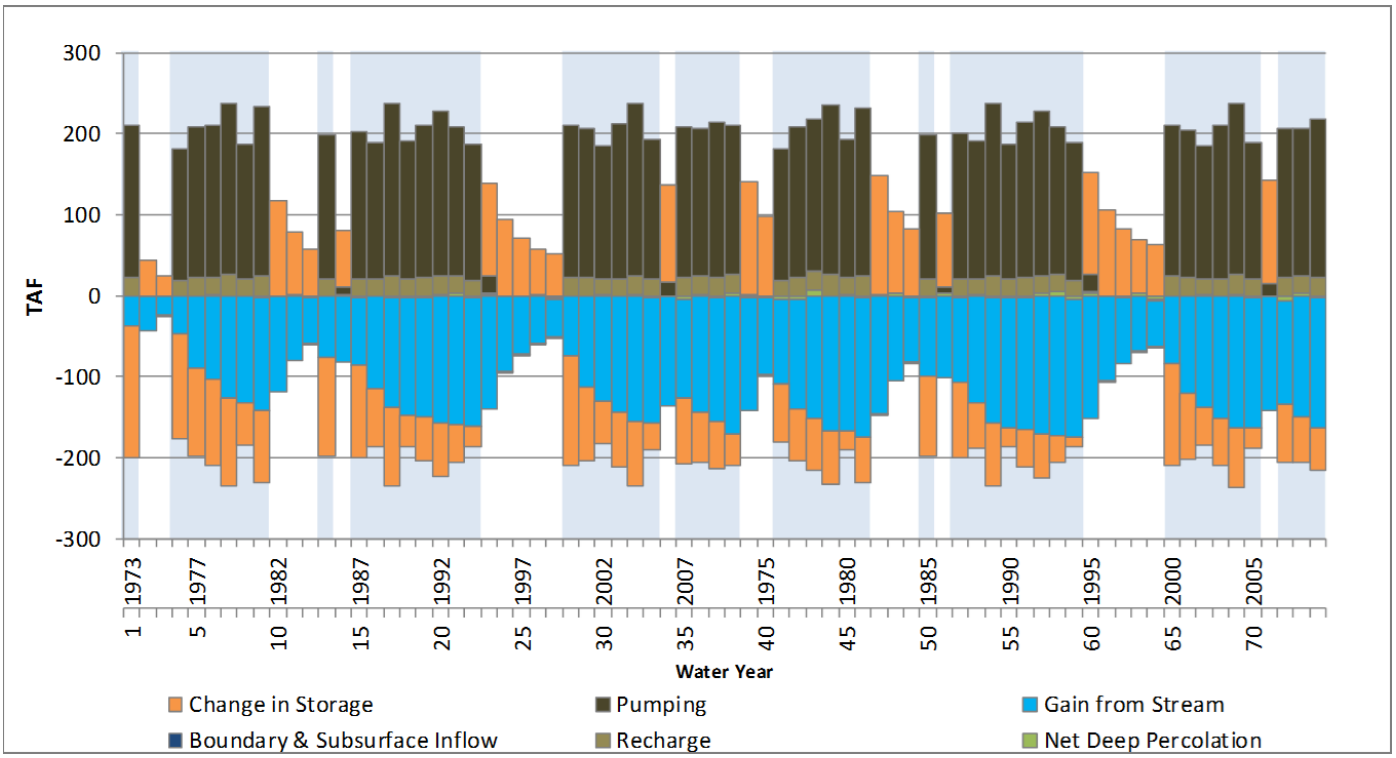


Figure 82 - Change in Groundwater Budget for Scenario 1b (Full Groundwater Substitution) Compared to Baseline

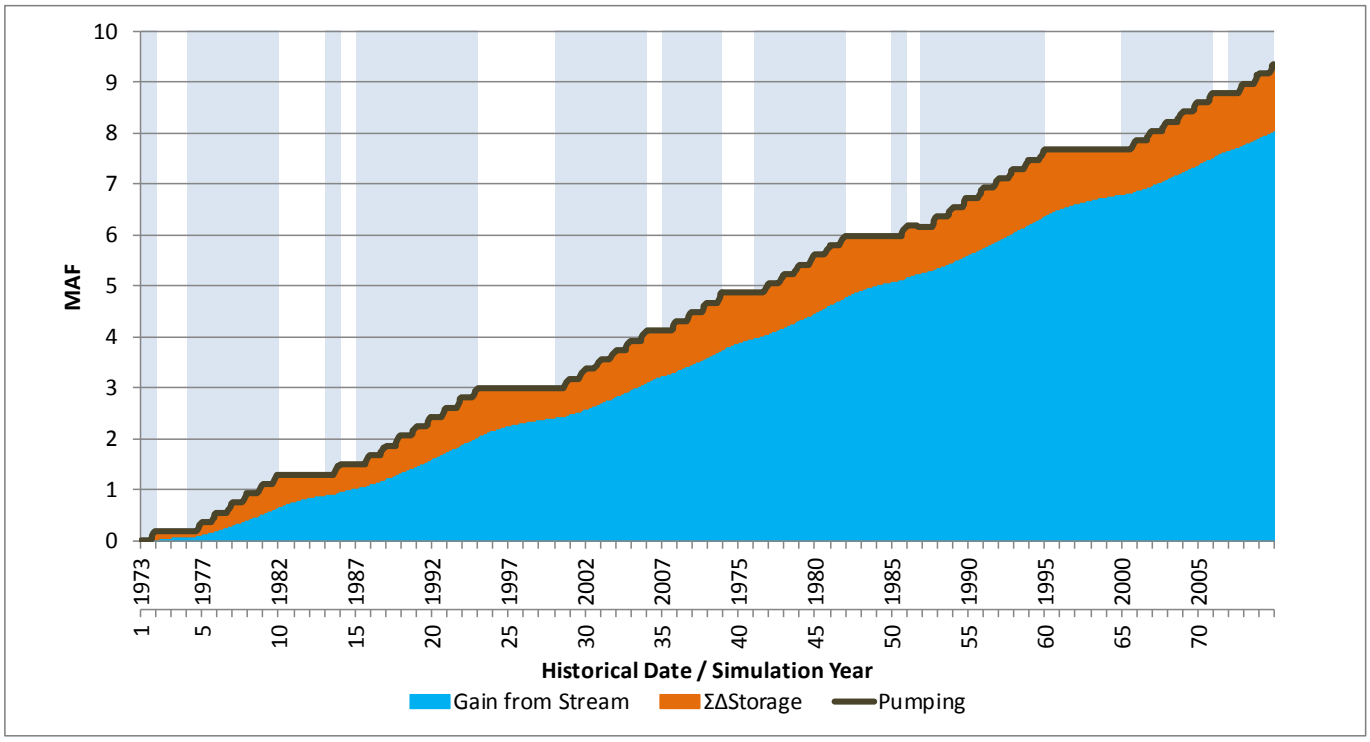


Figure 83 - Cumulative Contribution of Gain from Stream and Groundwater Storage for the Pumping for Scenario 1b (Full Groundwater Substitution) Compared to Baseline

Figure 84 - Overall Change in Stream and Groundwater Budget for Scenario 1b (Full Groundwater Substitution) Compared to Baseline

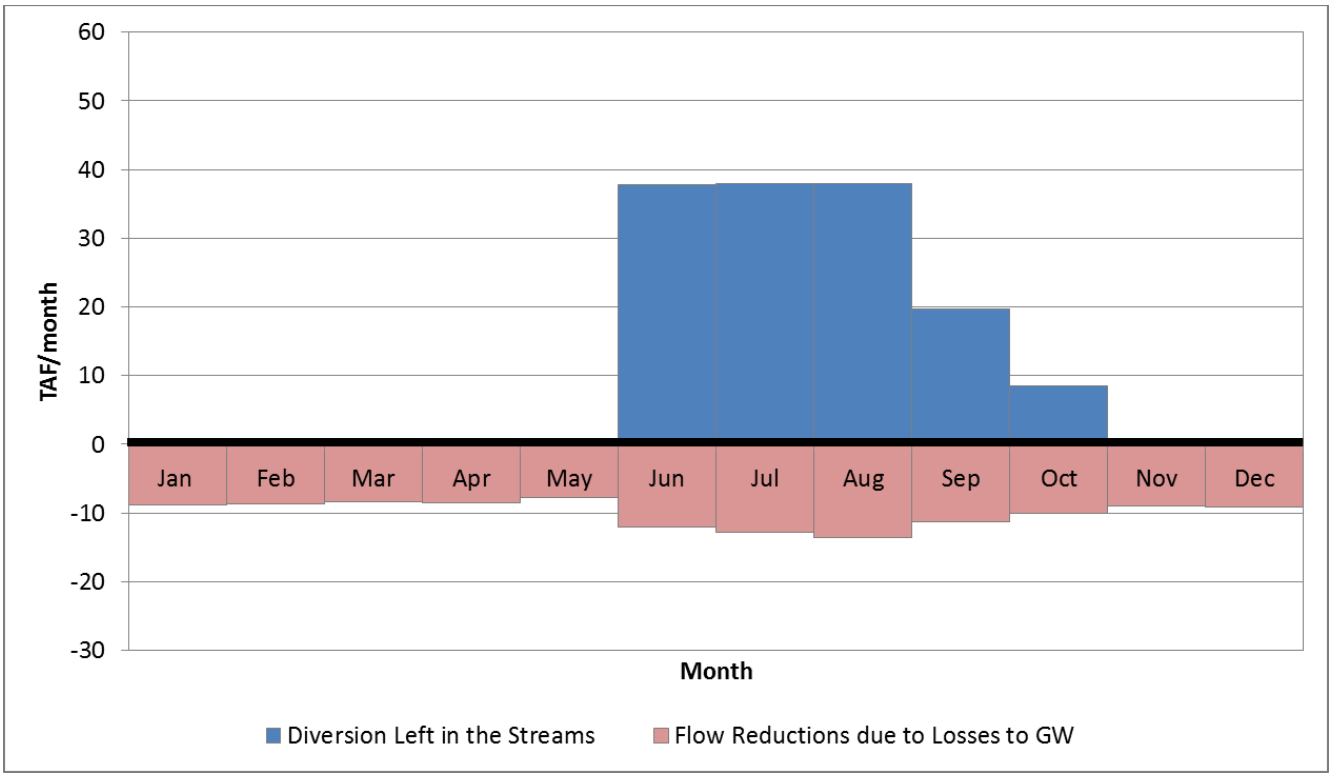


Figure 85 - Monthly Change in Stream Budget for Scenario 1b (Full Groundwater Substitution) Compared to Baseline – Average over the Whole Simulation Period

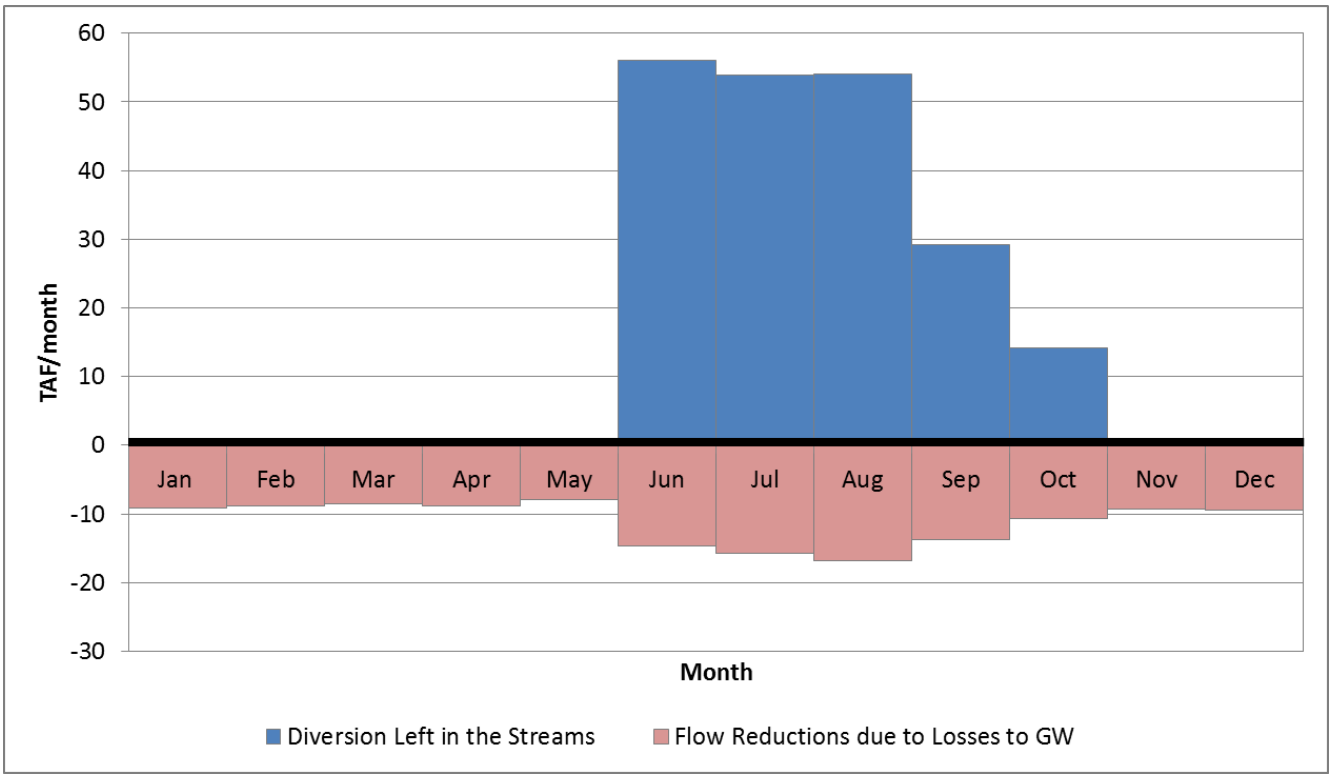


Figure 86 - Monthly Change in Stream Budget for Scenario 1b (Full Groundwater Substitution) Compared to Baseline – Average over the Transfer Years

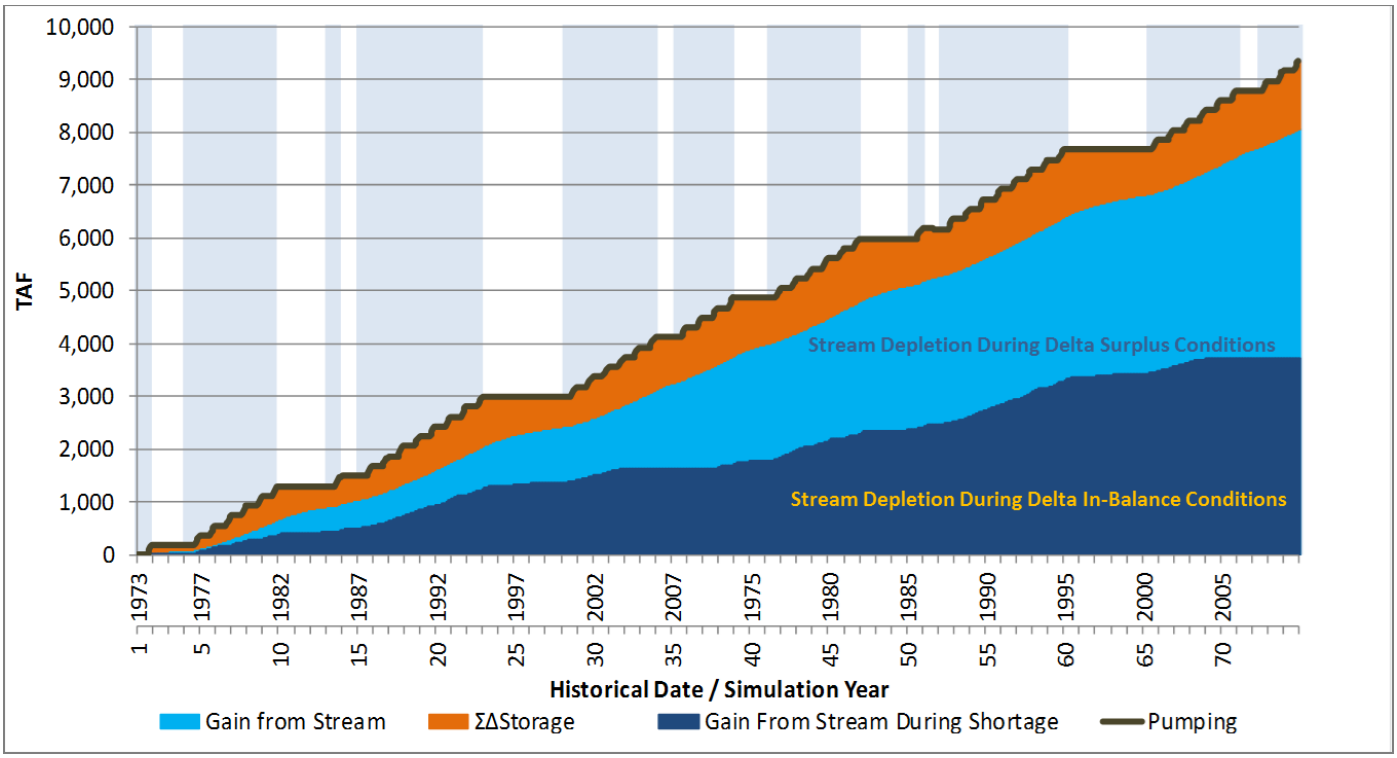


Figure 87 - Stream Depletion during Delta Surplus and In-Balance Conditions for Scenario 1b (Full Groundwater Substitution) Compared to Baseline

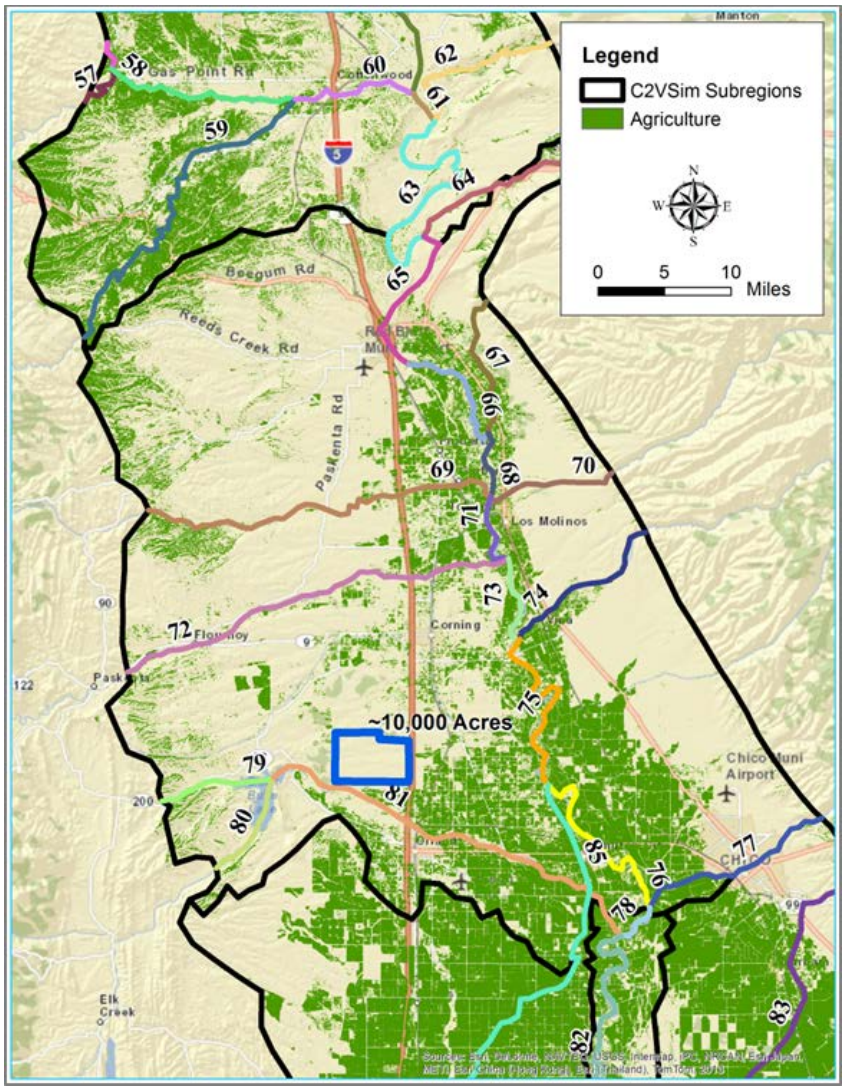


Figure 88 - Location of the Hypothetical Agricultural Land Development for Scenario 2 (Increased Agricultural Demand)

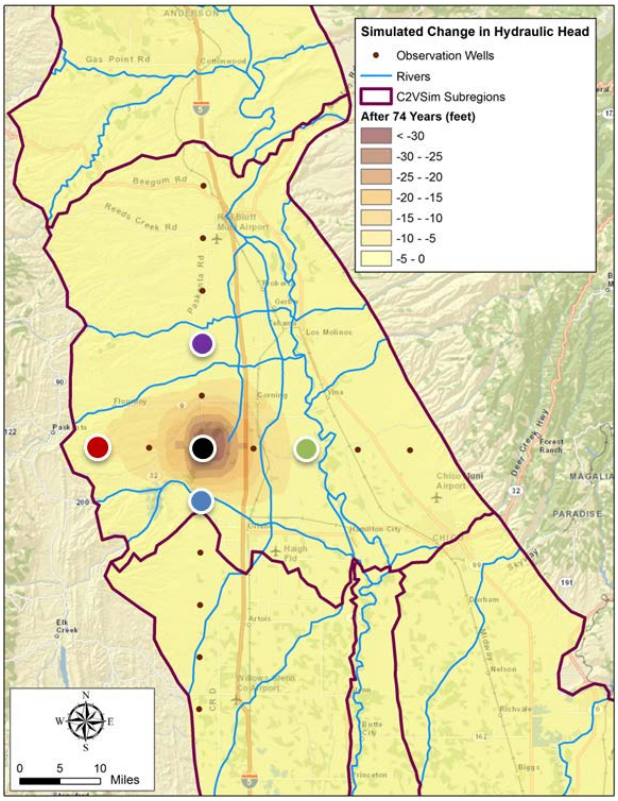


Figure 89 - Location of Groundwater Level Difference Hydrographs for Scenario 2 (Increased Agricultural Demand)

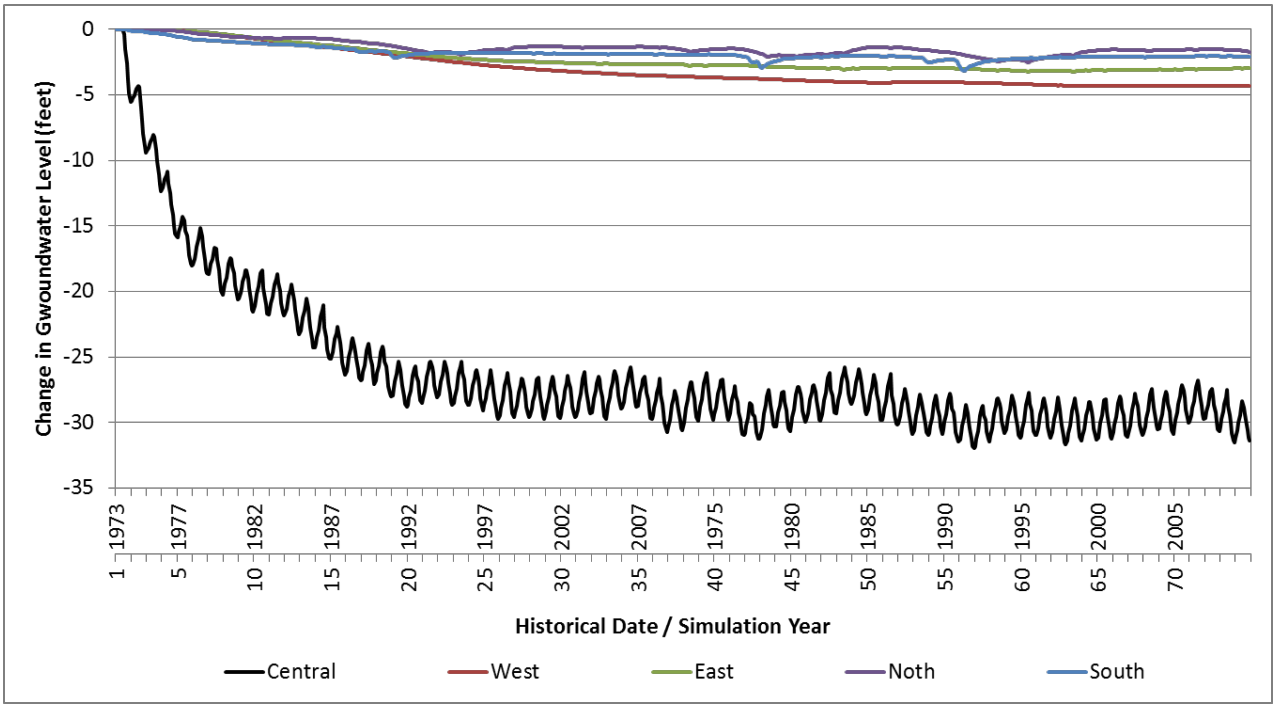


Figure 90 - Change in Groundwater Levels for Scenario 2 (Increased Agricultural Demand) Compared to Baseline

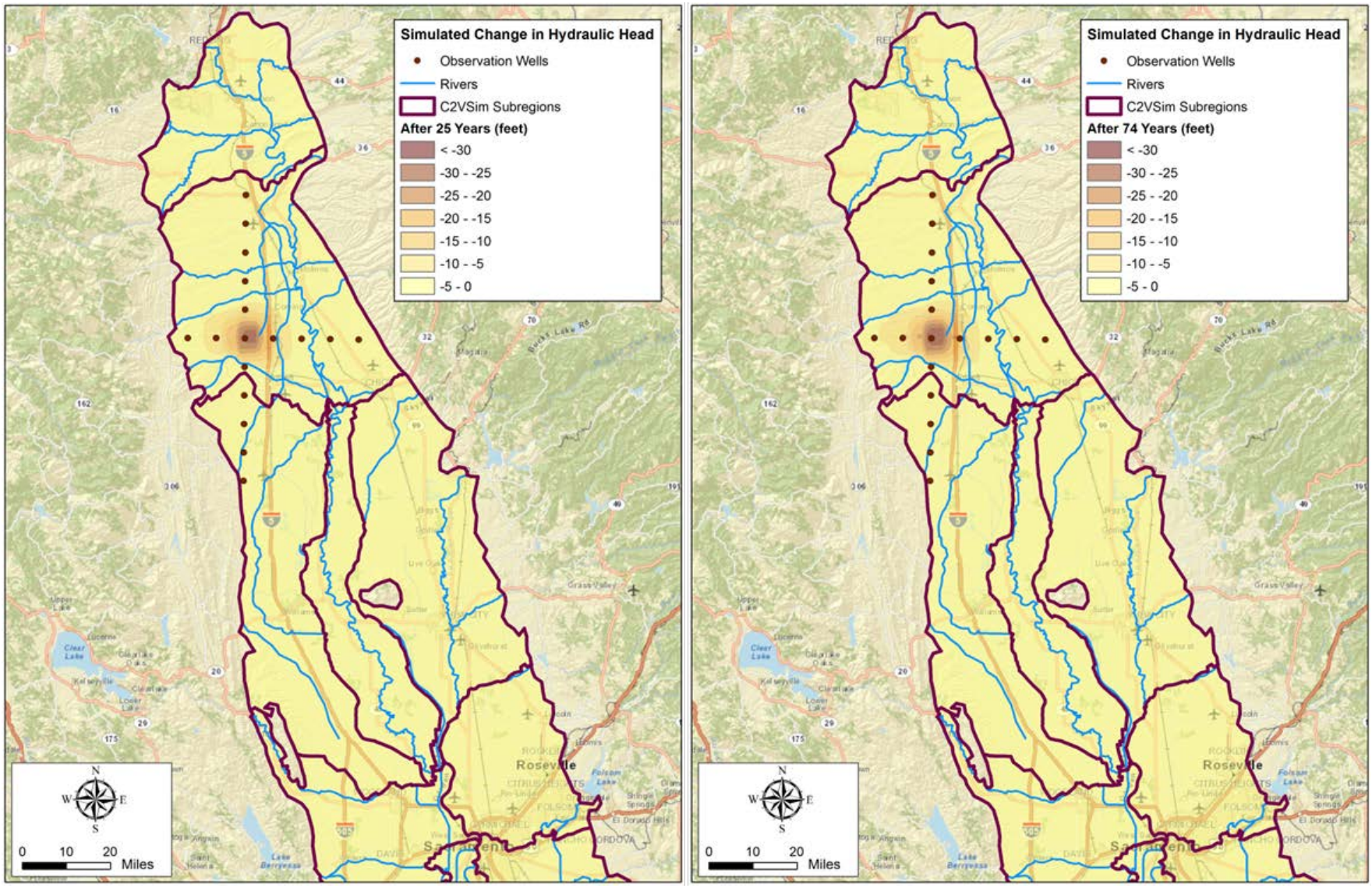


Figure 91 - Change in Groundwater Levels for Scenario 2 (Increased Agricultural Demand) Compared to Baseline after Simulation Year 25 at the and End of Simulation

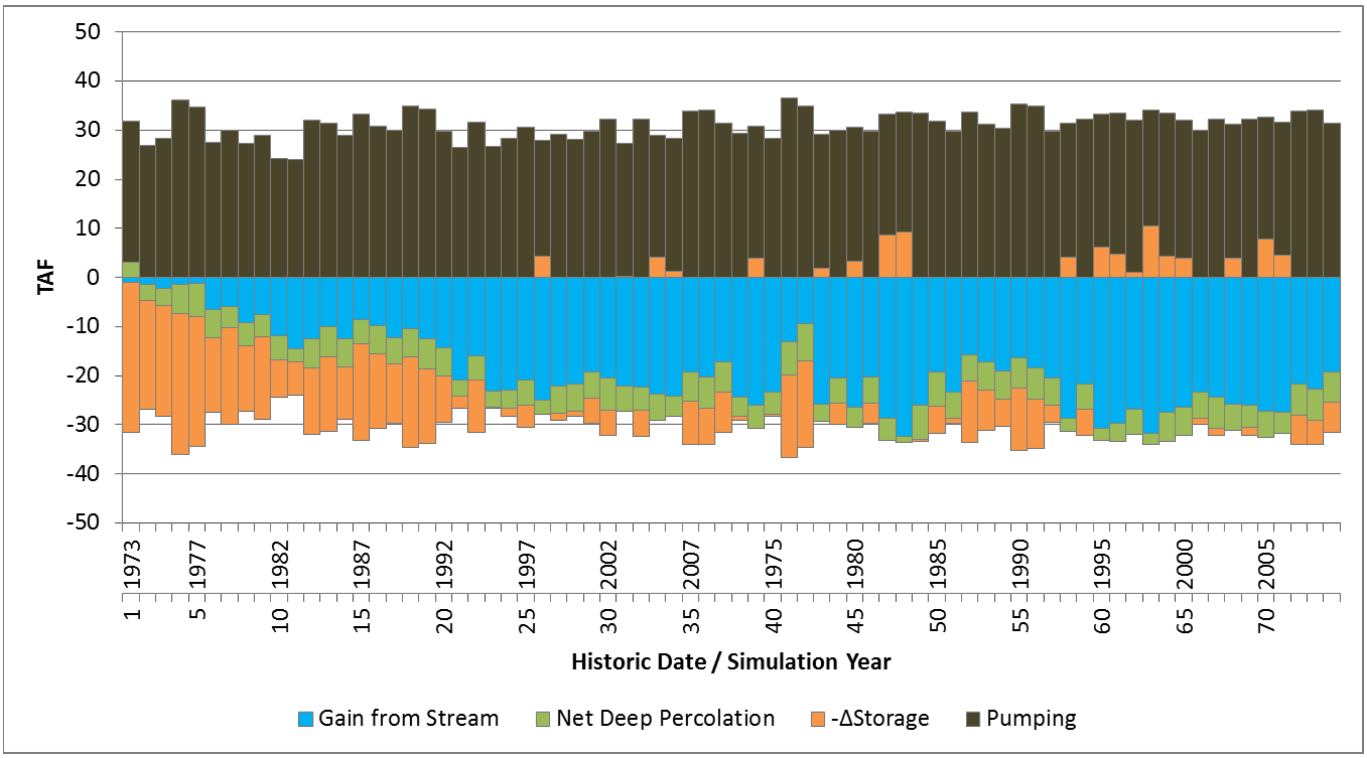


Figure 92 - Change in Groundwater Budget for Scenario 2 (Increased Agricultural Demand) Compared to Baseline

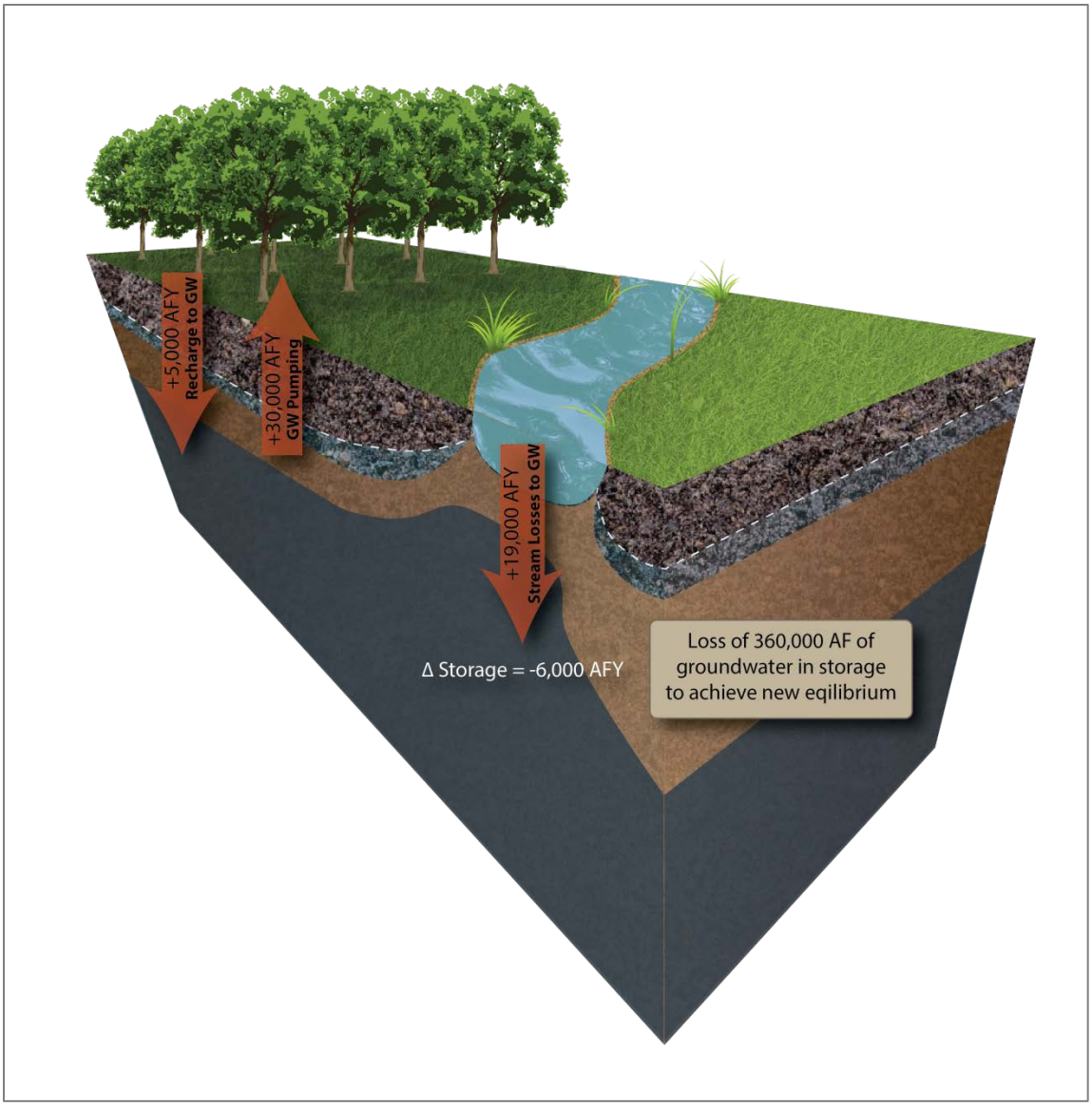
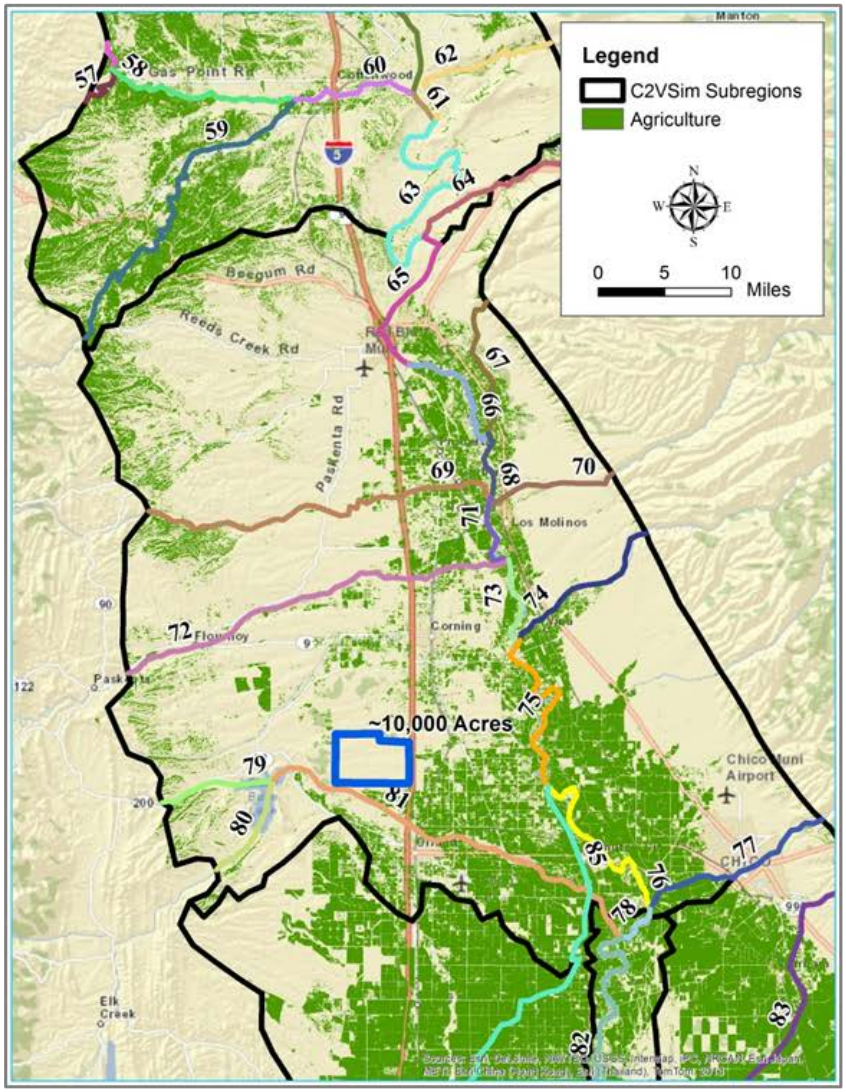


Figure 93 - Overall Change in Stream and Groundwater Budget for Scenario 2 (Increased Agricultural Demand) Compared to Baseline



Reach 65 – Sacramento River
Reach 66 – Sacramento River
Reach 67 – Antelope Creek Group
Reach 68 – Sacramento River
Reach 69 – Elder Creek
Reach 70 – Mill Creek
Reach 71 – Sacramento River
Reach 72 – Thomes Creek
Reach 73 – Sacramento River
Reach 74 – Deer Creek Group
Reach 75 – Sacramento River
Reach 76 – Sacramento River
Reach 77 – Big Chico Creek
Reach 78 – Sacramento River
Reach 79 – Stoney Creek
Reach 80 – Stoney Creek
Reach 81 – Stoney Creek
Reach 82 – Sacramento River

Figure 94 - Stream Reaches in the Project Area for Scenario 2 (Increased Agricultural Demand)

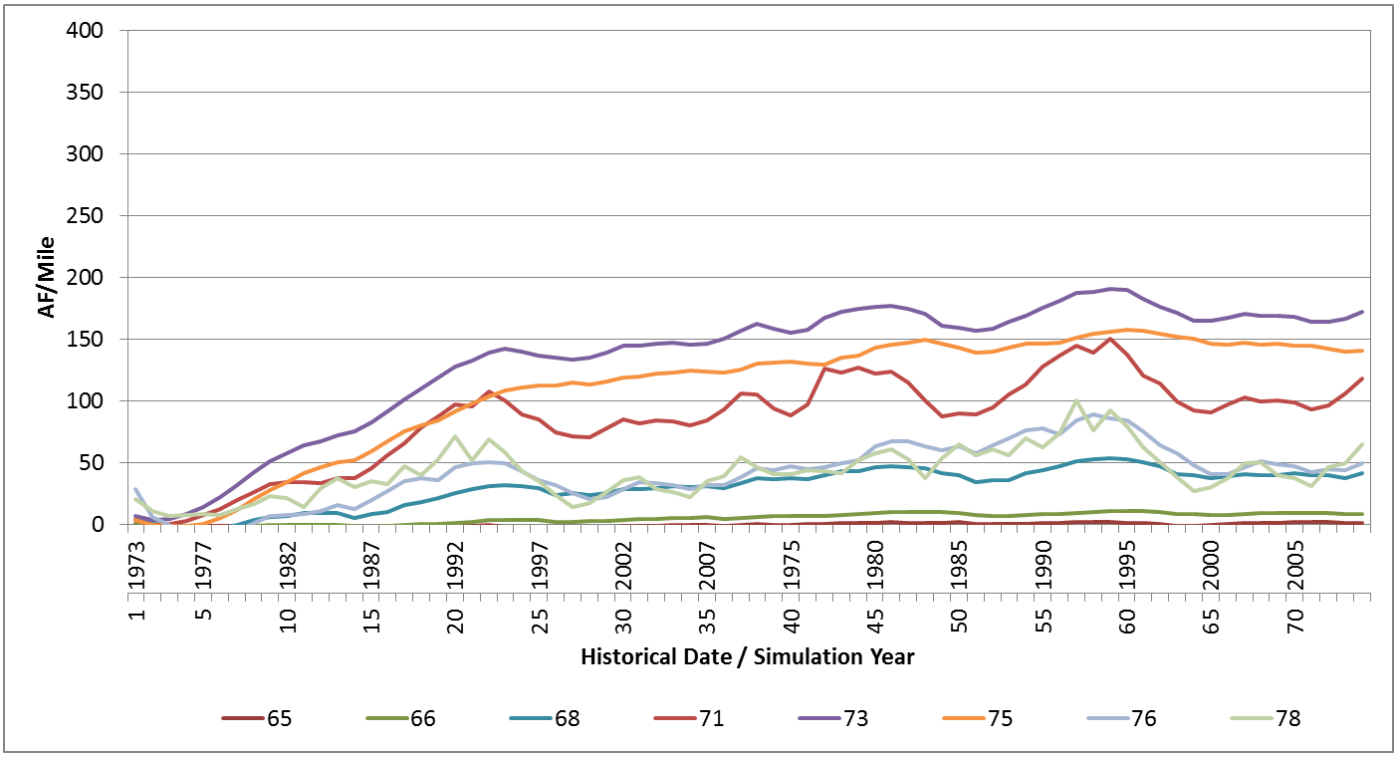


Figure 95 - Change in Stream Seepage by Stream Reach for Scenario 2 (Increased Agricultural Demand) Compared to Baseline - Sacramento River Reaches

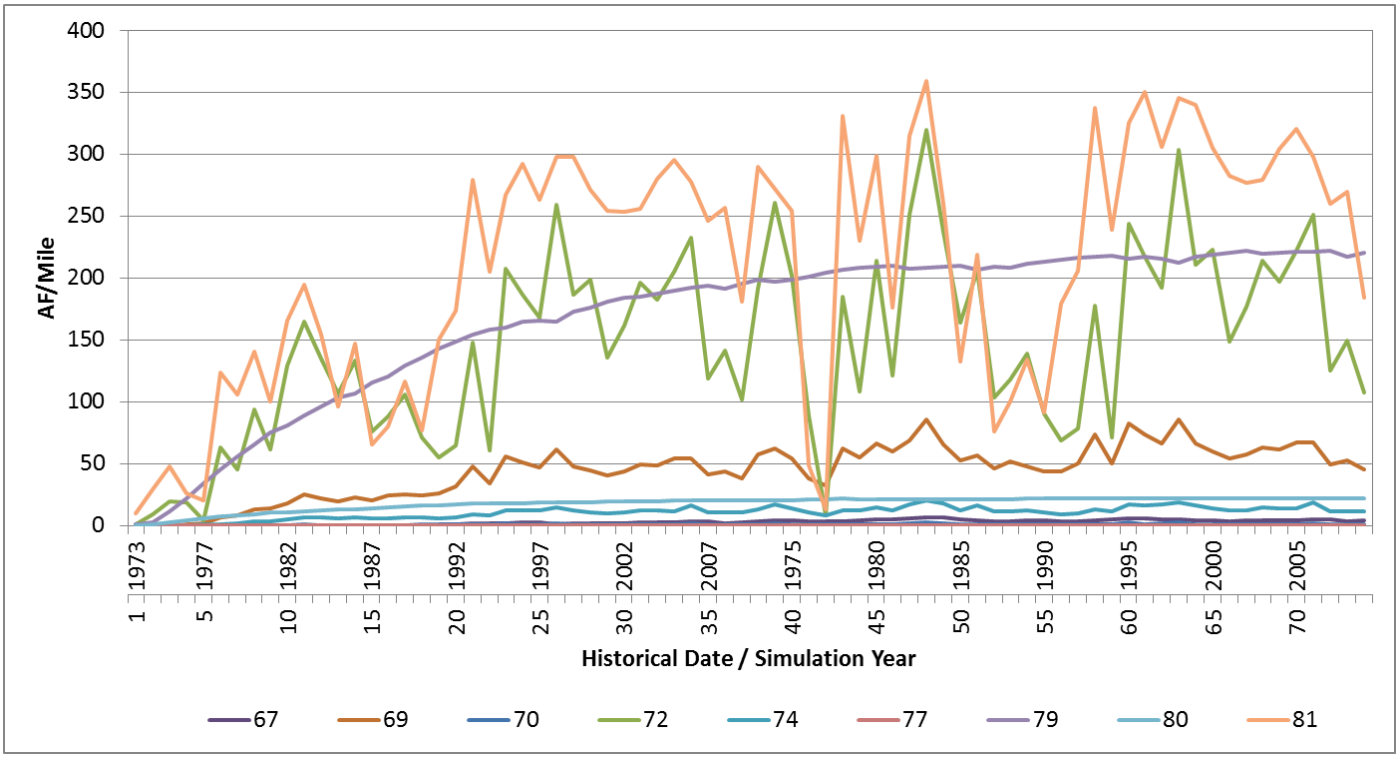


Figure 96 - Change in Stream Seepage by Stream Reach for Scenario 2 (Increased Agricultural Demand) Compared to Baseline –Tributaries to the Sacramento River

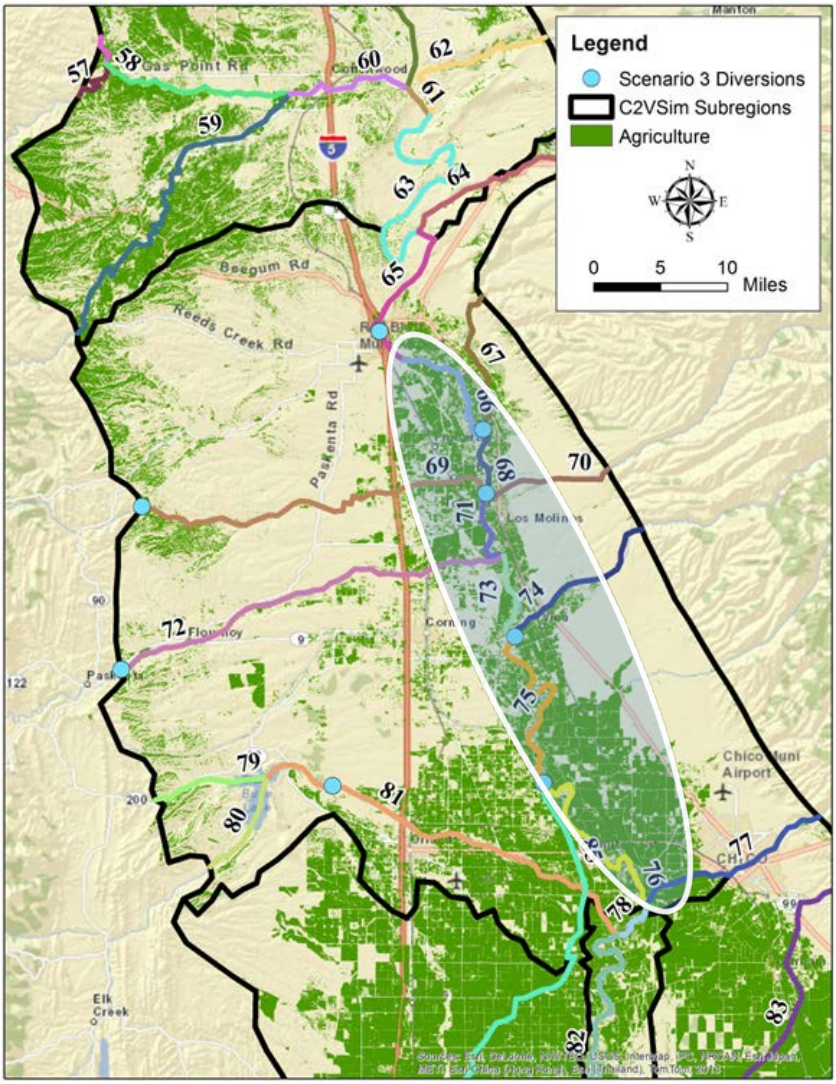


Figure 97 - Location of the Improved Irrigation Efficiency Implemented Area for Scenario 3 (Increased Irrigation Efficiency)

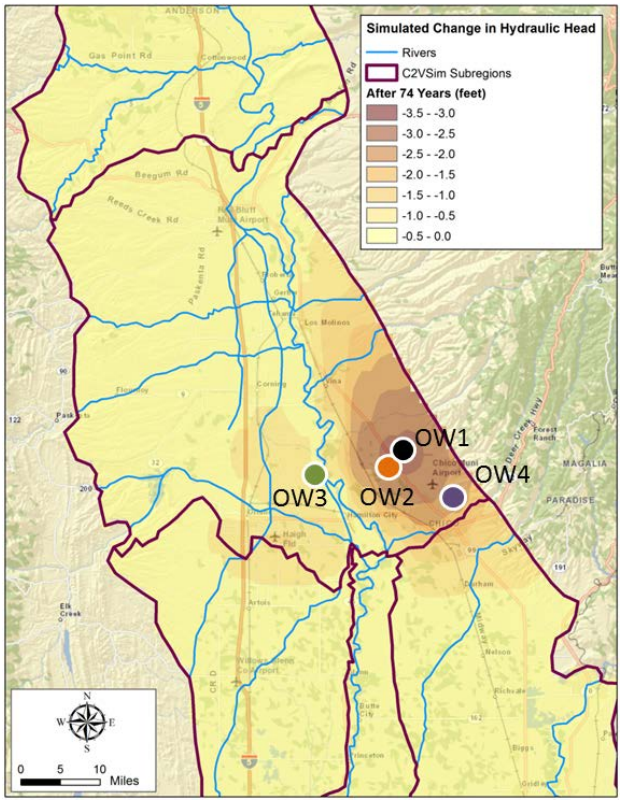


Figure 98 - Location of Groundwater Level Difference Hydrographs for Scenario 3 (Increased Irrigation Efficiency)

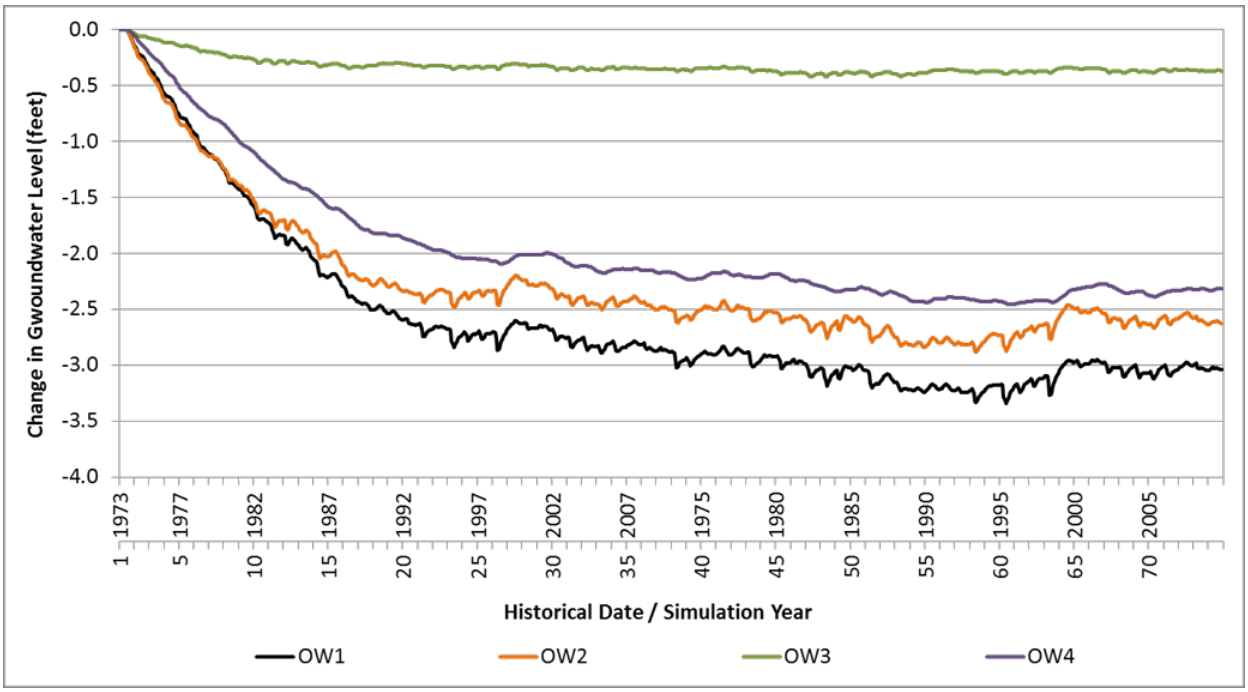


Figure 99 - Change in Groundwater Levels for Scenario 3 (Increased Irrigation Efficiency) Compared to Baseline

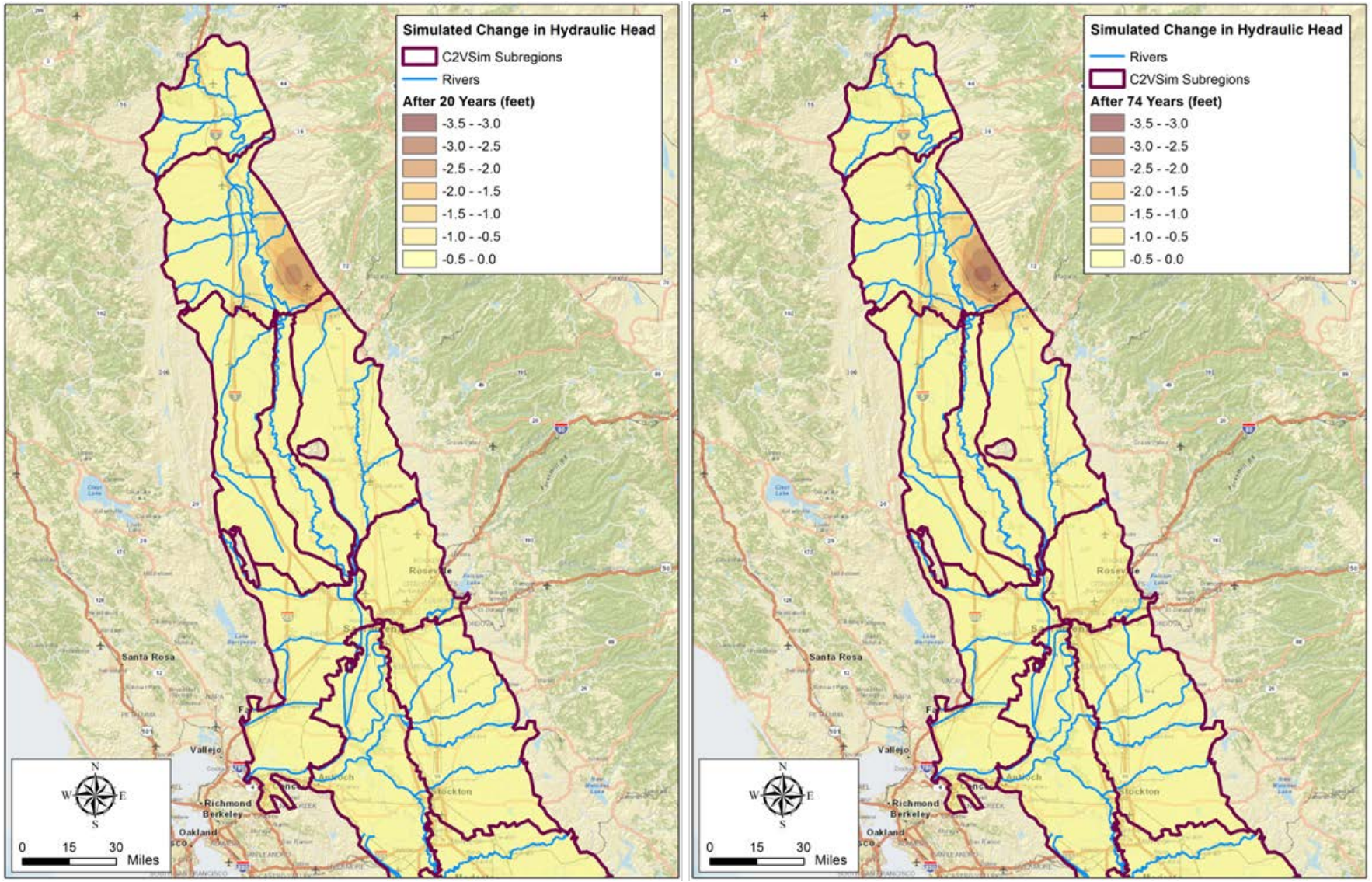


Figure 100 - Change in Groundwater Levels for Scenario 3 (Increased Irrigation Efficiency) Compared to Baseline after Simulation Year 20 and at the End of Simulation

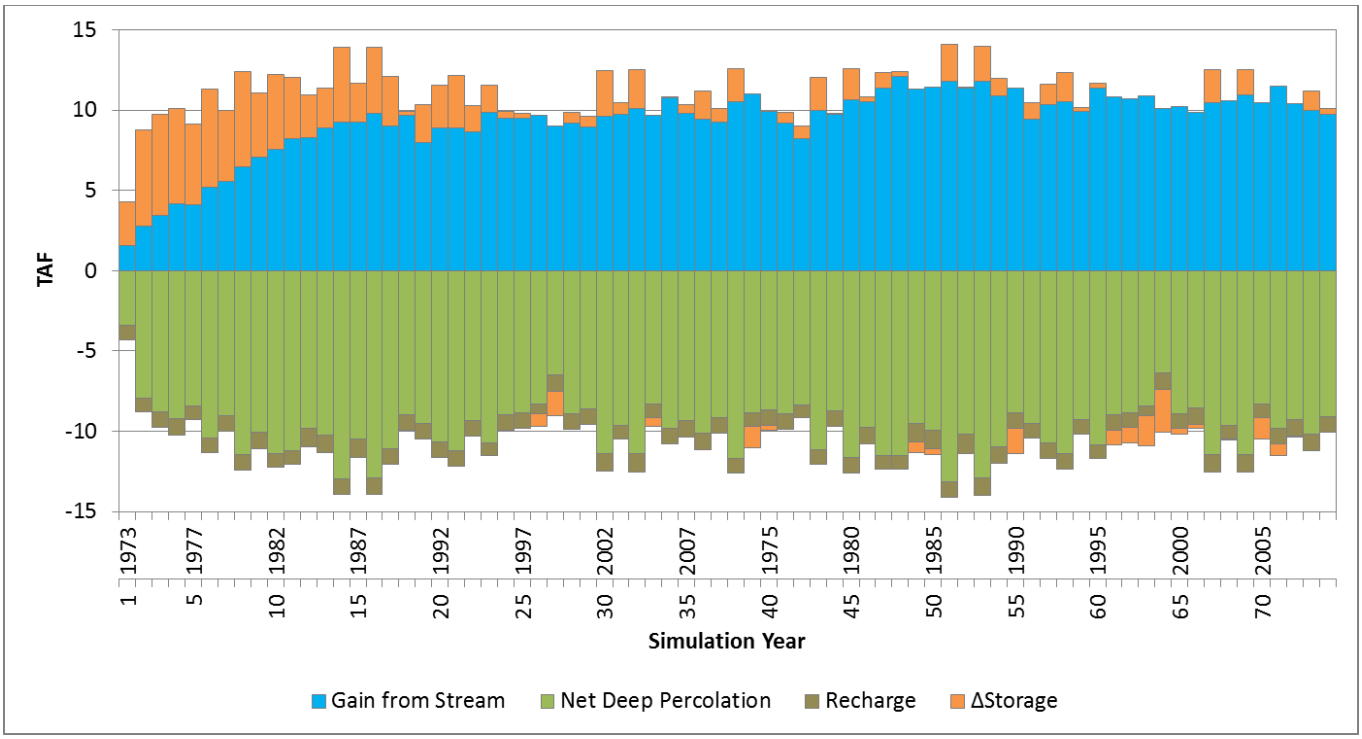


Figure 101 - Change in Groundwater Budget for Scenario 3 (Increased Irrigation Efficiency) Compared to Baseline

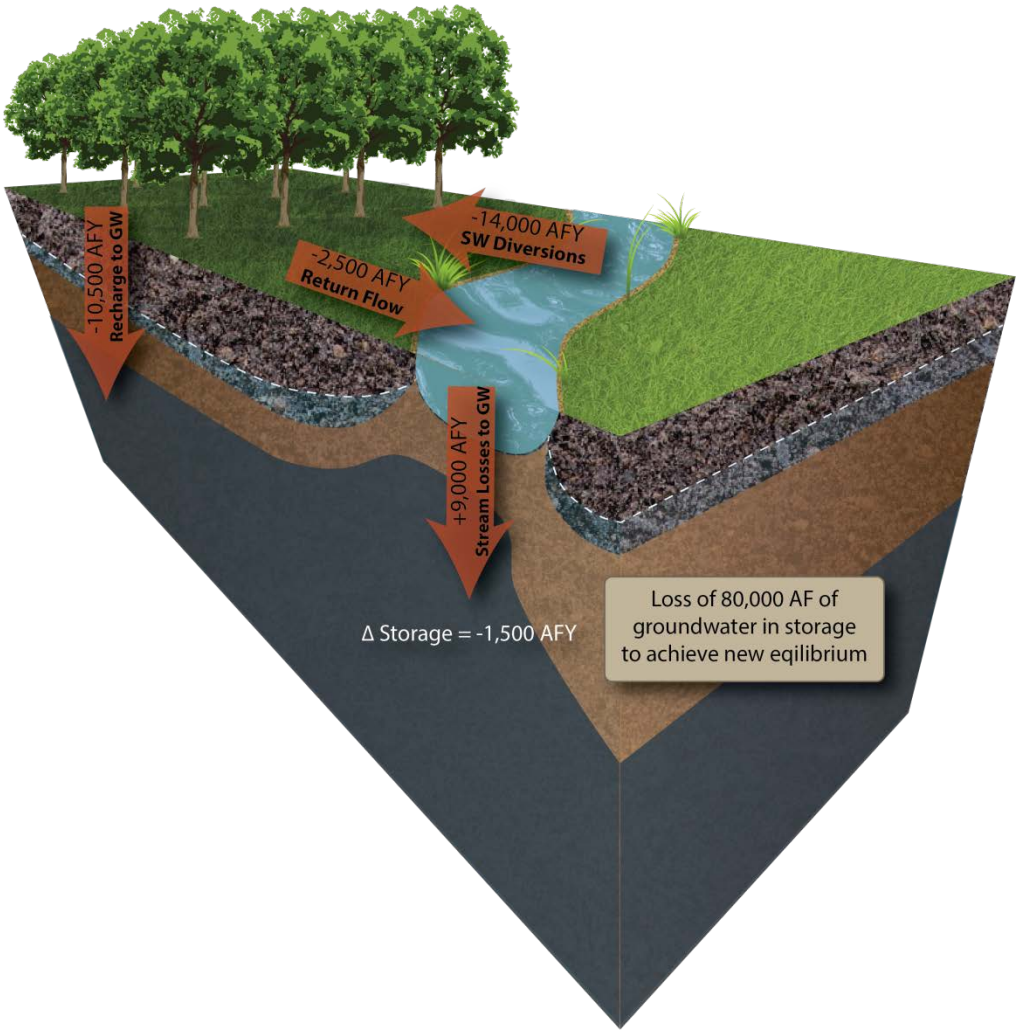


Figure 102 - Overall Change in Stream and Groundwater Budget for Scenario 3 (Increased Irrigation Efficiency) Compared to Baseline

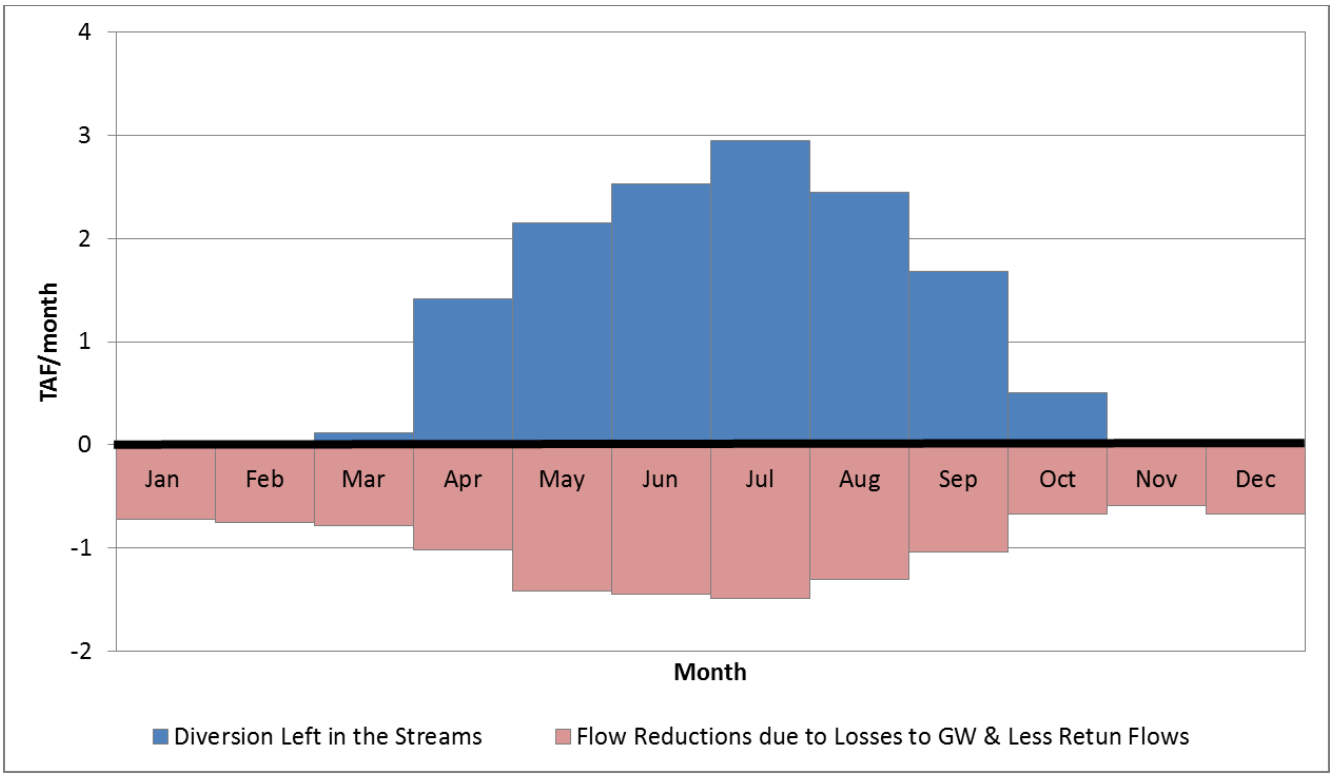
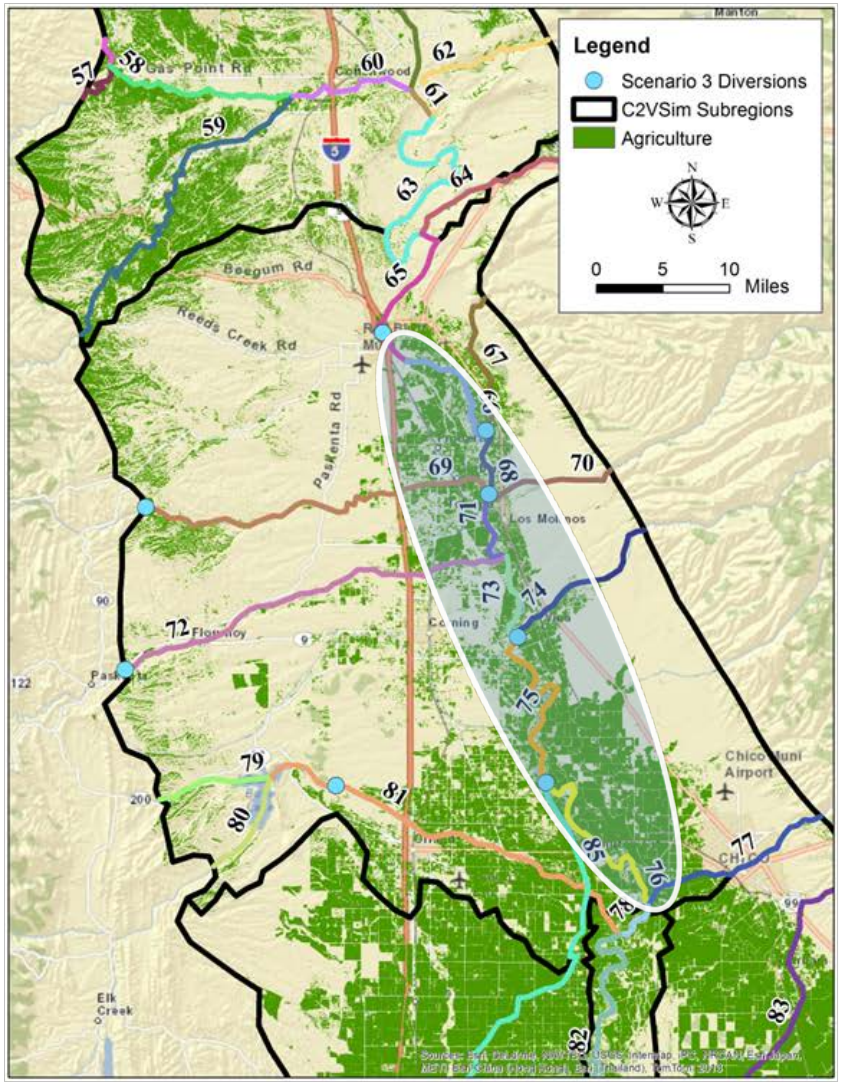


Figure 103 - Monthly Change in Stream Budget for Scenario 3 (Increased Irrigation Efficiency) Compared to Baseline - Average over the Whole Simulation Period



Reach 65 – Sacramento River
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Reach 71 – Sacramento River
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Reach 76 – Sacramento River
Reach 77 – Big Chico Creek
Reach 78 – Sacramento River
Reach 79 – Stoney Creek
Reach 80 – Stoney Creek
Reach 81 – Stoney Creek
Reach 82 – Sacramento River

Figure 104 - Stream Reaches in the Project Area for Scenario 3 (Increased Irrigation Efficiency)

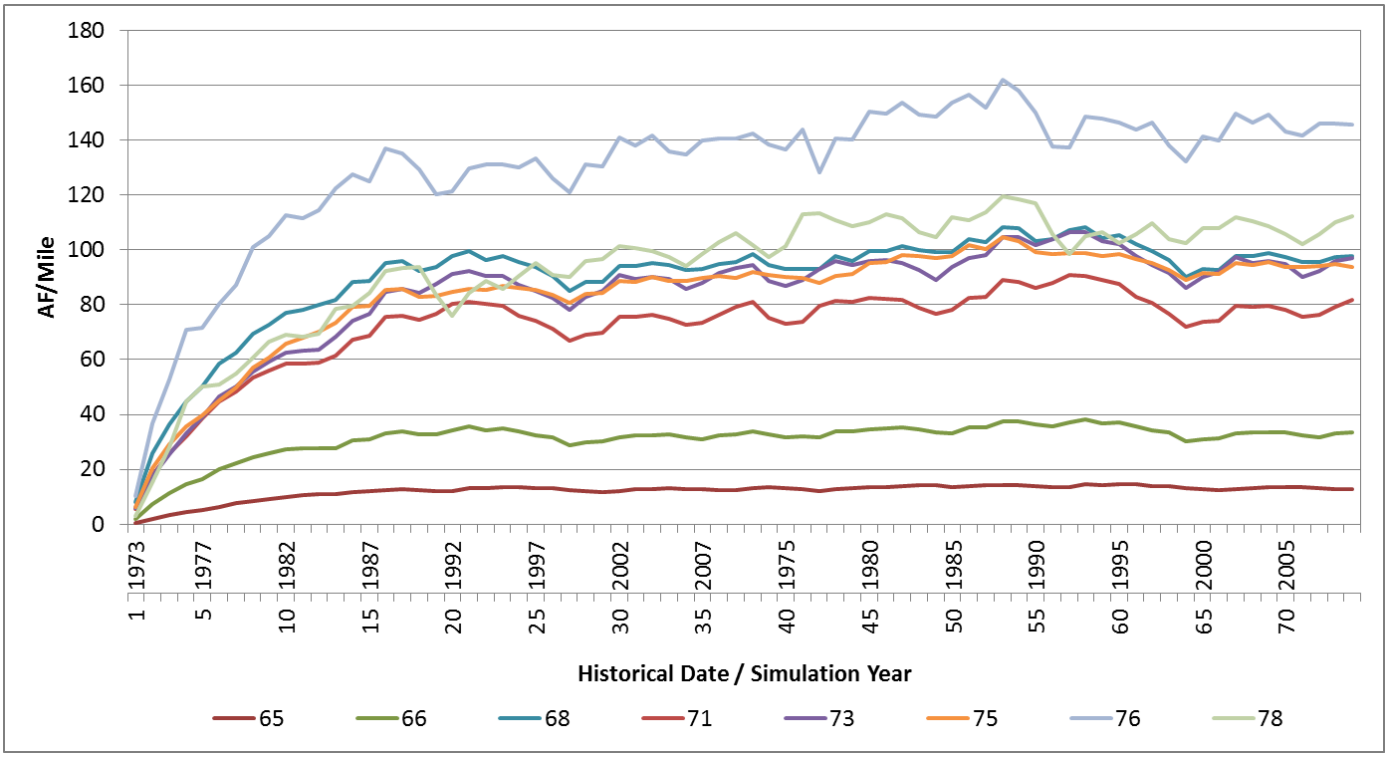

Figure 105 - Change in Stream Seepage by Stream Reach for Scenario 3 (Increased Irrigation Efficiency) Compared to Baseline – Sacramento River Reaches

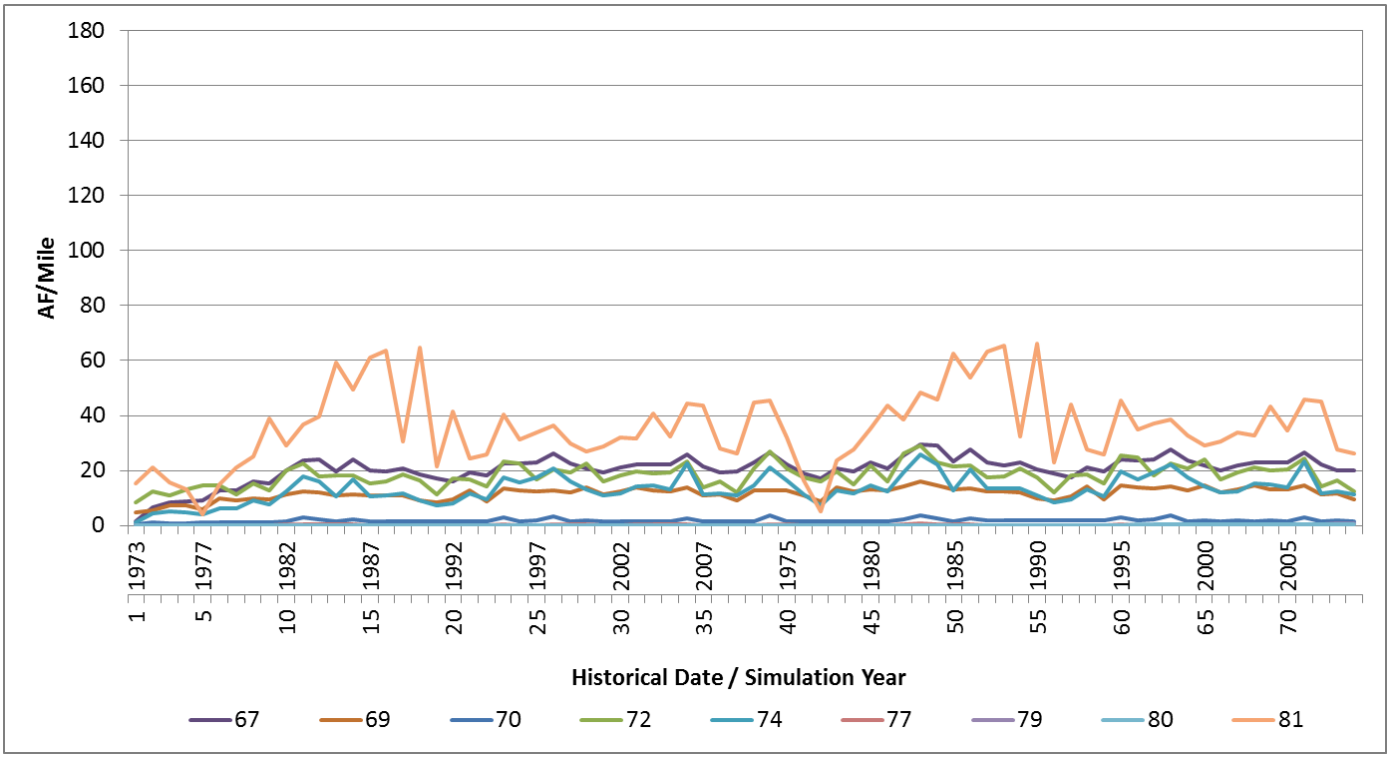

Figure 106 - Change in Stream Seepage by Stream Reach for Scenario 3 (Increased Irrigation Efficiency) Compared to Baseline –Tributaries to the Sacramento River

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Appendix A Hydrologic Modelling Platform Selection

1 Study Purpose

The Nature Conservancy's (TNC) California Water Program seeks to develop and advance policies and practices that lead to a reliable water supply for both people and nature throughout California. One of TNC's major strategies is to ensure that groundwater management directly addresses the connection between groundwater pumping and surface water supplies and better meets the needs of ecosystems that depend on surface flows or groundwater conditions. TNC's goal for a sustainable water future for California includes supporting implementation of improved groundwater management across the state to reduce impacts to surface water flows and the water users and ecosystems that depend on those flows.

The most widespread and relevant example of groundwater-surface water connection in California is the Central Valley. Thus, to achieve its goal of sustainable water future, TNC is conducting this study to analyze and document impacts of historical and potential future groundwater pumping on stream flow in the Central Valley. The objectives of this study include:

- Illustrate the effects of past, current, and future groundwater pumping in the Central Valley on surface water supplies and ecosystems
- Understand how groundwater pumping has affected stream flows and estimate the general magnitude of these effects
- Clarify the relative importance of different groundwater recharge mechanisms in different parts of the Central Valley
- Evaluate the regional-scale water supply and ecosystem impacts of future water management alternatives

This study will be conducted using a comprehensive integrated hydrological model of the Central Valley. There are several regional models available that cover parts of the Central Valley. However, there are only two existing models available for this study that cover the entire Central Valley and can potentially be used to simulate the groundwater-surface water connection in the Central Valley. These models are the U.S. Geological Survey's Central Valley Hydrological Model (CVHM) and the California Department of Water Resources' (DWR) California Central Valley Groundwater-Surface Water Simulation Model (C2VSim). The purpose of this Technical Memorandum is to review the robustness and suitability of these two models and recommend the more suitable model for conducting this project. The selected model will be used to extract information from historical condition simulations and conduct new simulations to reflect future management scenarios.

2 Model Platform Guidelines

The Central Valley hydrology varies greatly from north to south with abundant precipitation and large reservoir capacities in the north and lower precipitation and significant groundwater overdraft in the south. Stream-aquifer interaction is highly variable throughout the Central Valley. Some reaches of major rivers are losing water to groundwater, while in other reaches the groundwater is contributing flow to the river system. These conditions can be seasonal and can change from dry years to wet years. The following guidelines are considered for comparison of CVHM and C2VSim models and selection of the suitable model for this study.

- **Study Area** – The study area covers the entire Central Valley (Figure A1) and includes major rivers and streams.

- **Hydrologic Period** – Significant hydrological variations exists in California which includes dry, multiple dry, wet, and multiple wet years. A long hydrological period should be used for this study to incorporate the significant historical hydrological variations. Most DWR studies of the Central Valley include hydrology starting in the year 1922. A minimum of 30 years of historical hydrology should be used to simulate the long-term hydrological conditions. In addition, the model should have a hydrologic period that captures the significant changes that have occurred in the Central Valley, including:
    - The early part of the 20th century, prior to building and operation of major reservoirs, and
    - The latter part of the 20th century, when significantly more land went under cultivation and development.

  As this study will need to look at the impacts of the development on the stream-aquifer interaction, it is critical to have a sufficiently long period of hydrologic record to capture these changes.
- **Spatial Refinement** – The Central Valley covers 20,000 square miles and computationally there is a balance between a fine grid to provide detailed results and model run-times that allow for efficient work processes. However, with this balance in mind, the model grids should have sufficient resolution at areas of interest to capture important hydrological stresses such as stream-aquifer interactions and groundwater pumping. This resolution should be achieved without excessively long run-times that can impact work efficiency and cost.
- **Hydrologic Features** – The selected model should include the important hydrologic features of the Central Valley such as major streams including Sacramento and San Joaquin rivers and their major tributaries; surface water deliveries through State Water Project (SWP), Central Valley Project (CVP) and regional systems; major municipal pumping areas; major agricultural areas; agricultural and municipal water demands; surface water diversions; stream aquifer interactions; precipitation and runoff; and boundary groundwater and surface water inflows through small ungagged watersheds.
- **Water Budget Information** – The selected model should be capable of developing a water budget that includes: municipal and agricultural groundwater pumping, deep percolation, recharge, stream-aquifer interaction, stream flows, and surface water deliveries. The models should be capable of generating such water budgets for water management areas of interest such as service areas of irrigation districts, sphere of influence of cities and urban areas, historical water budget study areas of DWR or other water management agencies such as Depletion Study Areas (DSAs) and the smaller areas of Detailed Analysis Units (DAUs). DWR has been performing hydrological studies for DSAs and DAUs during the past several years. Model results could be compared with those form the DWR studies.

3 Model Alternatives

This section provides a brief introduction of the two models being considered for this model.

3.1 California Central Valley Groundwater-Surface Water Simulation Model (C2VSim)

DWR has developed the C2VSim model as a tool to aid in water management planning in Central Valley. C2VSim model simulates the response of the groundwater and surface water flow systems to surface and groundwater stresses for both historical and future conditions. C2VSim model was developed using

version 3.02 of DWR's Integrated Water Flow Model (IWFM). IWFM is a three-dimensional finite element model for simulation of groundwater flow and couples groundwater flow and land surface, river, lake, unsaturated zone, and small watershed process. IWFM also simulates water demands based on land use, soil and climate conditions, and agricultural management parameters. There are two versions of C2VSim model available: C2VSim-CG model with a coarse grid and C2VSim-FG model with a much finer grid. C2VSim-FG is evaluated for this study. C2VSim's ArcGIS Graphical User Interface (GUI) provides the model users with an interactive interface in an ArcGIS environment to perform model scenarios and display and interpret model results. Figure A2-a shows a map of the C2VSim-FG grid for the entire Central Valley and the model sub-regions. The references for C2VSim model include the following:

- C2VSim Brochure. DWR. 2012.
- Refinement of Spatial Resolution and Development of ArcGIS-Based Modeling Environment. WRIME. 2012.
- Hands-On Tutorial for C2VSim - DRAFT. DWR. 2013.
- Historical Rim Inflows, Surface Water Diversions and Bypass Flows for C2VSim – DRAFT. DWR. 2013.
- User Manual for C2VSim – DRAFT. DWR. 2013.
- DWR website for C2VSim: http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/index_C2VSIM.cfm

3.2 Central Valley Hydrologic Model (CVHM)

USGS has developed the CVHM model as a tool to aid water managers in Central Valley in understanding how water moves through the aquifer system, predicting water supply scenarios, and addressing issues related to water competition. CVHM model is an extensive, detailed three-dimensional model of the hydrologic system in the Central Valley and simultaneously accounts for changing water supply and demand across the landscape, and simulates surface water and groundwater across the entire Central Valley. CVHM model was developed using the USGS groundwater model, MODFLOW, plus the Farm Process module. Figure A2-b shows a map of the CVHM grid for the entire Central Valley and the water budget zones. The references for CVHM model include the following:

- Groundwater Availability of the Central Valley Aquifer, California. USGS. 2009. Professional Paper 1766.
- USGS website for CVHM: http://ca.water.usgs.gov/projects/central-valley/central-valley-hydrologic-model.html

4 Model Comparison

This section presents the comparison of C2VSim and CVHM models features and capabilities. Features of the models and their capabilities were compared and the results are presented in Table A1. Comparison of the model grids and model features for simulation of hydrological conditions and water management scenarios are shown at three levels:

- Entire Central Valley – Studies covering the entire Central Valley (Figure A2)
- Sacramento Valley - Regional studies (Figure A3)
- Sacramento Area – Local studies (Figure A4)

As shown in Table A1 and Figures A2 to A4, both models are capable of simulating hydrological conditions in the Central Valley. However, C2VSim model has a finer resolution along the major streams and canals and has 40 years more hydrological data covering 1921 to 1960 time period.

5 Conclusions

The model comparison shows several significant advantages of utilizing the C2VSim model for this effort

- Hydrologic period of 1922-2009, which provides information during the main development era in the Central Valley
- Finer resolution of C2VSim grid along the major streams and canals, which will result in a better simulation of stream-aquifer interaction and assessment of impacts of groundwater pumping on stream flows
- Detailed water budget information for surface processes, including land and water use system, stream and canal system, groundwater system, and soil system
- A user friendly Arc GIS-based Graphical User Interface (GUI) that will be useful to perform model scenarios and display and interpret model results

Based on the above description of the CVHM and C2VSim models and comparison of the two models it is recommended that the C2VSim model be used for this study.

Tables

Table A1 – Compariosn of Central Valley Hydrologic Mocel (CVHM) abd California Central valley Simulation Model (C2VSim)

Table 1 - Comparison of Central Valley Hydrologic Model (CVHM) and California Central Valley Simulation Model (C2VSim)

No.	Model Characteristics		Central Valley Hydrologic Model (CVHM)	California Central Valley Simulation Model (C2VSim)
1	Developer		USGS	DWR
2	Purpose		A numerical tool to assist in presenting status of groundwater resources in Central Valley, evaluate how these resources have changed over time, and assist in evaluating the system responses to stresses from human uses and climate variability and changes.	Simulate the historical hydrologic conditions in the Central Valley, and evaluate the hydrologic conditions under Baseline and projected land and water use and operational conditions within the Central Valley.
3	Numerical Engine		MODFLOW with Farm Process Package (FMP), Stream Flow Routing (SFR), Basin Characteristic Model, Subsidence (SUB), and Flow Barriers (HFB) MODFLOW used for simulation of groundwater FMP used for simulation of ag and urban water use and delivery of surface water	Integrated Water Flow Model (IWFM)
4	Model Resolution	Time	Monthly groundwater and surface water data from Oct 1961 to September 2003 (monthly stress periods)	Monthly groundwater and surface water data from Oct 1921 to September 2009 (monthly time step)
		Space	Uniform Horizontal Discretization of 1 X 1 mile Uniform cell size of 640 acres Model Area = 20,334 square miles Model cells = approximately 20,334	Finite Element Grid, Variable Horizontal Discretization * Average element size is approximately 400 acres (Min 4 acres along faults, and Max 1,750 acres, mostly at the boundary with little or no GW activitiy) Model Area = 20,850 square miles Model elements = 32,537 * The areas along the simulated streams in C2VSim-CG model have higher grid resolution than the remaining areas to allow for proper simulation of stream-aquifer interaction. C2VSim provides an average node spacing of 0.5 miles following the streams and gradually increases the spacing to an average of 1.5 miles.
		Layers	10 layers: (3 layers above E-Clay, 2 layers for E-Clay, 5 layers below E-Clay)	6 Layers: 3 Aquifer layers and 3 aquitard layers (1 layer above E-Clay, 1 layer for E-Clay, 2 layers below E-Clay)
5	Water Budgets	Units	Water-balance subregions (WBS)	Land and Water Use Budget Subregions
		Units used for Central Valley	21 Subregions (mostly based on Depletion Study Areas (DSAs)) used for the Central Valley consisting of: -7 Subregions in Sacramento Valley - 1 Subregion in Eastside Streams - 1 Subregion in Sacramento - San Joaquin Delta - 4 Subregions in San Joaquin River Basin - 8 Subregions in Tulare Lake Basin	
		Analysis	The budget program tabulates the simulation output at subregion-scale , allowing the user to generate the following tables: - Groundwater Budget - Landscape Water (Farm) Budget	The budget program tabulates the simulation output at subregion-scale , allowing the user to generate the following tables: - Land & Water Use Budget - Stream Flow Budget - Root Zone Moisture Budget - Groundwater Budget - Lake Budget - Stream Reach Budget - Diversion Detail Report
6	Data Used	Groundwater Pumping	- Agricultural pumpage is estimated - Urban pumpage is based on data, where data was not available the it is estimated	
		Surface Water Delivery	Water delivery and diversion data were obtained from DWR. Surface water diversions are specified at 110 locations, including: - 2 inactive diversions - 66 diversions from simulated rivers - 42 diversions from canals or non-simulated streams which are simulated as imports No surface water bypasses	Surface water diversions are specified at 246 locations, including: - 139 diversions from rivers (12 of which are exported outside the model area) - 107 diversions from canals which are simulated as imports Surface water bypasses are specified at 12 locations, including: - 6 bypasses to simulate weir flows to flood basins located in Sacramento Valley - The remaining 6 bypasses are located south of the Delta
		Intentional Recharge Operations	Not Included	Not Included
		Land Use Data	1961, 1973, 1992, 1998, and 2000	1954, 1960, 1973, 1992, 1998, and 2000
		Soils	The Central Valley soil were simplified into sandy loam, silty clay, and silt from the State Soil Geographic Database STATSGO.	Hydrologic soil properties for C2VSim model were determined based on the SSURGO soil map coverage with data gaps filled using the STATSGO soil map coverage.
		Precipitation	Gridded regional estimates of precipitation are obtained at a 1.24-mi spatial resolution for the Climate Source (2006) and compared to CIMIS data for 5 stations.	The precipitation rates were calculated as the area-weighted average from the parameter-elevation Regressions on Independent Slopes Model (PRISM) 2km x 2km monthly precipitation datasets.
		Surface Water Network	CVHM surface water network is composed of: - 2284 stream nodes - 43 streams/canals - 208 stream reaches - 43 surface water boundary inflows	C2VSIM surface water network is composed of: - 4529 stream nodes - 69 streams/canals - 105 stream reaches - 41 surface water boundary inflows - 2 lakes (Buena Vista Lake and Tulare Lake)
7	Model Applications		- Compare CVHM with previously developed models and water budgets (CA-DWR) - Evaluate climate-change on Central Valley Hydrologic System (NOAA California Application) - Utilize CVHM to examine impacts of San Joaquin River Restoration flows on Central Valley aquifer system (BOR) - Utilize CVHM to analyze potential water-level declines and subsidence along canals (BOR)-refine grid and water balance areas, add banking - Modify CVHM to examine impacts of Bay Delta Conservation Plan (BDCP) as part of EIS/EIR (BOR/CA-DWR)	- CVPIA PEIS hydrologic analysis of Central Valley operations - Model integration with the CVP/SWP OPerations models and economics models - Central Valley land subsidence study - Groundwater Substitution Water Transfer: Sacramento Valley Water Management Program - Potential Impacts of Climate Change I: Aquifer Response to Extended Drought - Potential Impacts of Climate Change II: Aquifer Response to Extended Drought with Economic Adaptation - GRACE Collaboration: Downscaling Remote Sensing Observations with C2VSim - California Water Foundation: Central Valley Groundwater Recharge Opportunities
9	Reference		Groundwater Availability of the Central Valley Aquifer, California. USGS Professional Paper 1766. 2009.	Draft User Manual for the Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG. Charles F. Brush, Emin C Dogrul. 2013

Figures

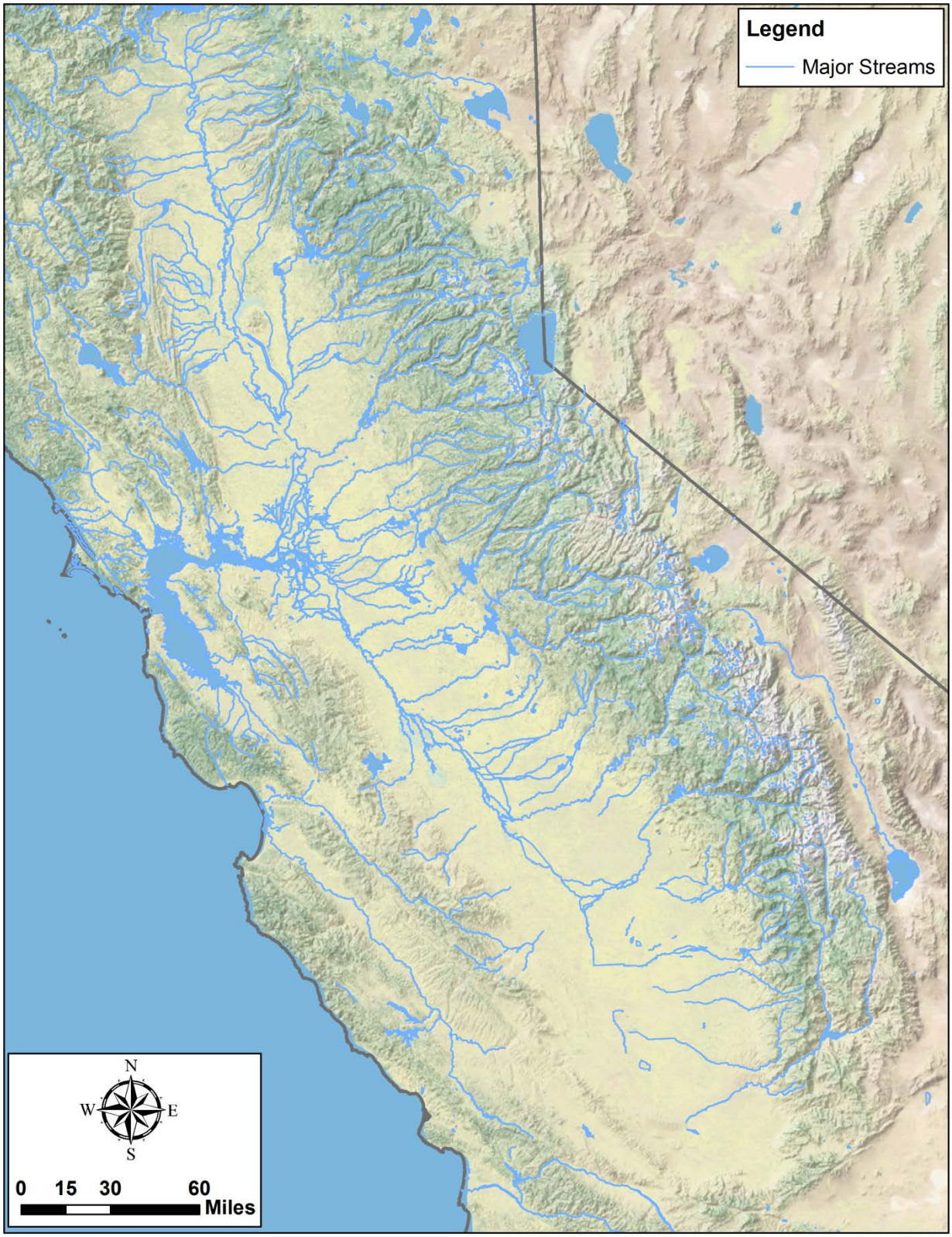

Figure A1. Study Area

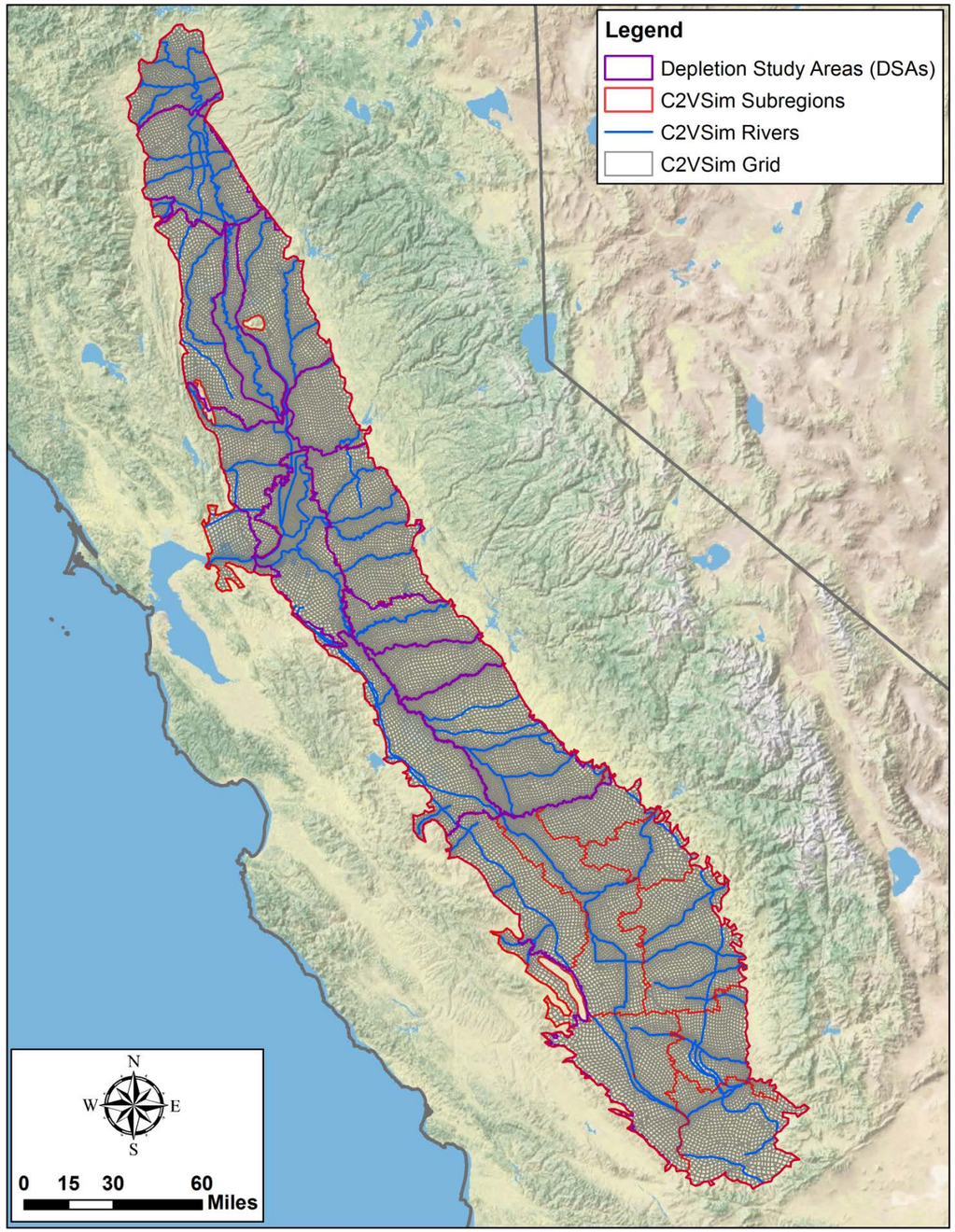

Figure A2-a. C2VSim-FG Model Grid

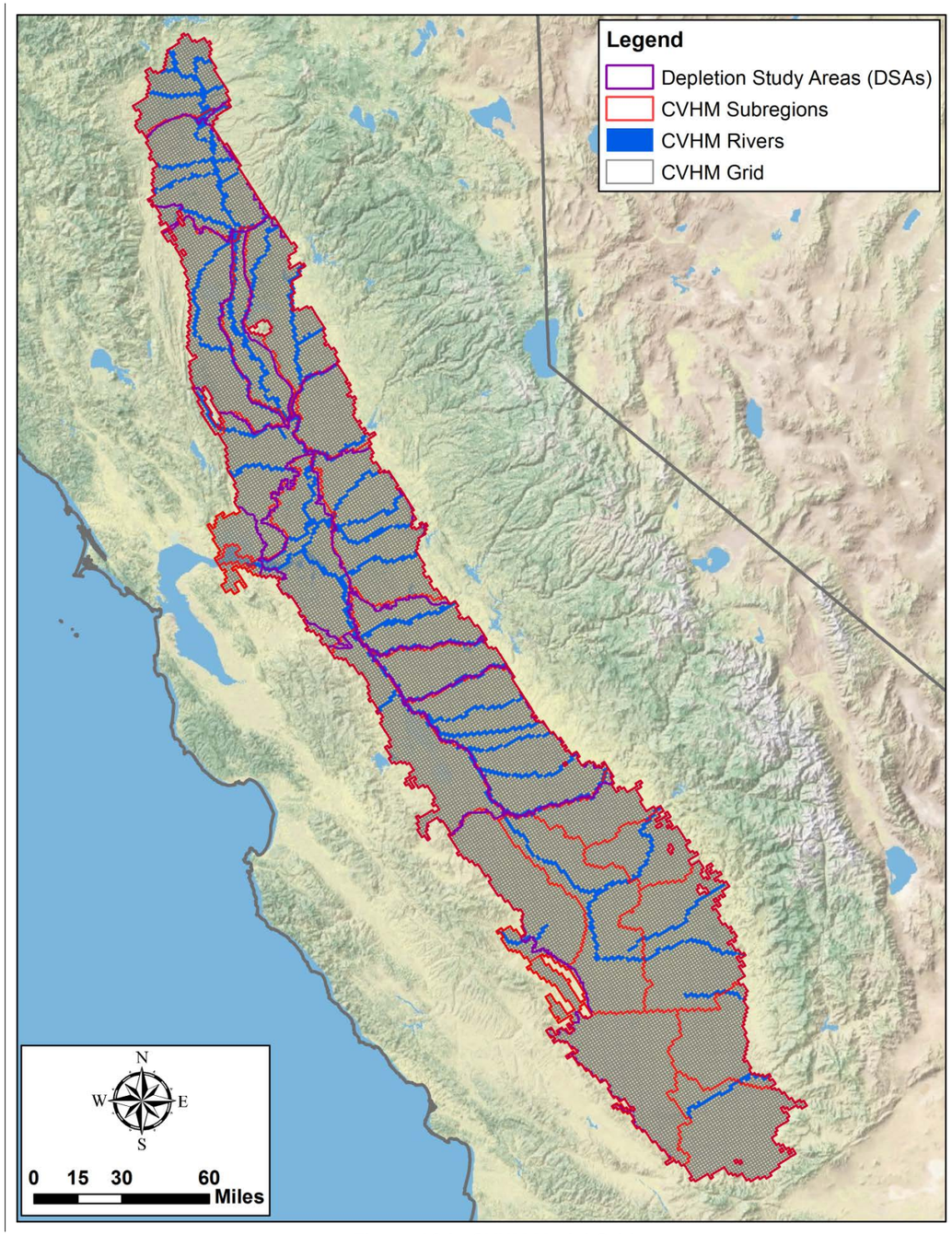

Figure A2-b. CVHM Model Grid

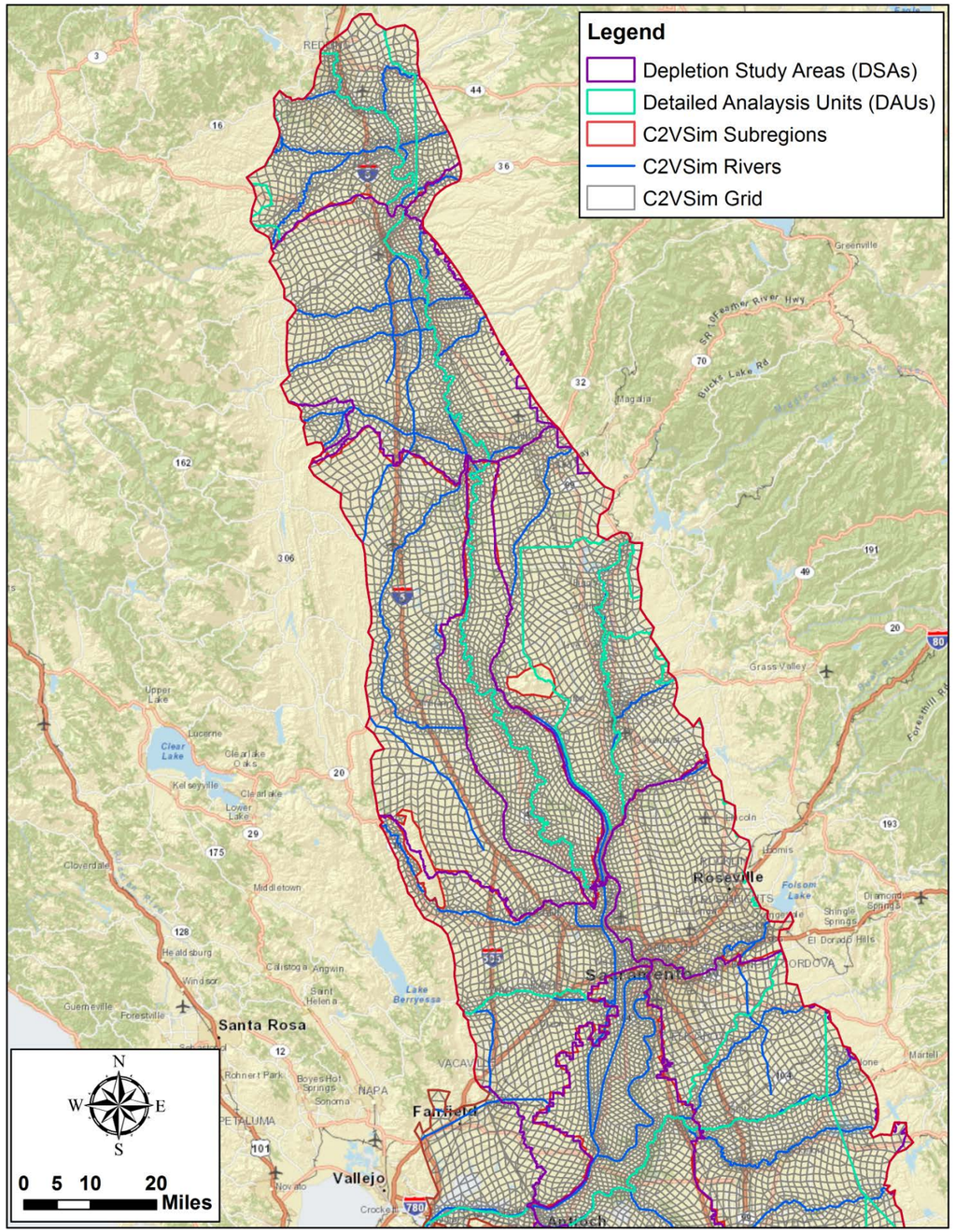

Figure A3-a. C2VSim-FG Model Grid in Sacramento Valley

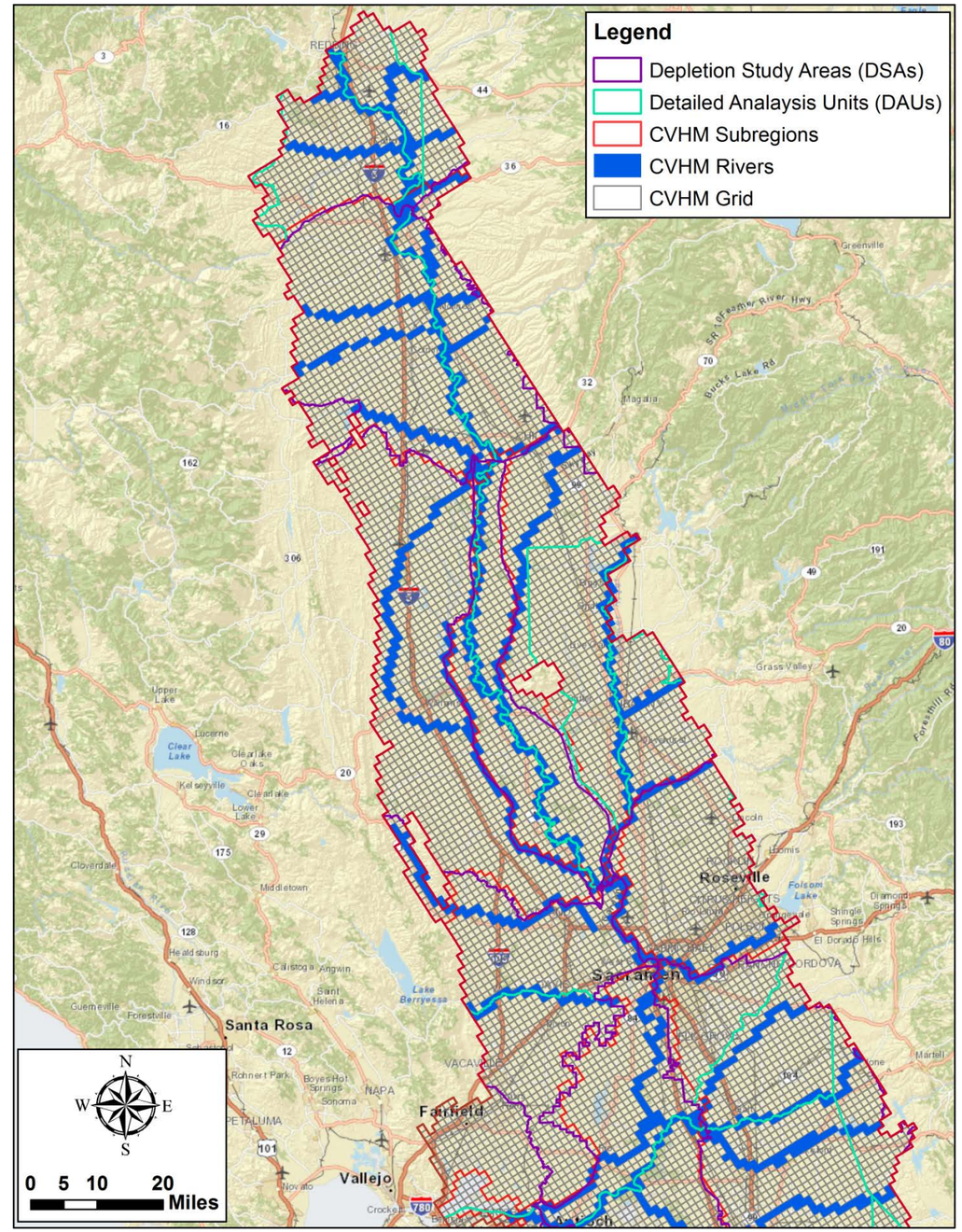

Figure A3-b. CVHM Model Grid in Sacramento Valley

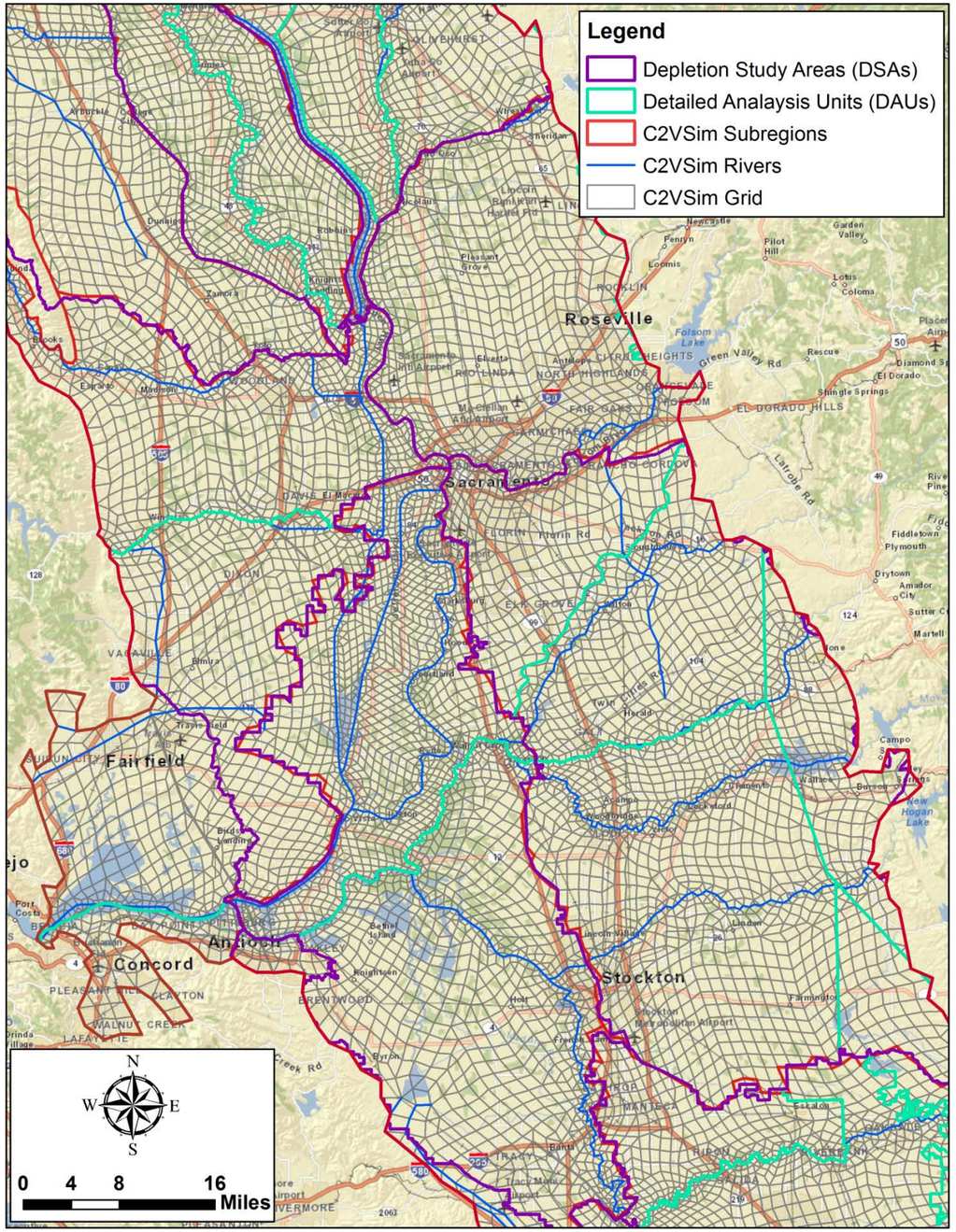

Figure A4-a. C2VSim-FG Model Grid in Sacramento Area

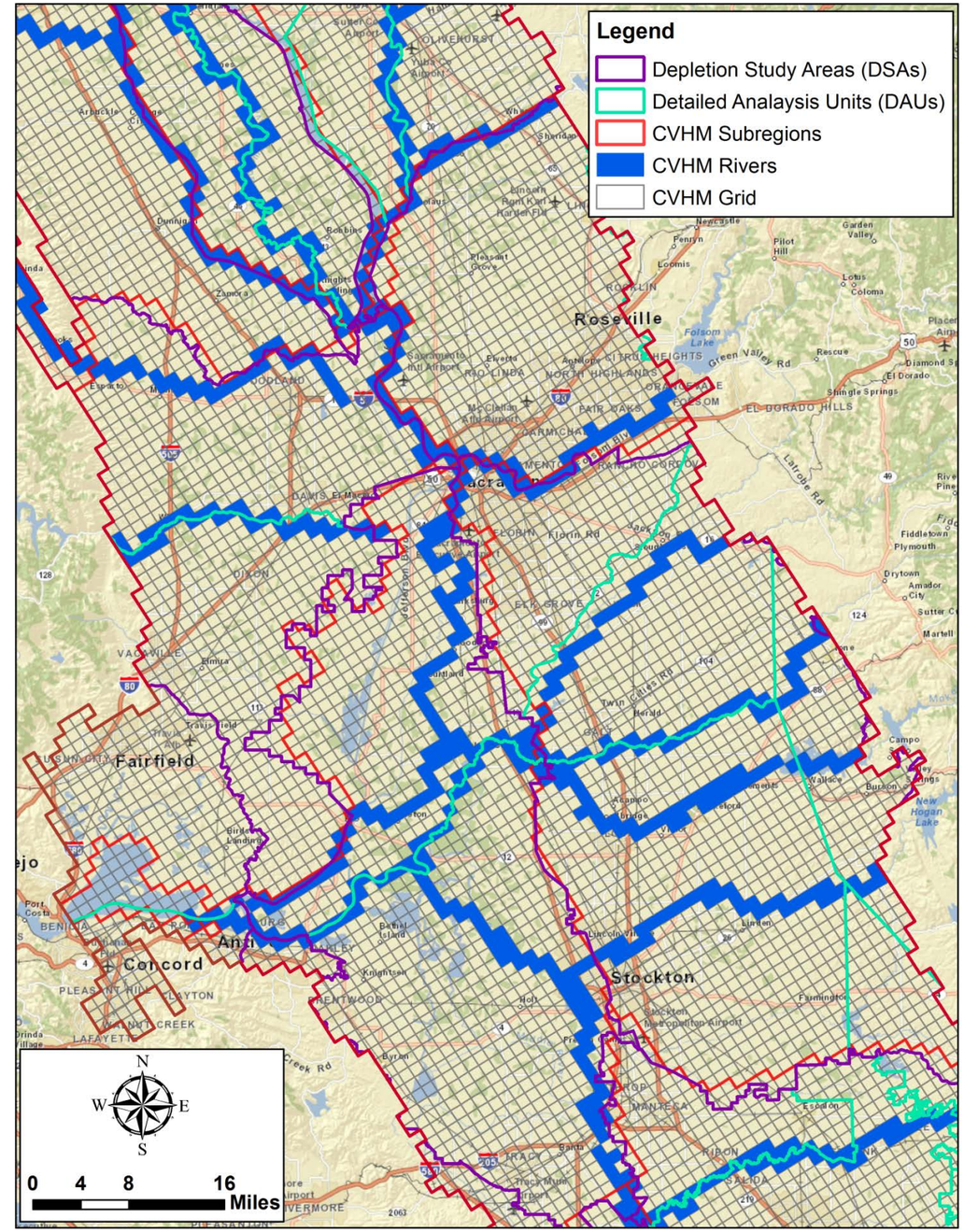

Figure A4-b. CVHM Model Grid in Sacramento Area