Representing Groundwater Management in California's Central Valley: CALVIN and C2VSIM

By

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Abstract

Updates were made to CALVIN, a hydro-economic optimization model of California's intertied water delivery system, to improve groundwater representation in the Central Valley. Revisions are based on the Department of Water Resources C2VSIM numerical groundwater model. Additionally, updates are made on the constraints of Delta Exports from major pumping plants as well as constraints on the required Delta Outflows based on current CALSIM II model. The updated CALVIN model is used to examine economical pumping and surface water deliveries with two overdraft management scenarios for 2050 projected land use. Finally a C2VSIM simulation with optimized CALVIN water allocations – surface diversions and pumping – is used to study the Central Valley aquifer responses with these management cases as well as the role of pumping and artificial recharge in the conjunctive use of water for reliable supplies. Although improvements in CALVIN and Central Valley groundwater modeling are considerable, in some regions CALVIN, C2VSIM and CVHM differ substantially.

Dedication

For Dr. Megan Wiley-Rivera, who introduced me to
science research and whose generosity and love of
teaching I should like to replicate.

Acknowledgements

The completion of this thesis as well as the knowledge I have gained in this process would not be possible without Heidi Chou, Josué Medellín-Azuara, Christina Buck and Kent Ke. They were present to meet, to skype to get clarifications on things and pushed to make sure all work necessary to set up model was done and made their time available to edit most of this work. Thanks also to Michelle Lent who was recruited into this effort much later but worked with incredible efficiency and positivity and helped us get things done.

I would like to thank Prof. Jay Lund for his guidance, encouragement, enthusiasm and suggestions through the project that helped us get unstuck without whom this thesis would not have been completed, as well as his editorial assistance in preparing this document.

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Chapter One: Introduction

This research examines the groundwater management in the Central Valley. Two models are used in this study; CALVIN the CALifornia Value Integrated Network model developed by the U.C. Davis research group and C2VSIM developed by the Department of Water Resources, California. CALVIN is a hydro-economic model of California's intertied water supply and delivery system, it is an optimization model with an objective of minimizing statewide water supply operating and scarcity costs (Draper et al, 2003). CALVIN covers 92% of California's populated area and 90% of its 9.25 million acres of irrigated crop area (Howitt et al. 2010).

C2VISM is a hydrologic model, which simulates the hydrology of the Central Valley including surface-water deliveries and groundwater pumping and reflects spatial and temporal variability in climate, water availability, and water delivery and simulates surface water and groundwater flow (CDWR, 2010). C2VSIM is a Central Valley application of the Integrated Water Flow Model (IWFM) an integrated surface-groundwater simulation model that considers surface water hydrology, land-use dependent soil-water budgets, surface water –groundwater interaction and groundwater flow (CDWR, 2012).

The California Central Valley stretches from Shasta County to Kern County - some 450 miles long and typically 40 to 60 miles wide. It supplies 8 percent of U.S. agricultural output and produces one quarter of the Nation's food. In addition, the Central Valley's urban population is expanding with a population of 6.5 million people in 2005 (California Department of Finance, 2007). Most land in the Valley is used for agriculture (Figure 1-1). Competition for water in the Central Valley among agricultural, urban, industrial users and ecosystems has intensified; water supply in the Valley is sustained by extensive system reservoirs and canals and available groundwater. The Central Valley is the second most pumped aquifer system in the U.S. (Faunt, et al, 2009). However, Central Valley wide data on groundwater use is not available. As a result numerical models like C2VSIM are best tools available to estimate water-budget components, assess and quantify hydrologic conditions, and estimate pumping.

The representation of the Central Valley groundwater system in the CALVIN network was revised using a C2VSIM historical run and used to estimate the economic management of water scarcity and potential costs for two overdraft management scenarios. In addition, C2VSIM was run with optimized CALVIN water allocations – surface water diversion and pumping – to study aquifer systems response i.e. changes in recharge and discharge patters and water table elevations under the two development scenarios. The optimization algorithm in CALVIN does not cover for the groundwater hydraulics which require a simulation to quantify the relationship between pumping and aquifer heads. To determine if optimal pumping rates suggested in CALVIN meet levels of groundwater pumping that do not cause long term overdraft or drastic decline in groundwater elevations - C2VSIM was used to simulate aquifer response with the two scenarios optimal water deliveries to look at whether the suggested CALVIN pumping rates are indeed “optimal” with respect to sustainable yield.

Given the economic importance of the Central Valley, effective groundwater management should address the economics of water development, as well as sustainability of groundwater resources. Pumping can cause overdraft conditions which, when prolonged, result in severe problems including depletion of the resource, land subsidence lower water tables and consequently increased cost of pumping. Natural or incidental recharge from percolation into the basin from rainfall, streams or excess water applied to crops may not be adequate to prevent overdraft; in these cases artificial recharge may help replenish storage and ‘bank’ water during wet years for use during dry periods. However, artificial recharge is however costly and depends on available surface water supplies. CALVIN is used to provide insights on the economics of water management (see also Chou, 2012), the model suggests amount of water that should be delivered per month to each demand area for projected 2050 conditions to minimize overall system water scarcity cost. Monthly volume of surface water and groundwater to demand areas from the CALVIN optimization run is referred to as ‘optimized CALVIN water allocations or deliveries’ throughout this paper.

This Chapter lays out the objectives of this study. Chapter 2 describes the C2VSIM groundwater model and provides details of model structure, physical aquifer characterization, flow rates, and groundwater levels and model water budget accounting. Chapter 3 details the CALVIN model, the updating of the groundwater representation of the Central Valley basins in the CALVIN model based on the historical C2VSIM run, updates of constraints on major Delta Export facilities and required Delta Outflow based on CALSIM II and the calibration process for the Updated Base Case.

Chapter 4 looks at how updates in CALVIN, mainly groundwater recharge and calculated groundwater storage, compare to C2VSIM output for recharge and groundwater storage when run with pumping rates and surface water diversions suggested in CALVIN. To update CALVIN a historical run of C2VSIM was used to calculate required parameters and extract groundwater recharge time series; details are in Chapter 3. The historical C2VSIM run consists of changing annual land use patterns based on historical surveys. However, given that in the CALVIN optimization, land use is set at a current level of development for the entire model run, it is expected that there may be differences in groundwater recharge-discharge inventory when C2VSIM is ran with optimized pumping and surface diversions from CALVIN and land use set at 2005 levels for the simulation period 1921 to 1993. Chapter 4 tests how well the updated CALVIN model tracks groundwater changes in C2VSIM.

Chapter 5 compares C2VSIM simulation results for the two management scenarios: 1) Base Case CALVIN 2) “No Overdraft” case. These two cases represent different constraints in CALVIN to meet two groundwater allocation policies by setting different values of groundwater basin ending storage. For the Base Case ending storage in CALVIN is set higher or lower than beginning storage as determined by historical overdraft rates from C2VSIM for 1980-2009. For the ‘No Overdraft’ case, ending groundwater basin storage in CALVIN is set equal to beginning storage. The C2VSIM simulations of these scenarios was used to determine if suggested pumping rates of CALVIN lead to sustainable basin conditions over the 72-years (1921 to 1993). Harou et al’s (2008) paper ‘Ending groundwater overdraft in hydrologic-economic models’ examines effect of different constraints on ending storage in CALVIN, included was the hypothetical ‘No Overdraft’ policy, this study goes further to determine if overdraft conditions in CALVIN are representative of estimated overdraft in a numerical simulation model and if optimal CALVIN pumping result in sustainable yield of the groundwater resource. In addition, conjunctive use of ground water and surface water in the Central Valley is discussed in this chapter, particularly the role of artificial recharge. Overall Conclusions summarize key findings of this study and future work.

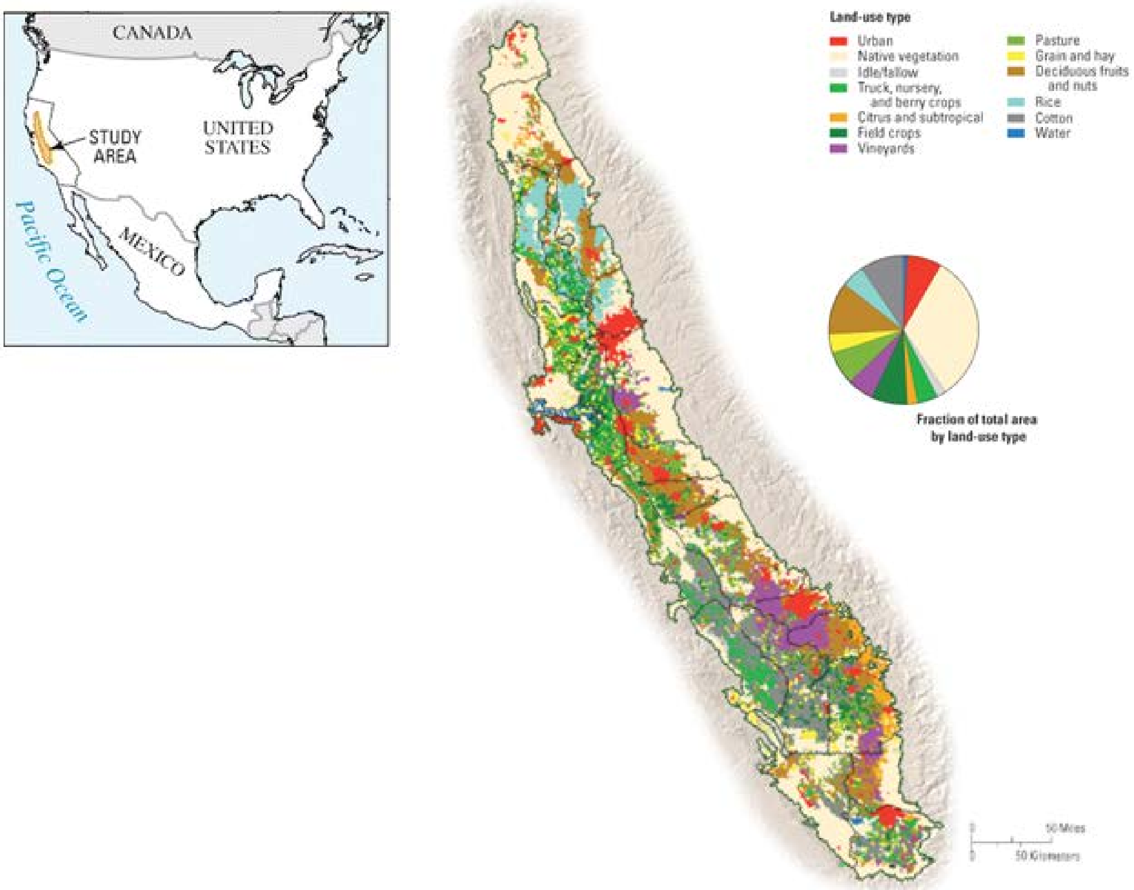


Figure 1- 1. Central Valley Location, Hydrologic Regions and 2000 land use distribution

(Source: Faunt et al, 2009)

Chapter Two: C2VSIM and Central Valley Groundwater

This chapter describes the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), a numerical model of the groundwater flow system in the Central Valley aquifer. The model considers surface water hydrology, land-use dependent soil-water budgets, surface water-groundwater interaction, and groundwater flow. Hydrologic variables modeled in C2VSIM include soil-moisture accounting in the root zone, surface water runoff and infiltration, unsaturated flow between root zone and the ground water table, and the routing of water in streams. C2VSIM groundwater flow is quasi-3D and uses a 3-layered 1392 element finite element grid that overlays the entire Central Valley.

The Central Valley is roughly 400 miles long and averages about 50 miles in width (Thiros et al, 2010). The drainage area for the Central Valley is about 49,000 square miles and includes the crest of the Sierra Nevada to the east and the Coast Ranges to the west. The Sacramento Valley occupies the northern third part of the Central Valley and the San Joaquin Valley the southern two-thirds. The San Joaquin Valley includes the San Joaquin basin in the northern part which drains to the San Joaquin River and the Tulare Basin in the south which is internally drained (Figure 2- 1). The climate in the Valley is Mediterranean with hot, dry summers and cool, wet winters. Approximately 85% of annual precipitation falls during November through April. Most streamflow originates as snowmelt runoff from the Sierra Nevada during January through June and most surface-water flow is controlled by dams, which capture and store water for use during the dry season, which is distributed through a complex system of streams and canals.

Regional scale models such as C2VSIM in addition to software and numerical methods to simulate flow also require data that accurately describes the spatially distributed hydrogeologic properties and hydraulic conditions at aquifer boundaries. The Department of Water Resources and the U.S. Geologic Survey have gathered much information on the systems. All groundwater models start with a conceptual model, which provides a general understanding of geological and hydrogeologic characterization, water use and land use history, regional groundwater circulation patterns, recharge and discharge mechanisms, surface water interaction and water levels. Sections below provide summary of data in the C2VSIM model used to characterize the physical system and to estimate contributions to groundwater systems recharge and discharge.

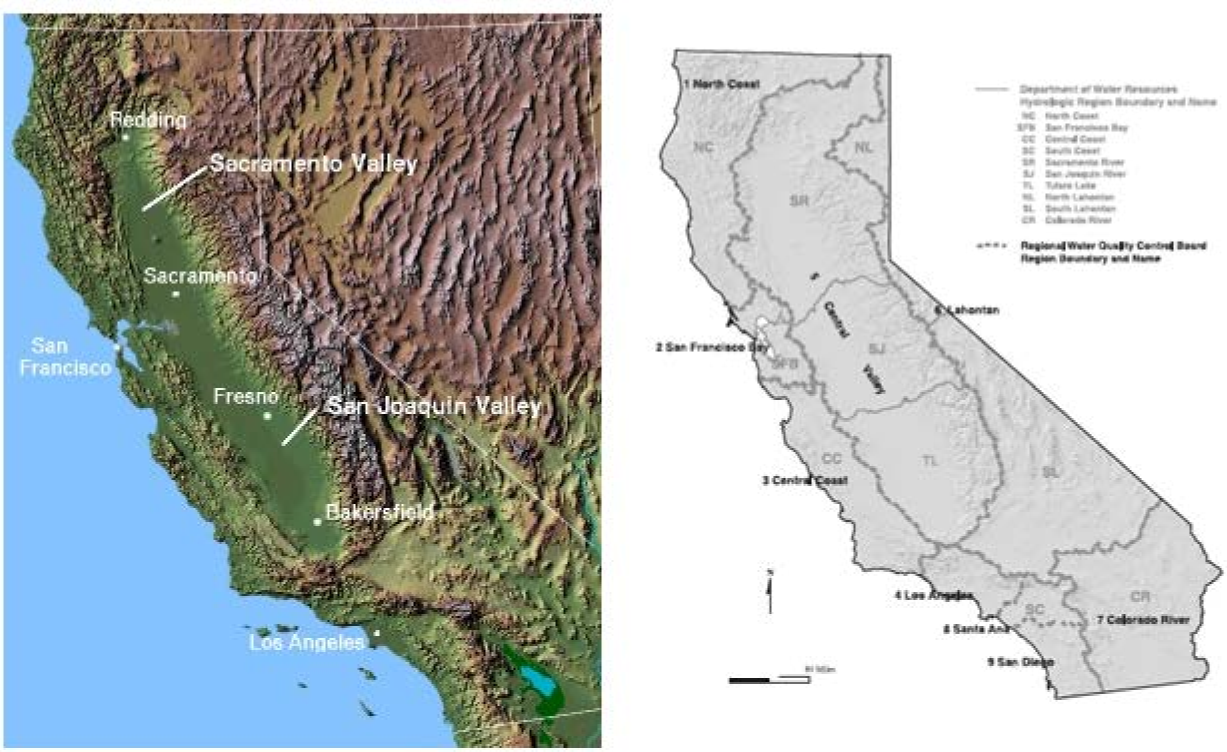


Figure 2- 1. Central Valley and corresponding DWR Hydrologic Regions

(Source: Wikipedia & DWR, 2003)

2.1 Description of C2VSIM

C2VSIM is an application of the Integrated Water Flow Model (IWFM) to the Central Valley. IWFM (CDWR 2012) simulates groundwater and surface water flows, and applied to the Central Valley, the model produces hydrologic simulations for the entire region. The finite element grid produces a basis for calculations over time and space; C2VSIM is therefore able to simulate groundwater heads, surface flows and the interactions of surface and subsurface systems over a month time step. The water accounting unit or water budgeting reporting volume is called a subregion. The Central Valley has 21 subregions in three hydrologic regions – Sacramento (subregion 1-9), San Joaquin (subregion 10-13) and Tulare (subregion 14-21) (Figure 2- 2). Areas of these subregions are shown in Table 2- 1. The model has a three-dimensional finite element grid with 1393 nodes forming 1392 triangular or quadrilateral elements. Element areas average 9,190 acres with minimum area of 1,365 acres and maximum area of 21,379 acres. The model grid extends vertically to form three model layers (Figure 2- 2).

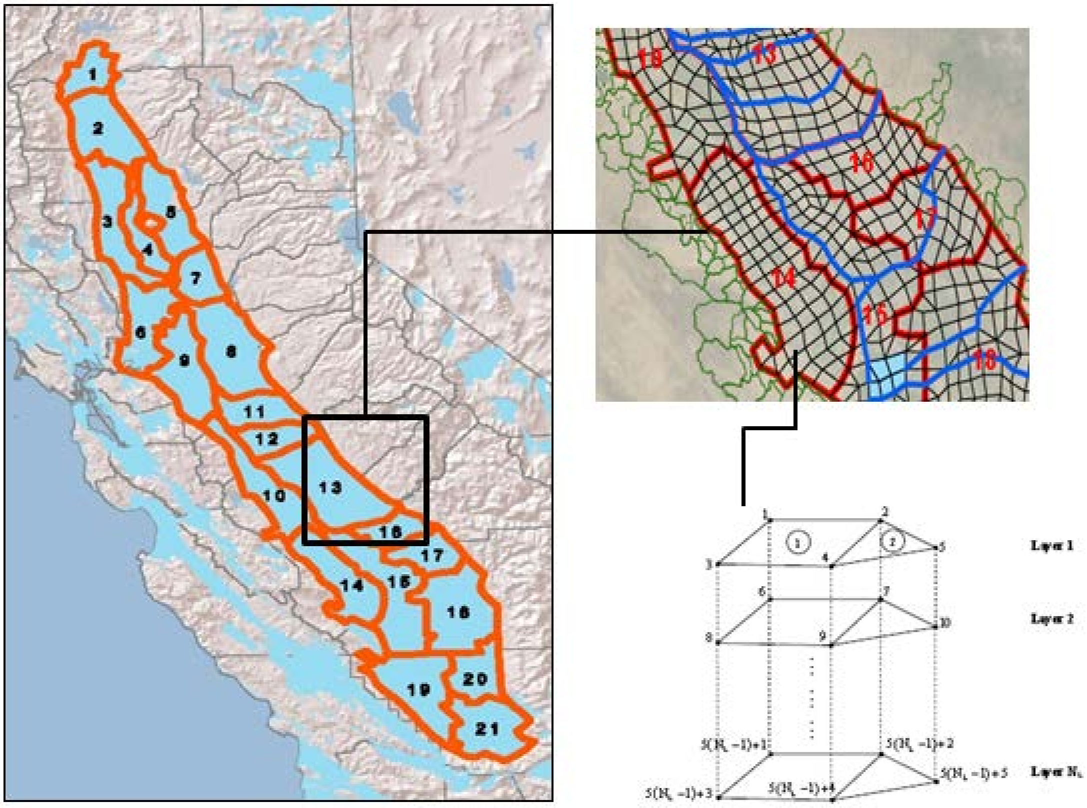


Figure 2- 2. CVSIM Central Valley Subregions, Finite Element & multilayer aquifer representation

Source: CDWR-California Department of Water Resources. (2012). Theoretical Documentation, User's Manual and Z-Budget: Sub-Domain Water Budgeting Post-Processor for IWFM. Sacramento (CA): State of California, The Resources Agency

Table 2- 1. Subregion areas in the Central Valley

Subregion	Total Area (ac.)
1	328,278
2	698,014
3	689,108
4	351,576
5	613,756
6	657,863
7	349,858
8	895,534
9	725,454
10	668,072
11	412,543
12	340,336
13	1,037,638
14	670,229
15	904,472
16	302,449
17	372,889
18	897,091
19	801,420
20	423,713
21	652,847
Sacramento	**5,309,439**
San Joaquin	**2,458,589**
Tulare	**5,025,110**
Total Central Valley	**12,793,139**

The area of each of four land use types – Agricultural, Urban, Native Vegetation and Riparian Vegetation – is specified annually for each element. Each month, the Land Surface Process balances water inputs and outputs for each land use type in each subregion. The groundwater pumping rate is calculated for each subregion and is allocated to the elements. The resulting outflows, including deep percolation to groundwater and flows to surface water, are allocated to the elements of each subregion according to the land use distribution. Inflows and outflows modeled in C2VSIM for the rootzone, unsaturated zone below the rootzone and saturated zone or groundwater are shown in Figure 2- 3, and a summary of inflows and outflows for each control volume are shown in Table 2- 2. For each element, groundwater and surface water flows are quantified. These are calculated based on geologic properties, land use, soil type, precipitation, initial conditions and bordering elements boundary conditions. Physical aquifer characterization, flow rates, and water table elevations, are topics covered in later sections.

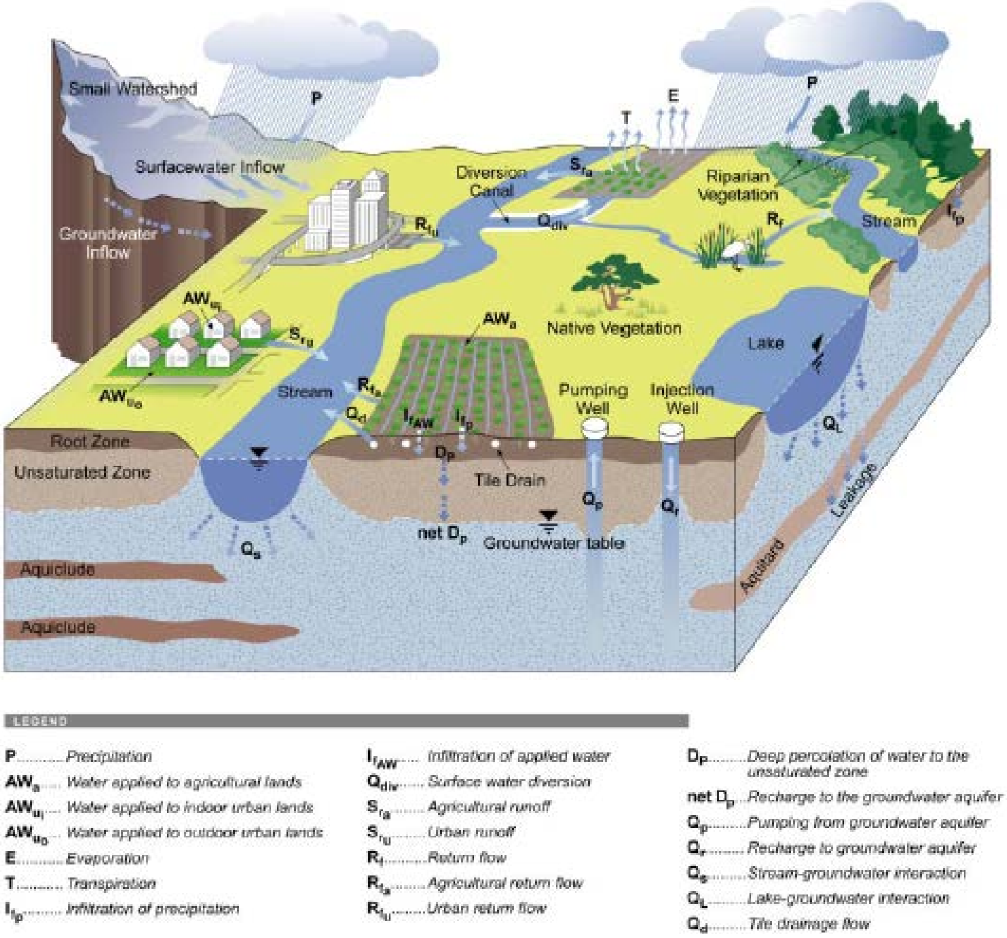


Figure 2- 3. Hydrologic fluxes modeled in C2VSIM

Source: CDWR-California Department of Water Resources. (2012). Theoretical Documentation v. 4.0. The Resources Agency

C2VSIM simulates the flow of water through the network of groundwater nodes and streams nodes. Vertical or horizontal flow imports or exports water for each element for each time step. The model considers fate of water as it enters the element from a neighboring element or from outside model or within the element boundary as surface water inflow, groundwater, precipitation or applied water from agricultural and urban areas.   Over each time step, water may remain in the element as it entered or it may flow horizontally or vertically. Horizontal flows represent water movement across an area such as stream flow, irrigation diversions and groundwater seepage. Vertical flows represent fluxes between ground and surface water, these include infiltration, evapotranspiration, groundwater pumping, artificial recharge and subsurface outflows.

The governing groundwater flow equation is a second order partial differential equation (PDE), which combines expressions for conservation of mass and conservation of momentum (Darcy equation). The resulting transient groundwater flow equation through a heterogeneous anisotropic saturated porous medium becomes (Freeze and Cherry, 1979):

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)+Q=S_s\frac{\partial h}{\partial t}$$

$Q - source\ or\ sink\ term$

$S_s - specific\ storage$

$h - piezometric\ head$

$x, y, z\ - direction\ of\ flow$

$K - hydraulic\ conductivity$

$\frac{\partial h}{\partial t} - change\ in\ hydraulic\ head\ per\ time$

Given appropriate initial and boundary conditions to account for water entering or leaving the model, the equation is numerically solved to obtain piezometric head as a function of time and space - h(x,y,z,t). Examples of processes represented by boundary conditions are pumping wells, recharge from or groundwater discharge to rivers or lakes, groundwater discharge to agricultural drains, subsurface inflow or outflow to or from a groundwater basin. Numerical approximation techniques in the case of

C2VSIM, finite element is used to discretize the domain with a grid and solve for h(x,y,z,t) at all nodes. Figure 2- 4 shows grid corresponding to finite element numerical approximation.

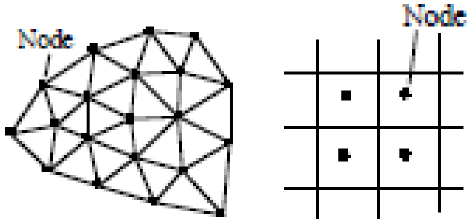


Figure 2- 4. Finite Element and Finite Difference division of model subdomain

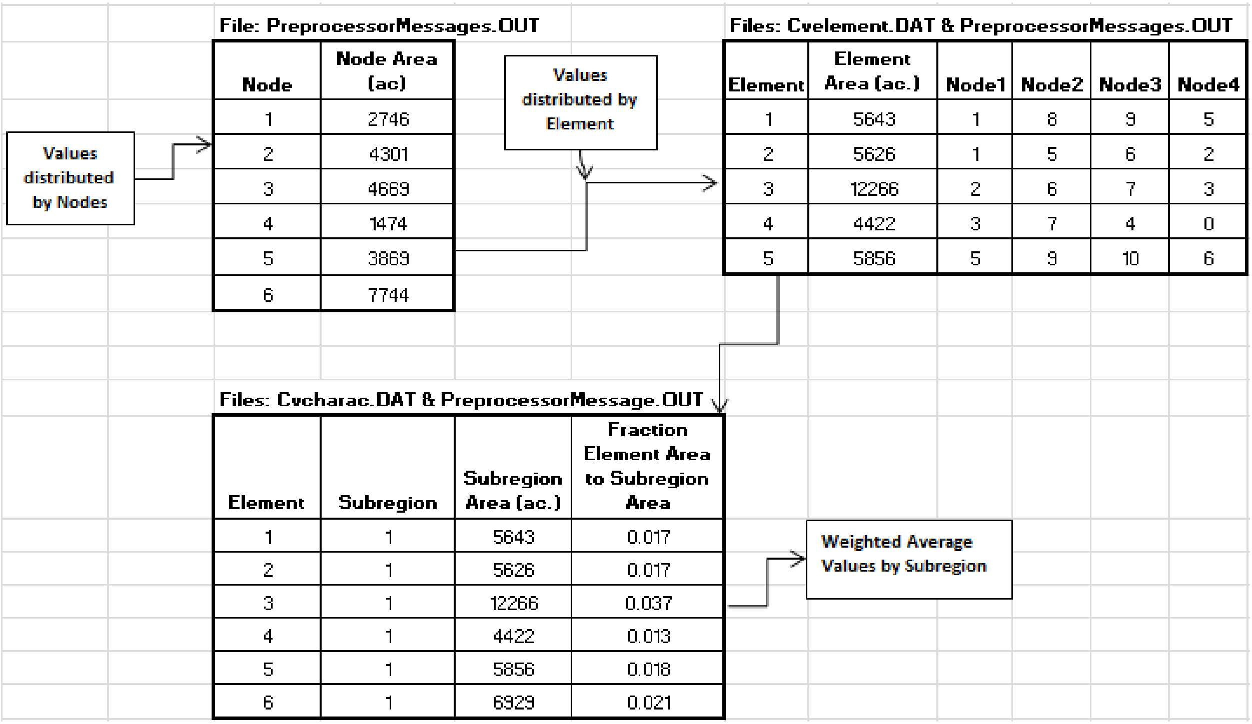
(Source: Fogg, class notes HYD269, UC Davis)

For details on the numerical computation for finite element grid see Wang et al, 1982 chapter 7.

Table 2- 2. Inflows & Outflows modeled in C2VSIM

	Rootzone	**Unsaturated Zone**	**Saturated Zone**
Inflows	Precipitation - aggregated over 4 land use areas (Ag, Urban, Native Vegetation & Riparian Vegetation)	Precipitation	Precipitation & Applied Water fluxes from Unsaturated Zone
			Loosing Stream fluxes
			Lake or Open Water Bodies Inflows
	Applied Water from Ag & Urban areas	Applied Water	Conveyance losses from Surface Water Diversions
			Artificial Recharge
			Storage gain from previously subsided aquifer layers
Outflows	Evapotranspiration	Precipitation & Applied exceeding Soil Moisture Storage Capacity	Tile Drain outflows
			Pumping
			Fluxes to Gaining Stream
			Fluxes to gaining Lakes
			Loss in storage due to Subsidence

To derive average parameters for water transport, system characterization, and hydraulic heads from C2VSim for use in CALVIM, we created a post-processing spreadsheet that relates characteristics distributed over nodes, or elements to get weighted averaged values for each subregion. Input data characterizing the system in C2VSIM is in form of text files. Subregion weighted average values were calculated using information of correlation between nodes, elements and subregions as shown in Figure 2- 5, vlookup functions were used as search function for correlating nodes, element and subregion values.



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Node	Node Area (ac)
1	2746
2	4301
3	4669
4	1474
5	3869
6	7744

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Element	Element Area (ac.)	Node1	Node2	Node3	Node4
1	5643	1	8	9	5
2	5626	1	5	6	2
3	12266	2	6	7	3
4	4422	3	7	4	0
5	5856	5	9	10	6

Files: Cvcharac.DAT & PreprocessorMessage.OUT

Element	Subregion	Subregion Area (ac.)	Fraction Element Area to Subregion Area
1	1	5643	0.017
2	1	5626	0.017
3	1	12266	0.037
4	1	4422	0.013
5	1	5856	0.018
6	1	6929	0.021

Figure 2- 5. Post-processing input or results distributed by nodes or elements to get weighted average values for each subregion

2.2 Geology of the Central Valley Geology and Flow Parameters in C2VSIM

One challenge for groundwater flow modeling is the lack of data on geological characterization and therefore estimation of hydraulic parameters. The general conceptual model for groundwater flow in the Central Valley is that of a heterogeneous aquifer system comprising confining units, unconfined, semi-confined and confined aquifers. Alluvial sediments transported from the surrounding Sierra Nevada and Coast Ranges make up the aquifer system. Unconfined or semi-confined conditions occur in shallower deposits and along the margins of the valley. The aquifer system become confined in most areas within a few hundred feet of land surface because of overlapping lenses of fine-grained sediments, which are generally discontinuous and are not vertically extensive but are laterally extensive. Corcoran Clay is a particularly laterally extensive confining bed that separates the basin fill deposits over a large area in the central, western and southern parts of the San Joaquin Valley into an upper unconfined to semiconfined zone and a lower confined zone (Thiros et al, 2010). Figure 2- 6 shows a generalized geology of the central valley.

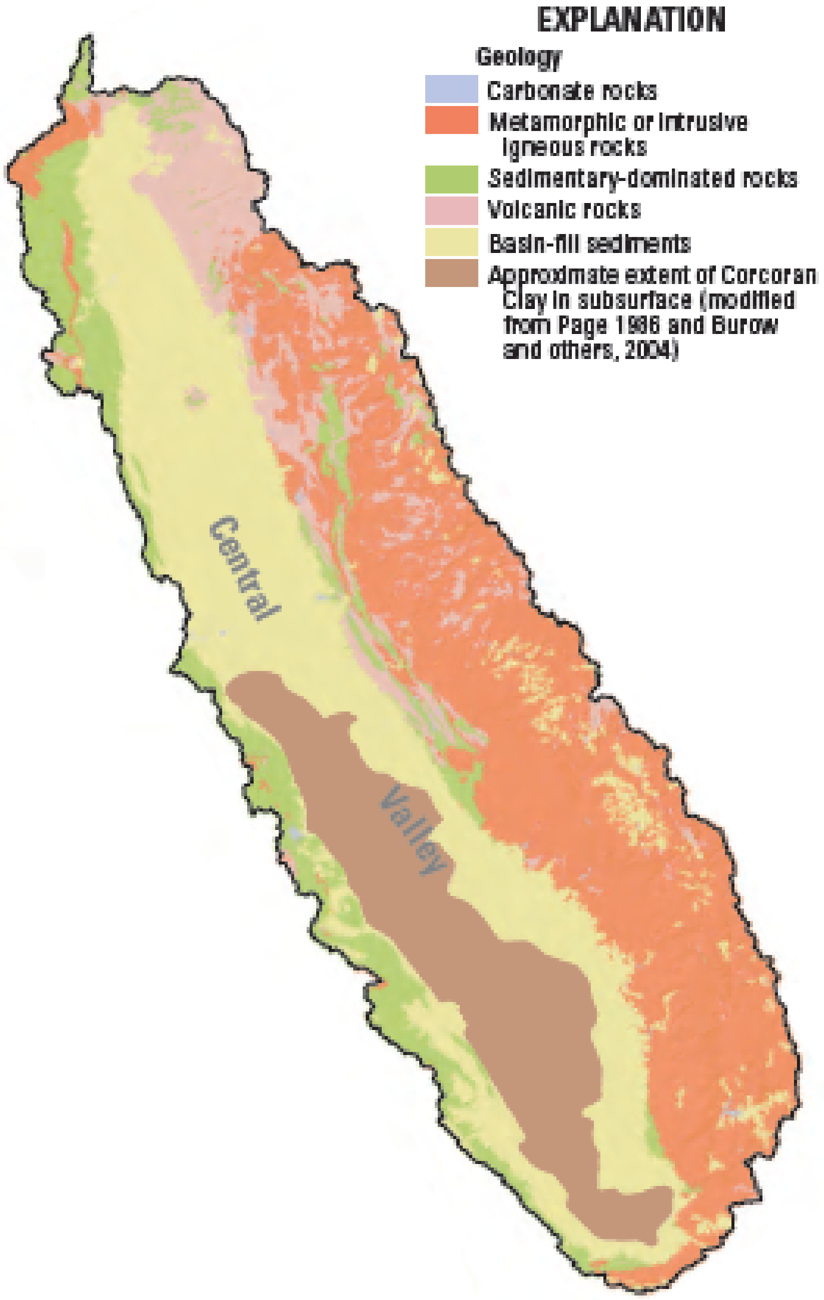

Figure 2- 6. Generalized geology of the Central Valley, California

(Source: Thiros et al, 2010)

2.2.1 Hydrogeologic Layers

The stratigraphy data represents the geology that deals with the origin, composition, distribution and succession of subsurface layers. Stratigraphy data at each node include; ground surface elevation with respect to common datum, bottom elevation of aquifer layer, thickness of aquitard and thickness of aquifer layer. Table 2- 3 shows the weighted average flow model layer thicknesses in feet for the Central Valley subregions (water accounting units), summarized from C2VSIM CVstrat.dat file. Subregions 10 and 15 have a confining layer, this represents the distribution of the Corcoran clay in San Joaquin and Tulare basins.

Each element has characteristics based on its specific location, or assigned more generally by sub-region. These values are determined by a variety of physical parameters and land use data, including area, elevation, soil type, crop type, and hydrologic connectivity to streams, porosity, storativity, hydraulic conductivity, boundary conditions and other elements. Aquifer properties attributed to the region's geological conditions in the model are effective horizontal and vertical hydraulic conductivity and specific yield and specific storage for each layer. Hydraulic conductivity parameterizes the rate of transport of water through layers per unit head gradient; storage coefficients define estimated release of water from storage due to unit change in hydraulic head. Table 2- 4 and Table 2- 5 show weighted average hydraulic conductivity and storage coefficients for all aquifer or aquitard units in the subregion, C2VSIM CVparam.dat file contains this data.

Average weighted specific yield and specific storage values in Table 2-5 are material physical properties that characterize the capacity of an aquifer to release groundwater from storage in response to a decline in hydraulic head. In an unconfined aquifer, the volume of water released from groundwater storage per unit surface area of aquifer per unit decline in the water table is known as specific yield, since the elastic storage component is relatively small. Confined aquifers on the other hand, the amount of water absorbed or expelled as head increases or decreases is largely due to the soil matrix skeleton either expanding or contracting, specific storage is used to compute volume of water released from an aquifer as head lowers. In Table 2-5 “=” is used in the case the storage coefficient is not applicable to aquifer layer.

Table 2- 3. Weighted Average Flow Model Layer Thicknesses (feet)

Subregion	Aquifer Layer 1	Aquitard Layer 2	Aquifer Layer 2	Aquifer Layer 3
1	353	0	238	241
2	379	0	256	703
3	365	0	265	675
4	317	0	325	556
5	337	0	270	385
6	394	0	347	1086
7	358	0	245	516
8	419	0	245	792
9	314	0	263	687
10	410	68	316	121
11	326	0	240	413
12	309	0	233	318
13	297	0	314	319
14	759	0	946	255
15	652	54	526	707
16	333	0	184	727
17	346	0	274	989
18	443	0	525	1142
19	760	0	565	122
20	744	0	620	870
21	798	0	758	1615

Table 2- 4 shows average hydraulic aquifer parameters representing heterogeneity of the underlying material, all layers show direction dependent hydraulic conductivity and therefore are anisotropic. The ratio of anisotropy is defined by Kv/Kh.

Table 2- 4. Average Weighted Effective Hydraulic Conductivity for Unconfined and Confining Units

Subregion	Layer 1			Layer 2					Layer 3	
	Horizontal HK (ft/month)	Aquifer Vertical HK (ft/month)	Kv/Kh	Horizontal HK (ft/month)	Aquifer Vertical HK (ft/month)	Aquitard Vertical HK (ft/month)	Aquifer Kv/Kh	Aquitard Kv/Kh	Horizontal HK (ft/month)	Aquifer Vertical HK (ft/month)
1	1767	1.7	9.90E-04	1994	2	=	1.00E-03	=	143	1.1
2	1731	1.7	1.00E-03	1978	2	=	1.00E-03	=	212	2.1
3	1459	3.8	2.60E-03	1642	4	=	2.40E-03	=	438	4.3
4	1701	2.7	1.60E-03	1892	2.9	=	1.50E-03	=	103	0.9
5	1944	2	1.00E-03	2232	2.3	=	1.00E-03	=	242	2.2
6	948	5.4	5.60E-03	996	5.4	=	5.40E-03	=	200	1.9
7	1602	1.6	1.00E-03	1876	1.9	=	1.00E-03	=	211	1.9
8	1390	1.3	9.60E-04	1585	1.6	=	9.90E-04	=	279	2.7
9	1363	1.8	1.30E-03	1567	2	=	1.30E-03	=	303	2.7
10	1199	4.8	4.00E-03	1547	2	0.03	1.30E-03	0.015	471	3
11	1704	1.3	7.70E-04	1526	1.5	=	9.90E-04	=	153	1.7
12	1518	1.3	8.40E-04	1632	1.5	=	9.10E-04	=	104	1.1
13	1480	2.1	1.40E-03	2027	1.5	=	7.50E-04	=	170	1.6
14	755	5.4	7.20E-03	1066	5.5	=	5.20E-03	=	82	1
15	999	3.8	3.90E-03	1118	4	0.03	3.50E-03	0.008	335	5.4
16	1463	1.2	8.50E-04	1414	1.4	=	1.00E-03	=	120	1.7
17	1255	1.3	1.00E-03	1561	1.6	=	1.10E-03	=	150	5.4
18	1321	1.6	1.20E-03	1353	1.8	=	1.30E-03	=	342	8.5
19	813	7.8	9.60E-03	553	6	=	1.10E-02	=	324	3.7
20	1505	2.2	1.40E-03	1102	2	=	1.80E-03	=	181	2
21	1140	4.5	3.90E-03	1019	3.4	=	3.30E-03	=	154	1.8

Table 2- 5. Average Weighted Specific Storage & Specific Yield for Confined and Unconfined Units

Subregion	Layer 1	Layer 2		Layer 3	
	Specific Yield Aquifer (1/ft)	Specific Yield Aquifer (1/ft)	Specific Storage Aquitard (ft/ft)	Specific Yield Aquifer (1/ft)	Specific Storage Aquitard (ft/ft)
1	0.20	0.10	=	0.13	=
2	0.17	0.18	=	0.19	=
3	0.18	0.36	=	0.42	=
4	0.16	0.08	=	0.09	=
5	0.17	0.17	=	0.21	=
6	0.16	0.16	=	0.20	=
7	0.20	0.16	=	0.19	=

8	0.18	0.23	=	0.28	=
9	0.17	0.24	=	0.30	=
10	0.19	=	5.7E-05	=	5.84E-05
11	0.17	0.14	=	0.17	=
12	0.18	0.09	=	0.11	=
13	0.20	0.14	=	0.16	=
14	0.21	0.07	=	0.08	=
15	0.23	=	4.3E-05	=	4.38E-05
16	0.22	0.10	=	0.13	=
17	0.20	0.14	=	0.18	=
18	0.20	0.30	=	0.39	=
19	0.21	0.27	=	0.35	=
20	0.20	0.14	=	0.18	=
21	0.31	0.12	=	0.16	=

2.2.2 Rootzone Representation

Hydrologic processes modeled in the rootzone include surface water inflows which enter the subregion from streams, as runoff from precipitation and as applied water. Outflows from the rootzone include evaporation and transpiration (modeled as a combined flux- evapotranspiration) and vertical flux to the unsaturated zone if infiltrated water minus evapotranspiration exceeds field storage capacity. Vertical interaction between surface and groundwater across the rootzone is performed and balanced across the control volume such that:

$$Inflows + Outflow = Change\ in\ soil\ water\ storage\ in\ rootzone$$

Soil parameters used in C2VSIM are hydraulic conductivity, field capacity and curve number (CN), input in CVparam.DAT file, weighted average values for each subregion are shown in Table 2-6. These are measures of permeability, soil capacity to retain water and runoff potential respectively. Table 2- 6 shows the variability of dominant soil types for each subregion. Subregions 1 has the lowest hydraulic conductivity value indicating that this subregion's soil is clay dominated, followed by subregion 3 with 0.64 ft/month, Subregion 5 with 0.77 ft/month, all in the Sacramento region.

Table 2- 6. Average Soil properties used in the model for each subregion

			Soil Parameters			Curve Number			
Subregion	Weighted Average Soil Type	Corresponding NRCS Soil Group	Field Capacity (volume water/unit volume of soil)	Total Porosity	Hydraulic Conductivity of Rootzone (ft/month)	Agriculture	Urban	Native Vegetation	Riparian Vegetation
1	3	C	0.107	0.4	0.34	92	94	90	84
2	3	C	0.107	0.4	1	93	95	91	86
3	4	D	0.128	0.46	0.64	96	97	95	89
4	3	C	0.107	0.4	0.99	93	95	92	87
5	4	D	0.128	0.46	0.77	96	97	95	89
6	4	D	0.128	0.46	0.99	96	97	95	89
7	4	D	0.128	0.46	1	96	97	95	89
8	4	D	0.128	0.46	0.95	96	97	95	89
9	3	C	0.107	0.4	1	94	95	92	89
10	3	C	0.107	0.4	0.95	95	96	94	90
11	3	C	0.107	0.4	0.95	94	95	92	89
12	2	B	0.175	0.48	0.95	89	91	90	85
13	3	C	0.107	0.4	0.98	95	96	93	90
14	3	C	0.107	0.4	1	95	96	94	92
15	3	C	0.107	0.4	1	95	96	94	92
16	3	C	0.107	0.4	0.87	95	96	93	90
17	1	A	0.08	0.44	1	86	89	87	85
18	3	C	0.107	0.4	1	95	96	94	90
19	3	C	0.107	0.4	1	96	97	96	93
20	3	C	0.107	0.4	0.85	95	96	94	92
21	2	B	0.175	0.48	1	91	93	92	88

2.2.3 Unsaturated Zone Representation

Vertical outflow from the rootzone becomes inflow into the unsaturated zone. C2VSIM computes routed (delayed) net outflow through this control volume to the water table at each monthly time step. Outflow from the unsaturated zone to water table represents net deep percolation from irrigation and precipitation, routing is a function of soil layer transport properties including thickness, porosity and vertical hydraulic conductivity. Weighted average vadose zone properties for each subregion these are assigned at each groundwater node taken from C2VSIM CVparam.dat file (Table 2- 7).

Table 2- 7. Weighted Average Unsaturated Zone Properties

Subregion	Layer Thickness (ft)	Total Porosity	Vertical Hydraulic Conductivity (ft/month)
1	64.1	0.11	1
2	39	0.11	1
3	50.8	0.11	0.9
4	7.5	0.1	0.6
5	16	0.11	0.9
6	21.8	0.1	0.8
7	32.1	0.1	0.8
8	55.2	0.11	1
9	16.7	0.11	0.9
10	47.8	0.12	0.9
11	29.2	0.12	1
12	29.5	0.12	1
13	30.9	0.12	1
14	101.5	0.11	0.6
15	30.6	0.12	1
16	33.1	0.12	1
17	24.5	0.12	1
18	41.6	0.12	1
19	168.6	0.12	1
20	144.5	0.12	1.2
21	190.2	0.12	1.8

2.3 Water Budgets

The primary effort of this modeling effort is determining the monthly water flow rates in and out of each subregion. We are concerned with each subregion's surface water and groundwater movements and monthly volumes for the following components:

- Water use for irrigation & urban demands through surface deliveries and pumping

- Evapotranspiration
- Deep Percolation of precipitation & applied water
- Reuse of irrigation water within subregion
- Stream-Aquifer interaction
- Lake-Aquifer interaction
- Boundary Inflows
- Inter-basin Flows
- Diversion or Conveyance Losses to groundwater
- Tile Drain Outflows
- Pumping
- Managed or Artificial Recharge
- Subsidence

Sections below describe how C2VSIM calculates these fluxes and summarizes model inputs representative of subregion's characteristic use of land and model input parameters for computing each of these fluxes.

2.3.1 Water Use (Surface Water & Groundwater for Agriculture and Urban Demands)

Mechanisms available in C2VSIM for providing water to meet agricultural and urban demands are surface water diversions and pumping. Re-use of return flow is also available within or outside of the subregion. There are 246 surface water diversion locations and 12 bypasses simulated in C2VSIM, of these 131 serve irrigated areas and 37 serve urban areas, Appendix B lists diversions and end uses for water delivered water (agricultural and urban). Two options can be specified by the user for allocating water in C2VSIM: 1) to calculate water demand as a function of land use and crop type and supply is adjusted to meet demand; 2) to set fixed allocations for surface water diversions and pumping with no adjustment to meet demand. The equation used to calculate demand depending on land use or crop type is:

$$Demand = \frac{CUAW}{I.E.}$$

Where CUAW is the consumptive use of applied water and I.E. is the irrigation efficiency. If supply adjustment is specified in input file Unit 5 and Unit 12, the user can specify two options for surface water supply calculations:

$$Surface\ Water\ Div. = \ Total\ Demand - Groundwater\ Pumping$$

or

$$Surface\ Water\ Div. = \ Total\ Demand$$

The option for water supply adjustment can be turned off, as is done in for runs in Chapter 4 and 5 of this study, which uses optimized CALVIN water deliveries to run C2VSIM. In this case, time series of diversions and pumping are specified in input file Units 26 and 24 respectively.

2.3.2 Evapotranspiration

Moisture in the root zone flows downward due to gravity and water in the soil is drawn out through plant roots for transpiration and evaporation. The combination of transpiration and evaporation is modeled in C2VSIM as a combined flux evapotranspiration (IWFM, 2012). Evapotranspiration is the primary consumptive use of water. Each crop type modeled has a characteristic potential crop evapotranspiration (ETc) under standard field conditions. This ET varies among crops and subregions as well as between development stages, so monthly ETc for each crop varies with water needs per growth stage. Table 2- 8 and Table 2- 9 show root depths for each crop and average ETc rates, taken from C2VSIM CVparam.dat and CVevapot.dat files respectively. Crop root depths mark a point within the root zone where withdrawal of infiltrated water for plant uptake ceases.

In addition to computation of ET within the model boundary, C2VISM also calculates ET fluxes for small unmonitored watersheds adjacent to the model boundary. There are 210 small watersheds contributing baseflow to groundwater nodes within model area and runoff to stream nodes within the model area. Average ETc for these small watersheds is 3.8 inches/month and 3.9 inches/month, for native vegetation and soil cover respectively.

Evapotranspiration fluxes are computed in the root zone and are fed at monthly time steps by stored soil moisture in the root zone, infiltrated precipitation and applied water. Water balance in the rootzone is therefore computed so that (IWFM, 2012):

$$\begin{aligned} & Infiltration\ from\ precipitation\ \&\ applied\ Water + Soil\ moisture\ begining\ of\ period \\ & \quad - Evapotranspiration = Soil\ moisture\ end\ of\ period \end{aligned}$$

Table 2- 8. Crop Root Depths

Crop Type	Crop Root Depth (ft)
Pasture	2.0
Alfalfa	6.0
Sugar Beets	5.0
Field Crop	4.0
Rice	2.0
Truck Crop	3.0
Tomato	5.0
Tomato (Hand Picked)	5.0
Tomato (Machine Picked)	5.0
Orchard	6.0
Grain	4.0
Vineyard	5.0
Cotton	6.0
Citrus & Olives	4.0
Urban	2.0
Native Vegetation	5.0
Riparian Vegetation	5.0

Table 2- 9. Average Crop Evapotranspiration rates

	Average ET rates (inches/month)																	
Subregion	**Pasture**	**Alfalfa**	**Sugar Beet**	**Field Crops**	**Rice**	**Truck Crops**	**Tomato**	**Tomato (Hand Picked)**	**Tomato (Machine Picked)**	**Orchard**	**Grains**	**Vineyard**	**Cotton**	**Citrus & Olives**	**Urban**	**Native Vegetation**	**Riparian Vegetation**	**Soil**
1	4.1	4.0	3.3	2.9	4.7	2.6	3.6	3.5	3.2	3.7	2.0	3.2	3.5	2.9	4.0	4.0	5.4	4.0
2	4.1	4.0	3.3	2.7	4.7	2.5	3.5	3.5	3.2	3.5	2.0	3.2	3.5	2.8	4.0	4.0	5.4	4.0
3	4.1	4.0	3.2	2.6	4.7	2.4	3.4	3.4	3.1	3.4	2.0	3.2	3.4	2.8	4.0	4.0	5.3	3.9
4	4.1	4.0	3.2	2.6	4.6	2.3	3.3	3.4	3.1	3.3	2.0	3.1	3.4	2.8	4.0	4.0	5.3	3.9
5	4.1	4.0	3.3	2.7	4.7	2.5	3.4	3.5	3.2	3.6	2.0	3.1	3.5	2.8	4.0	4.0	5.3	4.0
6	4.1	4.0	3.3	2.7	4.7	2.4	3.4	3.5	3.2	3.5	2.0	2.9	3.4	2.8	4.0	4.0	5.3	3.9
7	4.5	4.4	3.6	3.0	5.2	2.7	3.8	3.8	3.5	4.0	2.2	3.4	3.8	3.1	4.4	4.4	5.9	4.3
8	3.6	3.5	3.0	2.2	4.3	1.8	2.9	3.0	2.7	3.1	1.7	2.6	3.1	2.4	3.6	3.6	4.9	3.6
9	3.9	3.9	3.3	2.6	4.6	2.7	2.9	2.9	2.9	3.4	2.0	2.9	3.4	2.7	3.8	3.8	4.7	3.8
10	4.2	4.0	3.3	2.5	4.7	2.0	2.6	3.3	3.0	3.4	2.0	2.9	3.2	2.7	3.7	4.1	5.4	4.1
11	4.1	4.0	3.2	2.5	4.6	1.9	2.6	3.2	3.0	3.4	1.9	2.8	3.2	2.7	3.7	4.0	5.4	4.0
12	4.1	4.0	3.2	2.5	4.6	1.9	2.6	3.2	3.0	3.4	1.9	2.8	3.2	2.7	3.7	4.0	5.4	4.0
13	3.9	3.8	3.1	2.4	4.4	1.8	2.5	3.0	2.8	3.2	1.8	2.7	3.0	2.5	3.5	3.8	5.1	3.8
14	3.9	3.8	2.8	2.3	4.3	1.8	2.9	3.2	2.6	3.0	1.4	2.6	3.0	2.5	3.5	3.8	5.1	3.5
15	4.3	4.2	3.1	2.6	4.7	1.9	3.2	3.5	2.8	3.3	1.6	2.9	3.3	2.8	3.8	4.2	5.6	3.9
16	3.6	3.5	2.6	2.2	4.0	1.6	2.7	3.0	2.4	2.8	1.3	2.4	2.8	2.3	3.2	3.6	4.7	3.3
17	4.0	3.8	2.8	2.4	4.4	1.8	2.9	3.3	2.6	3.0	1.4	2.6	3.0	2.5	3.5	3.9	5.2	3.6
18	3.6	3.5	2.6	2.2	4.0	1.6	2.7	3.0	2.4	2.8	1.3	2.4	2.8	2.3	3.2	3.5	4.7	3.3
19	4.9	4.7	3.5	2.9	5.4	2.2	3.6	4.0	3.2	3.7	1.8	3.3	3.8	3.1	4.4	4.8	6.4	4.4
20	5.1	4.9	3.6	3.0	5.6	2.3	3.7	4.2	3.3	3.9	1.8	3.4	3.9	3.3	4.5	5.0	6.6	4.6
21	5.8	5.6	4.1	3.4	6.4	2.6	4.3	4.7	3.8	4.4	2.1	3.8	4.4	3.7	5.1	5.6	7.5	5.2

2.3.3 Deep Percolation of Precipitation and Irrigation Return Flows

Monthly precipitation rates from PRISM are assigned for each element within the model as well as small watershed elements outside the model. Precipitation in excess of infiltration becomes direct runoff and contributes to streams or lakes. Similarly applied water that does not infiltrate contributes to surface water flows as return flow. Infiltrated precipitation and applied water that is not used for evapotranspiration fluxes is transported vertically from the root zone to the unsaturated zone as ‘Deep Percolation’ and finally recharges the groundwater table as ‘Net Deep Percolation’.

Chapter 3 Section 3.5.1 describes how the net deep percolation term was divided for agricultural and urban areas to get separate contributions for application in CALVIN.

2.3.4 Reuse of Irrigation Water

Surface diversions and pumping contribute to applied water. Agricultural return flow of applied water can be re-used within the model area. Reuse of agricultural return flows can therefore be considered as a source of a subregion’s applied water supply. C2VSIM simulates monthly volumes of agricultural return flow and re-use is computed by a specified ratio of initial return flow.

2.3.5 Stream flow and Stream-Aquifer Interaction

Surface water flow is controlled by the timing and volume of stream inflows defined within the model. C2VSim specifies 43 stream nodes where stream inflow occurs. Inflows in river channels are specified for 36 streams along with monthly historical inflow volumes. Canals discharges of imported water to river beds (for diversion downstream) are specified at seven locations. A summary of average annual inflows, minimums and maximums is in Table 2- 10, flows are taken from C2VSIM CVinflows.dat file. Stream inflows limit surface water available for agricultural and urban demands. The Sacramento River, Feather

River and American River are the three highest inflows with annual average flows at 6.1 MAF, 3.7 MAF and 2.6 MAF respectively. These streamflows enter the model downstream of regulating reservoirs.

Table 2- 10. Stream Inflow for Central Valley streams included in model

Stream	Average (taf/yr)	Min. (taf/yr)	Max. (taf/yr)
Sacramento River	6117	2504	13199
Cow Creek	457	48	1096
Battle Creek	345	96	893
Cottonwood Creek	583	68	1965
Paynes and Sevenmile Creek	52	0	126
Antelope Creek Group	202	53	447
Mill Creek	213	68	417
Elder Creek	64	5	219
Thomes Creek	207	16	559
Deer Creek Group	375	104	841
Stony Creek	332	14	1337
Big Chico Creek	99	18	247
Butte and Chico Creeks	351	84	740
Feather River	3659	863	8424
Yuba River	1888	306	4140
Bear River	341	10	966
Cache Creek	268	6	1396
American River	2580	530	6410
Putah Creek	318	23	1144
Consumnes River	345	16	1221
Dry Creek	95	0	481
Mokelumne River	568	125	1737
Calaveras River	145	12	553
Stanislaus River	585	5	1678
Tuolumne River	1625	504	4478
Oristimba Creek	11	0	65
Merced River	902	252	2736
Bear Creek Group	51	1	391
Deadman's Creek	40	0	313
Chowchilla River	66	1	323
Fresno River	79	3	334
San Joaquin River	901	48	3592
Kings River	1594	392	4160

Kaweah River	407	75	1389
Tule River	111	11	607
Kern River	674	184	2364
FKC Wasteway Deliveries to Kings River	0	0	0
FKC Wasteway Deliveries to Tule River	3	0	50
FKC Wasteway Deliveries to Kaweah River	11	0	142
Cross-Valley Canal deliveries to Kern River	8	0	95
Friant-Kern Canal deliveries to Kern River	10	0	140
MADC spills to Fresno River	3	0	103
MADC spills to Chowchilla River	1	0	32

Streams are divided into 75 reaches with nodes that define location along reach, groundwater nodes connecting stream to groundwater and stream node into which the reach flows to. A total of 449 stream nodes are defined in C2VSIM. At each stream node, a rating table or stage-discharge relationship is specified, as well as the bottom elevation of stream bed. These rating curves are also used to calculate the head difference between the stream node and the groundwater node (Δh_{sg}) to determine the vertical flux through the stream bed associated with a given stream flow rate. Vertical flux between stream node and aquifer node is modeled as:

$$Q_{st} = \frac{K_{st} w_{st} L_s}{d} \Delta h_{sg}$$

$Q_{st} - flow\ rate\ between\ stream\ section\ and\ aquifer$

$K_{st} - vertical\ Hydraulic\ conductivity\ of\ streambed\ material$

$w_{st} - width\ of\ stream\ section$

$d - thickness\ of\ stream\ bed\ material$

$L_s - length\ of\ stream\ section$

$\Delta h_{sg} - difference\ between\ the\ head\ in\ stream\ node\ and\ head\ in\ aquifer\ node$

The above equation is used if head at the groundwater node exceeds the river bottom elevation, so saturated conditions exist between river and the aquifer. However, if unsaturated conditions exist (hydraulically disconnected stream aquifer interaction), the head at aquifer node is less than the elevation of river bottom, and C2VSIM simulates river vertical flow to aquifer as:

$$Q_{st} = K_{st} w_{st} L_s (\frac{s}{d})$$

This approximation assumes the streambed is not saturated at all times and re-wetting of streambed may not take place within a month time step following dry conditions; therefore, when stream stage is small compared to the thickness of the streambed, s/d will be much less than 1, and the stream flow will likely be used in re-wetting the streambed and no seepage will occur (Niswonger et al, 2010). As a result this expression produces less seepage rates when stream stage is small. Stream bed parameters including hydraulic conductivity of stream bed, thickness of stream bed and wetted perimeter are listed in the Unit 7, CVparam.DAT file. $\frac{K_{st}}{d}$ is reduced to streambed conductance at all nodes by assigning a uniform stream bed thickness of 1.0 foot. Hydraulic conductivity of stream bed ranges from 0 ft/month (Glenn Colusa Canal, which is turned off in the model) to 1952.4 ft/month (Feather River) with an average of 86.9 ft/month. Wetted perimeter ranges from 50 ft (Cache Creek) to 200 ft (Stony Creek) with an average of 372.8 ft.

2.3.6 Lake-Aquifer Interaction

Lake storage is modeled in C2VSIM, two lakes are represented in the model: Buena Vista and Tulare Lakes. Hydrologic components that affect lakes are precipitation, evaporation, groundwater interaction inflows from and overflow to streams. Lake geometry are inputs with geological properties in Table 2-11**.**, elevation data from C2VSIM CVmaxlake.dat file and thickness and hydraulic conductivity values from CVparam.dat file.

Table 2- 11. Lake parameters defined in C2VSIM

Lake	Area (ac)	Top Elevation (ft)	Bottom Elevation (ft)	Lake bed thickness (ft)	Lake bed Hydraulic Conductivity (ft/month)
Buena Vista	36,920	321	291	1	20
Tulare	56,504	206	185	1	20

Vertical leakage from a lake to groundwater is computed as:

$$Q_{leakage} = \frac{K_v A}{b}(h_{lake} - h_{gw})$$

$Q_{leakage} - flow\ rate\ between\ lake\ and\ aquifer$

$K_v - vertical\ hydraulic\ conductivity$

$A - cross - sectional\ area\ for\ vertical\ flow\ at\ node$

$b - thickness\ of\ lake\ bed$

$h_{lake} - lake\ water\ elevation$

$h_{gw} - groundwater\ head\ at\ node$

2.3.7 Diversion Losses

Surface water diversion losses are categorized as recoverable or non-recoverable losses. Recoverable losses define percolation of surface water from diversion systems to groundwater due to canal leakage. Non-recoverable losses are due to evaporation or transpiration. In C2VSIM, diversion losses for each diversion are specified as a fraction of total diversions. These fractions are input in file Unit 25 CVdivspec.DAT. Appendix B lists loss fractions for all diversions.

2.3.8 Tile Drain Outlows

Tile drain outflows define fluxes from groundwater through subsurface structures set to control rise in groundwater table in some irrigated areas. These facilities are present in subregions 10 and 14. File Unit 17 CVtiledrn.DAT, includes tile drain specifications hydraulic conductance of the interface between aquifer and the drain, elevation of drain and stream node into which drain flows into. Outflow from tile drains go to diversions. Average elevation of tile drains is 158.8 ft and hydraulic conductance is 0.1 ft^2/month. Flow between groundwater and tile drains is calculated as:

$$Q_{td} = C_{td}(z_{td} - h)$$

$Q_{td} - Flow\ from\ groundwater\ to\ tile\ drain$

$C_{td} - conductance\ of\ interface\ between\ aquifer\ and\ drain$

$z_{td} - elevation\ of\ tile\ drain$

$h - groundwater\ head\ at\ drain\ location$

2.3.9 Artificial Recharge

Artificial recharge refers to managed systems that send surface water to groundwater by spreading or direct recharge wells. C2VSIM simulates spreading facilities in subregions 13 and 15 to 21. Artificial recharge is important particularly in depleted aquifers so that groundwater-surface interaction patterns can be returned to normal seasonal and inter-annual fluctuations. In C2VSIM artificial recharge fluxes are calculated for each diversion allocated for spreading with a fraction of recoverable flow. These fractions are input in file Unit 25 CVdivspec.DAT. Recoverable fraction is 0.95 for all diversions for spreading.

2.3.10 Boundary Inflow

Precipitation for small watersheds outside of model area (Figure 2- 7)becomes either direct runoff and may join connected streams into the model area or becomes base flow which contributes to groundwater flow to the model area through connected groundwater nodes. The simulation for evapotranspiration fluxes for these areas is described in section 2.3.2 of this chapter. Direct runoff generated outside of model is routed to stream node in model that receives runoff from corresponding small watershed. Nodes to receiving stream nodes are specified in Unit 8 CVbound. DAT file.

The simulation for base flow and percolated surface water flow from small watersheds to groundwater within the model area is simulated by setting boundary conditions in CVbound.DAT file that specify groundwater node numbers the flow is routed through corresponding maximum recharge rate for these nodes and the groundwater node that receives baseflow from the small watershed(s).

There are 210 small watersheds simulated in C2VISM with areas ranging from 1,386 to 293,160 acres and maximum groundwater flow from outside the model to groundwater node for each monthly time step ranges from 10 ac-ft to 200 ac-ft.

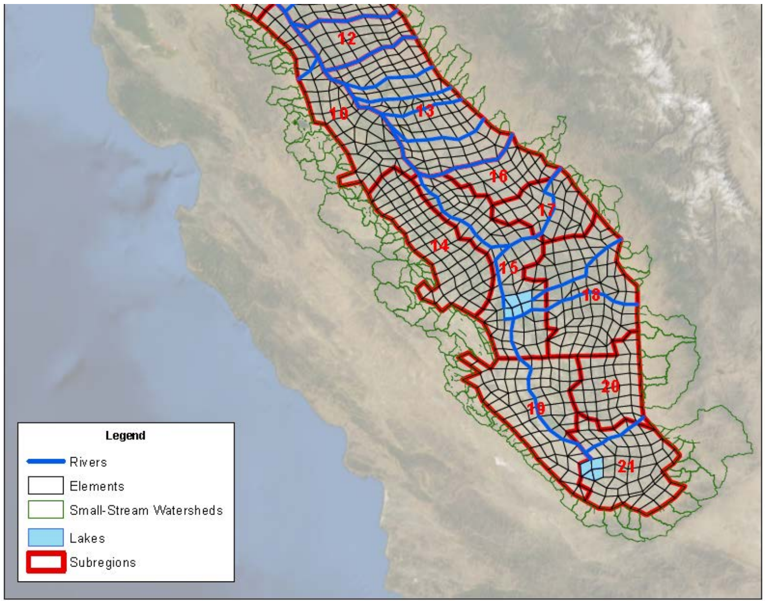

Figure 2- 7. C2VSIM Central Valley Finite Element, model boundaries and discretization watersheds outside model area

(Source: CDWR-California Department of Water Resources. (2012). Theoretical Documentation, User's Manual and Z-Budget: Sub-Domain Water Budgeting Post-Processor for IWFM. Sacramento (CA): State of California, The Resources Agency)

2.3.11 Interbasin Inflow

Groundwater flow between subregion boundaries is termed interbasin flow. These are head dependent fluxes representative of subregional horizontal flow. Given that horizontal hydraulic conductivities are significantly larger than vertical hydraulic conductivities, the major flow directions for this regional model are horizontal.

2.3.12 Subsidence

Land subsidence due to the compaction of aquifer systems is a consequence of groundwater withdrawal in some parts of the Central Valley. As groundwater is removed by pumping, the groundwater head can drop to levels that cause buried clay layers to compact. This compaction can occur elastically (recoverable) or inelastically (irrecoverable) causing temporary or permanent subsidence respectively, depending on the stress history and properties of interbeds and confining units (Bear, 1979).

An interbed is used to define a poorly permeable bed within a relatively permeable aquifer, these are assumed to (1) consist of highly compressible clay and silt deposits from which water flows vertically to adjacent course-grained beds, (2) be of insufficient lateral extent to be a confining unit that separates adjacent aquifers, (3) have relatively small thickness compared to lateral extent and (4) have significantly lower hydraulic conductivity than the surrounding aquifer material, yet be porous and permeable enough to uptake or release water in response to head changes in the adjacent aquifer material. Compression of sediments of interbeds and confining units define storativity – volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area – therefore water derived from these layers is due to compressibility of the matrix (Hoffmann et al, 2003).

Details on IWFM accounting for changes in storage due to subsidence can be found in IWFM theoretical document (CDWR, 2007) and summarized briefly here. C2VSIM simulates vertical compaction only. Controlling properties are changes in effective stress for a given change in head within the interbeds and interbed thickness. In C2VSIM, preconsolidation head which is an input in CVparam.DAT file is used to switch between elastic and inelastic storage properties; specific storage is changed to inelastic values whenever the hydraulic head dropped below the precompression hydraulic head. Change in thickness of interbed layers is defined as:

$$\Delta b = S_k * \Delta h$$

Δb *is change in interbed thickness*

S_k *is skeletal storage coefficient of interbed*

Δh *is the change in hydraulic head*

Table 2- 12 shows a summary of weighted average hydrogeological parameters for fine-grained sediments used in C2VSIM from CVparam.dat file. Negative compaction signifies an expansion or increased thickness of the interbed. Storage changes and the corresponding compaction in the interbed are computed at each monthly time step. The flux into groundwater derived from the storage change per unit area at each node *i* is total elastic and inelastic skeletal storage change is according to:

$$q_i^m = \frac{S_{k(inelastic)}}{\Delta t^m}(h^m - h^{m-1}) + \frac{S_{k(elastic)}}{\Delta t^m}(h^m - h^{m-1})$$

q_i^m *is flux derived from storage change per unit area at not i at this time step*

$S_{k(inelastic)}$ *and* $S_{k(elastic)}$ *are inelastic and elastic skeletal storage coefficients of interbed*

h^m *is head at this time step*

h^{m-1} *is head at previous time step*

Table 2- 12. Weighted Average hydrologic properties of the fine-grained sediments used in C2VSIM

	Weighted Average Interbed parameters											
	Elastic Storage Coefficient			Inelastic Storage Coefficient			Interbed Thickness (feet)			Precompression Hydraulic Head (feet)		
Subregion	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
1	4.2E-06	6.4E-06	3.3E-06	1.0E-06	8.0E-07	8.0E-07	10.2	6.3	1.6	562.2	432.7	428.3
2	2.7E-06	2.8E-06	3.6E-06	1.0E-06	1.5E-06	1.5E-06	10.4	35.1	2.9	530.3	555.0	492.9
3	3.0E-06	6.0E-06	8.9E-06	1.0E-06	2.1E-03	3.0E-06	7.1	92.5	5.9	408.8	553.8	397.1
4	3.4E-06	3.8E-06	1.8E-06	1.0E-06	5.1E-04	6.3E-07	13.6	26.7	1.2	427.1	-3.7	-57.6
5	2.4E-06	2.1E-06	3.1E-06	1.0E-06	1.4E-06	1.4E-06	13.2	50.0	2.7	504.7	109.3	52.1

6	3.1E-06	3.9E-06	4.5E-06	1.0E-06	3.5E-03	1.4E-06	6.5	67.7	2.7	243.5	92.7	-55.7
7	1.8E-06	2.0E-06	2.8E-06	1.0E-06	1.3E-06	1.3E-06	24.5	37.6	2.6	273.0	90.8	91.2
8	2.5E-06	2.5E-06	4.2E-06	1.0E-06	1.9E-06	1.9E-06	7.4	71.2	3.7	165.4	228.0	231.8
9	2.8E-06	2.7E-06	5.7E-06	1.0E-06	1.9E-03	2.0E-06	11.1	71.2	3.7	178.0	228.0	231.8
10	3.0E-06	3.6E-06	2.7E-06	1.0E-06	1.2E-03	2.5E-06	52.8	70.0	4.0	115.1	-24.5	-166.2
11	1.6E-06	1.6E-06	1.6E-06	1.0E-06	1.1E-06	1.1E-06	7.8	43.0	2.4	104.9	116.2	97.2
12	9.7E-07	1.3E-06	7.6E-07	1.0E-06	7.5E-07	7.5E-07	15.0	32.4	2.7	37.9	96.8	86.9
13	2.1E-06	1.9E-06	1.6E-06	1.0E-06	3.1E-04	1.1E-06	29.2	64.0	20.7	61.0	192.2	161.9
14	3.0E-06	5.7E-06	1.4E-06	1.0E-06	1.6E-04	5.5E-07	318.7	144.3	171.7	44.9	169.2	136.6
15	2.9E-06	5.0E-06	6.6E-06	1.0E-06	3.7E-03	2.3E-06	158.3	356.7	234.9	86.2	248.8	-33.4
16	2.8E-06	3.4E-06	2.6E-06	1.0E-06	4.6E-06	8.2E-07	78.2	77.6	42.3	186.1	246.7	224.9
17	3.0E-06	3.8E-06	4.0E-06	1.0E-06	3.3E-06	1.1E-06	71.0	114.1	53.8	27.0	351.0	299.2
18	3.1E-06	2.8E-05	7.3E-06	1.0E-06	9.5E-03	2.5E-06	89.5	390.8	21.4	74.3	766.5	554.1
19	2.6E-06	5.4E-05	4.3E-06	1.0E-06	7.6E-03	2.2E-06	106.4	337.0	6.7	24.4	1060.3	978.0
20	2.7E-06	6.0E-05	2.8E-06	4.0E-05	6.5E-04	1.1E-06	94.8	179.8	3.3	82.2	589.6	563.9
21	3.2E-06	3.6E-06	3.5E-06	1.0E-06	3.3E-03	1.0E-06	42.0	64.3	2.9	10.4	568.6	513.5

2.3.13 Pumping

Groundwater pumping is simulated in C2VSIM by well locations or on an elemental basis for urban areas and agricultural areas respectively. There are 133 wells simulated in C2VSIM with 1 foot diameters; summary of well screen dimensions and elevation are in Table 2- 13. Elevations of well screens bottom and top perforations are input in CVwells. DAT file Unit 12. Total pumping for each subregion is distributed to wells assigned for pumping in that subregion as a fraction of total pumping. Fraction of vertical distribution of pumping for each aquifer layer to account for the effects of partial penetration of a well in aquifer layers that are hydraulically connected through the interface is given by:

$$f_m = l_s[1 + 7\sqrt{\frac{r}{2 * b * l_s}}\cos\left(\frac{\pi l_s}{2}\right)]$$

$f_m\ is\ the\ fraction\ of\ pumping\ from\ layer\ m$

$l_s\ is\ well\ screen\ length\ as\ a\ fraction\ of\ aquifer\ thickness$

$r\ is\ well\ radius$

$b\ is\ aquifer\ thickness$

Pumping from each aquifer layers is proportional to the length of the well screen and transmissivity of the aquifer layer and is computed as:

$$Q_{Pm} = Q_{Ptotal} \frac{f_m * T_m}{\sum_{i=1}^{N_L} f_i * T_i}$$

$Q_{Pm}\ is\ pumping\ from\ aquifer\ layer\ m$

$Q_{Ptotal}\ is\ total\ pumping\ assigned\ to\ well$

$T\ is\ aquifer\ layer\ transmissivity$

$N_L\ is\ number\ of\ aquifer\ layers\ in\ C2VSIM = 3$

$f\ is\ fraction\ of\ vertical\ distribution\ for\ each\ layer$

If a well dries up, head at that node is below bottom of aquifer during the time step, C2VSIM reduces the computed pumping by

$$\frac{difference\ between\ computed\ head\ and\ bottom\ aquifer\ elevation * Specific\ Yield * node\ area}{length\ of\ time}$$

iteratively until the difference between pumping rates in consecutive iterations converges. Pumping demands not assigned to dried wells is distributed to other wells in the subregion. This is because C2VSIM simulates saturated groundwater flow. A convergence subroutine checks if the aquifer at any node dries up during the time step and if so, pumping fractions are readjusted for the computation of actual water pumped from the dried node.

Table 2- 13. Summary of well data used in C2VSIM - Screening Lengths and Perforation Elevations

Subregion	Number of Wells	Well Screen Length (ft)	Average Elevation of Top Perforations (ft)	Average Elevation of Bottom Perforations (ft)
1	4	125	325	200
2	6	167	117	-50
3	3	183	33	-150
4	1	200	0	-200
5	9	133	-28	-161
6	8	134	-63	-197

7	8	100	-44	-144
8	9	100	-150	-250
9	4	100	-138	-238
10	7	100	-50	-150
11	10	100	-50	-150
12	5	100	-50	-150
13	8	88	63	-25
14	2	60	-265	-325
15	9	100	-389	-489
16	4	100	125	25
17	9	100	167	67
18	12	100	140	40
19	5	100	-260	-360
20	4	100	25	-75
21	5	100	100	0

C2VSIM distributes agricultural pumping to elements as a relative proportion of total area pumping such that:

$$Q_{Pe} = f_e * Q_{PT}$$

$Q_{Pe}\ is\ pumping\ at\ element, e$

$f_e\ is\ fraction\ pumping\ allocated\ to\ element, e$

$Q_{PT}\ is\ total\ area\ pumping$

Furthermore, fractions are specified for the distribution of element pumping for each aquifer layer. Table 2- 14 shows weighted average fractions distributing element pumping among the three aquifer systems layers.

Table 2- 14. Weighted average fractions for distributing element pumping for each aquifer layer

Subregion	Layer 1	Layer 2	Layer 3
1	0.68	0.32	0.00
2	0.68	0.32	0.00
3	0.55	0.45	0.00
4	0.62	0.38	0.00
5	0.69	0.31	0.00
6	0.63	0.37	0.00
7	0.69	0.31	0.00

8	0.55	0.45	0.00
9	0.52	0.48	0.00
10	0.11	0.89	0.00
11	0.49	0.51	0.00
12	0.27	0.73	0.00
13	0.23	0.77	0.00
14	0.03	0.97	0.00
15	0.13	0.87	0.00
16	0.70	0.30	0.00
17	0.60	0.40	0.00
18	0.25	0.75	0.00
19	0.40	0.62	0.00
20	0.22	0.78	0.00
21	0.16	0.84	0.00

Chapter Three: Updating CALVIN based on C2VSIM

This chapter describes the updated groundwater representation in CALVIN using the new Central Valley groundwater model that succeeds CVGSM, called C2VSIM, an integrated hydrologic model of California's Central Valley developed by the California Department of Water Resources (DWR). A description of C2VSIM is provided in Chapter 2. Originally in 2001, groundwater in CALVIN was based on the Central Valley Ground Surface Water Model (CVGSM) No Action Alternative (NAA) (USBR 1997), a predecessor of C2VSIM. The updates to groundwater in CALVIN are discussed in this chapter and CALVIN Appendix J (Davis et al, 2001) details how groundwater was represented in previous versions of CALVIN. The United States Geological Survey (USGS) Central Valley Hydrologic Model (CVHM), based on MODFLOW, was also studied extensively for this CALVIN groundwater update project and a comparison between C2VSIM, CVHM, and CVGSM can also be found in Chou (2012) and summary tables in Appendix D. Chou, also details challenges in using CVHM model current updates in CALVIN, these include issues with mass balance due to different CVHM postprocessors.

Data sources and procedures for extraction of terms and monthly groundwater hydrology for this update were generated from C2VSIM Run 356 ran on April 11, 2012. Procedures for extracting required terms from the physical model for CALVIN are discussed in this chapter. The chapter is organized around four topics: (1) Groundwater Conceptualization and Goals of CALVIN, (2)Location of Groundwater Reservoirs, (3) Update of Groundwater Representation in CALVIN based on DWR C2VSIM Historical Run R356 and DWR current ground water monitoring data, (4) Calibration Process for Updated Base Case CALVIN (5) Concluding remarks and limitation. References to supporting computer files are made. These files can be found in the “Software and Data Appendices” under “Groundwater Hydrology Update” in the electronic version of the CALVIN project reports.

3.1 Groundwater Conceptualization and goals of CALVIN

CALVIN (California Value Integrated Network) (Jenkins et al, 2001; Draper et al, 2003) provides time series of optimal surface and groundwater monthly operations, water use, and allocations to maximize net statewide economic benefit. CALVIN optimizes water management over a 72-year hydrology (1922-1993) for a particular level of infrastructure and land use development. Base Case CALVIN represents 2005 level of development and infrastructure. Water demands are represented as economic penalty functions, which represent each water user's economic willingness-to-pay for water deliveries (Howitt et al, 2001). Operation costs for pumping, artificial recharge, and treatment are also represented. CALVIN's computational engine is the HEC-PRM software which uses a generalized network flow optimization algorithm to perform multi-period optimization (HEC 1999). The network flow algorithm restricts the optimization model to find a solution within specified constraints such as mass balance, capacity and minimum flow constraints. Figure 3- 1 shows California areas and infrastructure modeled in CALVIN.

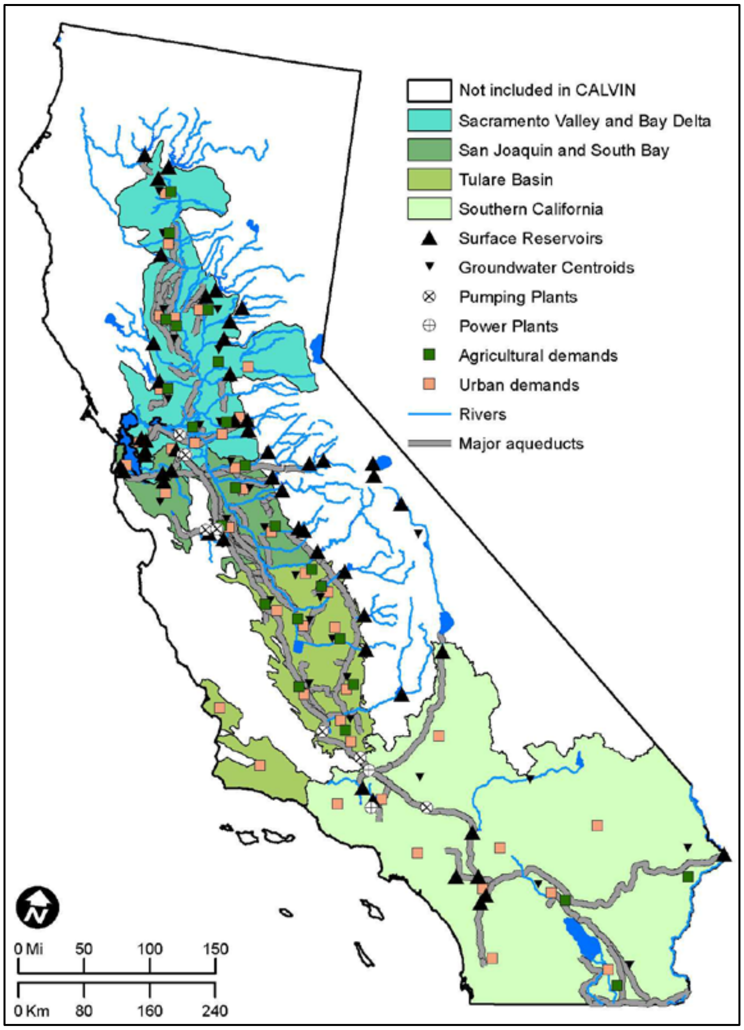

Figure 3- 1. CALVIN Coverage Area and Network

Groundwater basins are represented as lumped reservoirs with a known capacity, and treated similarly to surface reservoirs. The model does not dynamically quantify groundwater flow within and between groundwater sub-basins. Instead CALVIN uses fixed series of flows for streamflow exchanges, deep percolation from precipitation, inter-basin flows, tile drain outflows, subsidence and conveyance losses derived from historical levels used in C2VSIM, with some adjustments to accommodate for understood current aquifer conditions and interactions. The aforementioned monthly flows from these processes are summed and included in CALVIN as "Net External Inflow". While Net External Inflows are fixed in CALVIN, recharge to groundwater from applied water in agricultural and urban areas is dynamic. A fixed factor (amplitude) is assigned to each area specifying the portion of return flow to groundwater of applied water. This effectively creates the link between the groundwater basin and 'overlying' land use area. A constant unit pumping cost is assumed (fixed head, see section on Pumping cost below), estimated for an average depth to groundwater. The simplified representation of aquifers is required due to limitations imposed by the network flow solver, and by lack of data regarding the groundwater hydrology and use. Additionally since CALVIN does not relate pumping stress and aquifer heads C2VSIM is used to estimate sustainable yield.

3.2 Location of Groundwater Reservoirs

The Central Valley groundwater "reservoirs" in CALVIN represent 21 subbasins (GW-1 to GW-21) and conform with the Central Valley Production Model (CVPM) subbasins and subregions defined in C2VSIM (Figure 3- 2). These subregions make up the Central Valley's Sacramento River (GW-1 to GW-9), San Joaquin River (GW-10 to GW-13) and Tulare Lake (GW-14 to GW-21) Hydrologic Regions (HR). C2VSIM produces monthly mass balance budgets for each of the 21 regions. Table 3- 1 shows basin names per DWR, Bulletin 118 -2003 (CDWR, 2003), for each C2VSIM and therefore CALVIN groundwater subbasins.

The Sacramento River basin covers approximately 17.4 million acres and extends south from the Modoc Plateau and Cascade Range at the Oregon border, to the Sacramento-San Joaquin Delta. Significant features of the region include Mount Shasta and Lassen Peak in the southern Cascades, Sutter Buttes in the south central portion of the Sacramento Valley and the Sacramento River, which is the longest river in the system in the State of California with major tributaries the Pit, Feather, Yuba, Bear and American Rivers. This region is the main water supply for California agricultural and urban areas with nearly one-third of the State's annual runoff estimated at 22.4 MAF. There are 40 major surface water reservoirs in the region, the largest being the USBR's Shasta Lake (Central Valley Project) on the upper Sacramento River and Lake Oroville (DWR's State Water Project) on the Feather River, which provide about 76% of the state's water supply with groundwater supplementing the rest of the water demand (CDWR, 2003).

Table 3- 1. Location of Groundwater basins & correspondence between CALVIN & DWR Basins

C2VSIM (Subregions-SR)	CALVIN	Location	DWR Subbasins Bulletin 118-2003
1	GW-1	Redding Basin	Redding Basin
2	GW-2	Chico Landing to Red Bluff	North portion of Sacramento Valley
3	GW-3	Colusa Trough	Midwest portion of Sacramento Valley
4	GW-4	Colusa Landing to Knight's Landing	Central portion of Sacramento Valley
5	GW-5	Lower Feather R. and Yuba R.	Midwest portion of Sacramento Valley
6	GW-6	Sacramento Valley Floor, Cache Creek, Putah Creek and Yolo Bypass	Southwest portion of Sacramento Valley
7	GW-7	Lower Sacramento R. below Verona	Mideast portion of Sacramento Valley
8	GW-8	Valley Floor east of Delta	Southeast portion of Sacramento Valley, Sacramento County Basin and north portion of Eastern San Joaquin County Basin
9	GW-9	Sacramento -San Joaquin Delta	Tracy Basin and west portion of Sacramento County Basin
10	GW-10	Valley Floor west of San Joaquin River	Delta-Mendota Basin
11	GW-11	Eastern San Joaquin Valley above Tuolumne R.	Modesto Basin and south portion of Eastern San Joaquin County Basin
12	GW-12	Eastern Valley floor between San Joaquin R. and Tuolumne R.	Turlock Basin
13	GW-13	Eastern Valley Floor between San Joaquin R and Merced R.	Merced Basin, Chowchilla Basin and Madera Basin
14	GW-14	Westland	Westside Basin
15	GW-15	Mid-Valley Area	Tulare Lake Basin and east portion of Kings Basin
16	GW-16	Fresno Area	Northeast portion of Kings Basin
17	GW-17	Kings R. Area	Southeast portion of Kings Basin
18	GW-18	Kaweah R. and Tule R. Area	Kaweah Basin and Tule Basin
19	GW-19	Western Kern County	West portion of Kern County Basin
20	GW-20	Eastern Kern County	Northern portion of Kern County
21	GW-21	Kern R. Area	South portion of Kern County Basin

The San Joaquin River basin covers approximately 9.7 million acres; it includes the northern half of the San Joaquin Valley, the southern part of the Sacramento-San Joaquin Delta, the Sierra Nevada and Diablo Range. San Joaquin counties include Calaveras, Tuolumne, Mariposa, Madera, San Joaquin, Stanislaus, most of Merced and Amador counties, and parts of Alpine, Fresno, Alameda, Contra Costa, Sacramento, El Dorado and San Benito counties. The region is heavily groundwater reliant, 31 percent of the State's overall supply for agricultural and urban uses is from the ground (DWR 2003). Since nearly the beginning of the region's agricultural production, groundwater has been used conjunctively with surface water to meet demands.

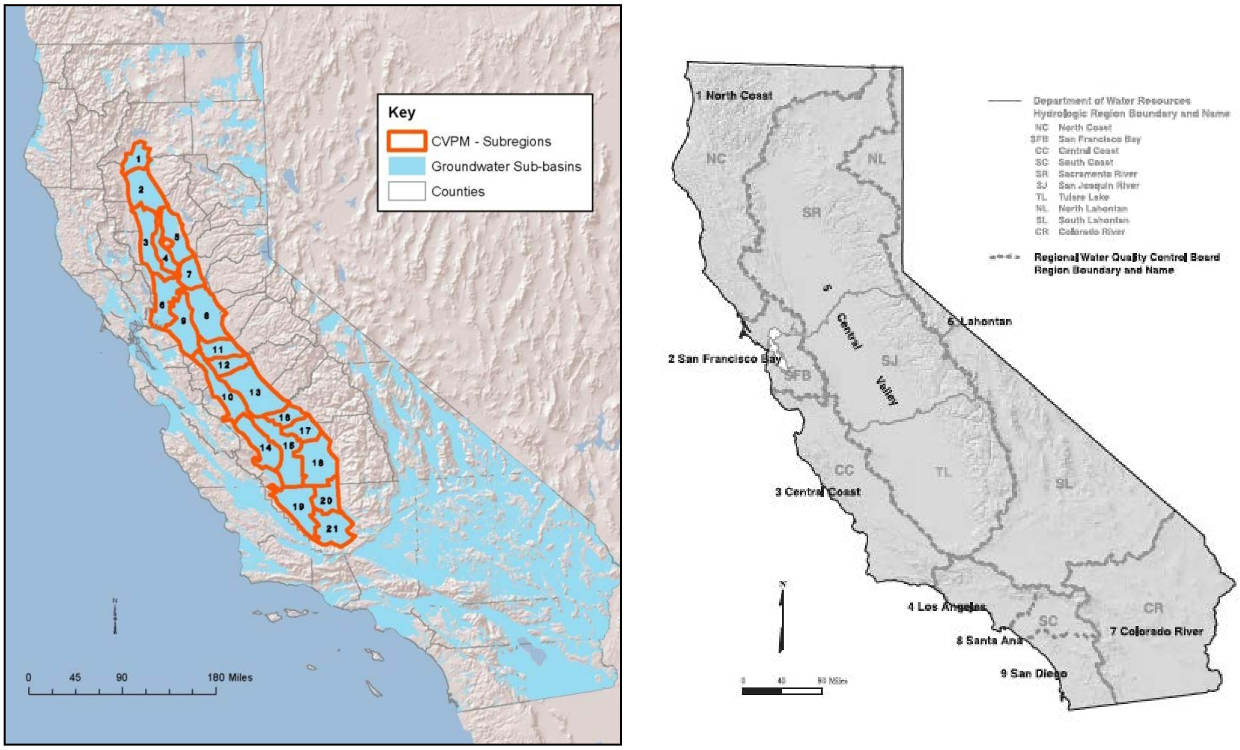

Figure 3- 2. Central Valley groundwater basins in CALVIN are represented by the Central Valley Production Model (CVPM) subregions and corresponding Hydrologic Regions (CDWR, 2003)

The Tulare Lake basin covers approximately 10.9 million acres and includes the southern half of the San Joaquin Valley and the Temblor Range to the west, the Tehachapi Mountains in the south and the southern Sierra Nevada to the east. The region consists of Kings, Tulare, and most of Fresno and Kern Counties. The cities of Fresno and Visalia entirely depend on groundwater for supply with Fresno being the second largest city in the United States reliant solely on groundwater. Groundwater use in the region represents about 10 percent of the State's overall supply for agricultural and urban uses (DWR 2003).

3.3 Groundwater Conceptualization and Interaction with Other Elements in CALVIN

Figure 3- 3 shows the conceptual water balance of groundwater in CALVIN for the Central Valley subregions, terms in this figure are listed in Table 3- 2 and are further described in section 3.4 below. This table and schematic were updated from previous versions to include terms in C2VSIM not previously represented in CALVIN. Additional nodes and links simplify the direct interaction with the groundwater sub-basins. Details on CALVIN schematic update are in Appendix A; these better accommodate components related to groundwater for the agricultural, urban sectors and artificial recharge and to facilitate calibration.

Table 3- 2. Groundwater Data Required to Run CALVIN for each sub-basin in Central Valley

Item	Groundwater Components for CALVIN	Data type
1	Agriculture return flow split (GW & SW)*	Fraction (a+b=1)
2	Internal reuse	Amplitude (>1)
3	Agricultural areas return flow of total applied water	Amplitude (<1)
4	Net External Flows sum of:	Monthly time series
4a	Inter-basin Inflows	
4b	Stream exchanges	
4c	Lake exchanges	
4d	Conveyance seepage	
4e	Deep Percolation of Precipitation	
4f	Boundary Inflow	
4g	Subsidence	
4h	Tile Drain Outflow	
5	GW Basin Storage Capacity (Initial, Maximum, Ending)	Number (Volume)
6	Lower-bound pumping for Ag. (minimum)	Number value
7	Upper-bound pumping for Ag. (maximum)	Number value
8	Average Pumping Depth Representative Depth to GW (Pumping Cost)	Cost (2008 dollars)
9	Surface Water Losses including Evaporation & Diversion losses to GW	Fraction (<1)

10	Artificial Recharge Operation cost	Cost (2008 dollars)
11	Infiltration Fraction of Artificial Recharge	Fraction (<1)
12	Urban Return Flow to GW	Fraction (<1)

*Notes: * Ag Demand GW represents the non-consumptive use portion of irrigation water that deep percolates to groundwater, and Ag Demand SW represents the portion that returns to surface water systems as tailwater.*

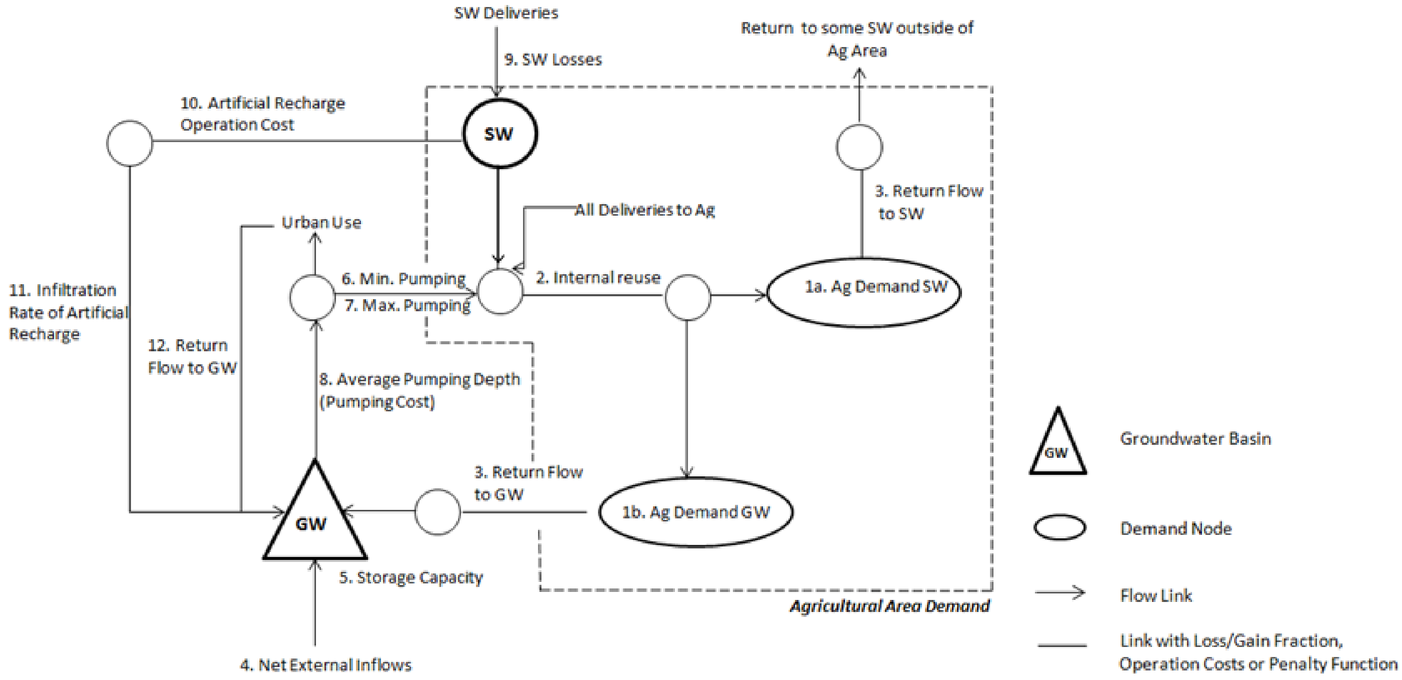

Figure 3- 3. Conceptual Groundwater Mass Balance Schematic

Section 3.4 below gives details of aspects of C2VSIM input and output used to drive CALVIN. All terms in the schematic were calculated from C2VSIM historical run or taken from C2VSIM input data. Most components in CALVIN were updated using output from 1980-2009 as these years better represent current infrastructure and land use, with the exception of time series of 'Net External Inflow'; components of C2VSIM that drive Updated CALVIN are :

- Agricultural return flow split – Calculated from groundwater and rootzone budget output for historical run 1980-2009
- Internal reuse - Calculated from land and water use budget output for historical run 1980-2009

- Agricultural and urban areas return flow of total applied water – Calculated from rootzone budget output for historical 1980-2009
- Net External Flows – Extracted from groundwater budget output for historical run 1922-1993 time series of recharge components, time series before 1951 were adjusted to account for changes in groundwater use after 1951 when the Central Valley Project started delivering surface water through the Delta-Mendota Canal
- Upper bound pumping for agriculture – Absolute maximum monthly pumping from land and water use budget output file for historical run 1980-2009
- Lower bound pumping for agriculture – Absolute minimum monthly pumping from land and water use budget output file for historical run 1980-2009
- Surface water losses incl. evaporation and diversion losses to groundwater – fraction losses in C2VSIM input data

3.4 Update of Groundwater Representation in CALVIN

Base Case demands in CALVIN represent a 2005 level of land use, generated using the Statewide Agricultural Production Model –SWAP (Howitt et al, 2001). CALVIN parameters listed in Table 3- 2 were calculated or extracted from C2VSIM input or output with the exception of the representative depth to groundwater. Publications on the C2VSIM model are available on DWR’s website these include details on model features, conservation equations, mathematical model and numerical model used to simulate hydrologic processes (CDWR, 2012 v. 3.02 rev. 36); user manual (CDWR, 2012 v. 3.02); details on the Z-budget post-processing (CDWR, 2010) and details on model testing (Ercan, 2006).

C2VSIM R356 simulates monthly groundwater flow, stream flow, and surface-groundwater interaction from 1921 to 2009, as a historical model with annually varying land use reflecting historical land distributions. Water demands are calculated based on land use, atmospheric, and hydrologic conditions.

Surface diversions are based on measured or observed reservoir releases. Pumped groundwater volume is calculated as the difference between calculated demand and surface water supply. CALVIN however uses a current or future level of development for water demands for the entire simulation period 1922 to 1993 with a fixed set of infrastructure (reservoirs, conveyance, etc.) operating over the entire model period. To account for influences of current major water supply infrastructure, only 1980 to 2009 C2VSIM output was used to calculate terms 1-3, 5-7 and 9-12 in Table 3-2 used in CALVIN.

Representative depths to groundwater for each subregion were calculated using DWR well monitoring data 2000 levels, these were used to compute pumping costs. For term 4 (Table 3- 9) - monthly time series inflows to groundwater – historical time series of inflows from C2VSIM budget outputs were used with some adjustments to stream flow exchanges to represent current aquifer conditions and to correct for direction fluxes (surface water –ground water interactions) prior to the 1950’s, where groundwater use was higher due to lack of surface water delivery infrastructure. Sub-sections below detail algorithms used to extract and calculate CALVIN’s terms and input time series.

3.4.1 Split Agricultural Return Flows to Surface Water and Ground Water (Terms 1a and 1b)

Applied water is the volume of water used for agricultural demand which includes crop demand and considerations of irrigation inefficiency. Non-consumptive water use, refers to applied water that is not used for plant evapotranspiration or field evaporation, this water returns either to groundwater as deep percolation or surface water as tailwater. CALVIN needs to split the water as it comes “in” to the farm (Figure 3- 3 -1a and Figure 3- 3- 1b), to divide the return flow between tailwater and deep percolation (Figure 3- 3, 3). Agricultural groundwater (Ag GW) in Figure 3- 3 represents the non-consumptive use portion of irrigation water that deep percolates to groundwater and ‘Ag SW’ represents the portion that returns to surface water systems as tailwater.

The HEC-PRM (USACE, 1999) solver used in CALVIN and the goal of CALVIN to reflect the interaction between surface and groundwater dynamically require separating percolation of applied water from surface return flows and other sources of percolation such as precipitation. The IWFM, a land-surface process computes infiltration and runoff from precipitation using the NRCS curve number method. The water budget process uses crop acreages and evapotranspiration rates to estimate crop water demand, and subtracts available root zone soil moisture to estimate irrigation water demand. Irrigation demand for agricultural and urban land uses is met with surface water diversions and groundwater pumping. At the end of each time step, if the water stored in the root zone exceeds the storage capacity, the excess is apportioned between runoff (Return Flow) and deep percolation. Moisture traveling from the root zone into the unsaturated zone is termed ‘Deep Percolation’, and moisture travelling from the unsaturated zone to the groundwater is termed ‘Net Deep Percolation’ in the C2VSIM *Groundwater Budget* output file(CDWR, 2012).

C2VSIM’s *Root Zone Budget* output file presents agricultural and urban land monthly water accounting; descriptions of terms in file output are listed in Table 3- 3.

Table 3- 3. C2VSIM Root zone budget terms

Term	Definition
Prime Applied Water	Total surface water diversion and groundwater pumping before any re-use takes plane
Return Flow	Net return flow of irrigation on agricultural lands after re-use to surface water bodies
Runoff	Direct runoff of precipitation that falls on agricultural lands
Actual Evapotranspiration	Actual evapotranspiration in agricultural lands computed based on ET rates and root zone moisture values
Beginning Storage	Root zone moisture in agricultural lands at the beginning of time step
Ending Storage	Root zone moisture at the end of time step
Infiltration	Total infiltration computed as summation of precipitation and applied water less runoff and return flow
Deep Percolation	Deep percolation from root zone to the unsaturated zone

C2VSIM performs moisture routing through the root zone from natural sources (precipitation) and applied water. For CALVIN it is necessary to separate the deep percolation volume due to precipitation from that resulting from applied water to compute fractions of non-consumptively used applied water that returns to groundwater and surface water (as deep percolation and run off, respectively). The following equations detail the computation of these fractions.

For each monthly time step for 1980-2009 historical run:

$$(1)\ \mathit{Applied\ Water\ in\ Infiltration} = \mathit{Applied\ Water} - \mathit{Return\ Flow}$$

$$(2)\ \mathit{Precipitation\ Infiltration} = \mathit{Precipitation} - \mathit{Runoff}$$

$$\mathit{Water\ in\ Rootzone} = (1) + (2)$$

Assuming water that leaves the root zone goes to the unsaturated zone within the monthly time step:

$$\begin{aligned}(3)\ &\mathit{Water\ to\ unsaturated\ zone}\\ &\quad = \mathit{Beginning\ storage\ in\ rootzone} + \mathit{Infiltration} - \mathit{Actual\ ET}\\ &\quad - \mathit{Ending\ storage\ in\ rootzone}\end{aligned}$$

$$(4)\ \mathit{Fraction\ applied\ water\ in\ Infiltration} = (1)/\mathit{Infiltration}$$

$$(5)\ \mathit{Deep\ percolation\ from\ applied\ water} = (4) * (3)$$

$$(6)\ \mathit{Total\ non - consumptive\ use\ applied\ water} = (5) + \mathit{Return\ Flow}$$

$$(7)\ \mathit{Fraction\ non - consumptive\ use\ applied\ water\ to\ GW} = (5)/(6)$$

$$(8)\ \mathit{Fraction\ non - consumptive\ use\ applied\ water\ to\ SW} = \mathit{Return\ Flow}/(6)$$

Final subregion fractions of non-consumptive use applied water to groundwater and to surface water were taken as average of weighted annual average amplitudes. Table 3- 4, shows fractions for each subregion that represent the split of agricultural applied water demands to represent flow returning to surface and groundwater in the CALVIN network.

Table 3- 4. Central valley Applied Water Return Flow Fractions to Surface and Groundwater

Subregion Number	Fractions of applied water return flow to GW (1b)	Fraction of applied water return flow to SW (1a)
1	0.28	0.72
2	1	0
3	0.6	0.4
4	0.99	0.01
5	0.72	0.28

6	0.98	0.02
7	1	0
8	0.93	0.07
9	1	0
10	0.94	0.06
11	0.94	0.06
12	0.94	0.06
13	0.97	0.03
14	1	0
15	1	0
16	0.84	0.16
17	1	0
18	1	0
19	1	0
20	0.82	0.18
21	1	0

3.4.2 Amplitude for Internal Reuse (Term 2)

The schematic representation of root zone flow processes simulated in C2VSIM called IWFM Demand Calculator (IDC) (CDWR, 2007) is shown in Figure 3- 4. The “U” term in this figure represents the reuse portion of initial return flow i.e. return flow from upstream farms in a grid cell (which can cover multiple farms) that is re-used by the downstream farms in the same grid. This reflects re-use within the subregion. Another type of reuse occurs when the return flow from a grid cell crosses the cell boundary and flows into a downstream grid cell where it is captured and re-used. The latter type of re-use is not included in the U term.

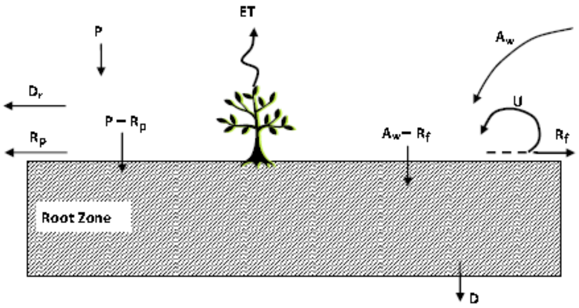

Figure 3- 4. Schematic representation of root zone flow processes simulated in C2VSIM

P-precipitation, A_w-Applied Water ie Irrigation, R_p-direct runoff of precipitation, ET-Evapotranspiration, D_r-outflow due to the draining of rice and refuge ponds, U-re-used portion of the initial return flow, D- deep percolation (Source: downloaded 14 July 2011 http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/IDC/IDCv4_0/downloadables/IDCv4.0_Documentation.pdf)

The C2VSIM *Land and Water Use Budget* output file provided monthly re-used volume and prime applied water (the total surface water diversion and groundwater pumping before any re-use takes place) that were used to calculate the fraction of applied water re-used such that:

$$Amplitude\ for\ Internal\ Reuse = \frac{Prime\ Applied\ Water + Re - used\ Water}{Prime\ Applied\ Water}$$

An average of monthly re-use fractions for 1980-2009 historical simulation for all Central Valley subregions are listed in Table 3- 5; are for irrigation months (April to October).

Table 3- 5. Central Valley amplitude for internal agricultural re-use

Subregion	Reuse Amplitude
1	1
2	1
3	1.183
4	1.001
5	1.1
6	1.001
7	1.056
8	1.009
9	1.012
10	1.009
11	1.052
12	1.037

13	1.001
14	1.013
15	1
16	1.082
17	1
18	1
19	1
20	1.003
21	1.012

3.4.3 Amplitude for Agricultural Return Flow of total applied water (<1) – Agricultural Areas (Term 3)

Potential Consumptive Use of Applied Water (Potential CUAW) is the applied water needed for adequate crop production by maintaining ET rates at their potential levels, soil moisture losses to deep percolation are minimized, and minimum soil moisture requirements at all times. Consumptive use depends on soil type, crop type and climatic data.

Return flow, deep percolation, and losses from irrigation are considered to be part of the non-consumptive use irrigation water (Figure 3- 5). The C2VSIM Root zone budget output file gives the monthly return flow, flow from the root zone to the unsaturated zone, and total applied water. Volume of applied water flowing to the unsaturated zone and therefore saturated zone (assumed within the monthly time step) is computed as shown in equation (6) of Section 3.4.1 above. The fraction of applied water that is non-consumptively used for each subregion is calculated for each month such that:

$$Fraction\ Irrigation\ water\ to\ SW\ \&\ GW = \frac{Return\ Flow}{Total\ Applied\ Water}$$

Subregion amplitudes of return flow were taken as the average of weighted annual average amplitudes, shown in Table 3- 6. Section 3.5.2 below discusses changes in some of the fractions computed from C2VSIM during calibration to better represent systems scarcities.

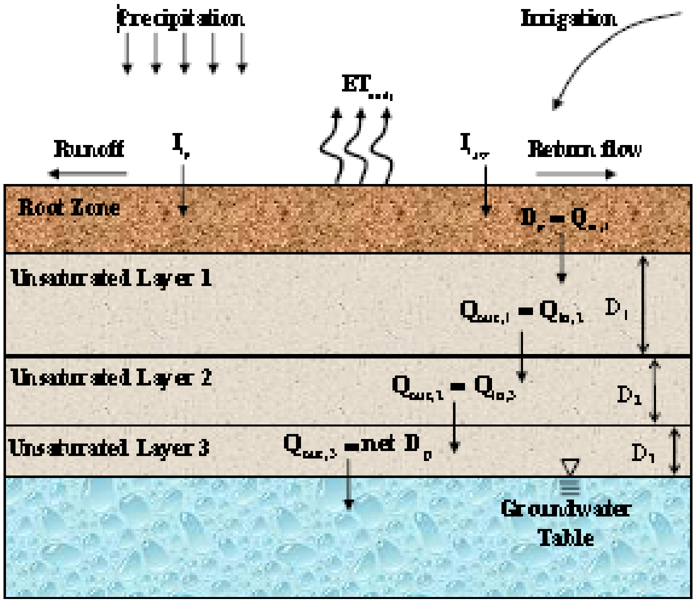

Figure 3- 5. C2VSIM simulation of non-consumptive use (Return Flow + Deep Percolation) applied water from Agricultural and Urban lands

(Source: downloaded 14 July 2011 http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/IDC/IDCv4_0/downloadables/IDCv4.0_Documentation.pdf)

Table 3- 6. Central Valley amplitude for agricultural return flow of applied water

	Fraction of Return flow of Applied Water for AG areas	
Subregion	**C2VSIM**	**Calibrated CALVIN**
1	0.47	0.47
2	0.14	0.26
3	0.2	0.2
4	0.14	0.14
5	0.21	0.21
6	0.06	0.1
7	0.25	0.25
8	0.12	0.12
9	0.09	0.1
10	0.2	0.2
11	0.22	0.22
12	0.16	0.18
13	0.12	0.13
14	0.18	0.18
15	0.12	0.12
16	0.28	0.28
17	0.13	0.13

18	0.18	0.18
19	0.03	0.03
20	0.1	0.1
21	0.1	0.1

3.4.4 Net External Inflows to Groundwater (Term 4)

Chapter 2 Section 2.3 details the computation of water budget terms simulated in C2VSIM. Head-dependent fluxes to and from groundwater basins are computed within the monthly time step and reported in the *Groundwater budget output* file. Hydrologic processes which define inflows and outflows to groundwater within each Central Valley subregion are detailed in chapter 2 section 2.3.

Groundwater pumping to agricultural and urban areas is computed dynamically in CALVIN to meet consumptive demands (evapotranspiration rates and urban usage) computed using the SWAP model. Return flow to groundwater from urban and agricultural regions are also dynamically represented by the return flow fraction, terms 3 and 12. The volume of artificial recharge is optimized in CALVIN based on foreseen needed storage for the entire simulation considering capacity constraints and the overall cost minimization objective. The other terms therefore are not dynamic in CALVIN but are fixed time series input to the model to ensure the groundwater mass balance in CALVIN is as close as possible to balances simulated in the C2VSIM groundwater model. The monthly sum of boundary inflows, streamflow exchange, lake exchange, subsidence, diversion losses, inter-basin inflows and deep percolation of precipitation is termed “Net External Flows” in CALVIN.

A best case for extracting these flows for current conditions Base Case CALVIN would be to run C2VSIM with constant land use set to 2005 levels as well as current diversions for each year’s hydrology from 1922 – 1993. However, a time series of diversions to match current infrastructure levels was too difficult to create, even based on regression for 1980-2003 diversion and gaged inflows to major surface water bodies. Consequently, more recent years from the historical C2VSIM run were used to develop this inflow time series. As a historical model, C2VSIM land use varies each year reflecting past land distribution, surface diversions are based on historical measured or observed reservoir releases, and groundwater pumping is calculated to match historical demand with supply.

Historical use of groundwater and surface water in California is such that in the 1930's improved deep-well turbine pumps and rural electrification enabled large and deep groundwater sources to be tapped, lowering groundwater heads in the Central Valley. The Central Valley Project began to use water from the San Joaquin and Sacramento Rivers to irrigate several million acres in the San Joaquin Valley diverted through the Madera and Friant-Kern Canals in the mid-1940s. The Central Valley Project started delivering surface water through the Delta-Mendota Canal in 1951. Changes in available delivery infrastructure and use of newly available surface water supplies allowed groundwater levels to recover continuing to 1951. The 1950's groundwater level responses in a historical model should therefore indicate less dependence on groundwater (Faunt et al, 2009).

The Net External Inflow term is given significant attention since the change in groundwater storage is a function of pumping and recharge. Given pumping from wells disrupts a natural equilibrium, such that over a long term when groundwater is mined, a cone of depression is formed; this cone is initially taken from aquifer storage. However as the cone of depression grows, eventually the periphery of the cone arrives at the rivers, lakes, ponds and wetlands; at this point water will either stat to flow from the stream into the aquifer or discharge from the aquifer to the stream will diminish or cease (Sophocleous, 2000). The cone will continue to expand with continued pumping until a new equilibrium is reached in which induced recharge from surface water balances pumping. At this point all pumping is balanced by flow from surface water bodies. This is a crucial issue, especially insofar as water rights and environmental issues are concerned. With induced recharge the water right used for a pumped unit of water is no longer a groundwater right but is supplied by a surface water right (Harou et al, 2008). It is important to make sure that changes in aquifer head and therefore surface-ground water interactions are represented appropriately in CALVIN.

Monthly budgets, included in the Net External Inflow term, are simulated in C2VSIM as head dependent fluxes. This means as groundwater levels in an aquifer change due to surface water availability changing land use and irrigation practices, the hydraulic connection between groundwater and surface water changes over time and affects groundwater- surface water interactions. However, since we cannot rerun C2VSIM with current initial heads since surface diversion time series and pumping for a projected land use case are difficult to extrapolate, we have used historical time series of inflows and outflows time series after 1951. Adjustments to some inflows before 1951 were made. Table 3- 7 shows differences in annual average inflow components before and after 1951. Annual averages presented by decade for each subregion are shown in Appendix C.

Table 3- 7 shows a total 1.11 Million acre-feet annual average difference in streamflow exchange after 1951 compared to annual average streamflow exchange before 1951 for the entire Central Valley. After 1951, most streams reversed from gaining to losing and therefore contribute more to groundwater basins. Other large differences overtime are recoverable diversion losses (472 taf/yr) and deep percolation from precipitation (634 taf/yr).

Table 3- 7. Differences between Historical Annual Average Flows before and after 1951 (taf/yr) in the Central Valley (computed as Average 1951-2009 – Average 1922 -1950)

Subregion	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precipitation
1	-7	3	0	8	0	0	13	-24
2	143	6	0	29	0	0	17	27
3	5	23	0	12	1	0	-63	24
4	69	30	0	0	2	0	14	42
5	59	53	0	3	0	0	16	59
6	112	11	0	2	1	0	19	49
7	23	18	0	27	0	0	-6	0
8	33	3	0	14	0	0	133	49

9	123	15	0	6	0	0	-123	10
10	-9	97	0	5	7	14	-47	31
11	77	24	0	0	0	0	-33	19
12	20	23	0	0	0	0	16	15
13	51	34	0	1	12	0	42	90
14	0	63	0	8	-20	0	105	5
15	234	-47	48	1	43	0	58	66
16	4	27	0	2	0	0	-85	52
17	10	28	0	2	0	0	25	37
18	-55	85	0	3	19	0	-156	80
19	138	-42	0	0	21	0	62	-13
20	2	9	0	4	40	0	-66	48
21	80	10	17	6	-25	0	58	-31
Central Valley Total	**1112**	**473**	**65**	**133**	**101**	**14**	**0**	**635**

Inter-basin inflows are horizontal groundwater flow between subregions. In C2VSIM model, these fluxes depend on relative head differences between neighboring basins. But the total flow is contained within the Central Valley, so the Central Valley total in Table 3- 7 for interbasin flow is zero. Changes in inter-basin flow occur due to changes in aquifer dynamics that may be driven by a combination of: increased/decreased recharge or deep percolation of applied water, changed stream-aquifer interaction, increased/decreased pumping in one basin relative to another, etc. Changes in infrastructure and operations before and after 1951 affect surface water flow to groundwater and therefore groundwater hydraulic heads and in turn the direction and magnitude of groundwater flow between basins. Although the direction of historical fluxes between neighboring basins have changed, it would be difficult to adjust these for current conditions without running the entire model for 2005 level of development for the 1922-2009 hydrology. As a result historical volumes for the interbasin term were used for the Base Case CALVIN update.

For recoverable diversion losses, differences before 1951 are largely due to diversion infrastructure built after 1951. On a subregion basis, these are rather small, the largest is 97 taf/yr for subregion 10. However, since this difference is only 9% of total Central Valley natural recharge, the historical time series was left unchanged.

Precipitation in C2VSIM infiltrates at a rate dictated by the soil type, land use and soil moisture. If soil infiltration capacity is less than the precipitation rate, the excess precipitation becomes direct runoff. The Soil Conservation Service method used estimates the amount of precipitation that becomes direct runoff based on the Curve Number (CN) method which is developed for a specific land use type, soil type and management practice.

The CN number is used to develop a retention parameter which is a function of the CN and soil moisture content. Therefore, calculated deep percolation of precipitation depends on hydrologic conditions (i.e. precipitation rates) in addition to land use, soil type and management practices. Adjusting this term would require adjusting surface water streamflows in corresponding regions to reflect changed runoff compared to historical gages. To maintain mass balance and avoid tampering with this rather complicated computation, the time series of deep percolation of precipitation was left untouched. The greatest change in annual average deep percolation of precipitation before and after 1951 occurs in subregion 10. The 90 taf/yr in Table 7 indicates average annual deep percolation of precipitation after 1951 is larger than before 1951 by 90 taf/yr. It is difficult to know how much this change is due to land use changes versus hydrology.

Tables in Appendix C show changes in direction and magnitude of flow between groundwater and rivers over time. Overall, less water goes from groundwater to streams after this time due to large changes in groundwater levels. If the historical time series of streamflows is used for example roughly a million acre-feet per year of water may not be accounted for correctly in the Central Valley. As a result streamflow exchanges before 1951 were adjusted using the annual average difference for subregions above 50 taf/yr, so that monthly inflows before 1951 were adjusted as (annual average difference in Table 3- 7). Adjusted subregions are 2, 4, 5, 6, 9, 11, 13, 15, 18, 19 and 21. To maintain mass balance of water available within the subregion, the difference between historical and adjusted stream inflows is accounted for in the depletion areas of respective subregions or as depletions or accretions to a major stream in these subregions. Table 3- 8 also shows depletion and accretion areas and streams corresponding to subregions as well as nodes per CALVIN network and monthly flows that need to be adjusted in respective depletion or accretion areas . Details on depletion areas and how they are used in CALVIN are in the original Appendix I (Draper, 2000).

Table 3- 9 shows annual average Net External Inflows used in CALVIN based on C2VSIM. The second column was used in CALVIN. Comparisons of average yearly flows under this term from CVHM the USGS Central Valley groundwater model and CVGSM which represents flows originally in CALVIN are also shown Chou (2012) details how Net External Inflows were calculated from the CVHM model. C2VSIM Net External Inflows represent annual average for 1921-2009 simulation; CVHM on the other hand represents average for 1980-1993.

Table 3- 8. Adjusted monthly flows to depletion and accretion areas in the Central Valley due to changes in historical streamflow exchanges before and after 1951.

Subregion	Depletion Area or Stream	Nodes in CALVIN network	Adjusted monthly inflows (taf/month)
2	10	D76a - DA10 Depletion	11.9
4	15	D66 - DA15 Depletion	5.8
5	69	D37 - DA69 Depletion	4.9
6	65	C20 - DA65 Depletion	9.3
9	55	D509 - D55 Depletion and Accretion	10.3
11	San Joaquin River to Tuolumne to Stanislaus	D688 – Depletion	6.4
13	Merced River	D643 - Depletion Upper Merced River	0.2
		D647 - Depletion Lower Merced River	0.3
	Chowchilla River	D634 - Depletion Chowchilla River	0.4
	Fresno River	D624 - Depletion Fresno River	1.4
	San Joaquin River	D605 - Depletion San Joaquin River	1.9
15	Kings River	C53 - Depletion Kings River	19.5
18	Kaweah River	C89 - Accretion Kaweah River	0.1
	Tule River	C57 - Accretion Tule River	4.5
19 and 21	Kern River	C97 - Depletion Kern River	18.2

Table 3- 9. Annual Average Net External Inflows[a] in the Central Valley

Note a) C2VSIM flows include streamflow exchange, lake exchange, tile drain outflows, subsidence, boundary inflows, interbasin inflows, deep percolation of precipitation and diversion losses. CVHM flows exclude diversion losses, tile drain outflows and lake exchange.

Subregion	**Net External Inflows to Groundwater (taf/yr)**			
	C2VSIM		**CVHM**	**CVGSM**
	w/ Adjustments to Streamflow Exchange	**w/out Adjustment to Streamflow Exchange**		
1	28	28	51	-96
2	235	177	419	189
3	-9	-9	237	77
4	-68	-96	407	227
5	91	67	409	6
6	225	180	**610**	302
7	168	168	327	242
8	402	402	748	686
9	134	85	1398	-118
10	72	72	229	262
11	29	-1	67	303
12	49	49	130	129
13	365	344	575	781
14	278	278	209	267
15	688	594	935	1130
16	51	51	3	273
17	96	96	167	309
18	241	263	344	402
19	424	368	260	121
20	101	101	-69	194
21	322	290	-56	322
Sacramento	**1206**	**1002**	**4606**	**1515**
San Joaquin	**515**	**464**	**1001**	**1475**
Tulare	**2201**	**2041**	**1793**	**3018**
Central Valley Total	**3922**	**3507**	**7400**	**6008**

3.4.5 Groundwater Basin Storage Capacity (Term 5)

Groundwater basin storage in CALVIN is estimated from C2VSIM *Groundwater Budget output file* in which monthly groundwater beginning and ending storages are computed. Since CALVIN does not simulate groundwater flow in a head-dependent manner, groundwater storage capacities are represented by (1) Maximum storage, which defines the total amount of available water in groundwater for each subregion, (2) Initial storage, defines the amount of water available in groundwater under current conditions (2005 level of development) (3) Ending storage defines constraint imposed on groundwater available for use within the subregion, such that, Initial – Ending = Allowable groundwater storage depletion or overdraft.

The updated version of CALVIN uses a maximum storage capacity taken as maximum historical storage for 1980-2009. Volumes for maximum storage were taken for each subregion as the maximum of Ending Storage reported in C2VSIM *'Groundwater budget output"* for 1980-2009, to represent current aquifer storage capacity conditions. Initial storage is taken as the Ending Storage for 2005. Ending storage specified in CALVIN is derived by the following steps:

$$(1)\ Determine\ Annual\ Average\ Historical\ Overdraft\ for\ 1980-2009\ (\frac{taf}{yr})$$

$$\begin{aligned}(2)\ &Apply\ this\ historical\ annual\ average\ overdraft\ for\ 72\ years\ simulation\ in\ CALVIN\\ &= (1) * 72, represents\ allowable\ groundwater\ overdraft\ for\ Base\ Case\ run\end{aligned}$$

$$(3)\ Ending\ Storage\ Constraint = \ \ Initial\ Storage - (2)$$

Table 3- 10 shows values of maximum storage, initial storage, allowed overdraft for 72 year simulation and ending storage for each of the Central Valley subregions. The reported storage volumes in Table 3-10, account for storage in all three layers of the aquifer, however water in the bottom third layer in practice is not considered "Usable water", the 2.9 Billion AF, of maximum storage is in fact not all available for use as pumping takes place in the first two layers only.

Table 3- 10. CALVIN Central Valley Subregion Groundwater Capacity & Overdraft Constraints

(Notes: a) (-) represent non-overdraft subregions.)

	(TAF)			
Subregion	**Maximum Storage**	**Initial Storage**	**Ending Storage**	**Overdraft over 72 year simulation**^{a}
1	38,510	38,447	39,437	-990

2	136,757	136,494	137,376	-882
3	133,958	132,687	131,748	939
4	61,622	60,728	60,508	220
5	92,020	91,113	90,457	656
6	175,719	174,968	175,275	-307
7	58,484	56,539	51,210	5,330
8	193,433	190,665	182,829	7,836
9	139,752	139,472	139,834	-362
10	91,920	90,210	87,055	3,155
11	59,302	58,838	58,246	592
12	43,510	42,602	40,865	1,737
13	142,508	138,216	128,560	9,656
14	181,001	178,840	172,009	6,831
15	313,759	309,643	306,666	2,977
16	64,915	64,696	64,438	257
17	98,836	97,214	93,653	3,561
18	322,480	321,375	332,438	-11,063
19	147,060	141,750	128,223	13,526
20	141,457	137,073	125,136	11,937
21	351,327	341,142	313,239	27,903
Sacramento	**1,030,255**	**1,021,114**	**1,008,673**	**12,441**
San Joaquin	**337,241**	**329,867**	**314,726**	**15,140**
Tulare	**1,620,834**	**1,591,732**	**1,535,803**	**55,930**
Central Valley Total	**2,988,329**	**2,942,713**	**2,859,201**	**83,511**

3.4.6 Minimum & Maximum Pumping Constraints (Term 6 & 7)

Monthly constraints on pumping volumes are imposed in CALVIN to represent existing pump capacities. Minimum pumping represents subregions that use groundwater even in wet years due to lack of access to surface water supplies. Pumping constraints are updated only for agricultural areas. For urban constraints refer to Appendix J of the original CALVIN model (Davis, 2001). Lower bound and upper bound pumping constraints were calculated as the minimum and maximum pumping volumes over 1980-2009 C2VSIM historical simulation, respectively. Lower bound pumping values were found to be zero for agricultural areas in Central Valley subregions. These constraints on monthly pumping volumes are however not related to sustainable yield considerations, in the C2VSIM run with optimized CALVIN deliveries for some subregions these pumping rates exceeded what is regarded as sustainable yield, this is explored in Chapter 5. Areas of the Central Valley with only access to groundwater are not yet represented as such in the current C2VSIM groundwater model. Monthly pumpage values are in the C2VSIM *Land and Water Budget output file*. Upper bound pumping values are shown in Table 3- 11 for all subregions.

Table 3- 11. Central Valley subregion Monthly GW pumping constraints for Agricultural demand areas

Subregion Number	Maximum AG Pumping (taf/month)	Minimum AG Pumping (taf/month)
1	7.2	0
2	93.2	0
3	175.8	0
4	109.2	0
5	240.1	0
6	85.7	0
7	120.5	0
8	185.6	0
9	43.9	0
10	185.2	0
11	64.9	0
12	86.9	0
13	225.8	0
14	221.1	0
15	335.3	0
16	61.8	0
17	152.6	0
18	238.4	0
19	213.7	0
20	125.3	0
21	265.6	0

3.4.7 Representative Depth to Groundwater and Pumping Cost - Extracted from DWR Well Monitoring Data for year 2000 (Term 8) (by Christina Buck)

An estimated pumping lift for each CVPM region is required for calculating pumping costs in CALVIN. Instead of using modeling results from C2VSIM to estimate lifts, it was decided using measured field data of groundwater heads would be best.

The pumping lift is the length that water must be lifted from the ground water surface in a well to the ground surface elevation. DWR monitors water levels throughout the Central Valley typically twice per year, once in the spring and then in the fall, usually close to the start and end of the irrigation season. A variety of well types make up their monitoring network, including irrigation, domestic, stock, monitoring, industrial, observation, recreation wells, and some wells no longer in use. Data from this monitoring effort are available online from the Water Data Library. The State is currently migrating these data to the online CASGEM (California Statewide Groundwater Elevation Monitoring) system.

In CALVIN, a single value represents typical pumping lifts in irrigation wells in each sub-region. Water level data was obtained by Aaron King from DWR. The full data set includes wells in regions 2-21 from years 1990-2011. The year 2000 was chosen to establish a representative pumping lift.

Measurements were tagged as Spring or Fall measurements based on a cutoff of July (July and earlier being a spring measurement, August and later being a fall measurement). This allowed for calculating the average 2000 spring measurement and fall measurement independently. DWR data includes ground surface elevation, distance between the reference point and the water level in the well (RPWS), the measured distance from the ground surface to the water level in the well (GSWS), the elevation of the measured groundwater level relative to mean sea level (WSE), etc. Ground Surface Water Surface (GSWS) is the measured distance from the ground surface to the water level in the well. These data were used to calculate a representative pumping lift.

There are a variety of well types in DWR's monitoring network. Wells in the categories of irrigation, irrigation and domestic, stock, unused irrigation wells, observation, and undetermined were used in the calculation. This served to focus mainly on irrigation related wells while still including enough categories to maintain a good sample size. The distribution of wells with measurements taken in 2000 is shown in Figure 3- 6.

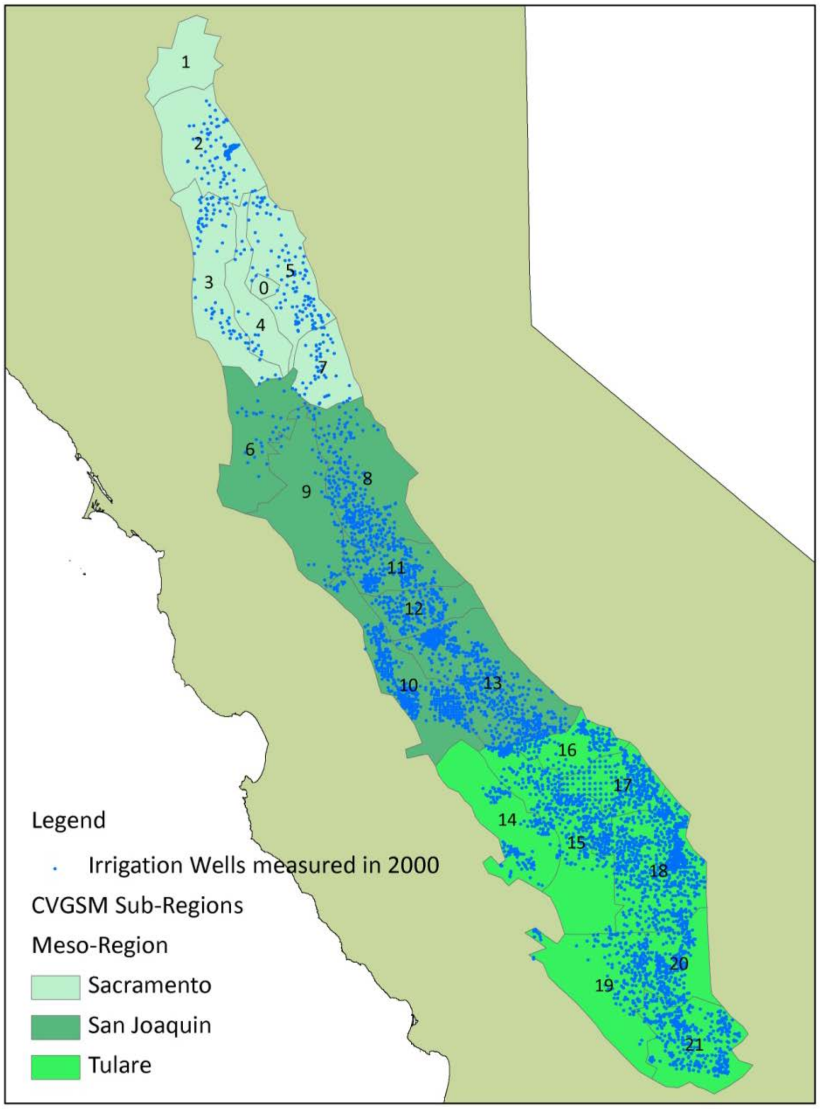

Figure 3- 6. Distribution of wells measured in 2000 used for the estimate of pumping lift

(courtesy of Aaron King)

Table 3- 12 shows averaged measurements taken any time during year 2000, average of fall and spring measurements, and the total number of measurements used for the year 2000 average (Count).

Table 3- 12. Average GSWS (feet) for measurements taken in 2000, Fall 2000, Spring 2000 and the total count of measurements used for the Year 2000 average

CVPM region or Subregion	GSWS (ft)			Count*
	Year 2000	Fall 2000	Spring 2000	
1	71	70	73	31
2	40	45	38	529
3	27	33	23	258
4	16	19	13	221
5	27	29	26	294
6	25	26	23	155
7	40	39	42	210
8	90	99	84	589
9	24	27	22	104
10	17	77	16	439
11	47	43	48	319
12	68	=	68	177
13	75	=	75	641
14	235	245	150	136
15	93	140	92	377
16	57	=	57	145
17	34	=	34	271
18	80	=	80	857
19	139	=	139	179
20	298	178	298	282
21	191	=	191	379

*Measurement count for Year 2000

Cells that have (=) indicate that no data was available during that time or for that area. Spring values tend to be less than fall indicating that water levels in the spring and early summer are closer to the ground surface than by the end of irrigation season. This is due to winter recharge rates that are greater than winter pumping rates, “refilling” the groundwater basin, and summer extraction rates that are greater than recharge rates that draw down water levels. In some places where surface water deliveries are much greater than groundwater extraction, fall levels can exceed spring levels (example, region 20).

Following procedure detailed in CALVIN Appendix J (Davis et al, 2001), agricultural groundwater pumping costs are limited to O&M of pumping facilities, which includes important components of energy consumption. CALVIN assumes $0.20 af/ft lift, based on year 2000 costs; a factor of 1.296 is applied to the cost to convert to 2008 costs. Agriculture pumping is assumed to occur near the point of water use. Three components make up the pumping depth in the Central Valley: (1) pumping lift (from DWR 2000 well data), (2) drawdown consistent with current CALVIN estimate, and (3) adjustment for 2020 conditions. Adjustment for 2020 was extracted from the economic analysis conducted for the Draft CVPIA PEIS (USBR 1997) as detailed in Appendix J and G. The trends leading to changes in water levels between 1990 and 2020 as previously modeled are likely to have a similar affect between 2000 and 2050 so the same adjustments were used. The pumping costs for CALVIN run are constant throughout the analyses, actual costs however depend on changes in groundwater depths, which is not explicitly accounted for in CALVIN, as a result actual costs can vary from the fixed CALVIN pumping costs. An analysis on the sensitivity of the model to pumping costs can be performed to observe how pumping costs affect overall water allocation in the model. The values of the total pumping head (DWR 2000 well data), drawdown, and pumping cost are shown in Table 3- 13.

Table 3- 13. Estimated Agricultural Pumping Costs

Subregion	Pumping Depth - DWR 2000 well data (ft)	Drawdown (ft)	Pumping Head (ft)	Change in Lift (ft)	Total Dynamic Head (ft)	Pumping Cost, 2000$ ($.20af/ft)	Pumping Cost, 2008$ ($/af)
1	71	20	91	0	91	18.2	23.59
2	40	20	60	1	61	12.2	15.82
3	27	20	47	-1	46	9.2	11.93
4	16	20	36	0	36	7.2	9.33
5	27	20	47	-1	46	9.2	11.93
6	25	20	45	1	46	9.2	11.93
7	40	30	70	19	89	17.8	23.07
8	90	30	120	3	123	24.6	31.89
9	24	20	44	2	46	9.2	11.93
10	17	20	37	-2	35	7	9.07
11	47	30	77	-2	75	15	19.45
12	68	30	98	-2	96	19.2	24.89
13	75	30	105	-5	100	20	25.93
14	235	30	265	2	267	53.4	69.22
15	93	30	123	-7	116	23.2	30.08
16	57	30	87	-11	76	15.2	19.7
17	34	30	64	-2	62	12.4	16.07

18	80	30	110	-4	106	21.2	27.48
19	139	30	169	4	173	34.6	44.85
20	298	30	328	-4	324	64.8	84
21	191	30	221	8	229	45.8	59.37

3.4.8 Surface Water Losses including Evaporation & Diversion losses to GW (Term 9)

The C2VSIM diversions are described in the simulation application's CVdivspec.dat File. This file contains data specifying the locations, properties and recharge zones for surface water diversions and bypasses. Properties for each diversion include the river node where water is diverted, the recoverable and non-recoverable losses, and the model subregion the water is delivered to. The recoverable loss fraction refers to the portion that leaks from canals and pipes and enters the groundwater system as recharge. The non-recoverable loss fraction refers to the portion that evaporates.

In the CALVIN network the amplitude for surface water losses (Term 9) includes both recoverable and non-recoverable surface water losses, specified on delivery links for each surface water diversion. These parameters are lumped as a result of the network flow formulation restriction, however volumes of diversion losses to groundwater that correspond to this loss are specified as monthly time series in the "Net External Inflow", see Section 3.4.4. Appendix B shows updated amplitudes for surface water conveyance losses, the fraction in brackets are final values used in CALVIN based on the initial calibration and understood available water in subregions since some C2VSIM fractions appeared to be unreasonably high, for details on Base Case CALVIN calibration see section 6 below. Destination subregion indicates the subregion to which groundwater is recharged by diversion losses, CALVIN links which carry this loss amplitude are shown in bold.

3.4.9 Artificial Recharge Operation Costs (Term 10) and Infiltration Fraction of Artificial Recharge (Term 11)

Subregions 13 and 15-21 can manage their groundwater supplies with artificial recharge of imported or local surface water. Artificial recharge to groundwater is reported as C2VSIM diversions described in the simulation application's *CVdivspec.dat* file, which specifies diversions for spreading and destination subregions for infiltration facilities. In C2VSIM spreading facilities have an efficiency of 0.95 (assumed 5% consumptive loss). The monthly groundwater budget output file has a 'Recharge' term, which includes both diversion losses and water from spreading facilities. To separate artificial recharge from from total recharge volume, infiltration efficiency of 0.95 was applied to monthly diversion volumes for surface water diversions for spreading. Diversions for spreading are listed in Table 3- 14 for subregions 13 and 15-21. Given that a fraction of infiltration efficiency is used in C2VSIM and therefore CALVIN 'artificial recharge' refers to potential recharge as infiltration routing is not simulated to compute the downward movement of water through an unsaturated bed by taking into account stepwise movement of the wetting front and changes of water changes of water stored in each soil layer, which will be a more accurate estimate of volumes that end up as groundwater.

Table 3- 15 shows annual average historical artificial recharge per C2VSIM simulation and operation costs of artificial recharge facilities. Costs are calculated to reflect operating costs for groundwater recharge activities including facility operations and the opportunity cost of land per CALVIN Appendix G (Newlin et al, 2001).

Table 3- 14. Surface Water Diversion for Spreading in southern Central Valley subregions

C2VSIM Stream Diversion Number	Link in CALVIN Network	Destination Subregion	Infiltration fraction of Artificial Recharge	Non-recoverable Losses	Land Use	Description
120	D634-HAR13	13	0.95	0.05	Spreading	Chowchilla R riparian SR13 Spreading
123	D624-HAR13					Fresno R riparian SR13 Spreading
141	C52-HAR15	15				Kings R North Fork to SR15 Spreading
143						Kings R South Fork to SR15 Spreading
145						Kings R Fresno Slough to SR15 Spreading

133	C53-HAR16	16				Kings R to Fresno ID SR16 Spreading
214	C49-HAR16					Friant-Kern Canal to SR16 Spreading
139 & 135	C53-HAR17	17				Kings R to Consolidated ID SR17 Spreading
137						Kings R to Alta ID SR17 Spreading
217	C49-HAR17					Friant-Kern Canal to SR17 Spreading
147	C56-HAR18	18				Kaweah R Partition A to SR18 Spreading
149						Kaweah R Partition B to SR18 Spreading
151						Kaweah R Partition C to SR18 Spreading
153						Kaweah R Partition D to SR18 Spreading
155						Kaweah R to Corcoran ID SR18 Spreading
157	C58-HAR18					Tule R riparian to SR18 Spreading
220	C688-HAR18					Friant-Kern Canal to SR18 Spreading
159	C73-HAR19	19				Kern R to SR19 Spreading
198	D850-HAR19					California Aqueduct to SR19 Spreading
223	C62-HAR19					Friant-Kern Canal to SR19 Spreading
162	C65-HAR20	20				Kern R to SR20 Spreading
226	C64-HAR20					Friant-Kern Canal to SR20 Spreading
241	C74-HAR20					Cross-Valley Canal to SR20 Spreading
167	C65-HAR21	21				Kern River to Subregion 21B spreading
170						Kern River to Subregion 21C spreading
203	C689-HAR21					California Aqueduct to SR21 Spreading
229	C688-HAR21					Friant-Kern Canal to SR21 Spreading
243	C74-HAR21					Cross-Valley Canal to SR21 Spreading

Table 3- 15. Artificial Recharge Operation Costs

CALVIN Groundwater Basin	CALVIN Link	Diversions for Spreading	Annual Average historical Artificial Recharge (taf/yr)	Operating Cost ($/af)[a]
GW-13	HAR13_GW-13	Chowchilla R riparian & Fresno R riparian	4	6.5
GW-15	HAR15_GW15	Kings R	138	6.5
GW-16	HAR15_GW16	Kings R & Friant-Kern Canal	24	6.5
GW-17	HAR15_GW17	Kings R & Friant-Kern Canal	23	6.5
GW-18	HAR15_GW18	Kaweah R, Tule R riparian & Friant-Kern Canal	178	6.5
GW-19	HAR15_GW19	California Aqueduct, Kern R and Friant-Kern Canal	79	6.5
GW-20	HAR15_GW20	Kern R, Friant-Kern Canal & Cross-Valley Canal	66	6.5

GW-21	HAR15_GW21	Kern R, California Aqueduct, Friant-Kern Canal & Cross Valley Canal	208	6.5

Notes: a) Appendix G 2000 dollars (5 $/af) converted to 2008 dollars (1.29 multiplier)

3.4.10 Urban Return Flow to groundwater (Term 12)

As with agricultural areas, C2VSIM simulates land use processes within urban areas including groundwater pumping and surface water are used for urban demands. Flow is returned to surface water bodies or to groundwater. In urban areas, the *Rootzone budget output* file, tabulates monthly volumes of precipitation, runoff, applied water to urban regions, net return flow of applied water to surface water, and water entering the unsaturated zone as deep percolation. The algorithms for separating infiltration of applied water from the total monthly volume infiltrated and calculation of total return flows to surface water and groundwater are similar to that described in Section 3.4.1 above. Table 3- 16 shows the fraction of return flows for each subregion to surface water or ground water. Calculated fractions reflect the C2VSim assumption that for the Sacramento region, all water returned from urban areas returns to surface water, whereas for the San Joaquin and Tulare regions all urban return flow infiltrates to ground water.

Table 3- 16. Central Valley amplitude for urban return flow of applied water

Subregion	Amplitude for Return Flow to ground water	Amplitude for Return Flow to surface water
1	0	0.496
2	0.001	0.521
3	0.001	0.495
4	0.001	0.497
5	0.001	0.508
6	0.004	0.524
7	0.002	0.519
8	0.002	0.532
9	0.001	0.524
10	0.455	0
11	0.477	0

12	0.474	0
13	0.464	0
14	0.452	0
15	0.449	0
16	0.476	0
17	0.471	0
18	0.468	0
19	0.448	0
20	0.5	0
21	0.465	0

3.5 Calibration Process for Updated Base Case CALVIN

This section describes the assumptions used to calibrate the groundwater hydrology, agricultural return flows, surface water losses and the incorporated CALSIM II output for required Delta outflows in CALVIN to arrive at a new Base Case model set. Base Case CALVIN represents 2005 or 2050 projected population, water demands, infrastructure, and environmental flow requirements. The new Base Case model set includes changes to groundwater hydrology based on the Department of Water Resources' (DWR) California Central Valley Simulation (C2VSIM) groundwater model and required Delta Outflows following the 2009 CALSIM reliability (CDWR, 2010). Figure 3- 7 presents the flow of data through CALVIN, input is divided into 6 categories:

1. Network representation of California's rivers, reservoirs, aquifers, canals, aqueducts and demands
2. Surface water and groundwater inflow hydrology
3. Urban economic penalty functions
4. Agricultural economic penalty functions
5. Environmental flow requirements
6. Physical constraints

Details on data in current model and previous improvements in CALVIN can be found in the following work:

- Surface hydrology and calibration in CALVIN Appendix I & 2H (2001)
- Physical Constraints and Infrastructure in CALVIN Appendix H (2001) and Southern California updates in Bartolomeo, 2011
- Agricultural economic penalty functions in Howitt et al 2010, 2008 and 2001 & Brunke et al, 2004
- Urban economic penalty functions in CALVIN Appendix 2B and Southern California updates in Bartolomeo, 2011
- Environmental flow requirements in CALVIN Appendix F and updates of required Delta Outflows per CALSIM II study in Section 6.3 of this thesis and & Chou, 2012
- Groundwater hydrology in CALVIN Appendix J, 2H and Section 5 of this Thesis and Chou (2012)

For this update, the Central Valley's groundwater hydrology was changed including the natural recharge timeseries ("Net External Flows"), applied water return flow, internal reuse of applied water, pumping capacities, artificial recharge infiltration rates and capacities, and current overdraft conditions for the 21 groundwater basins (subregions) based primarily on the DWR C2VSIM Central Valley groundwater model. The previous CALVIN calibrated Base Case model (Bartolomeo, 2011) -from which updates were made - indicated an average of about 2,079 taf/year of Central Valley water was removed from the model as calibration flows. These calibration flows were needed to represent the known scarcity distribution and match hydrology of old CALVIN (based on DWRSIM) as a basis for reservoir operations and rim flows and CVGSM as a basis for groundwater flow (Jenkins, 2001). The update to the groundwater representation improves the distribution of water and better represents available water and conjunctive use of ground and surface water resources in the Valley and reduces calibration flows from the 2001 Base Case calibration.

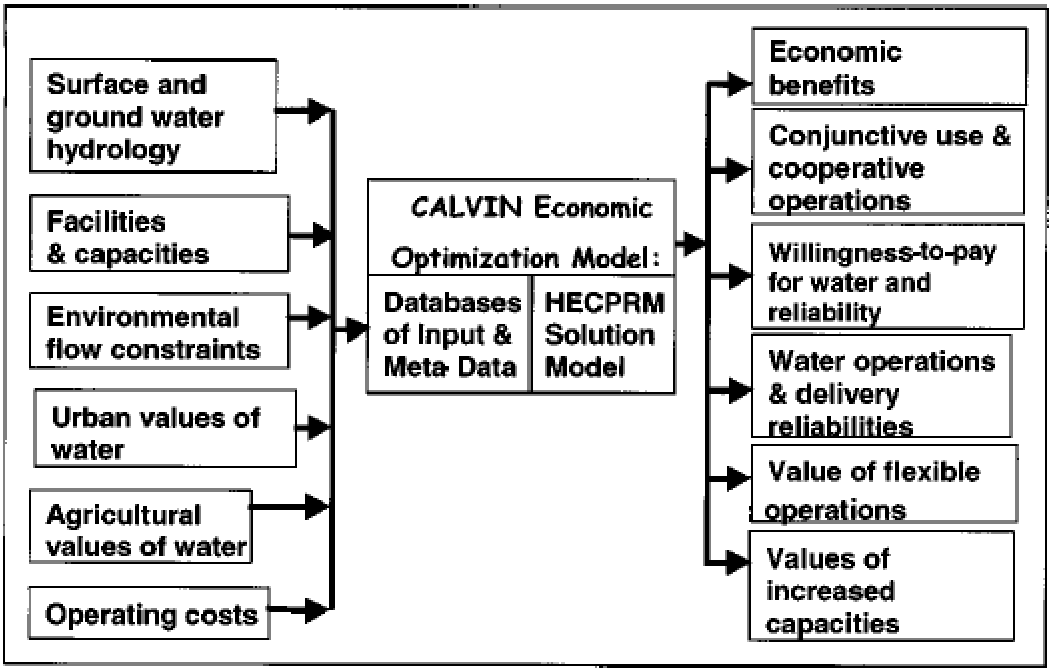

Figure 3- 7. Data Flow for the CALVIN model (Draper et al, 2003)

The surface water hydrology was not changed in this update short of ground-surface water interaction parameters (surface water losses & return flows). A feasible Updated Base Case CALVIN run was achieved and post-processing done to calculate water deliveries in each subregion. Scarcity and scarcity costs for each region were scrutinized. Scarcity is defined as the difference between water deliveries and the maximum economic demand of water users; some scarcity may be preferable to paying the costs of additional supplies or demand management. The updated Base Case run initially showed higher scarcities in subregions known to not experience frequent water shortages. As a result a calibration of parameters at the subregion scale was used to provide more reasonable operations at that scale. The calibration for this update was such that:

- Scarcities for the updated Base Case should be similar to previous Base Case as they are regarded as reasonable levels of scarcity for each region.
- Water shortages should not be evident in the Sacramento and San Joaquin for wet years (e.g. 1983), and should be much reduced elsewhere as this is not representative of “true” scarcity in the regions; wet year shortages in early model runs often represent poor representation of hydrology and infrastructure.
- Consistent water shortages throughout the simulation time (1922-1993) indicate local capacity constraints, which should be investigated to make sure access to water is indeed representative of physical constraints.

Details of the calibration process are organized into four parts 1) Description of the network representation of California’s intertied water system, 2) Base Case calibration of CALVIN with groundwater update only, 3) Base Case calibration of model with groundwater and CALSIM, 2009 required Delta outflow and 4) Constraints to Delta Water Exports.

3.5.1 Description of the network representation of California’s intertied water system

Network flow programming involves representing the system as an interconnected network of nodes and links. In water resources systems, storage nodes are links in time, and may represent either surface reservoirs or groundwater basins. Non-storage or junction nodes represent points of diversion, return flow locations or other fixed point features (Draper, 2001). The links include capacity and flow system constraints, operation costs, coefficients to represent system losses and penalties to satisfy overall water mass balance and to calculate the economic costs of water scarcity.

Typical components in the CALVIN network are shown in Figure 3- 8. On the surface water side, the network has nodes for surface storage and links representing boundary inflows (or Rim flows representing streams that enter the system), reservoir evaporation, releases, and diversion penalties.

Junction nodes occur at facilities such as pumping, power or water treatment plants, diversion points and points of confluence, and links that carry amplitudes for surface water loss and minimum instream flow requirements (Draper, 2001).

Junction nodes also occur on model boundary outflow locations and within the boundary for local water supplies (accretions and depletions) which include surface water originating within the modeled region either from direct runoff or through surface water-groundwater interaction.

Associated with each groundwater storage node are links representing natural and artificial recharge, pumping, and groundwater delivery. Demand nodes and links represent agricultural, urban and industrial demands for water. Delivery links to these areas have shortage penalties. Consumptive use is represented by a fraction of water transmission loss at the diversion link, so water not consumptively used returns to the stream network or to groundwater by deep percolation.

CALVIN hydrology input consists of a 72-year time series based on the historical record October 1921 to September 1993. This period contains extremes of California's weather. It includes three severe droughts on record: 1928-1934, 1976-1977 and 1987-1992, with the most severe being 1976-1977 and extremely wet years, 1982-1983 (CDWR, 1998). In CALVIN, historical flows originating upstream and outside of the modeled region are modified to reflect the stream flow that would have occurred with the current infrastructure in place as well as operations projected under 2050 or 2005 land uses. CALVIN Appendix I (Draper, 2000) defines in detail extraction of unimpaired surface water (SW) external inflows (Rim flows), from the now old California Department of Water Resources reservoir operation model, DWRSIM. These are inflows from watersheds upstream of major Central Valley rim reservoirs. Annual average inflows input to CALVIN are summarized in Appendix I, Table I-12 (Draper, 2000).

To simulate model outflow for 2050 conditions with changes in land use affecting direct runoff and surface-groundwater interaction, local water supply junction nodes (local accretions and depletions) take into account projected land use gains and losses from and to groundwater and direct runoff from rainfall. Summary of annual average inflows for local water supplies are shown in Appendix I, Table I-12 (Draper, 2000). Adjustments to local surface water inflows based on these groundwater updates per C2VSIM are shown in section 5.4 Table 3- 8. Calibration flows are included to match output of CVPIA PEIS (USBR 1997) for local surface supplies, deliveries, and DWRSIM Run 514a output for surface water. Previous groundwater calibration flows have been removed in the updated CALVIN. Details on the previous CALVIN calibration effort can be found in Appendix 2H (Jenkins, 2001).

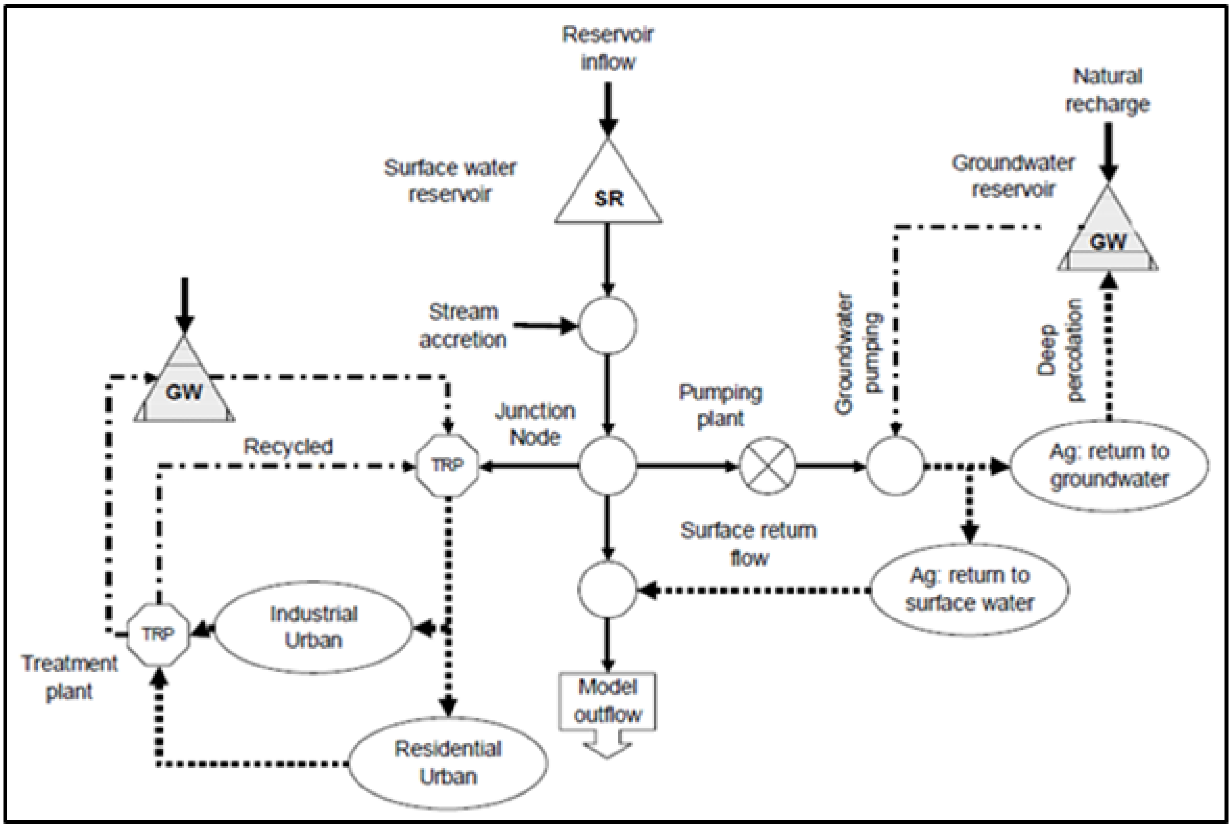

Figure 3- 8. Example CALVIN network nodes and links (Draper, 2001)

CALVIN demands are estimated from a static agricultural production model and a static urban demand model for year 2005 or 2050 conditions. The time-varying hydrology represents the range of possible flows and their implicit spatial and temporal correlation structure. Results from CALVIN should be expressed in terms of supply reliability rather than interpreted as a specific sequence of deliveries

(Draper, 2001). Economic penalty functions for reservoir releases, agricultural demands, urban demands and some environmental water needs ensure that operation and allocation made by CALVIN are driven by economic values of different demands in different parts of the state. CALVIN allocates water according to the user's willingness-to-pay, which defines the amount a rational informed buyer should be willing to pay for each additional unit of water.

Constraints (physical, institutional or environmental) are represented as upper bound, lower bound or equality constraints on flow through a particular link during a particular time step. Model output consists of prescribed monthly time series of flows and volumes that minimize costs over the 72-year period of analysis, that satisfy the total minimized penalty for a particular model run. This output can be post-processed to produce time series of shortages and shortage costs to urban and agricultural users (CALVIN Appendix E). Furthermore, a time series of Lagrange multipliers on binding flow constraints and marginal values of additional water supply at each node are provided as model output.

In HEC-PRM, the Lagrange multipliers (Dual values) on a link upper bound constraint indicate the expected value of an additional unit of capacity expansion; the marginal value indicates the opportunity cost of water of a node. Calibration of the updated CALVIN Base Case looked closely at the model output dual values and marginal values such that for subregions reporting higher or different scarcities than those in previous Base Case CALVIN are scrutinized for:

- Shortages (or marginal willingness to pay values) reported in 1983 hydrology (extremely wet year), in which no real water shortages were observed
- Shortages and willingness to pay values reported for 1983 vs. 1977 hydrology that should reflect expected magnitude difference for wet year vs. drought year for the subregion
- Dual values reported throughout the 72-year analysis, which indicate that upper constraints are consistently hit.

The check on the dual values for subregions of concern serves to determine if capacities in the network for surface water nodes reflect existing physical constraints (which are checked against reported DWR or water agency capacities). Dual values for groundwater storage are used to determine if set constraints on groundwater capacities and overdraft from C2VSIM per calculation in section 3.4 reflect on-ground conjunctive use of the resource and if the constraint needs to be loosened without disturbing the subregion's mass balance. Sections 3.5.2 and 3.5.3 detail the calibration process and parameters changed to arrive at a feasible updated CALVIN Base Case with meaningful Central Valley subregion water deliveries and shortages.

3.5.2 Base Case Calibration

A feasible updated CALVIN Base Case with C2VSIM based groundwater representation was run and output of this run was post-processed to produce time-series of shortages and shortage costs to agricultural users in the Central Valley. Table 3- 17 shows agricultural demands for Old and Updated CALVIN, the differences in the water delivery targets can be attributed to improvements made in SWAP crop production model (Howitt et al, 2012) so that some CVPM regions were further discretized (A and B regions for CVPM 3, 10, 14, 15, 19 and 21) for better representation.

Annual water shortages (Delivery Target – Surface water and groundwater to subregion) were computed for Old vs. Updated CALVIN, the initial feasible run for Updated CALVIN (S07I05) showed higher scarcity than Old CALVIN for subregions 2, 4, 6, 10, 12,13, 17, 18, 20 and 21 (Table 3- 18). However based on demand targets in Table 3- 17 subregions 2, 4, 12, 17, 20 and 21 targets are lower for the Updated CALVIN than Old CALVIN yet scarcities are reported in Updated CALVIN that were not reported in Old CALVIN for the entire 72 year analysis. Subregion 12 scarcities on the other hand are similar for Old and Updated Base Case runs, 22.0 taf/yr and 27.0 taf/yr respectively. However, subregion 6, 10, 13 and 18 demand targets for Updated CALVIN are larger than Old CALVIN by 18%, 34%, 10% and 17% respectively. The increase in scarcity can be expected but whether this scarcity is “true” or results from mi-specified infrastructure or hydrologic parameters is necessary to make sure available water and capacity constraints represent on-ground conditions.

Table 3- 17. Agricultural water demands for Central Valley subregions

Agricultural Demand Area	Annual Average Water Delivery Targets (taf/yr)	
	Old CALVIN Base Case	Updated CALVIN Base Case
CVPM 1	126	139
CVPM 2	497	473
CVPM 3	2196	1315
CVPM 4	956	884
CVPM 5	1313	1485
CVPM 6	619	732
CVPM 7	429	413
CVPM 8	802	737
CVPM 9	926	1208
CVPM 10	919	1403
CVPM 11	855	777
CVPM 12	772	760
CVPM 13	1506	1679
CVPM 14	1358	1129
CVPM 15	1701	1828
CVPM 16	345	368
CVPM 17	797	739
CVPM 18	1759	2119
CVPM 19	887	842
CVPM 20	829	640
CVPM 21	1195	999
Sacramento	**7864**	**7386**
San Joaquin	**4052**	**4620**
Tulare	**8871**	**8664**
Central Valley Total	**20787**	**20670**

Description of changes and reasons for such changes made for subregion 2, 4, 6, 10, 12, 13, 17, 18, 20 and 21 are detailed below, a subsequent CALVIN run with these changes S07I08 resulted scarcities shown in Table 3- 18.

Table 3- 18. Annual Average Agricultural Scarcity Updated Base Case CALVIN

Agricultural Demand Area	CALVIN Schematic Demand Node	CALVIN Total Delivery Link	Annual Average Water Shortages (taf/yr)		
			Old Base Case_R17I03	Updated Base Case_S07I05	Calibrated Updated Base Case_S07I08
CVPM 1	Ag-GW	HU1-CVPM 1G	0	0.7	0.8
	Ag-SW	HU1-CVPM 1S	0	0.4	0.7
CVPM 2	Ag-GW	HU2-CVPM 2G	0	189	0
	Ag-SW	HU2-CVPM 2S	0	0	0
CVPM 3	Ag-GW	HU3-CVPM 3G	0	0	0
	Ag-SW	HU3-CVPM 3S	15	0	0
CVPM 4	Ag-GW	HU4-CVPM 4G	0	70.7	0
	Ag-SW	HU4-CVPM 4S	0	1.7	0
CVPM 5	Ag-GW	HU5-CVPM 5G	0	0	0
	Ag-SW	HU5-CVPM 5S	0	0	0
CVPM 6	Ag-GW	HU6-CVPM 6G	0	45.5	7.3
	Ag-SW	HU6-CVPM 6S	0	1.2	0.5
CVPM 7	Ag-GW	HU7-CVPM 7G	0	0	0
	Ag-SW	HU7-CVPM 7S	0	0	0
CVPM 8	Ag-GW	HU8-CVPM 8G	0	0	0
	Ag-SW	HU8-CVPM 8S	0	0	0
CVPM 9	Ag-GW	HU9-CVPM 9G	0	8.3	0.1
	Ag-SW	HU9-CVPM 9S	0	0	0
CVPM 10	Ag-GW	HU10-CVPM 10G	0	48.4	48.7
	Ag-SW	HU10-CVPM 10S	0	3.3	3.4
CVPM 11	Ag-GW	HU11-CVPM 11G	0	0.3	0.3
	Ag-SW	HU11-CVPM 11S	0	0	0
CVPM 12	Ag-GW	HU12-CVPM 12G	0	25.4	22.6
	Ag-SW	HU12-CVPM 12S	22	1.6	1.1
CVPM 13	Ag-GW	HU13-CVPM 13G	0	75.9	74.5
	Ag-SW	HU13-CVPM 13S	0	2.4	2.3
CVPM 14	Ag-GW	HU14-CVPM14G	0	0	0
	Ag-SW	HU14-CVPM14S	0	0	0
CVPM 15	Ag-GW	HU15-CVPM15G	0	0	0
	Ag-SW	HU15-CVPM15S	0	0	0

CVPM 16	Ag-GW	HU16-CVPM16G	0	7.8	8
	Ag-SW	HU16-CVPM16S	0	2.6	2.6
CVPM 17	Ag-GW	HU17-CVPM17G	0	33.6	33.6
	Ag-SW	HU17-CVPM17S	0	0	0
CVPM 18	Ag-GW	HU18-CVPM18G	0	151	107.6
	Ag-SW	HU18-CVPM18S	0	0	0
CVPM 19	Ag-GW	HU19-CVPM19G	0	0	0
	Ag-SW	HU19-CVPM19S	0	0	0
CVPM 20	Ag-GW	HU20-CVPM20G	0	25.5	22.1
	Ag-SW	HU20-CVPM20S	0	5.3	4.8
CVPM 21	Ag-GW	HU21-CVPM21G	0	42.6	39.9
	Ag-SW	HU21-CVPM21S	0	0	0
Sacramento			**15**	**317.6**	**9.3**
San Joaquin			**22**	**157.3**	**152.9**
Tulare			**0**	**268.5**	**218.7**
Central Valley Total			**37**	**743.3**	**380.8**

From the post-processed result of the Updated CALVIN run S07I05, scarcities for subregions were scrutinized for drought year 1977 and extremely wet year 1983. Table 3- 19 shows annual averages of water shortage and month maximum for 1977 and 1983. For the 1983 hydrology, which is extremely wet, shortages in the Sacramento and San Joaquin basins should not be observed - the scarcities in Table 3- 18 are taken as true scarcities for the Updated Base Case, this means that shortages for these subregions can be taken to reflect unmet demands due to a scarce water resource. Parameters for subregions 10, 17 and 21 are therefore left unchanged; there is no need to proceed with the calibration of these subregions.

However, scarcities for subregions 4, 6, 12, 18 and 20 indicate that an upper bound constraint in the local network limits delivery of water to these subregions, since the scarcities for wet and drought years are identical. The dual time series for conveyance to these subregions help assess if the capacities and upper bounds represents the physical or regulatory system. Although scarcity is lower for subregion 2 in wet years, this value is not believed to reflect field conditions. Subregion 2 is in the Sacramento Region and has available both groundwater and surface water resources. In a very wet year, there should be no water scarcity in this subregion. Analysis of Lagrange multipliers (Dual_Term values), which define the marginal value of additional water at the terminal node of a link in $/af, for the conveyance link connected to each subregion were analysed to find binding constraints and to identify parameters to adjust to get reasonable scarcities.

Table 3- 19. Analysis of Scarcities for Wet and Critical water year hydrologies

	Shortages 1977 Drought Year		Shortages 1983 Wet Year		Annual Average WTP ($/AF)
	Annual Average (taf/yr)	Month Max. (taf/month)	Annual Average (taf/yr)	Month Max. (taf/month)	
CVPM 2	21.6	91.3	14.2	41.8	162.4
CVPM 4	6.1	37.8	5.9	36.4	51
CVPM 6	4.1	15.8	4.1	15.8	57.5
CVPM 10	5.2	12.4	0	0	37.6
CVPM 12	2.2	6.7	1.6	6.7	34.1
CVPM 13	6.8	17.2	1.2	14.5	58.4
CVPM 17	3.1	8	0	0	37.9
CVPM 18	15.4	42.4	12.3	42.4	56.9
CVPM 20	2.2	5.97	1.7	5.97	120.7
CVPM 21	4.04	8.9	0	0	61.9

Table 3- 20. Dual_Term values for SW Diversion links

	CALVIN SW Diversion Link	Dual_Term Value ($/taf)			
		1977- Drought Year		1983 - Wet Year	
		Annual Average	Month Max	Annual Average	Month Max
CVPM 2	C6-HU2	248.3	619.2	248.3	619.2
CVPM 4	C14-HU4	28.7	172.3	28.7	172.3
CVPM 6	C17-HU6	32.2	96.4	32.2	96.4
CVPM 12	C45-HU12	13.70	54.40	13.7	54.4
CVPM 13	C46-HU13	22.30	79.40	22.3	79.4
CVPM 18	C60-HU18	91.60	117.80	91.6	117.8
CVPM 20	C63-HU20	63.30	81.40	63.3	81.4

Dual_Term values of surface water conveyance links to subregions shown in Table 3- 20 are the same for drought and wet years, this shows that upper bounds on surface water delivery links are always limiting. Among a few changes made on Old CALVIN to establish an Updated CALVIN Base Case was the surface water loss fractions based on C2VSIM estimated recoverable and non-recoverable diversion losses, representing losses that recharge groundwater and evaporation losses respectively (Appendix B). Loss fractions are larger for most of conveyance systems in the Updated CALVIN. These large losses result in less available water to demand areas. CALVIN Appendix H (Ritzema et al, 2001) details that the capacities for diversions to agricultural and urban areas were often unknown and capacities were adopted from the CVGSM No Action Alternative as maximum monthly deliveries from the October 1921 to September 1993 time series. Capacities from results of other models often are not direct representations of physical delivery capacities. A check on capacity of Corning Canal (which delivers to CVPM 2) from the USBR website (www.usbr.org), showed that this canal capacity is 500 cfs (29.7 taf/month) compared to 12.7 taf/month in Old CALVIN. Conveyance capacities for subregions were increased as shown in Table 3- 21 such that 1) existing capacities were increased by a fraction =Old CALVIN surface water losses/C2VSIM surface water losses - to compensate for increase in losses or 2) taken from maximum of C2VSIM diversions for October 1921 to September 2003 or 3) based on capacities reported from agency resources.

Table 3- 21. Adjustments to SW diversion capacities for Agricultural areas

		Upper Bound Conveyance (taf/month)		
	CALVIN SW Diversion Link	**Old CALVIN**	**Calibrated New CALVIN**	**Source or Reason for Adjustment**
CVPM 2	D77-HSU2D77	12.7	29.7	USBR website
	C1-HSU2C1	1.8	1.98	Compensation for increased SW losses
	C11-HSU2C11	0.7	1.03	C2VSIM
	HSU2C9-C6	26.4	29.3	C2VSIM
CVPM 4	D30-HSU4D30	194.1	236	Compensation for increased SW losses
CVPM 6	C314_HSU6C314	32.1	34	Compensation for increased SW losses
	C16_HSUC16	36.3	38.5	Compensation for increased SW losses
	C21_HSUC21	40.5	42.9	Compensation for increased SW losses
CVPM 12	D645-HSU12D645	5.4	5.94	Compensation for increased SW losses
	D649-HSU12D649	12.2	13.42	Compensation for increased SW losses
	D662-HSU12D662	107.1	117.81	Compensation for increased SW losses
	D664-HSU12D664	2	2.2	Compensation for increased SW losses
	D699-HSU12D699	4.5	4.95	Compensation for increased SW losses
CVPM 13	D645-HSU13D645	111.4	122.54	Compensation for increased SW losses
	D649-HSU13D649	4.3	4.73	Compensation for increased SW losses
	D634-HSU13D634	42.9	47.19	Compensation for increased SW losses

	D624-HSU13D634	57.2	62.92	Compensation for increased SW losses
	D694-HSU13D694	0.5	0.55	Compensation for increased SW losses
CVPM 18	C56-HSU18C56	179.6	197.56	Compensation for increased SW losses
	C58-HSU18C58	23.1	25.41	Compensation for increased SW losses

Similarly Dual_Term values for groundwater delivery and return flow links were observed, as this informs on parameters that constrain available groundwater. Scarcities observed in subregion 2 as well as Dual_Terms reported in Table 3- 22 show that the allowable overdraft (-990 taf for the 72-year study) is not reflective of water conditions in this subregion. Particularly, the increase in the dual term for the last year of simulation means that water in the last time step is forced back to groundwater to meet the required ending storage, which is set higher than initial storage. Cases of this seemingly incorrect constraint on groundwater ending storage can be observed in other subregions. As a result, changes to ending storage and allowable overdraft as well as amplitude for return flow to groundwater were needed to achieve reasonable scarcities by increasing groundwater availability in these subregions. Table 3- 23 details changes made to groundwater parameters and constraints.

Table 3- 22. Dual_Term Values for Groundwater delivery links

	CALVIN GW Diversion & Return Flow to GW Links	**Dual_Term Value ($/taf)**		
		Monthly 1921-1992	**Annual Average 1993**	**Max Month 1993**
CVPM 2	GW-2-HGP2 & HGD2-GW-2	597.8	582.7	619.2
CVPM 4	GW-4-HGP4 & HGD4-GW-4	157.9	143.2	172.4
CVPM 6	GW-6-HGP6 & HGD6-GW-6	79.5	83.8	97.4
CVPM 12	GW-12-HGP12 & HGD12-GW-12	23.7	30.3	56.4
CVPM 13	GW-13-HGP13 & HGD13-GW-13	56.6	65.0	90.3
CVPM 18	GW-18-HGP18 & HGD18-GW-18	82.5	89.8	117.8
CVPM 20	GW-20-HGP20 & HGD20-GW-20	33.3	51.4	109.5

Table 3- 23. Adjustments to Groundwater parameters and constraints

Fraction Return Flow to GW		**Overdraft (taf)**		**Maximum Pumping Capacity (taf/month)**	
C2VSIM	**Calibrated Updated CALVIN**	**C2VSIM**	**Calibrated Updated CALVIN**	**C2VSIM**	**Calibrated Updated CALVIN**

CVPM 2	0.14	0.26	-882	0	-	-
CVPM 6	0.06	0.1	-	-	-	-
CVPM 9	0.09	0.1	-	-	43.9	50
CVPM 12	0.16	0.18	-	-	-	-
CVPM 13	0.12	0.13	-	-	-	-
CVPM 18	-	-	-11063	0	238.4	300
CVPM 21	-	-	27903	16840	-	

The return flow fraction of applied water to groundwater for C2VSIM was much lower than that calculated in the USGS Central Valley groundwater simulation model CVHM (0.27) or previous CVGSM based Old CALVIN (0.29) in Appendix D Table D-2. Given that CVPM 2 is in Sacramento Hydrologic Region, scarcities in this subregion for wet year 1983 should not be observed. C2VSIM reports a negative overdraft -882 taf for this subregion compared to CVHM (3,045 taf) or Old CALVIN (128 taf). Given that the latter models show a depletion of groundwater storage over the 72-years, adjustments to 0 taf overdraft for this subregion were seen reasonable; this means that for CVPM 2 pumping of groundwater is limited to natural recharge volumes only.

C2VSIM also calculates a negative overdraft (-11,063 taf) for subregion 18 compared to CVHM (+ 20,349 taf overdraft) or Old CALVIN (+ 6,828 taf overdraft). The overdraft volume for 18 was therefore adjusted to 0 taf. However to maintain the C2VSIM groundwater mass balance for the Tulare, subregion 18 (-) overdraft was added to subregion 21’s.

A Calibrated feasible Updated CALVIN Base Case was achieved (run S07I08) with scarcities shown in Table 3- 18. Although some scarcities differ from those in the Old CALVIN Base Case, analysis of the shortages time series for this run reflect zero scarcities for most subregions for the wet year 1983, Table 3- 18 shortages are therefore believed to be “truer” water shortages for the 72-year analysis.

3.5.3 Calibrated Base Case CALVIN with new CALSIM II Delta Outflow Requirements and Constraints to Delta Exports

In addition to representing agricultural and urban demands, CALVIN includes constraints for environmental flows. CALVIN Appendix F (Lienden, et al, 2001) details the procedure and current set flow constraints for minimum instream flow requirements and refuge demands. For this CALVIN update, Sacramento-San Joaquin Delta Outflows are updated as well as operation of the major State Water Project (SWP) and Central Valley Project (CVP) pumping stations, per *State Water Project Delivery Reliability Report 2011* (CDWR, 2011). This section details the incorporation of new required Delta Outflows into the San Francisco Bay as well as accompanied reductions of capacity of major pumping plants (Bill Jones (a.k.a. Tracy) and Banks) to reduce exports from the Delta to meet required Delta outflows.

The State Water Project Delivery Reliability Report (DWR 2011) is supported by CALSIM II modeling developed by DWR and the U.S. Bureau of Reclamation, which simulates existing and future operations of the SWP and CVP. The hydrology used in CALSIM II was developed by adjusting the historical flow record (1922-2003) to account for the influence of changes in land use and regulation of upstream flows.

CALSIM II includes current land use conditions as well as changes in operations of SWP and CVP project due to restrictions of Biological Opinions issued in December 2008 and June 2009 by the U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS). Operations in CALSIM II reflect institutional limitations, including:

- State Water Resources Control Board’s Water Rights Decision (D-1641), assigned primary responsibility for meeting many of the Delta water quality objectives to the SWP and CVP.
- Export curtailments for the Vernalis Adaptive Management Plan
- Operational restrictions contained in the USFWS and NMFS biological opinions

The Reasonable and Prudent Actions (RPA) from the biological opinion incorporated into CALSIMII include among 11 others:

- Implement fall X2 requirements.
- Implement water temperature requirements for Whiskeytown Lake Releases.
- Implement water temperature criteria between Balls Ferry and Bend Bridge from April 15 through October 31.
- Provide cold water releases to maintain suitable water temperature for steelhead downstream of Goodwin Dam.

CALVIN cannot internally calculate for these requirements, so CALVIN's Delta Outflow constraint is set as a time series of CALSIM II required Delta outflow. When compared with existing CALVIN minimum Delta Outflow it was discovered that for some months CALVIN flows exceed CALSIM II flows, it was decided therefore to set a most stringent case such that a maximum value between Old CALVIN and CALSIM II for each month for the Updated CALVIN minimum Delta outflow time series. Table 3- 24 compares required Delta Outflow from previous CALVIN, CALSIM II and Updated CALVIN.

Table 3- 24. Updated Delta Outflow Requirement Constraint

	Modeled period: 1922-1993		
	CALSIM II	**Old CALVIN**	**Updated CALVIN**
Annual Average (taf/yr)	12,429	11,602	12,625
Min (taf/month)	179	179	179
Max (taf/month)	11,562	11,537	11,562

Restrictions on Delta exports were set in CALVIN by adjusting constraints to pumping capacities at Banks and Tracy Pumping Plants to match as close as possible CALSIM II operation. Old CALVIN constraints on Banks were set as monthly time series for the simulation period and for Tracy as monthly varying maximum pumping constraints. In Updated CALVIN both Tracy and Banks pumping plant capacities have monthly varying upper bounds. Table 3- 25 compares maximum pumping from old CALVIN, CALSIM II and Updated CALVIN constraints. Constraints at Tracy were not changed, however at Banks, maximum CALSIM II constraint was tightened.

Table 3- 25. New Constraints on Banks Pumping Station to reduce Delta Exports

	CALSIM II	Old CALVIN	Updated CALVIN
Max. Pumping at Banks PP (taf/month)	472	523	465
Max Pumping at Tracy PP (taf/month)	283	283	283

Subregion scarcities for the new Calibrated Base Case CALVIN with updated groundwater and new Delta outflow requirements and pumping constraints at Banks and Tracy Pumping Plants are shown in Table 3-26.

Table 3- 26. Agricultural Scarcities for CALVIN Base Case with and without CALSIM II constraints

Subregion	Calibrated Updated Base Case_S07I08 (taf/yr)	Calibrated Updated Base Case with CALSIM II constraints_S07I16 (taf/yr)
1	2	2
2	0	0
3	0	0
4	0	0
5	0	0
6	7.8	21
7	0	0
8	0	0
9	0.1	2
10	52.1	56
11	0.3	0
12	23.7	24.1
13	76.8	77
14	0	0
15	0	0
16	10.6	11
17	33.6	35
18	107.6	106
19	0	0

20	26.9	27
21	39.9	39
Sacramento	**9.9**	**25**
San-Joaquin	**152.9**	**157.1**
Tulare	**218.6**	**218**
Central Valley Total	**381.4**	**400.1**

3.6 Limitations and Concluding Remarks

The representation of groundwater components in CALVIN is simplified. CALVIN suggest optimal allocations for projected 2050 condition. In Chapter 4 C2VSIM was run with optimal surface water diversion and pumping for two management scenarios in which the CALVIN model was constrained to meet two groundwater allocation policies "Base Case" and "No Overdraft". Comparing results of C2VSIM re-run that is groundwater inventory with updated CALVIN groundwater representation, CALVIN accomplished long term tracking of Central Valley groundwater use. Interaction between surface and groundwater and interaction between adjacent groundwater basins is deserving further attention. Modeled changes in storage for Sacramento and San Joaquin for CALVIN match C2VSIM well, but there are major discrepancies in the Tulare basin (Figure 3-9,Figure 3-13 and Figure 3-15). Overall the updates on groundwater representation in the Central Valley are an improvement compared to Old CALVIN.

Chapter Four: Comparing CALVIN and C2VSIM Groundwater Storage and Recharge

CALVIN does not quantify the relationship between pumping and aquifer heads, and therefore head dependent changes in recharge-discharge patterns. To examine the response of aquifers to optimized pumping from CALVIN, C2VSIM was run with historical inflows for water years 1922 to 1993. As in

CALVIN, C2VSIM was run with land use set to current levels of development (2005) for the entire 72-years simulation time. This C2VSIM run was done to test how well the Updated CALVIN model tracks groundwater changes by comparing storage and recharge of CALVIN with results of C2VSIM with optimized CALVIN deliveries. Given calibration changes in CALVIN, the two models hydrologic balances are not strictly comparable, but their comparison does illustrate the uncertainty ranges likely in estimates of water availability in Central Valley water and management models. Chou (2012) makes further comparisons between C2VSIM and CVHM as well as the economics of water management and surface water distribution under different overdraft constraints.

A further use of these data, although not part this thesis, could be to go make further changes to some parameters in CALVIN to better match C2VSIM. However, in updating the CALVIN model, deliberate departures were made from C2VSIM in several areas (Chapter 3 of this thesis; Chou, 2012). Substantial differences in Central Valley groundwater models CVHM and C2VSIM exist, so differences in models are not necessarily important, but can help us interpret and improve modeling.

This chapter outlines the procedure for setting up a C2VSIM run with CALVIN water demands and management decisions and compares CALVIN and C2VSIM’s groundwater storage and recharge.

4.1 Setting up C2VSIM for Future scenarios

A C2VSIM simulation run was developed with CALVIN water management decisions with the following settings:

- Initial aquifer heads at 2005 levels (based on historical run 1921-2005 final groundwater heads)
- CALVIN surface water diversions for agriculture use, urban use and for artificial recharge to groundwater
- CALVIN pumping for agricultural and urban uses

- Agricultural water supply requirement is read in from file Unit 19
- No adjustment for groundwater pumping read from file Unit 24
- No adjustment for streamflow diversion read from file Unit 26
- No adjustment of supply to agricultural and urban demands read from file Unit 12
- Crop acreage distribution is set constant for the simulation at 2005 levels read from file Unit 14
- Land use areas (Ag, Urban, Native Vegetation & Riparian Vegetation) for each element set at 2005 levels read from file Unit 13

Monthly surface water diversions from CALVIN for Oct-1921 to Sept-1993, were uploaded into C2VSIM CVdiversions.DAT Unit 26 file. Due to the CALVIN network structure some flow diversion links to demand areas lump together deliveries from several streams. An example is shown for deliveries through link HSU1D74-C3 to subregion 1 agricultural area (Table 4- 1).

Table 4- 1. CALVIN vs. C2VSIM stream diversion network to agricultural demand area in subregion 1

Subregion (SR)	CALVIN Diversion Link	C2VSIM Diversion Stream No.	Stream Diversion Description
1	HSU1D74-C3	6	Sacramento River Keswick to Red Bluff SR1 Ag
		8	Cow Creek riparian diversion to SR1 Ag
		9	Battle Creek riparian diversions to SR1 Ag
		10	Cottonwood Creek riparian diversions to SR1 Ag

Lumped diversions were separated to match one-on-one diversion streams in C2VSIM, and get monthly time series from CALVIN for the separated streams by:

1) Compute annual average historical C2VSIM diversions for 1980-2009 for all streams corresponding to CALVIN diversion link
2) Find fraction for each stream flow to total annual average computed in (1)

CALVIN monthly diversions for the lumped diversion link were multiplied by the fraction computed in (2) above to get time series diversions for corresponding C2VSIM streams. Table 4- 2 shows fractions applied for link HSU1D74-C3 in Table 4- 1 to get time series from CALVIN deliveries for C2VSIM diversion input.

Table 4- 2. Fraction used to split lumped CALVIN diversions to separate monthly flows for matching C2VSIM stream diversions

Subregion (SR)	CALVIN Diversion Link	C2VSIM Diversion Stream No.	Stream Diversion Description	Flow Diversion Fraction
1	HSU1D74-C3	6	Sacramento River Keswick to Red Bluff SR1 Ag	0.93
		8	Cow Creek riparian diversion to SR1 Ag	0.03
		9	Battle Creek riparian diversions to SR1 Ag	0.03
		10	Cottonwood Creek riparian diversions to SR1 Ag	0.02

Well and element pumping for urban and agricultural areas are limited to the first two aquifer layers. This is the case for the historical C2VSIM run as well as the run of C2VSIM with CALVIN water diversions. Areas to each land use type (Agricultural, Urban, Native Vegetation and Riparian Vegetation) corresponding to each element are defined in CVlanduse.DAT Unit 13 file. The distributed areas do not match exactly with CALVIN demands. Table 4- 3 shows differences between demands in CALVIN and 2005 C2VSIM demands. As a result we expect some discrepancies in evapotranspiration fluxes computed in C2VSIM and CALVIN for these runs. However given that pumping and surface diversion are locked per CALVIN allocations this simulation still provides a best way to understand how aquifers will respond to CALVIN management scenarios.

Table 4- 3. Agricultural demands C2VSIM 2005 vs. Updated CALVIN

Subregion	Annual Agricultural Demands (taf/yr)	
	C2VSIM 2005	Updated CALVIN
1	108	139
2	423	473

3	1,913	1,249
4	843	883
5	2,034	1,333
6	539	731
7	696	391
8	644	668
9	743	581
10	1,444	1,391
11	726	739
12	770	951
13	1,213	1,678
14	1,239	1,115
15	1,526	1,828
16	514	341
17	567	739
18	2,370	2,125
19	795	842
20	657	638
21	1,503	1,319
Sacramento	**7,943**	**6,447**
San Joaquin	**4,152**	**4,758**
Tulare	**9,171**	**8,946**
Central Valley Total	**21,267**	**20,151**

To make sure that groundwater available for withdrawals from the Central Valley for this future scenario makes sense or matches that allocated for the historical C2VSIM run, fractions for distributing element pumping for each aquifer layer were as set in Table 2- 14. However, for the future scenarios some elements had aquifer layers that dried up during the simulation, these are listed in Table 4- 4. Results of ground water heads at each node are reported in the results folder CVGWheadall.OUT file, for the end of each month for the three aquifer layers. Post processing for getting weighted average heads for each subregion was performed as shown in Figure 2- 5. Nodes that dry during the simulation are assigned a value that is too large ~ 20,000 feet.

The model however converged with the following mass balance discrepancies at subregions 6, 7, 9 and 12 of maximum 0.5 ac-ft/month, 0.1 ac-ft/month, 0.2 ac-ft/month and 0.8 ac-ft/month respectively for some time steps.

Table 4- 4. List of elements with aquifer layers that dried up during 72-years C2VSIM with CALVIN water deliveries

Element(s)	Subregion	Total Area (th-acres)	% area dry element to subregion area	Dry Layer(s)
2,3 & 4	1	22	7%	1
732 & 737	13	12	1%	1
1035	14	12	2%	1
1017	17	12	3%	1
1209	18	9	1%	1
1208	18	12	1%	1 & 2
1213 & 1245	19	21	3%	1
1212, 1228 & 1229	19	35	4%	1 & 2
1210, 1253 & 1255	20	37	9%	1 & 2

4.2 Groundwater Hydrology C2VSIM vs. Updated CALVIN

Groundwater parameters in CALVIN were represented based on C2VSIM as detailed in Chapter 3. Sections below compare storage and recharge estimated in CALVIN and C2VSIM for the two management scenarios: Base Case CALVIN and ‘No Overdraft’ CALVIN. Base Case refers to the CALVIN run with initial and ending storage per Table 3- 10 and Table 3- 23; ‘No Overdraft’ refers to an updated CALVIN run with initial storage set equal to ending storage for all Central Valley subregions.

4.2.1 Groundwater Storage

4.2.1.1 Base Case CALVIN

Base Case CALVIN constraints on ending storage are reported in Table 3- 10 and Table 3- 23, the differences between the set initial and ending storages, represent allowed groundwater basin overdrafts for each subregion over the 72-year simulation. A C2VSIM simulation with optimized CALVIN water deliveries with this management case was run; results comparing groundwater storage calculated in CALVIN and C2VSIM are presented here. Figure 4- 5 shows change in storage over 72-years from CALVIN and C2VSIM, the differences in estimated groundwater overdraft is due to differences in calculated recharge in C2VSIM as compared in section 4.2.2.1 of this chapter.

Table 4- 5. Change in Storage Base Case CALVIN vs. C2VSIM with Base Case Water Deliveries

Change in Storage [+] = overdraft volumes; [-] = accumulation volumes

	Change in Storage Over 72-years (TAF)		
Hydrologic Region	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Water Deliveries**	**Difference**
Sacramento	13,322	15,449	-2,127
San Joaquin	15,140	15,539	-399
Tulare	42,403	7,070	35,333
Central Valley Total	70,865	38,057	32,808

Table 4-5 shows differences between C2VSIM and CALVIN overdraft over 72-yrs, for the entire valley C2VSIM has 0.5 MAF/yr less overdraft than updated CALVIN. In Sacramento CALVIN calculates less overdraft volumes than C2VSIM over 72-years, however, annual groundwater storage in CALVIN for 1927 to 1976 is less than storage in C2VSIM due to differences in estimated recharge between the two models. The 'Net External Inflow' term in CALVIN is 684 taf/yr less than C2VSIM and recoverable diversion losses are 177 taf/yr less in CALVIN than C2VSIM; details on recharge differences are covered in section 2.2.1. Table 4- 6 shows a summary of subregion 4 recharge an example of how recharge estimated in C2VISM with CALVIN water allocations differs from that in CALVIN; C2VSIM calculates less flow from groundwater to streams, more deep percolation from precipitation and irrigation return flows as well as larger recoverable diversion losses.

The annual average difference in storage calculated from C2VSIM and CALVIN in Sacramento is 3.3 MAF/yr, CALVIN estimates less groundwater storage than C2VSIM (Figure 4- 1). Graphs comparing changes in storage from both models for all subregions are in Appendix F. On a subregion scale, for some subregions annual change in storage in C2VSIM matches CALVIN for example subregion 1 (Figure 4- 2); for some subregions there are larger discrepancies between C2VSIM and CALVIN annual storage changes (Figure 4- 3 and Figure 4- 4).

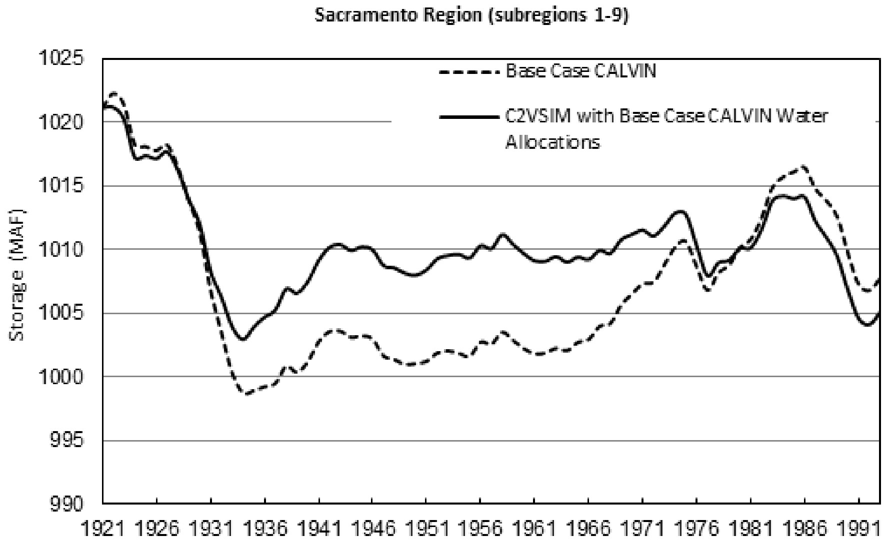

Figure 4- 1. Sacramento Region Groundwater Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Deliveries

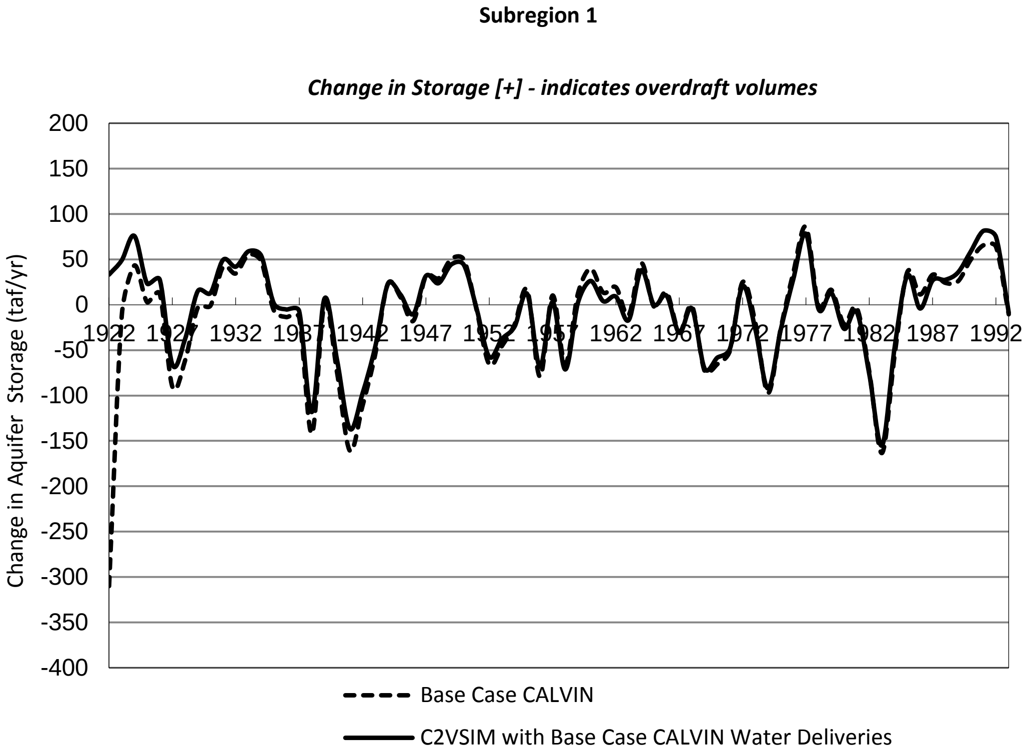

Figure 4- 2. Subregion 1 Groundwater Change in Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

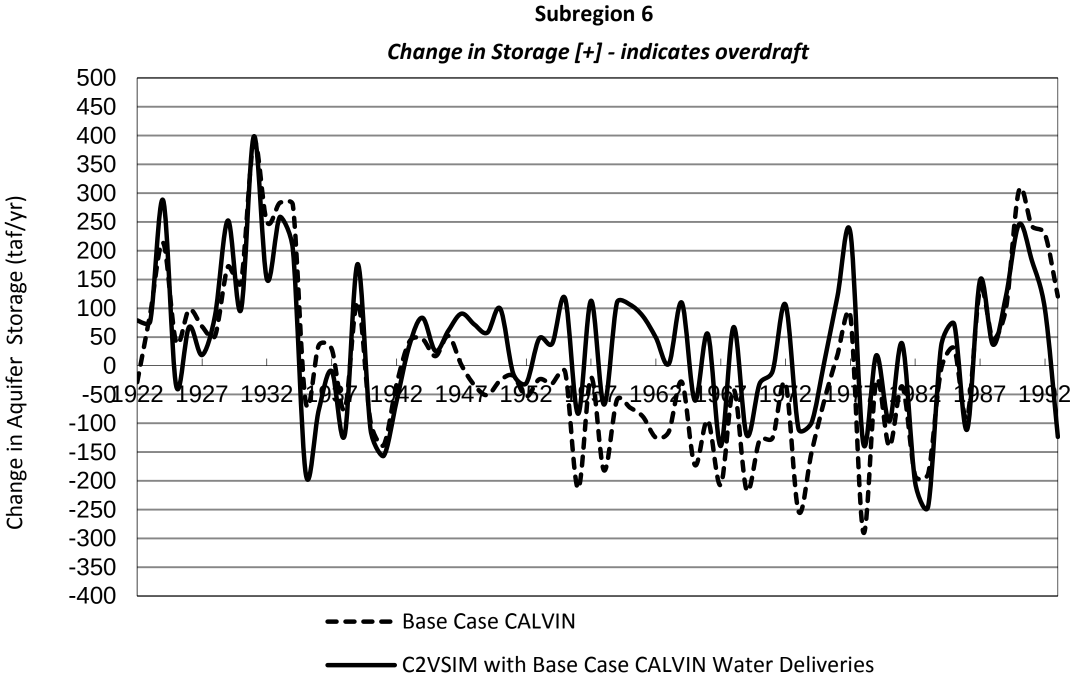

Figure 4- 3. Subregion 6 Groundwater Change in Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

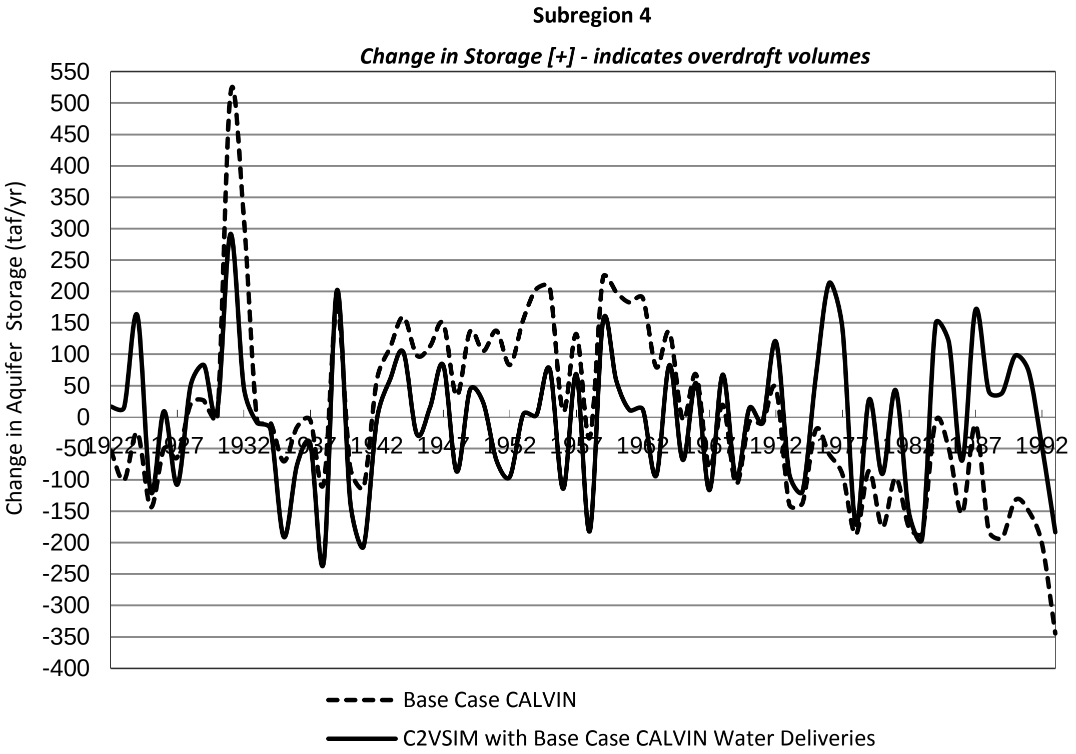

Figure 4- 4. Subregion 4 Groundwater Change in Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

Table 4- 6. Subregion 4 estimated recharge CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

	Annual Average Inflows (taf/yr)	
	Base Case CALVIN	**C2VSIM with Base Case CALVIN Deliveries**
Stream Exchange	-294	-232
Boundary Inflows	0	0
Inter-basin Inflow	49	-33
Subsidence	1	1
Deep Percolation from precipitation	100	67
Recoverable Diversion Losses	75	106
Deep percolation from irrigation return flows	123	192
Net Inflow	**54**	**101**

The annual average difference in storage calculated by C2VSIM and CALVIN in San Joaquin is 3.04 MAF/yr, with CALVIN storage lower than C2VISM in (Figure 4- 5). We find that for subregion 13, CALVIN matches C2VSIM closely (Figure 4- 6). However, for the rest of the subregions, we have some water years for which CALVIN estimates either larger or smaller storage changes than C2VSIM in Appendix F.

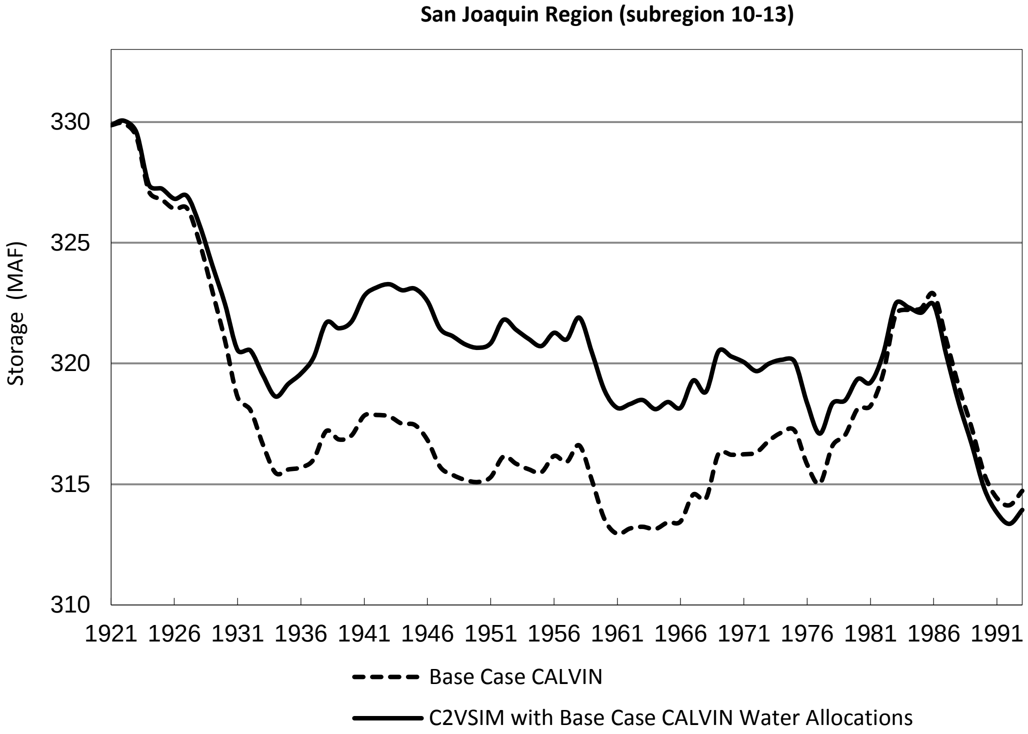

Figure 4- 5. San Joaquin Region Groundwater Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

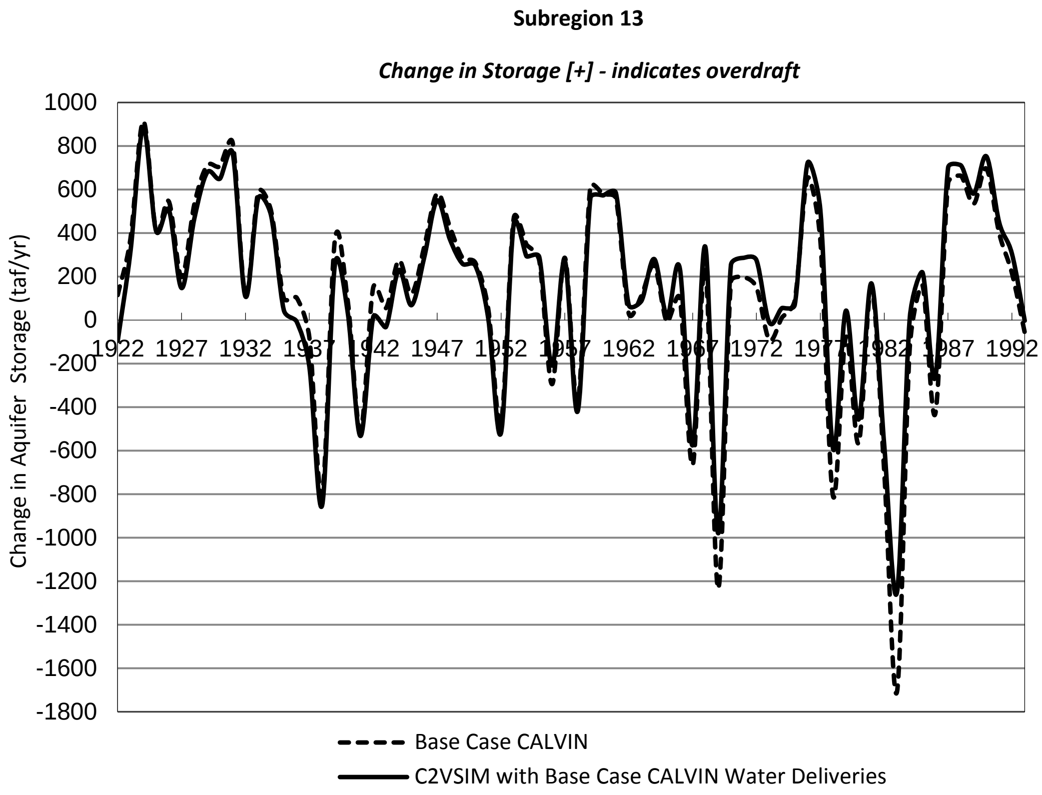

Figure 4- 6. Subregion 13 Change in Groundwater Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

The Tulare shows the largest discrepancy between CALVIN and C2VSIM groundwater storages; the difference is an average of 47.7 MAF/yr; CALVIN underestimates basin storage relative to C2VSIM (Figure 4- 7). Subregions 16, 18 and 20 show large differences between changes in groundwater storage between the two models in 1922; C2VSIM estimates for 1922 a negative overdraft larger than CALVIN by 3 MAF, 4.8 MAF and 1.4 MAF. In this year recoverable diversion losses are 5% to 8% larger than any other years losses; these are 4.1 MAF, 6.5 MAF and 1.5 MAF for subregion 16, 18 and 20 respectively.

Section 4.2.2.1 below compares recharge calculations in CALVIN and C2VSIM models and helps explain the overdraft differences between the two models. C2VSIM has more 'Net External Inflows' than CALVIN and higher return flows from irrigation for the Tulare (Table 4- 8; Table 4- 10).

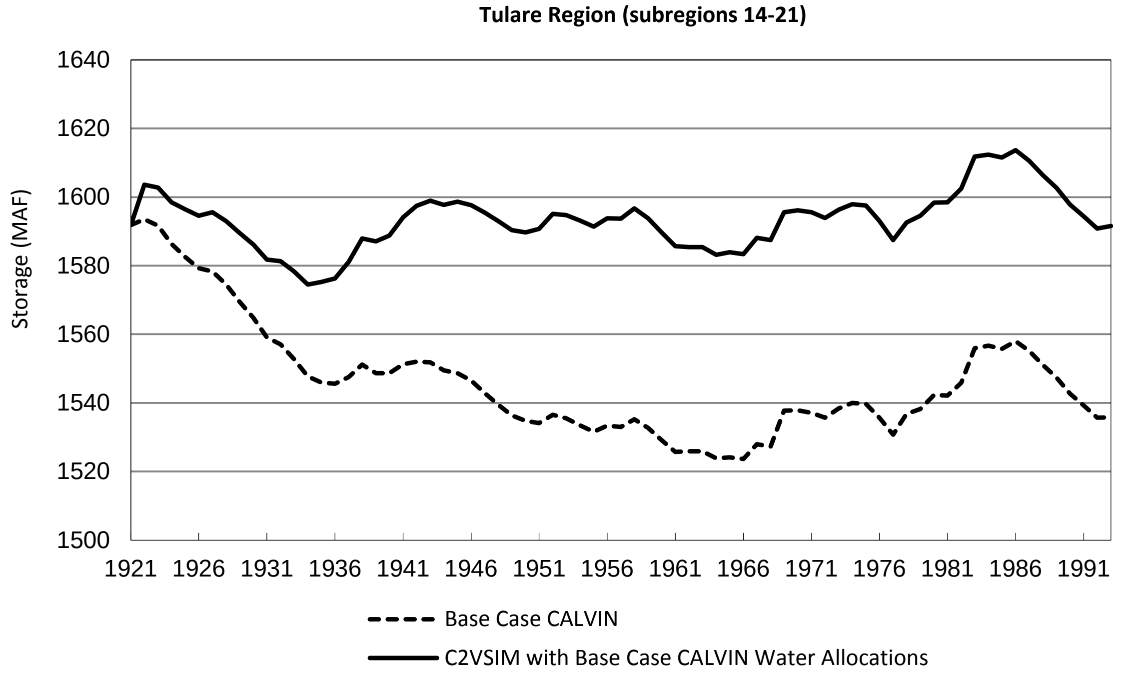

Figure 4- 7. Tulare Region Groundwater Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

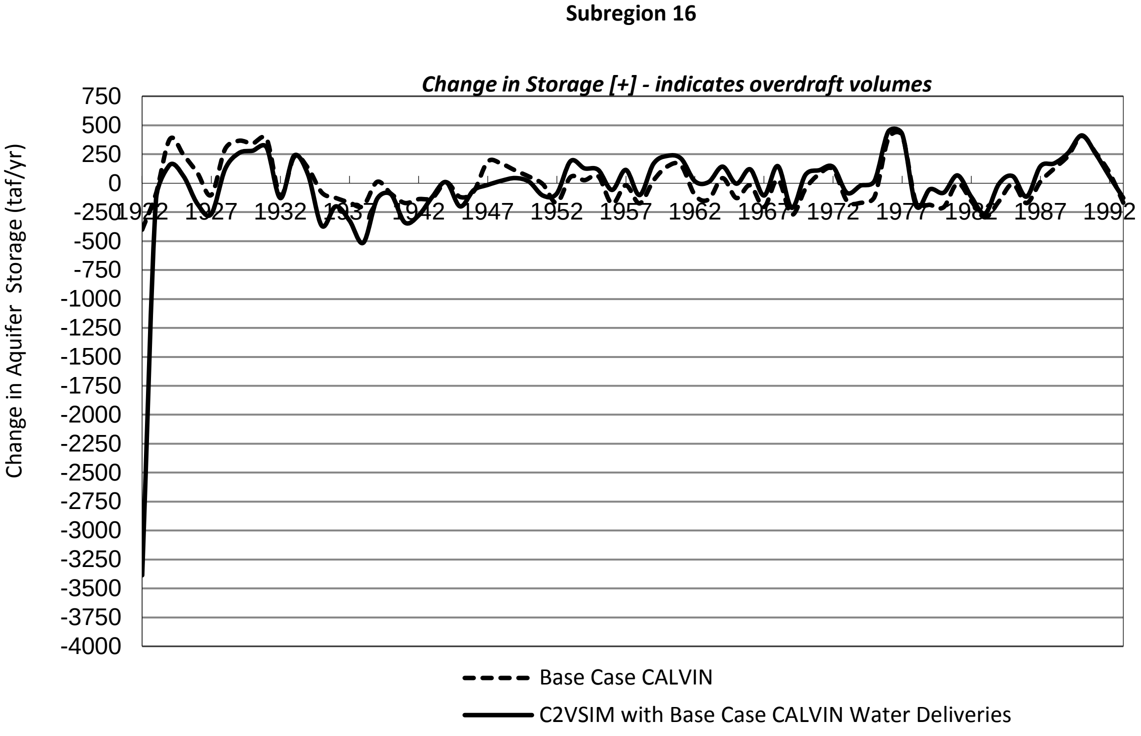

Figure 4- 8. Subregion 16 Change in Groundwater Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

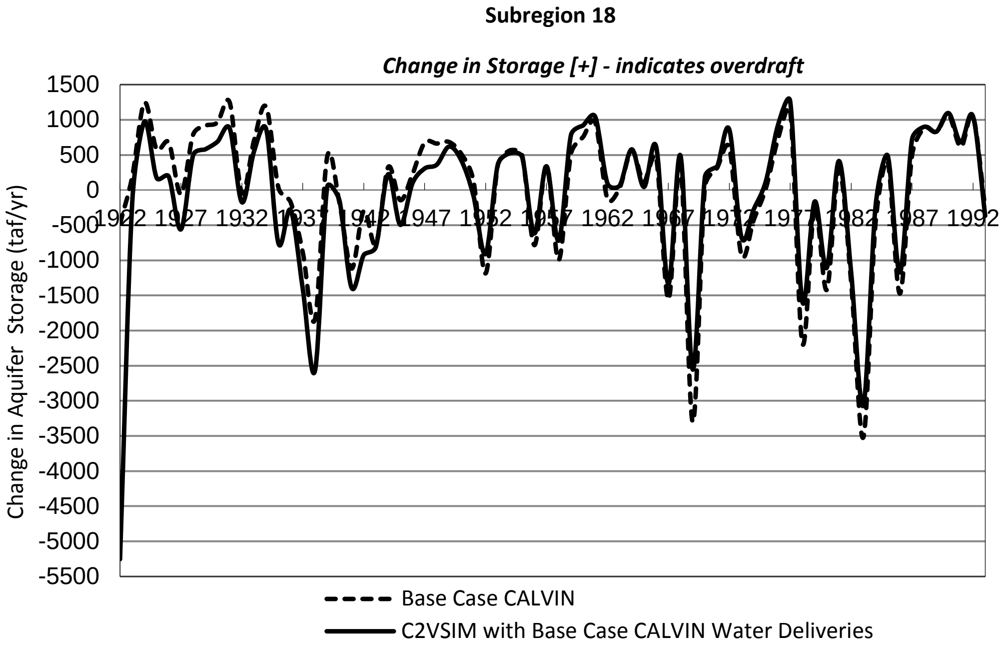

Figure 4- 9. Subregion 18 Change in Groundwater Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

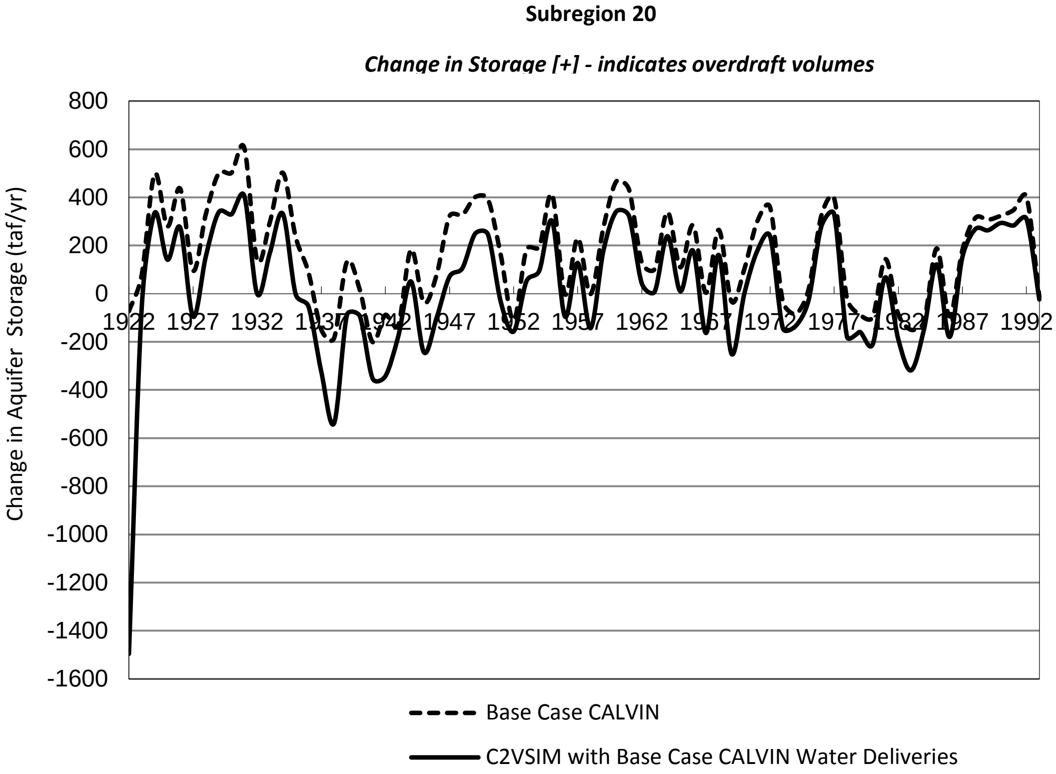

Figure 4- 10. Subregion 20 Change in Groundwater Storage Updated Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

4.2.1.2 'No Overdraft' CALVIN

'No Overdraft' CALVIN is constrained so initial storage equals ending storage for each subregion. This limits CALVIN pumping to come from recharge only, and if groundwater is taken from storage it will have to be replenished by the end of the 72-year period. A C2VSIM simulation with optimal CALVIN water deliveries under this management case was run; results comparing groundwater storage calculated in CALVIN and C2VSIM are presented here. Table 4- 7 compares change in storage in CALVIN and C2VSM for this case. The results show that zero change in storage in CALVIN is not representative of the simulation due to differences in recharge in the two models, discussed in section 4.2.2.2 of this chapter.

Table 4- 7. Change in Storage No Overdraft CALVIN vs. C2VSIM with 'No Overdraft' Water Deliveries

Change in Storage [+] = overdraft volumes; [-] = accumulation volumes

	Change in Storage Over 72-years (TAF)		
Hydrologic Region	**'No Overdraft' CALVIN**	**C2VSIM with 'No Overdraft' CALVIN Water Deliveries**	**Difference**
Sacramento	0	10,430	-10,430
San Joaquin	0	9,124	-9,124
Tulare	0	-21,785	21,785
Central Valley Total	0	-2,231	2,231

Results from these models shows differences in annual average groundwater storage between the models, that is the difference in computed annual storage from C2VSIM and CALVIN and the average of these for 72-years. C2VSIM storage is 0.17 MA/yr more than CALVIN in Sacramento; CALVIN storage is 0.42 MAF/yr more than C2VSIM in San Joaquin and C2VSIM storage is 29.9 MAF/yr more than CALVIN for Tulare (Figure 4- 11, Figure 4- 12 and Figure 4- 13).

Subregions 1, 10, 13 and 18 for example have best match of recharge calculations between the two models. Subregions 4, 6, 14 or 21 have major differences between CALVIN and C2VSIM estimated recharge. Graphs comparing changes in storage from both models for each subregion are in Appendix G.

Recharge in CALVIN differs from that calculated in C2VSIM, discussed in section 4.2.2.2 of this chapter. The 'Net External Inflows' in CALVIN are less than C2VSIM's largely due to underestimated diversion losses particularly in the Tulare (Table 4- 11 and Table 4- 12).

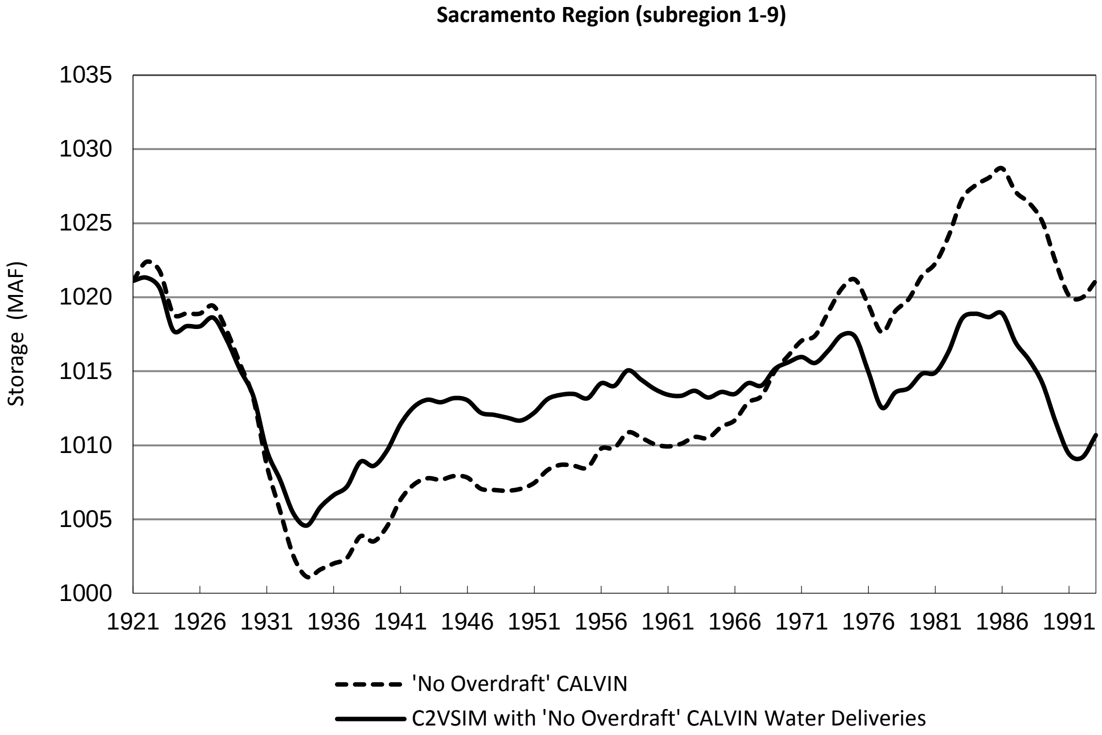

Figure 4- 11. Sacramento Region Groundwater Storage 'No Overdraft' CALVIN vs. C2VSIM with 'No Overdraft' Water Deliveries

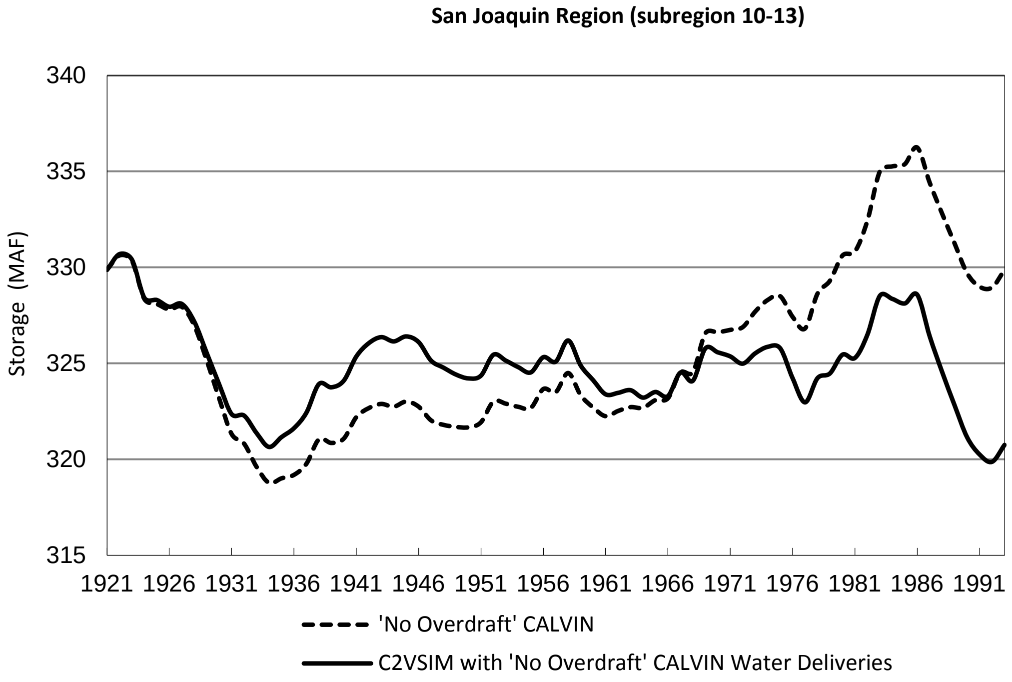

Figure 4- 12. San Joaquin Region Groundwater Storage 'No Overdraft' CALVIN vs. C2VSIM with 'No Overdraft' Water Deliveries

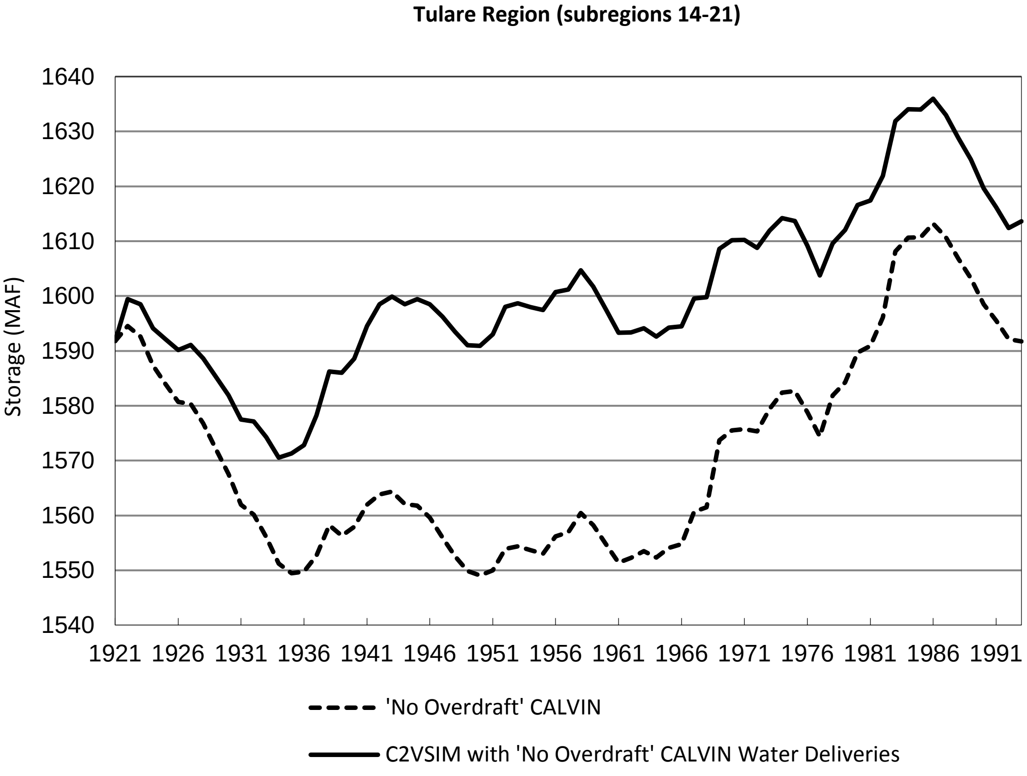

Figure 4- 13. Tulare Region Groundwater Storage 'No Overdraft' CALVIN vs. C2VSIM with 'No Overdraft' Water Deliveries

4.2.2 Groundwater Recharge

4.2.2.1 Base Case CALVIN vs. C2VSIM with Base Case CALVIN Water Deliveries

Some components of recharge and discharge to groundwater in CALVIN are represented as a time series of net inflows termed "Net External Inflows", these include streamflow exchange, lake exchange, tile drain outflows, subsidence, boundary inflows, interbasin inflows, deep percolation of precipitation and diversion losses. Deep percolation of return flow from urban or agricultural areas is dynamically computed as a fraction for each area of applied water returned to groundwater. CALVIN average annual storage is less than C2VSIM by 3.3 MAF/yr, 3.04 MAF/yr and 47.7 MAF/yr for Sacramento, San Joaquin and Tulare respectively for Base Case. Indicating that recharge from all sources in C2VSIM exceeds those in CALVIN.

Figure 4- 8 shows differences between the time series input 'Net External Inflows' in CALVIN and C2VSIM. CALVIN flows are 29% less than C2VSIM for the Central Valley with regional differences of 36%, 24% and 26% for Sacramento, San Joaquin and Tulare respectively. Major components of 'Net External Inflows" i.e. stream exchange, boundary and inter-basin inflows and deep percolation from precipitation are shown in Table 4-9. Comparison of all recharge components in Updated Base Case CALVIN and C2VSIM with optimized Base Case water allocations for each subregions are in Appendix E.

Flow from groundwater to streams in CALVIN is 31% or 391 taf/yr larger than C2VSIM for the Central Valley; loss of groundwater to streams in C2VSIM is 479 taf/yr and 165 taf/yr less than CALVIN's for Sacramento and San Joaquin respectively, however for Tulare C2VSIM losses to streams are 253 taf/yr more than in CALVIN's. Inter-basin inflows simulated in C2VSIM indicate a change in direction of horizontal flow in the region so that Tulare basins receive water from neighboring regions instead of water leaving the basin as in CALVIN input.

On the other hand C2VSIM calculates 19% larger boundary inflows volumes than CALVIN and 9% lower volumes from the deep percolation of precipitation. Deep percolation of precipitation in CALVIN is based on historical land use, C2VSIM with Base CALVIN is ran with 2005 land use for the entire 72-years simulation. Differences in land use and water demands could be explain the varying estimations in the deep percolation of precipitation volumes.

Table 4- 8. Net External Inflows Base Case CALVIN vs. C2VSIM with Base Case Water Deliveries

Note: Net External Inflow include streamflow exchange, lake exchange, tile drain outflows, subsidence, boundary inflows, interbasin inflows, deep percolation of precipitation and diversion losses

	Net External Inflows (taf/yr)		
Hydrologic Region	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Water Deliveries**	**Difference**
Sacramento	1,206	1,890	-684
San Joaquin	515	676	-161
Tulare	2,201	2,966	-765
Central Valley Total	3,922	5,532	-1,610

Table 4- 9. Major components of "Net External Inflows" Base Case CALVIN vs. C2VSIM with Base Case Water Deliveries (Streams, Inter-basin Inflows, Boundary Inflows and Deep Percolation from precipitation)

	Stream Exchange (taf/yr)		Inter-basin Inflows (taf/yr)		Boundary Inflows (taf/yr)		Deep Percolation from Precipitation (taf/yr)	
Hydrologic Region	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Deliveries**	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Deliveries**	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Deliveries**	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Deliveries**
Sacramento	-661	-182	61	141	498	526	970	603
San Joaquin	-419	-254	-72	-31	28	63	402	474
Tulare	-169	-422	11	-110	86	168	576	168
Central Valley Total	-1249	-858	0	0	612	758	1948	1245

Return flows from agriculture and outdoor use in urban areas are computed in CALVIN as a fraction of applied water to these areas. Return flows to groundwater in C2VSIM are higher than in CALVIN for Sacramento and Tulare by 833 taf/yr and 760 taf/yr respectively. Irrigation efficiencies in CALVIN should be too high for these regions. For the San Joaquin, return flows to groundwater in C2VSIM are less than in CALVIN by 400 taf/yr, so current CALVIN fractions for return flow are could be decreased to better match C2VSIM (Table 4- 10).

The largest recharge component in the Tulare is from diversion losses. The diversion losses time series in Updated CALVIN is based on historical C2VSIM (Chapter 3, section 3.4.4); major imports for example Friant-Kern, San Luis and Cross Valley Canals and Mendota Pool, were not operational until 1950's, however, since CALVIN has current land use and current infrastructure for the entire 72-years run high diversion losses are computed in C2VSIM with optimized CALVIN water deliveries.

Table 4- 10. Deep Percolation from Irrigation Return Flows, Diversion Losses and Artificial Recharge Base Case CALVIN vs. C2VSIM with Base Case Water Deliveries

	Deep Percolation from Irrigation Return Flows (taf/yr)			Diversion Losses & Artificial Recharge (taf/yr)		
Hydrologic Region	Updated Base Case CALVIN	C2VSIM with Base Case CALVIN Water Deliveries	Difference	Updated Base Case CALVIN	C2VSIM with Base Case CALVIN Water Deliveries	Difference*
Sacramento	1081	373	708	309	486	-177
San Joaquin	1110	915	195	580	550	30
Tulare	1436	1441	-5	1897	2844	-947
Central Valley Total	3627	2730	897	2786	3880	-1094

Note: * Difference is recoverable diversion Losses since artificial recharge is same for both models

4.2.2.2 'No Overdraft' CALVIN vs. C2VSIM with 'No Overdraft' Case Water Deliveries

The differences in storage from CALVIN and C2VSIM with this scenario are less than Base Case, shown in section 2.1.2 of this Chapter. Table 4- 11 compares CALVIN "Net External Inflows" with C2VSIM with 'No Overdraft' case, CALVIN underestimate these flows by an average annual of 596 taf/yr, 85 taf/yr and 839 taf/yr for Sacramento and San Joaquin and Tulare respectively, relative to C2VSIM.

On the other hand, CALVIN estimates higher return flows than C2VSIM in Table 4- 12. Sacramento and Tulare diversion losses differ significantly for CALVIN and C2VSIM, C2VSIM calculates 180 taf/yr and 822 taf/yr higher recharge from diversion losses than CALVIN for these regions. The differences indicate the components of recharge in CALVIN that could be modified to better match C2VSIM recharge patterns with a 'No Overdraft' case.

Table 4- 11. Net External Inflows 'No Overdraft' CALVIN vs. C2VSIM with 'No Overdraft' Water Deliveries

Note: Net External Inflow include streamflow exchange, lake exchange, tile drain outflows, subsidence, boundary inflows, interbasin inflows, deep percolation of precipitation and diversion losses

	Net External Inflows (taf/yr)		
Hydrologic Region	Updated 'No Overdraft' CALVIN	C2VSIM with 'No Overdraft' CALVIN Water Deliveries	Difference
Sacramento	1,206	1,802	-596
San Joaquin	515	600	-85
Tulare	2,201	3,040	-839
Central Valley Total	3,922	5,441	-1,519

Table 4- 12. Deep Percolation from Irrigation Return Flows, Diversion Losses and Artificial Recharge 'No Overdraft' CALVIN vs. C2VSIM with 'No Overdraft' Water Deliveries

	Deep Percolation from Irrigation Return Flows (taf/yr)			Diversion Losses & Artificial Recharge (taf/yr)		
Hydrologic Region	Updated 'No Overdraft' CALVIN	C2VSIM with 'No Overdraft' CALVIN Water Deliveries	Difference	Updated 'No Overdraft' CALVIN	C2VSIM with 'No Overdraft' CALVIN Water Deliveries	Difference*
Sacramento	1,053	320	733	309	489	-180
San Joaquin	1,098	896	202	603	581	22
Tulare	1,579	1,365	214	1,927	2,749	-822
Central Valley Total	3,730	2,581	1,149	2,840	3,820	-980

Note: * Difference is recoverable diversion Losses since artificial recharge is same for both models

4.3 Concluding Remarks

The simulations of C2VSIM with CALVIN diversions and pumping indicate that although the representation of groundwater hydrology in the CALVIN model is simplified largely because of the restrictions imposed by the large-scale optimization formulation. There are differences between CALVIN and C2VSIM computed changes in storage and recharge, largely in the Tulare region. Recharge components compared in Appendix E and section 4.2 of this chapter indicate which flows need further calibration to match Updated Base Case CALVIN and C2VSIM with 2005 land use (or projected 2050) which is taken as 'true' representation of groundwater hydrology in the Central Valley in this chapter (other Central Valley groundwater models may differ, for example CVHM). Amplitudes for return flow of irrigation water might be adjusted as might surface water-groundwater interactions particularly stream exchange, diversion losses and inter- basin flow exchanges.

The differences between CALVIN and C2VSIM do not undermine the goals of CALVIN as the current updates reflect an improved representation of available groundwater resources, although still limited in tracking changes in recharge and discharge patterns relative to C2VSIM model. CALVIN tends to overestimate groundwater overdraft over the 72-years by 32 MAF for Base Case and 2.2 MAF for 'No Overdraft Case'. This is due to changed water recharge patterns reflected in C2VSIM but not accounted for in CALVIN since groundwater updates are based on a historical C2VSIM run. The groundwater system has significant over-year storage; it is expected that the sequence of storages in the CALVIN model will differ from those obtained with a simulation model for some years will be optimistic or pessimistic (Harou et al. 2008 and Draper 2001). Furthermore, CALVIN re-calibration modified some historical C2VSIM results which seemed locally unreasonable relative to local conditions and other model results such as the USGS CVHM. On a subregion basis however, CALVIN matches C2VSIM recharge well in subregions 1, 10 and 13 for Base Case CALVIN and 1, 11, 13 and 16 for 'No Overdraft' case.

Chapter 5 compares C2VSIM simulation run with optimized water deliveries for the two management scenarios to study the response of aquifers. When comparing recharge components Net External Inflows and Irrigation Infiltration from C2VSIM for both of the two management cases (Sections 4.2.2.1 and 4.2.2.2) Base has higher flows than ‘No Overdraft’ 91 taf/yr and 148 taf/yr respectively for the Central Valley. However the difference in pumping between the two cases Base pumps 800 taf/yr more than ‘No Overdraft’ result in higher overdrafting with Base Case indicating that withdrawals end up being a big factor in storage depletion. Details of C2VSIM runs with CALVIN pumping are in Chapter 5.

Chapter Five: Aquifer Response to Pumping - C2VSIM with CALVIN Water Deliveries

CALVIN and C2VSIM are complementary models for groundwater management in the Central Valley. This loose coupling of CALVIN and C2VSIM yield projected 2050 response of aquifers given historical data –stream inflow and precipitation distribution – for the 72 year simulation (water years 1922 -1993) and land use set to 2005 level of development (projected 2050). Future water allocations – surface water and pumping - for this period are represented by CALVIN's optimized water deliveries. C2VSIM with CALVIN water deliveries serves to simulate the non-linear aspects of physical flows to give results that better represent aquifer responses to economically optimized water use in the region. Two scenarios are examined in this chapter:

1. Base Case CALVIN – overdraft constrained per Table 3- 10 and Table 3- 23
2. 'No Overdraft' CALVIN– initial storage set equal to ending storage in CALVIN for all Central Valley subregions

Chou, 2012 M.S. gives more details on shifts in surface water allocations under these two policies, overall system costs, operating costs etc. and noted that the Delta exports rise with ending overdraft by 759 taf/yr. A summary of resulting water scarcities with the two management cases is shown in Table 5-3 (from Chou, 2012). These constraints in available groundwater for pumping under these two scenarios provide are used to provide a picture of water management in the Central Valley. C2VSIM provides information on aquifer responses such as changes in storage, recharge and groundwater levels. The C2VSIM simulations of these scenarios was used to determine if suggested pumping rates of CALVIN lead to sustainable basin conditions over the 72-years (1921 to 1993). Harou et al, 2008 paper 'Ending groundwater overdraft in hydrologic-economic models' examines effect of different constraints on ending storage in CALVIN including the 'No Overdraft' case, this study goes further to determine if overdraft conditions in CALVIN are representative of estimated overdraft in a numerical simulation model and if suggested or optimal pumping rates are in fact sustainable yields.

Although Chou and Harou studies show using the CALVIN the economic aspect of overdraft management in the Central Valley, the CALVIN model does not provide insight into one major benefit of ending overdraft that is ensuring pumping rates do not result in groundwater levels that are permanently lowered, which increases pumping costs for all groundwater users. In addition CALVIN does not provide capture the spatial variability of the existence and extent of overdraft at different scales.

5.1 Aquifer Response to Development - Theory

In “The Source of Water Derived from Wells” (1940), Theis states that average discharge from the aquifer during recent geological equals the rate of input into it for predeveloped conditions. Therefore, under natural conditions, before development by wells, aquifers are in a state of approximate dynamic equilibrium, such that over a complete season or climatic cycle, fluctuations between discharge by natural processes and recharge balance each other. However, well pumping imposed a discharge upon a previously stable system and must be balanced by an increase in recharge to the aquifer or by a decrease in the old natural discharge, or by loss of storage in the aquifer or a combination thereof. Water discharging from a well comes from:

1. Increase in recharge
2. Decrease in other discharges (baseflow to streams, lakes, ponds)
3. Change in water storage

From Circular 1186 (USGS, 1999), these changes in the system that allow water to be withdrawn can written as:

$$Pumpage = Increased\ recharge + Water\ removed\ from\ storage + Decreased\ discharge$$

The change in storage in response to pumping is often transient; the contributions to the changes in storage, recharge and discharge evolve with time. Pumping ground water can increase recharge by inducing flow from a stream into the ground-water system, also if the water table drops, water that would typically runoff and contribute to flow in streams will now infiltrate into the unsaturated zone. Numerical models such as C2VSIM can estimate the amount of groundwater available for use with the ability to model transient flow of ground water and surface water together system wide.

Section 5.3 below evaluates the amount of water available from changes in ground-water recharge, in ground-water discharge and storage for two future levels of water use. C2VSIM simulation of cases shows the effects of extracting water at these levels on the ground-water and surface-water systems as well as the estimation of water available in the Central Valley. Additionally, though not covered in this thesis, a change in ground water use affects both the quantity and quality of streams, springs, wetlands and ground-water-dependent ecosystems. Evaluations should be made to set thresholds at which the level of change becomes undesirable (Sophocleus, 2000).

5.2 Groundwater Overdraft for Management Scenarios

In a natural equilibrium state, recharge (R_o) to the groundwater aquifer is balanced by the discharge (D_o) such that R_o equals D_o. Groundwater pumping disturbs this natural balance. As stated in section 2 of this chapter, new discharges superimposed on a previously stable system must be balanced by an increase in the recharge of the aquifer, by a decrease in the old natural discharge, or by a loss of storage in the aquifer, or by a combination of both (Theis, 1940). This relationship is expressed as (Bredehoeft, 1982):

$$\Delta R_0 - \Delta D_0 - Q = \frac{dV}{dt}$$

ΔR_0 – changes in mean natural recharge

ΔD_0 – change in mean natural discharge

Q - pumping rate

$\frac{dV}{dt}$ – rate of change of storage in the aquifer system

When $\frac{dV}{dt}$ is positive over a long-term average, overdraft exists. Overdraft in the context of long term groundwater management represents extraction of ground water at unsustainable rates. Water table elevations drop to levels that alter interactions between ground water and surface water, which can lead to adverse effects on the quantity and quality of streams and ecosystems that depend on groundwater or overdraft can lead to increasing pumping costs.

There are economic drivers of overdraft; Harou et al, 2008 examines the economic benefits of overdrafting in the Tulare region. While ultimately unsustainable, allowing overdraft without lowering aquifer levels to levels where pumping becomes uneconomic, lowers water scarcity. The Central Valley is a “mature water economy” (Hufschmidt, 1993); competition for access to fixed water supplies for urban and agricultural uses requires management and planning within the context of engineering, economic and environmental water resource systems.

C2VSIM simulates changes in the physical response of the groundwater system under a given policy. Section 5.3 details water budgets estimated in C2VISM with CALVIN allocations that are averaged over the 72-year future simulation, which shows changes in recharge and discharge.

“No Overdraft” represents a case with conservative pumping rates, 8.1 MAF/yr compared to 9.2 MAF/yr. in the Base Case. Consequently ‘No Overdraft’ C2VSIM simulation results in 2.2 MAF of additional groundwater storage, compared with 38.1 MAF simulated overdraft in the Base Case (Table 5-1). Section 5.3 below shows recharge, discharge, and storage for both cases for each region. These are compared with historical run of C2VSIM for 1980-2009.

Table 5- 1. Estimated Change in Groundwater Storage C2VSIM with CALVIN Water Deliveries

[+] = Overdraft and [-] = Increase in storage

	C2VSIM with Base Case CALVIN Water Deliveries		C2VSIM with "No Overdraft" CALVIN Water Deliveries	
Subregion	Annual Average (taf/yr)	Over 72-Years (taf)	Annual Average (taf/yr)	Over 72-Years (taf)
1	-5	-349	-4	-255
2	46	3,331	47	3,372
3	44	3,142	42	3,057
4	-2	-167	-2	-147
5	18	1,329	17	1,203
6	35	2,494	35	2,514
7	16	1,153	-5	-372
8	18	1,275	-24	-1,752
9	45	3,241	39	2,811
10	58	4,161	32	2,286
11	6	403	2	142
12	6	399	-1	-51
13	147	10,576	94	6,747
14	-24	-1,757	-116	-8,342
15	-7	-527	-27	-1,942
16	4	283	-49	-3,527
17	19	1,370	9	630
18	-50	-3,615	-64	-4,584
19	200	14,369	48	3,458
20	34	2,484	-58	-4,186
21	-77	-5,536	-46	-3,292
Sacramento	**215**	**15,449**	**145**	**10,430**
San Joaquin	**216**	**15,539**	**127**	**9,124**
Tulare	**98**	**7,070**	**-303**	**-21,785**
Central Valley Total	**529**	**38,057**	**-31**	**-2,230**

5.3 Comparison Ground water budgets for Base Case & No Overdraft Policies

To understand the effects of developing a groundwater system the components of the water budget (inflows, outflows and change in storage) must be accounted for in any management decision. This is because activities such as ground water pumping and irrigation change the natural flow patterns and affect the rate of water movement in the system. It is therefore important to evaluate the system's response for every water supply level to understand the effects on surface and ground water interaction and the effects of ground water pumping on ground water storage. Figure 5- 1 illustrates a water budget for a ground-water system under development conditions (USGS Circular 1186, 1999).

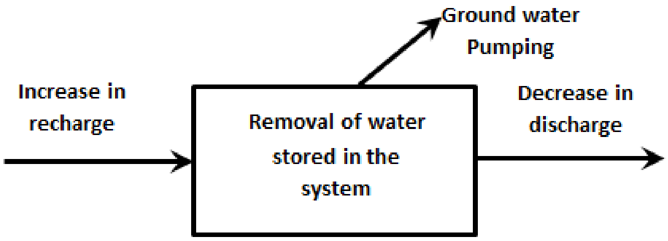

Figure 5- 1. Diagram illustrating water budgets for ground-water system for development conditions
(USGS Circular 1186, 1999)

Sections 5.4.1 to 5.4.3 discuss changes in water budgets for the three hydrologic regions (Sacramento, San Joaquin, and Tulare) with Base and "No Overdraft" cases for the 72-years projected period assuming historical hydrologic inflows (i.e. historical stream inflows and precipitation rates). These are compared with historical C2VSIM budgets for years 1980-2009. Appendix H has a breakdown by subregion.

Changes are examined in recharge pattern, groundwater storage and resulting groundwater levels for C2VSIM with optimized CALVIN water deliveries. Overall C2VSIM simulation results show that flow from the Valley's groundwater basins to streams slightly increased with "No Overdraft" case by 16 taf/yr. Changed recharge and discharge patterns for the two cases for the entire Valley are summarized in Table 5- 2. Recharge with 'No Overdraft' case decreased by 2% or 229 taf/yr; deep percolation from applied water and precipitation decreased by 225 taf/yr and contribution to groundwater flow from subsided formation decreased by 70 taf/yr. Recharge from diversion losses and artificial recharge increased with 'No Overdraft' by 66 taf/yr (artificial recharge alone increased by 116 taf/yr). Sub-sections below detail regional changes in recharge pattern with the two cases.

Table 5- 2. Ground water budget analysis – Central Valley

Central Valley	**Annual Average Water Budget Analysis (taf/yr)** **Base Case CALVIN**	**No Overdraft CALVIN Scenario**	**Difference**	**% Difference**
INFLOW				
Precipitation + Irrigation Return Flows	4,458	4,234	225	5%
Diversion Losses + Artificial Recharge	3,754	3,820	-66	-2%
Boundary Inflows	756	756	0	0%
Subsidence	234	164	70	30%
Total Recharge	***9,202***	***8,973***	**229**	**2%**
OUTFLOW				
Stream Exchange	851	868	-16	-2%
Lakes	72	62	10	14%
Tile Drains	17	22	-5	-28%
Total Discharge	***940***	***952***	***-11***	***-1%***
Pumping	8,790	7,991	800	9%
Change in Storage ([+] - indicates overdraft volumes)	529	-31	560	

Figure 5- 2 compares storage for Base and 'No Overdraft' cases, groundwater storage is recovered with 'No Overdraft', however on a subregion basis for example subregions 1, 18 and 21, Base storage exceeds 'No Overdraft' case (Appendix H). Table 5- 3 and Appendix H show the complexity in establishing Central Valley wide pumping levels for sustainable groundwater use as the system is interconnected and the new balance for recharge and discharge is not linear, so that reduced pumping does not necessarily end overdraft or recover water table elevations for some subregions.

Appendix H, details subregion water budgets, which help explain the differences in simulation results for the management cases.

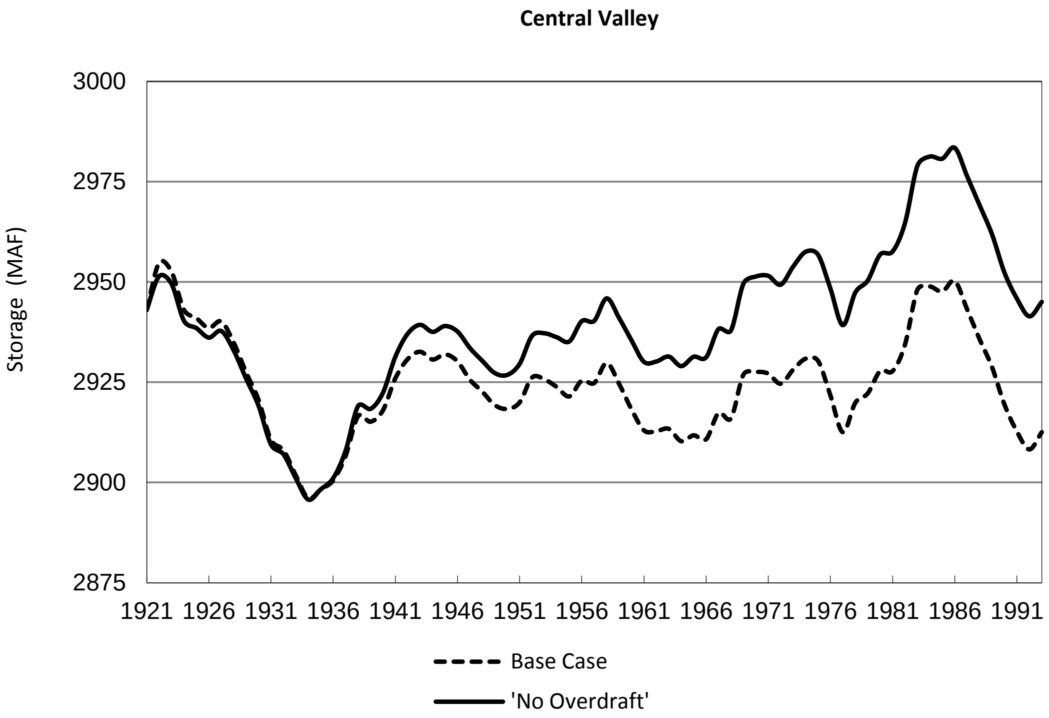

Figure 5- 2. Storage results of C2VSIM simulation with Base Case and 'No Overdraft' CALVIN water deliveries – Central Valley

Table 5- 3. Comparison C2VSIM simulation of groundwater basin response to Base Case CALVIN and 'No Overdraft' CALVIN water deliveries

	Change in Storage over 72-years (taf) [+]-indicates overdraft		Average Water Table Elevations (ft)		Scarcity (taf/yr)		Stream Exchange (taf/yr) [-] - indicates outflow to streams	
Subregion	C2VSIM with Base Case CALVIN Water Deliveries	C2VISM with 'No Overdraft' CALVIN Water Deliveries	C2VSIM with Base Case CALVIN Water Deliveries	C2VISM with 'No Overdraft' CALVIN Water Deliveries	C2VSIM with Base Case CALVIN Water Deliveries	C2VISM with 'No Overdraft' CALVIN Water Deliveries	C2VSIM with Base Case CALVIN Water Deliveries	C2VISM with 'No Overdraft' CALVIN Water Deliveries
1	-349	-255	479.7	478.8	2	21	-139	-130
2	3,331	3,372	257.3	256.7	0	19	20	21
3	3,142	3,057	80.4	81.6	0	0	-113	-117
4	-167	-147	33.9	32.7	0	16	-230	-232
5	1,329	1,203	73.8	71.8	0	0	-102	-110
6	2,494	2,514	25.4	25.3	21.3	32.3	107	101
7	1,153	-372	16.1	30.7	0	2	36	22
8	1,275	-1,752	10.0	19.3	0	59	105	96
9	3,241	2,811	-5.0	7.2	2	41	136	106
10	4,161	2,286	117.0	117.3	56	59	-76	-94

11	403	142	75.7	77.5	0	10	-137	-160
12	399	-51	111.9	116.9	24.1	28	-96	-110
13	10,576	6,747	101.8	110.1	77	142	56	33
14	-1,757	-8,342	93.2	48.5	0	0	0	0
15	-527	-1,942	185.5	177.5	0	0	-148	-163
16	283	-3,527	289.6	251.2	11	18	-27	-37
17	1,370	630	216.8	201.1	35	37	0	-4
18	-3,615	-4,584	340.0	293.9	106	204	-443	-277
19	14,369	3,458	111.2	128.5	0	0	36	30
20	2,484	-4,186	203.9	204.6	27	32	24	24
21	-5,536	-3,292	210.3	200.0	39	47	139	132
Sacramento	**15,449**	**10,430**			**25**	**190**	**-180**	**-242**
San Joaquin	**15,539**	**9,124**			**157**	**239**	**-253**	**-330**
Tulare	**7,070**	**-21,785**			**218**	**338**	**-418**	**-296**
Central Valley Total	**38,057**	**-2,230**			**400**	**767**	**-851**	**-868**

▨ **Groundwater basins that improved with 'No Overdraft' management- water table elevations and overdraft**

5.3.1 Sacramento Region – Water Budgets and Aquifer responses

C2VSIM simulated groundwater overdraft decreases with the ‘No Overdraft’ case by 5 MAF over 72-years. Table 5- 4 shows water budgets for the Sacramento region under the two cases. We are concerned with annual average budget for regional water flow. Comparison of these water budgets shows recharge decreased with the “No Overdraft” case, because return flows from applied water decrease by 53.3 taf/yr. Flow from groundwater to streams increased by 62 taf/yr with ‘No Overdraft’.

At a smaller scale, for subregion 2 ‘No Overdraft’ pumping increased water shortages by 888 taf/yr but groundwater storage and groundwater table elevations are not improved with this case. Table 5- 3 and Table 5- 4 compare storage and water table elevations for subregion 2 for both cases, average groundwater table elevation declines over time for both scenarios indicating unsustainable pumping.

For subregion 9, reduced pumping with ‘No Overdraft’ shorts the region by 1,476 taf/yr more than the Base Case, but, groundwater storage improves. ‘No Overdraft’ results in 429 taf/yr less storage depletion and increased water table elevations over time (Table 5- 5).

Table 5- 4. Ground water budget analysis – Sacramento Region

Sacramento Region	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	No Overdraft CALVIN Scenario	Historical 1980-2009
INFLOW			
1. Precipitation + Irrigation Return Flows	1279	1194	1853
2. Diversion Losses	484	489	409
3. Boundary Inflow	525	525	464
4. Inter-basin Inflow	140	141	82
5. Subsidence	15	15	6
Total Recharge	***2443***	***2363***	***2813***
OUTFLOW			
6. Stream Exchange	180	242	450
Total Discharge	***180***	***242***	***450***
7. Pumping	2478	2266	2752
Change in Storage ([+] - indicates overdraft volumes)	215	145	390

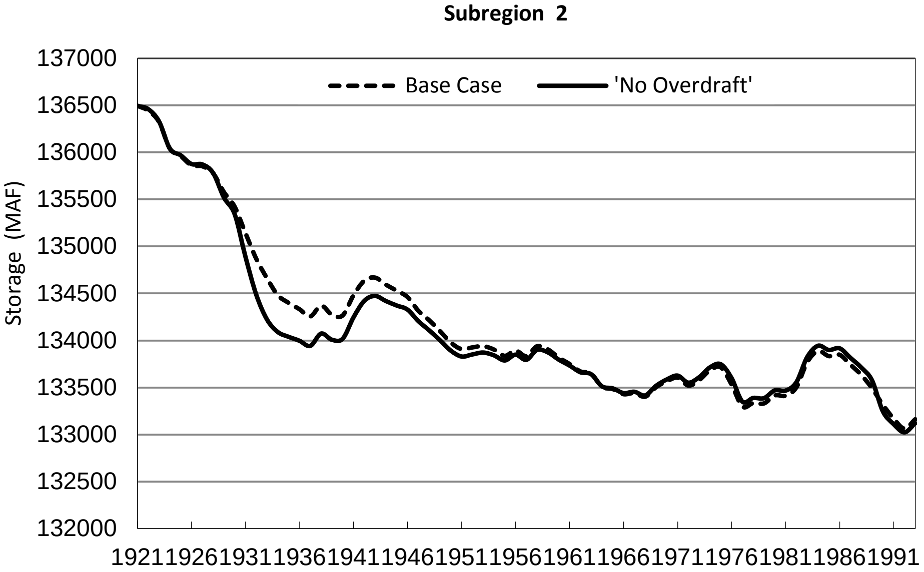

Figure 5- 3. Storage results of C2VSIM simulation with Base Case and ‘No Overdraft’ CALVIN water deliveries - subregion 2

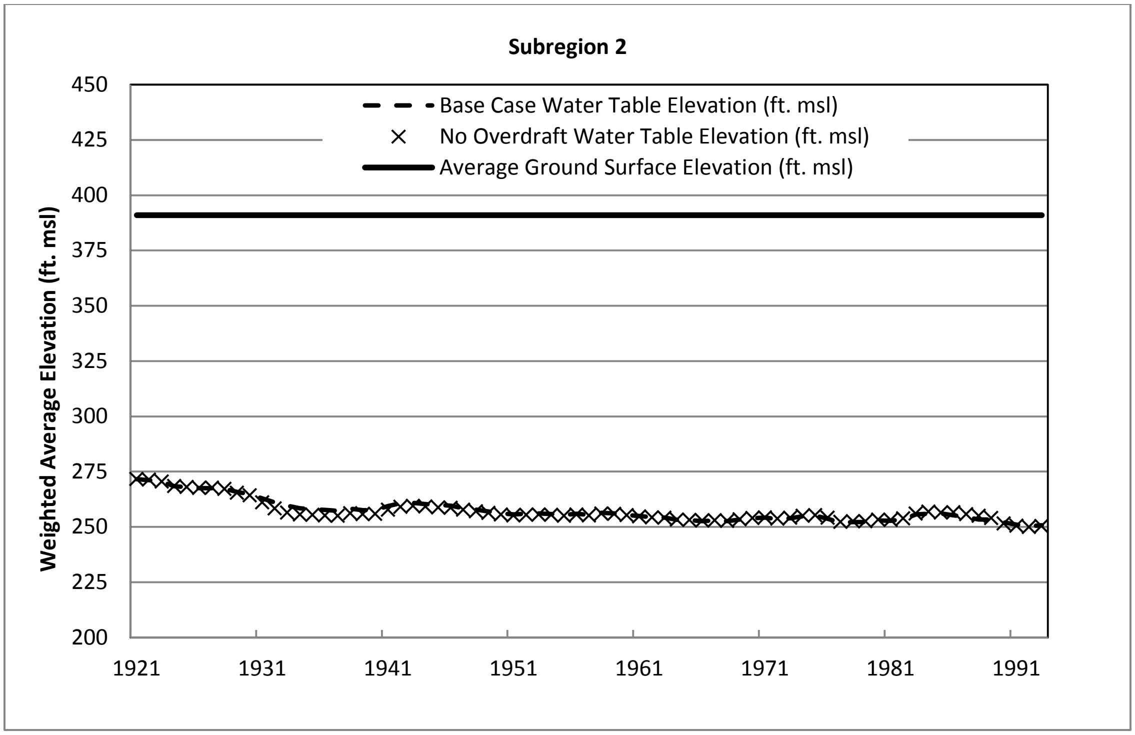

Figure 5- 4. Water Table Elevations for subregion 2 example of sustainable pumping levels with the two management cases

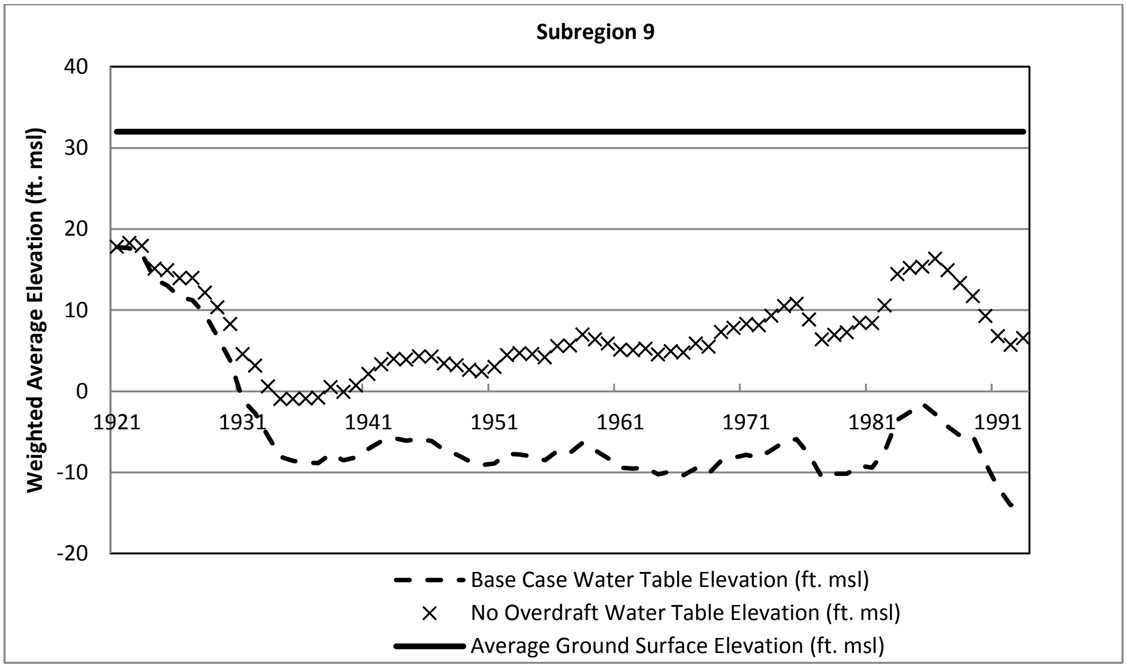

Figure 5- 5. Water Table Elevations for surgeon 9 example of improved elevations with 'No Overdraft' pumping

5.3.2 San Joaquin – Water Budgets and Aquifer Response

With ‘No Overdraft’ groundwater storage depletion decreases compared to Base Case for the San Joaquin region C2VSIM simulated ‘No Overdraft’ CALVIN operations has 6.4 MAF less overdrafting over 72-years but 9.1 MAF of overdraft remaining. Return flow of applied water decreased by 19 taf/yr with ‘No Overdraft’, subsidence rate decreased by 11 taf/yr and artificial recharge increased by 21 taf/yr.

For all subregions in San Joaquin, groundwater storage and water table elevations improved with ‘No Overdraft’ relative to the Base case in Appendix H and Table 5- 5.

Table 5- 5. Ground water budget analysis – San Joaquin Region

	Annual Average Water Budget Analysis (taf/yr)		
San Joaquin Region	**Base Case CALVIN**	**No Overdraft CALVIN Scenario**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flows	1246	1204	1026
2. Diversion Losses and Artificial Recharge	547	581	650
3. Boundary Inflow	63	63	70
4. Subsidence	35	24	66
Total Recharge	***1891***	***1872***	***1812***
OUTFLOW			
5. Stream Exchange	253	330	345
6. Inter-basin	31	24	62
7. Tile Drain Outflows	17	21	36
Total Discharge	***301***	***376***	***443***
8. Pumping	1807	1623	1587
Change in Storage ([+] - indicates overdraft volumes)	216	127	218

5.3.3 Tulare – Water Budgets and Aquifer Response

‘No Overdraft’ results in 21.8 MAF negative overdraft (storage accumulation) compared to Base Case which causes 7.1 MAF overdrafting over 72-years. Table 5-6 details water budget for the Tulare region the under different management cases. Flow to streams and return flows from applied water are less with 'No Overdraft' by 122 taf/yr and 19 taf/yr respectively. And artificial recharge increases by 95 taf/yr with the 'No Overdraft' case.

Subregion 21 is the only basin in the region for which 'No Overdraft' results in less storage and lower water table elevations than Base Case (Figure 5-6 and Figure 5-7).

Table 5- 6. Ground water budget analysis – Tulare Region

	Annual Average Water Budget Analysis (taf/yr)		
Tulare Region	**Base Case CALVIN**	**No Overdraft CALVIN Scenario**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	1933	1836	1519
2. Diversion Losses + Artificial Recharge	2723	2749	2218
3. Boundary Inflow	168	168	220
4. Subsidence	184	126	0
Total Recharge	***5007***	***4879***	***169***
OUTFLOW			
5. Stream Exchange	418	296	176
6. Inter-basin	109	116	20
7. Lake Exchange	72	62	29
8. Tile Drain Outflow	0	0	0
Total Discharge	***600***	***475***	***225***
9. Pumping	4506	4102	4932
Change in Storage ([+] - indicates overdraft volumes)	98	-303	1031

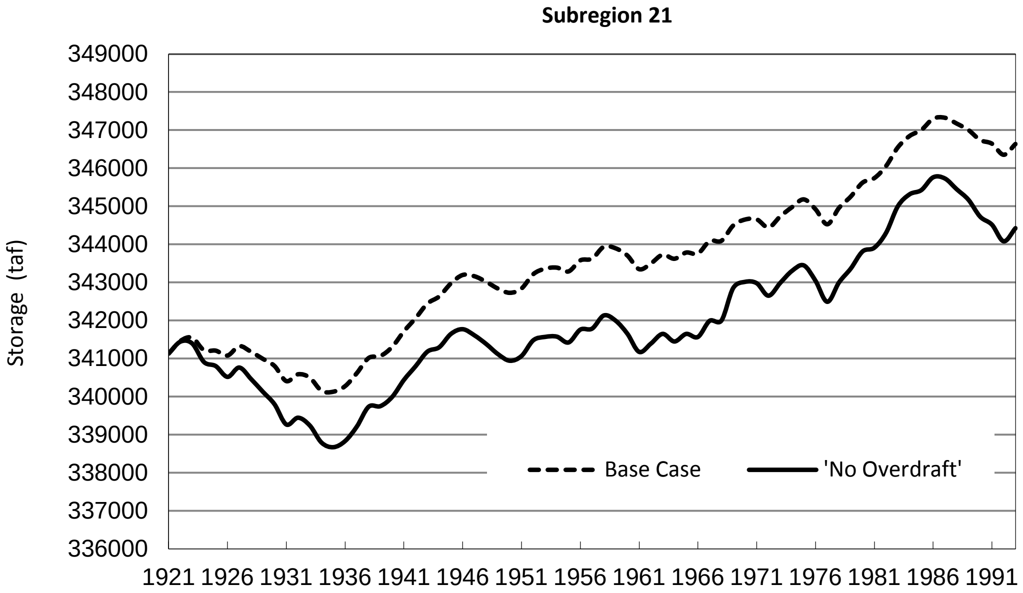

Figure 5- 6. Storage results of C2VSIM simulation with Base Case and 'No Overdraft' CALVIN water deliveries – Subregion 21

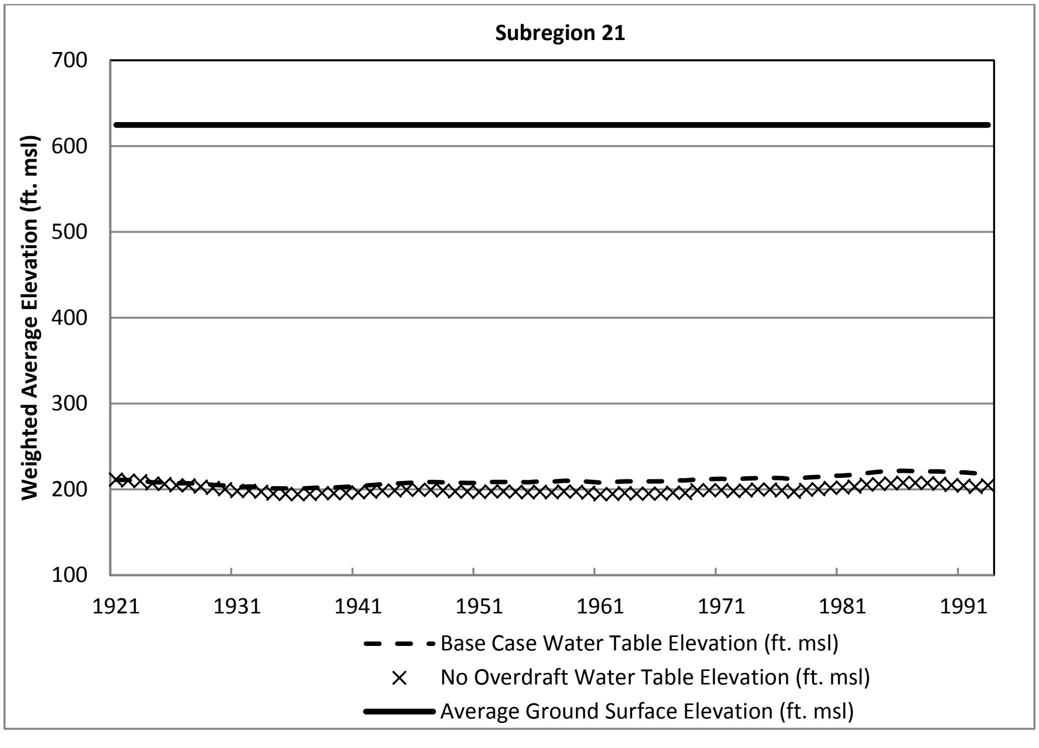

Figure 5- 7. Water Table Elevations for surgeon 21 example of improved elevations with Base Case pumping

5.4 Artificial Recharge in Conjunctive Use

With growing limitations on available surface water exported through the Sacramento-San Joaquin Delta and the potential impacts of climate change, reliance on groundwater through conjunctive management will become increasingly important in the Central Valley and throughout California. Conjunctive use is the integrated management of both surface and groundwater supply. It involves using surface water in periods of ample rainfall and runoff and groundwater supplied when surface water is limited or unavailable (Banks et al, 1954). Conjunctive Management is emerging as a major water management tool to balance supply variability.

The DWR's 2009 Water Plan details three elements for conjunctive management; 1) construction projects, which includes construction of treatment facilities, conveyance facilities recharge facilities, installation of monitoring, production and injection wells and drilling of test holes 2) implementing effective groundwater management programs, including reducing pumping demands, tracking groundwater levels and water quality and managing pumping patters and destroying abandoned wells to prevent cross-contamination of aquifers and 3) capacity building a process of equipping public agencies with skills, competences or upgraded performance capability by providing assistance, funding, resource and training (DWR, 2009). CALVIN and C2VSIM models can provide insight on the impacts of different groundwater overdraft management policies to meet objectives for reliable water supply and to study aquifer systems response to the ground water management.

Conjuctive use of surface and ground water sources is controlled by available surface water. Most inflows for the Central Valley are from the Sacramento, Feather, American, Yuba Toulumne and Kings rivers, with average historical inflow downstream of regulating reservoirs of 6.1 MAF/yr, 3.7 MAF/yr, 2.6 MAF/yr, 1.9 MAF/yr, 1.63 MAF/yr and 1.6 MAF respectively in Table 2- 10. In the current C2VSIM and CALVIN models artificial recharge facilities in the Sacramento region are not represented, this however may not reflect on ground recharge practice or potential for the region's aquifers for water banking; San Joaquin and Tulare have spreading facilities modeled in this study. Chou (2012) details estimated costs associated with the respective artificial recharge operations.

Effective artificial recharge for conjunctive use should account for available surface water; artificial recharge is potential artificial recharge since C2VSIM does not use an infiltration routing equation to compute water that seeps to groundwater from artificial recharge facilities instead a fraction of 0.95 is used to estimate volumes of surface water dedicated for artificial recharge that end up as groundwater. Figure 5- 8 shows Central Valley's total stream inflow for water years 1922 to 1993, representing flows that enter the model downstream of regulated reservoirs along with optimized volumes of surface water for artificial recharge. For some wet years, for example 1969, up to 14% of total inflow is banked in the ground for later use; CALVIN results suggest benefits from strategic management of ground water and surface water use as well as the role of groundwater basins as a buffer during drought years.

Sections below describe conjunctive use of groundwater and surface water for regions in the Central Valley with the two management scenarios.

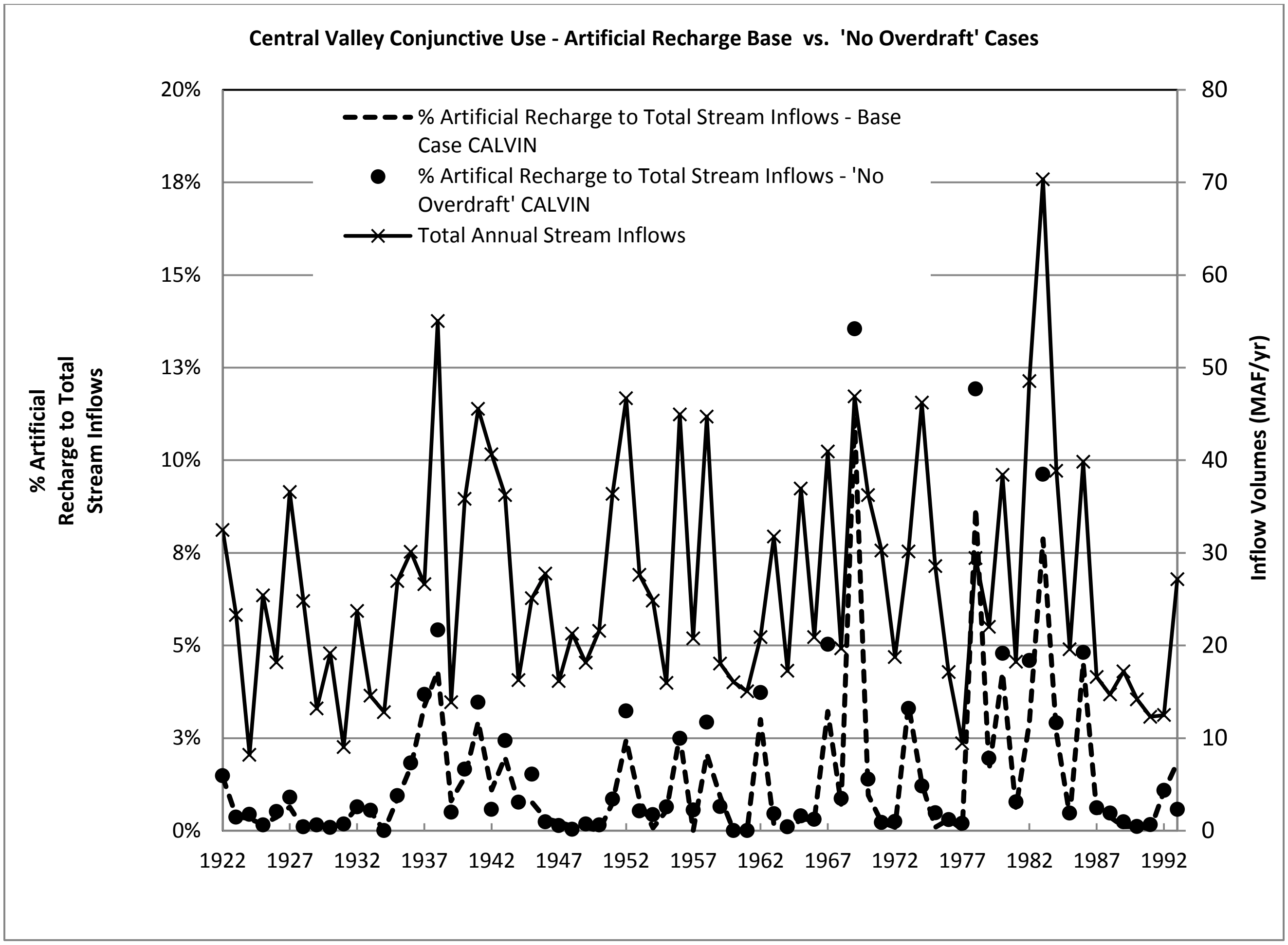

Figure 5- 8. Central Valley conjunctive use of ground and surface water – Total Stream Inflows vs. Artificial Recharge

5.4.1 Sacramento – Conjunctive Use of Ground and Surface Water

Optimized groundwater use in Sacramento shows that pumping accounts for about 20% of total water supply even in wet years with both Base and ‘No Overdraft’ cases. During drought years pumping increases to 56% or 57% of total annual water supply (Figure 5- 9 and Figure 5- 10). Pumping decreases in wet years and a higher percentage of recharge contributes to groundwater storage. However, with the ‘No Overdraft’ case, a larger percentage of recharge contributes to storage during wet years (Figure 5- 7).

Table 5- 7. Ground and Surface Water Conjunctive Use in Sacramento

Hydrologic Region	Year Type		% Annual Supply from Pumping		% Annual Net Recharge Contributing to Aquifer Storage		% Annual Artificial Recharge to Annual Net Recharge	
			Base Case	'No Overdraft'	Base Case	'No Overdraft'	Base Case	'No Overdraft'
Sacramento	Critical Years	1990	56	57	0	0	=	=
		1991	52	52	0	0	=	=
	Wet Years	1982	21	19	46	49	=	=
		1983	20	19	57	59	=	=

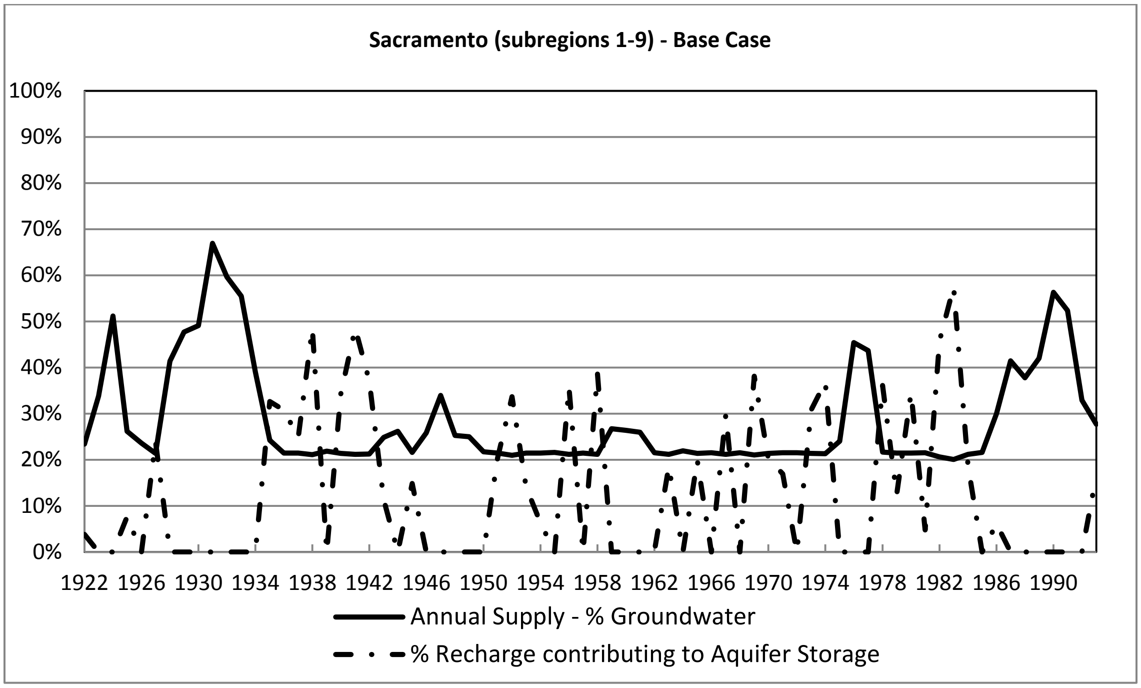

Figure 5- 9. Sacramento Region Base Case Conjunctive use of groundwater and surface water

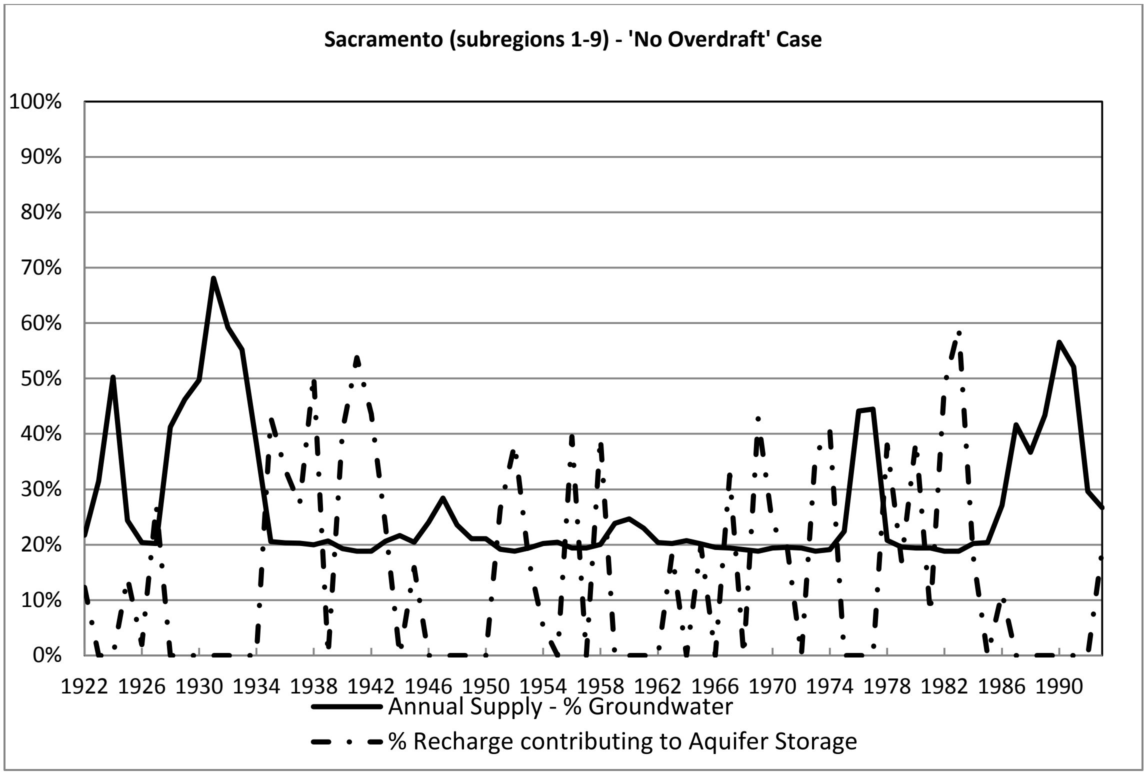

Figure 5- 10. Sacramento Region 'No Overdraft' Conjunctive use of groundwater and surface water

5.4.2 San Joaquin - Conjunctive Use of Ground and Surface Water

The San Joaquin basin has facilities for artificial recharge in subregion 13. Optimized groundwater use for this region indicates that pumping accounts for at least 14% of annual water supply in wet years for Base and 'No Overdraft' cases (Figure 5- 8). In wet years artificial recharge contributes up to 19% of annual net recharge during wet years for the Base case, and up to 56% of annual net recharge with the 'No Overdraft' case (Figure 5- 11 and Figure 5- 12). In critical water years up to 60% of annual pumping is from aquifers storage for both cases. For the San Joaquin basin, storing groundwater for dry years is important in the planning for adequate groundwater storage during critical years is important.

Table 5- 8. Ground and Surface Water Conjunctive Use in San Joaquin

Hydrologic Region	Year Type		% Annual Supply from Pumping		% Annual Net Recharge Contributing to Aquifer Storage		% Annual Artificial Recharge to Annual Net Recharge	
			Base Case	'No Overdraft'	Base Case	'No Overdraft'	Base Case	'No Overdraft'
San Joaquin	Critical Years	1990	65	60	0	0	0	0
		1991	50	46	0	0	0	0
	Wet Years	1982	14	14	46	60	7	33
		1983	14	14	57	72	19	56

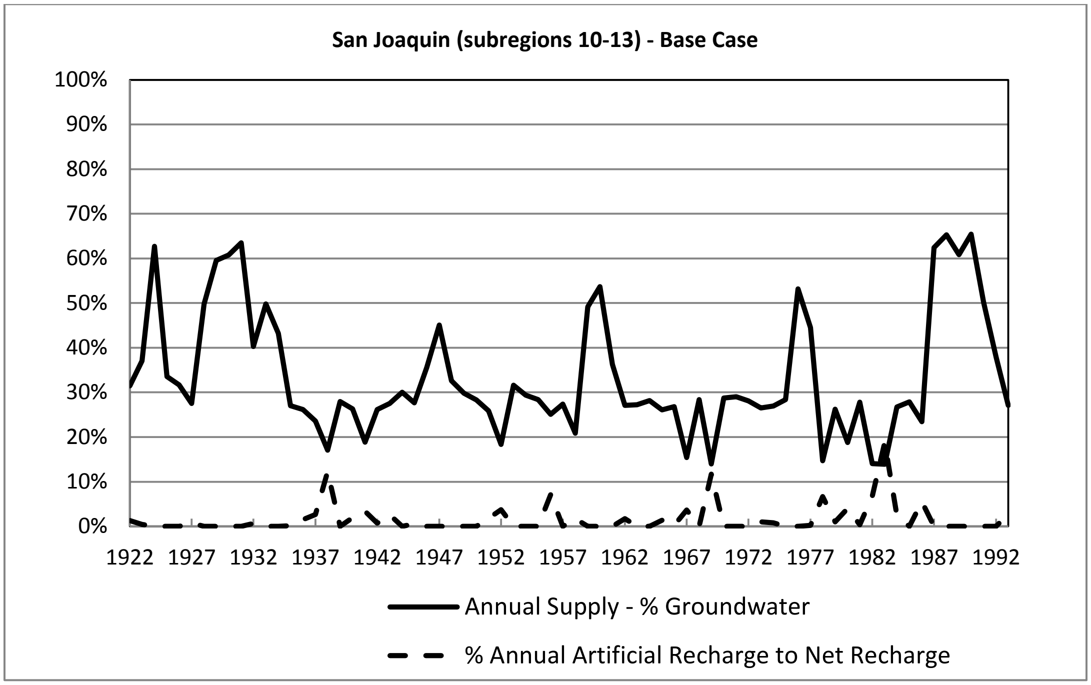

Figure 5- 11. San Joaquin Base Case Conjunctive use of groundwater and surface water

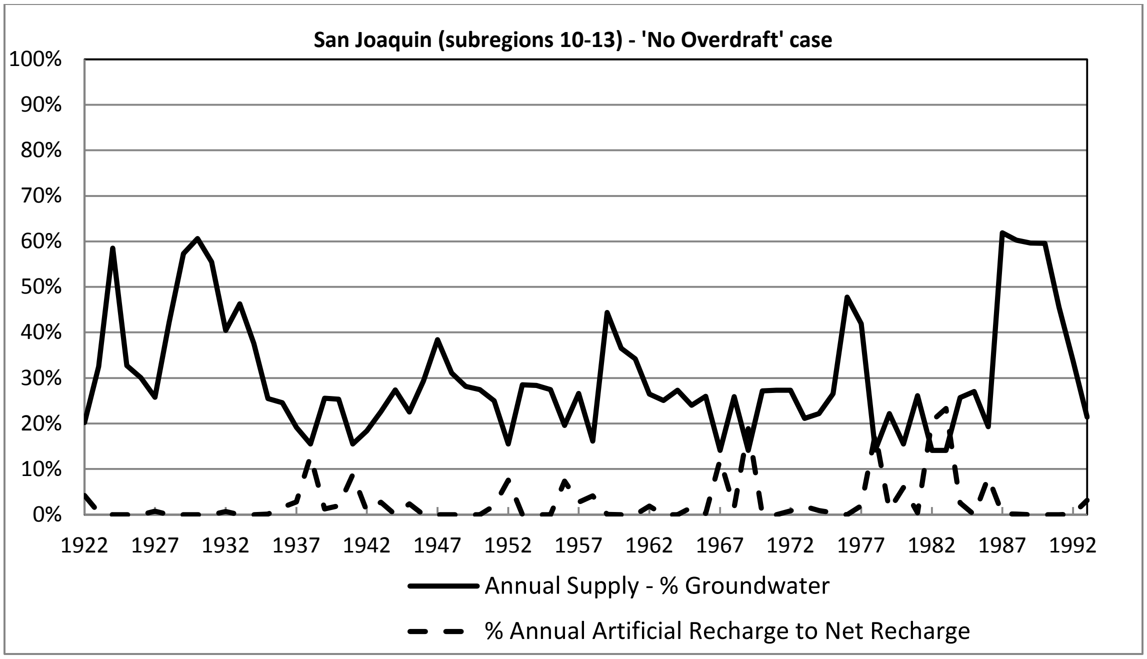

Figure 5- 12. San Joaquin 'No Overdraft' Conjunctive use of groundwater and surface water

5.4.3 Tulare – Conjunctive Use of Ground and Surface Water

Artificial recharge facilities are modeled in the Tulare subregions 15 to 21. Optimized groundwater use show that pumping accounts for 12% and 9% of total water supply for Base and 'No Overdraft' cases in wet years. In critical dry years groundwater provides up to 77% of total water use.

Induced infiltration plays an important role in recharge of aquifers for this region as it accounts for up to 49% of net recharge with Base Case and 56% with 'No Overdraft' case in wet years, however even in critical years artificial recharge accounts for 1% of total annual net recharge (Table 5- 9).

Table 5- 9. Ground and Surface Water Conjunctive Use in Tulare

Hydrologic Region	Year Type		% Annual Supply from Pumping		% Annual Net Recharge Contributing to Aquifer Storage		% Annual Artificial Recharge to Annual Net Recharge	
			Base Case	'No Overdraft'	Base Case	'No Overdraft'	Base Case	'No Overdraft'
Tulare	Critical Years	1990	75	77	0	0	1	1
		1991	69	65	0	0	0	1
	Wet	1982	17	11	68	81	24	33

	Years	1983	12	9	87	92	49	56

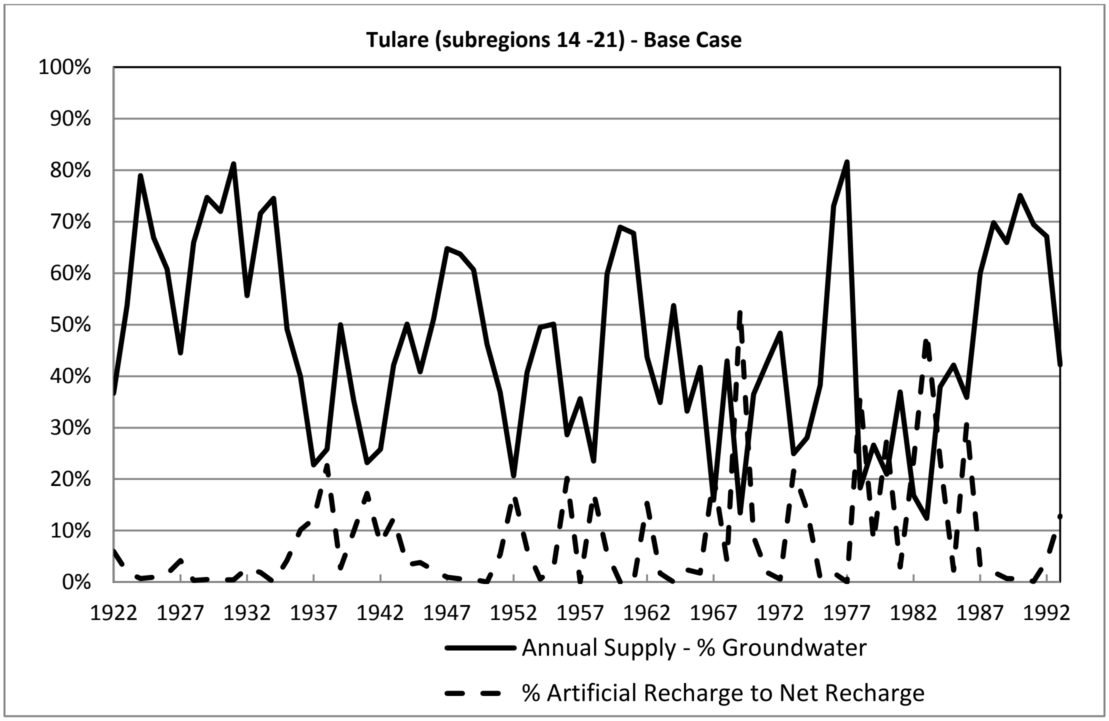
Tulare (subregions 14 -21) - Base Case

Figure 5- 13. Tulare Base Case conjunctive use of groundwater and surface water

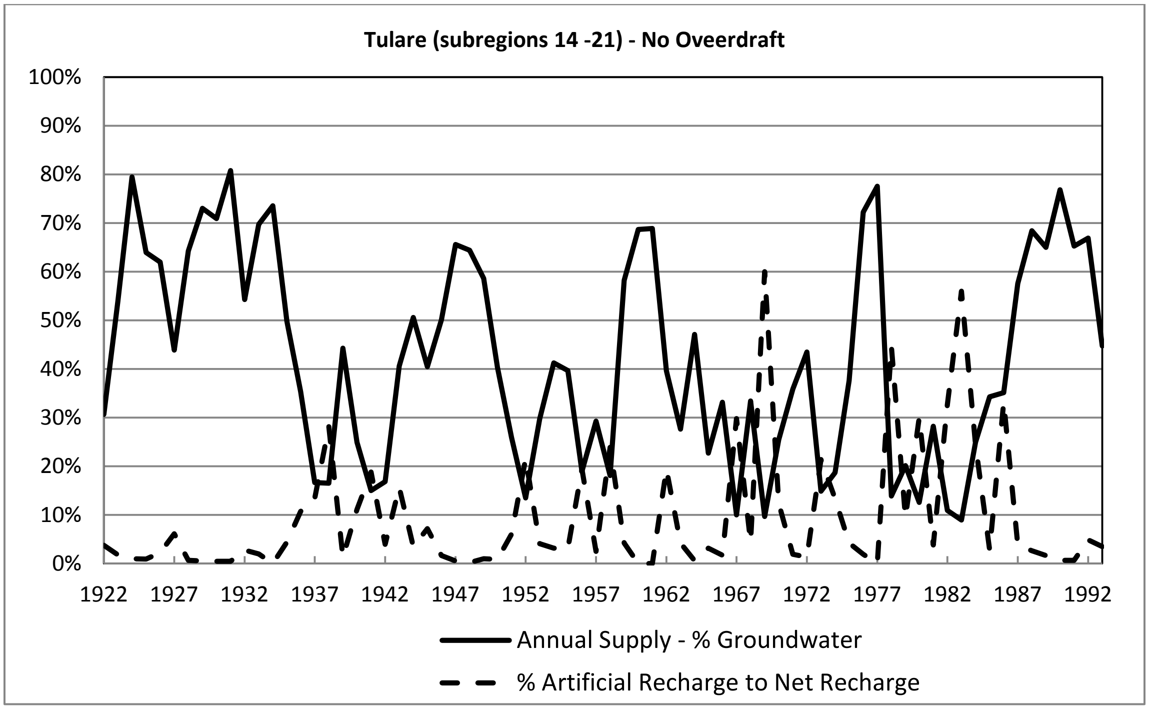
Tulare (subregions 14 -21) - No Oveerdraft

Figure 5- 14. Tulare ‘No Overdraft’ conjunctive use of groundwater and surface water

5.5 Concluding Remarks

The Central Valley is a “mature water” economy; effective water management in this region will benefit from modeling tools that suggest integrated, sustainable and economically efficient solutions. The CALVIN model represents hydrologic engineering systems while considering the economic nature of water demands and costs. Two management cases are considered in this chapter; Base Case which allows in CALVIN 70.9 MAF historical Central Valley groundwater overdrafting over the 72-years and a “No Overdraft” which set constraint for ending storage equal to beginning storage over the optimization time in CALVIN. The constraints groundwater basin ending storage in CALVIN as explained in above sections were imposed in the model to reflect limited elasticity with respect to groundwater pumping. C2VSIM was run and used in this chapter to compare the effects of optimized CALVIN deliveries on groundwater basins.

CALVIN results show that economically optimized average water use under these two cases for the Central Valley is 24,554 taf/yr and 23,817 taf/yr for Base and ‘No Overdraft’ cases respectively, with pumping accounting for at least 19% of total water supply for both cases. The reduced deliveries under the “No Overdraft” case cost the region $51.3 Million/yr compared to $20.0 Million/yr with Base Case deliveries. Water shortages increased for agricultural areas.

The C2VSIM simulation with optimized CALVIN water deliveries for two management cases are used to study aquifer response in recharge and groundwater levels. The Central Valley groundwater basins are a self-contained system, natural recharge from surface water and between neighboring basins changes as a result of pumping. Management of these basins benefits from a region wide perspective, as shown in section 5.3.

C2VSIM and CALVIN results show that the Base Case provides better economic benefits but 35.8 MAF higher groundwater overdrafts than ‘No Overdraft’ over 72-years. At a subregion scale the Base case has higher groundwater storages for 1 and 21 than ‘No Overdraft’. Some subregions have declining groundwater levels with both scenarios possibly indicating unsustainable pumping, for example subregion 2 (Appendix H).

Return flow of applied water decreases with ‘No Overdraft’ case by 91 taf/yr, as less water is delivered for use; flows from groundwater to streams decreases by 16 taf/yr compared to Base Case. Water contributions from subsided formation also decreased with ‘No Overdraft’ by 70 taf/yr, which means negative impacts of subsidence particularly in San Joaquin and Tulare are reduced with ‘No Overdraft’ management.

Artificial recharge has a critical role in recharging aquifers, particularly in the Tulare region. In wet years artificial recharge accounts potentially for 49% and 56% of total net recharge in the Base and ‘No Overdraft’ cases respectively. Even in critical dry years artificial recharge accounts for 1% of annual net recharge for both cases.

The two scenarios give insight on how decisions for surface water diversions affect pumping rates and sustainable aquifer use overtime. Restoring groundwater storage in the region as well as providing reliable water in dry years calls for a careful look at water banking, particularly in the Tulare and San Joaquin regions, however opportunities for managed ground water recharge in Sacramento region could increase water supply reliability for the entire region.

Chapter Six: Overall Conclusion

Integrated hydro-economic, modeling, like CALVIN, provides a versatile way to explore the advantages and drawbacks of various potential statewide and regional policies and plans. As an optimization model CALVIN suggests how the water supply systems might be operated to provide broad economic benefit while meeting physical and environmental requirements. But, no model can perfectly reflect a complex reality due to inevitable imperfections in data and mathematical representations. It is important to periodically revisit any model to make sure it continues to operate with the best data available. This project updated and improved CALVIN's Central Valley groundwater representation based on the C2VSIM groundwater flow model.

The updated CALVIN seems to strategically represent major features of the Central Valley groundwater system, as represented by C2VSIM. Change in storage in Appendices F and G, show that CALVIN tracks groundwater flow fairly well for some subregions for example 1 and 13, however for some subregions groundwater recharge in CALVIN needs adjustments. CALVIN groundwater recharge components which are based on C2VSIM a historical run with some adjustments differ from C2VSIM. For the entire Central Valley CALVIN calculates generally lower recharge than C2VSIM with 2005 land use and optimized CALVIN water deliveries (Chapter 4 and Appendices E, F and G).

CALVIN matches C2VSIM better for groundwater in the Sacramento and San Joaquin regions and is worse in the Tulare for both cases. With the 'No Overdraft' scenario, the CALVIN and C2VSIM groundwater match is improved for all regions.

Change in groundwater storage estimated in CALVIN is often not as represented in the C2VSIM model. Base Case in CALVIN is constrained to limit overdraft volume for the Central Valley to 70.9 MAF over 72 years. Using CALVIN Base Case diversion and pumping C2VSIM computes 38.1 MAF overdraft. This is similar to the overdraft differences between the C2VSIM and the USGS CVH model (Chou 2012). Likewise for the ‘No Overdraft’ scenario CALVIN limits zero change in storage for all basins, but C2VSIM computes 2.2 MAF additional storage volume for the Central Valley over 72-years. However, the groundwater ending storage constraints in CALVIN restrict pumping and prevent large pumping rates. It is important to impose in CALVIN some ending storage constraint, but overdraft in CALVIN should be checked with simulation models.

Management of pumping rates for reducing or ending groundwater overdraft proves to vary with scale. The two cases tested in this study show some subregions for example 1, 2 and 21 have higher storage volumes with Base compared to ‘No Overdraft’ case. CALVIN pumping rates with the ‘No Overdraft’ case when tested in the simulation model do not always end long term overdraf or maintaining stable groundwater elevations. This is the case for subregions 2, 6, 9, 13 and 19 in Chapter 5 and Appendix H. As Harou and Chou studies demonstrate that groundwater management policies and solutions to groundwater problems can be explored with the integrated hydro-economic model such as CALVIN. Chapter 5 of this study shows the importance of groundwater flow models in the determination of sustainable groundwater management as they can better capture the spatial variability of aquifer systems response to different overdraft management scenarios.

Groundwater is always an important source of water in the Central Valley even in wet years for almost all regions accounting at minimum for 19%, 11% and 9% of total water supply in Sacramento, San Joaquin and Tulare regions respectively with the restrictive ‘No Overdraft’ case. Given the important role of groundwater in providing reliable water supply, artificial recharge becomes important for reducing or ending overdraft or restoring groundwater levels. In San Joaquin basin, Base Case artificial recharge can account for up to 19% of annual net recharge in some wet years; if pumping is restricted as in ‘No Overdraft’ case this percentage becomes 56%. Management to increase groundwater storage or to restore water table elevation should consider artificial recharge projects. Similarly in the Tulare region with the Base Case, potential artificial recharge is up to 49% of net recharge, this increased with restrictions on pumping under ‘No Overdraft’ scenario to 56%.

Although this re-calibration of CALVIN’s Central Valley ground water is a great improvement, there is room and substantial need to further improve quantification of Central Valley groundwater. The time series of recharge termed ‘Net External Inflows’ requires some adjustment to match better stream flows and inter-basin flows in particular. Furthermore, some fractions for return flow of irrigation water may need to be adjusted to better match the flows simulated in the 2005 or projected 2050 level of development in Appendix E and chapter 4.

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Appendix A: Updates to CALVIN Schematic

Updates to the CALVIN schematic have been made to better accommodate components related to groundwater for the agricultural and urban sectors and to facilitate the calibration process. Hidden nodes and nodes for artificial recharge have been added to the PRMNetBuilder network.
Although, hidden nodes do not have a physical location, these nodes have been added to handle the following:

- Return flow of applied water to groundwater from agricultural areas (HGD)
- Return flow of applied water to surface water from agricultural areas (HSD)
- Return flow of applied water to groundwater for urban areas (HGU)
- Infiltration of surface diversions allocated for spreading-Artificial Recharge (HAR)
- Pumping to all demand areas (HGP)

The added hidden nodes link to physical downstream and upstream nodes and carry amplitude functions that represent any occurring physical losses. Hidden nodes for pumping (HGP) link groundwater to demand areas and have an amplitude of 1.0. It is assumed that pumps are located close to the demand areas so that no losses occur.

Hidden nodes for return flow (HGD and HGU) to groundwater for agricultural and urban areas link demand areas to groundwater and have a return flow amplitude representative of fraction of applied water that is returned to the ground. Artificial recharge nodes (HAR) consists of upstream and downstream links such that upstream links to surface water diversions allocated for spreading and carry amplitude that reflect fractions of diverted water that is lost to evaporation and the downstream link is artificial recharge flow to the groundwater basin. Hidden node for return flow to surface water (HSD) for agricultural and urban areas link demand areas to surface water and have return flow amplitude representative of fraction of applied water that is returned to surface water.

Figures A-1 and A- 2 below show an updated and detailed schematic for agricultural and urban sectors respectively. Urban sector figure represents updates to schematic regarding demand area groundwater interaction only. Details on the computation of these amplitudes based on C2VSIM can be found in Chapter 3.

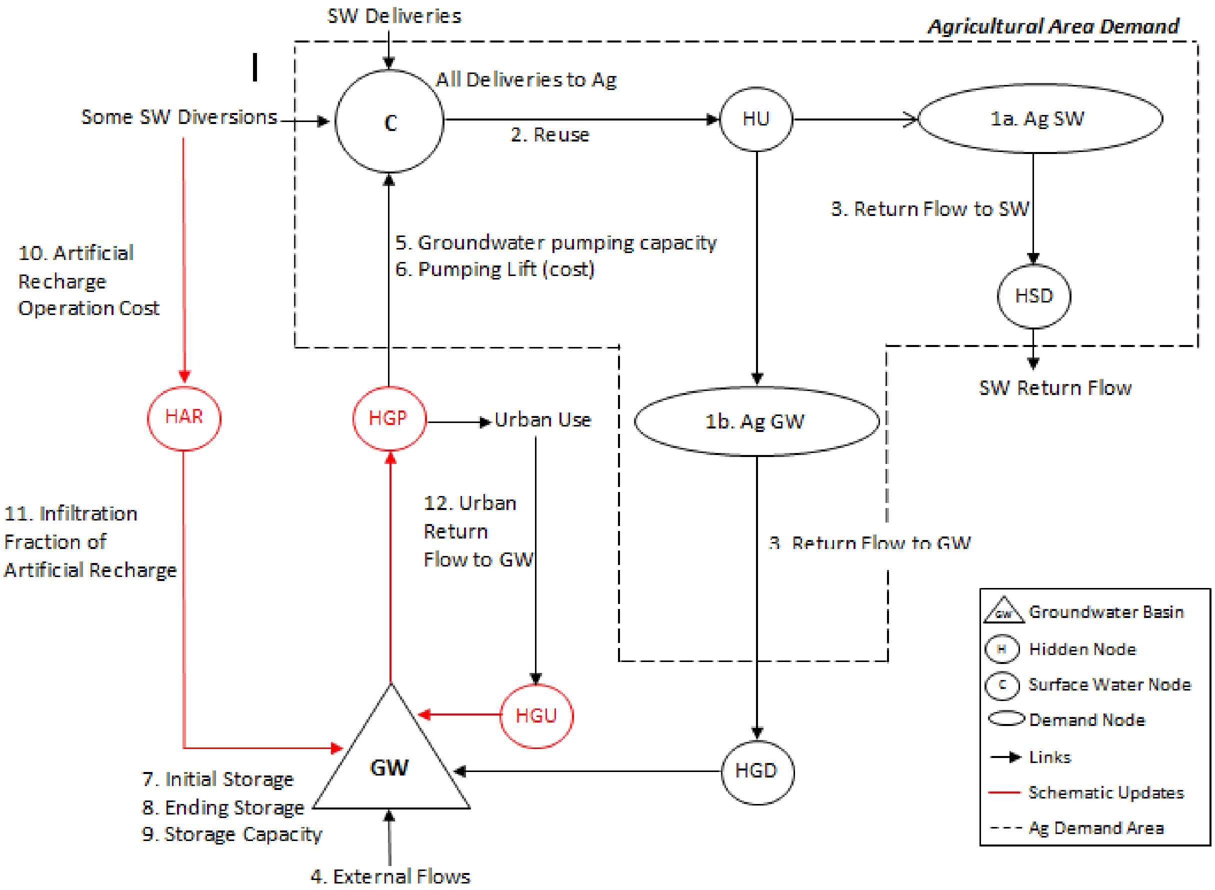


Figure A-1. Updated CALVIN Schematic for Agricultural Sector

Notes: a) Ag Demand GW represents the non-consumptive use portion of irrigation water that deep percolates to groundwater, and Ag Demand SW represent the portion that returns to surface water systems as tailwater.
b) Net External Flows represent net monthly timeseries inflows to groundwater from Streams, Lakes, Deep Percolation of Precipitation, Diversion losses, Boundary Inflows, Interbasin Inflows, Subsidence and Tile Drain Outflows

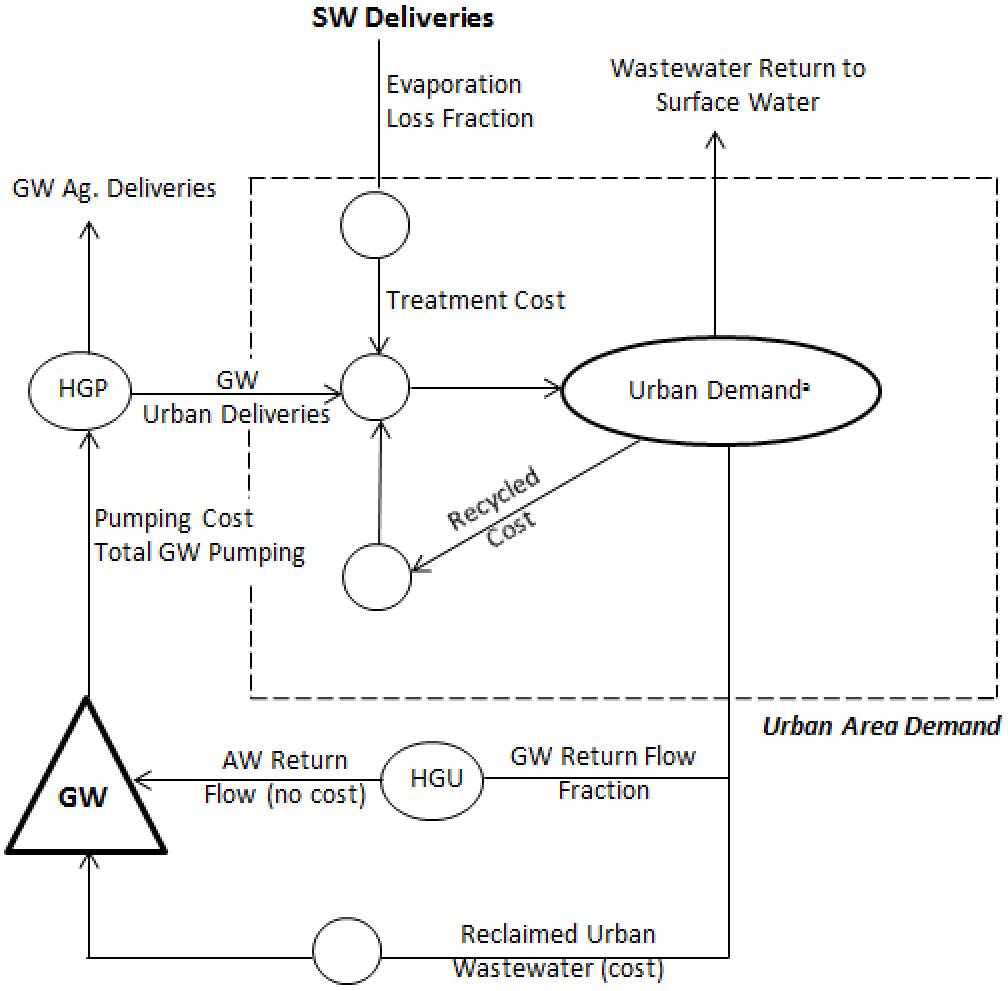


Figure A-2. Updated CALVIN Schematic for Urban Sector

Notes: a) Urban Demand in the CALVIN network are separated as Ext:CVPM representing outdoor use of delivered water and Int:CVPM which represent indoor use of delivered water.

Appendix B: C2VSIM Surface Water diversion losses used to update CALVIN

Table below shows updated amplitudes for surface water conveyance losses, fraction in bracket are final values used in CALVIN based on the initial calibration and understood available water in subregions since some C2VSIM fractions appeared to be unreasonably high. Destination subregion indicates the subregion to which groundwater is recharged by diversion losses, CALVIN links which carry this loss amplitude are shown in bold.

C2VSIM Diversion Number	Destination Subregion	Fraction Recoverable Losses (RL)	Fraction Non-Recoverable Losses (NRL)	Land Use	Old CALVIN RL & NRL Amplitude	Updated CALVIN RL & NRL Amplitude	Description / CALVIN NODESDiversion Description & CALVIN Nodes & Links for Fraction Update
1	1	0.03	0.01	Ag			Whiskeytown and Shasta imports for SR1 Ag
		0.03	**0.01**		**0.97**	**0.96**	**HSU1SR3_C3**
2		0.03	0.01	M&I			Whiskeytown and Shasta imports for SR1 M&I
4		0.03	0.01	M&I			Sacramento River to Bella Vista Conduit SR1 M&I
7		0.03	0.01	M&I			Sacramento River Keswick to Red Bluff SR1 M&I
		0.09	**0.03**		**1**	**0.88 (1)**	**T41_Ext: Redding & T41_Int: Redding**
3		0.03	0.02	Ag			Sacramento River to Bella Vista Conduit SR1 Ag
		0.03	**0.02**		**0.97**	**0.95**	**HSU1D5_C3**
6		0.1	0.02	Ag			Sacramento River Keswick to Red Bluff SR1 Ag
8		0.1	0.02	Ag			Cow Creek riparian diversions to SR1 Ag
9		0.1	0.02	Ag			Battle Creek riparian diversions to SR1 Ag
10		0.1	0.02	Ag			Cottonwood Creek riparian diversions to SR1 Ag
		0.4	**0.08**		**0.97**	**0.52**	**HSU1D74_C3**
18	2	0.1	0.02	Ag			Antelope Creek diversions to Los Molinos MWC SR2 Ag
19		0.1	0.02	Ag			Mill Creek to Los Molinos MWC SR2 Ag
22		0.1	0.02	Ag			Deer Creek to Los Molinos MWC SR2 Ag
12		0.03	0.02	Ag			Sacramento River diversions to Corning Canal SR2 Ag
11		0.1	0.02	Ag			Clear Creek riparian divereions to SR2 Ag
		0.43	**0.1**		**0.93**	**0.47 (0.88)**	**HSU2D77_C6**
20		0.1	0.02	Ag			Elder Creek riparian diversions SR2 Ag
21		0.1	0.02	Ag			Thomes Creek riparian to SR2 Ag
17		0.1	0.02	Ag			Sacramento River to SR2 Ag
		0.3	**0.06**		**0.93**	**0.64 (0.88)**	**HSU2C1_C6**
23		0.03	0.02	Ag			Sacramento River diversions to the Tehama Colusa Canal to SR2 Ag
		0.03	**0.02**		**0.93**	**0.95**	**HSU2C11_C6**
13		0.04	0.02	Ag			Stony Creek to North Canal SR2 Ag
14		0.04	0.02	Ag			Stony Creek to South Canal from Black Butte Reservoir SR2 Ag
		0.08	**0.04**		**0.93**	**0.88**	**HSU2C9_C6**
15	3	0.03	0.02	Ag			Stony Creek to to Tehama Colusa Canal and SR3 Ag
24		0.03	0.02	Ag			Sacramento River diversions to the Tehama Colusa Canal to SR3 Ag
		0.06	**0.04**		**0.95**	**0.9**	**HSU3C11_C302**
16		0.03	0.02	Ag			Stony Creek to Glenn-Colusa Canal and SR3 Ag

25		0.03	0.02	Ag			Sacramento River to Glenn Colusa Canal to SR3 Ag
26		0.03	0.02	Refuge			Sacramento River to Glenn Colusa Canal to SR3 Refuge (Ag)
		0.09	**0.06**		**0.95**	**0.85**	**HSU3C13_C302**
27		0.1	0.02	Ag			Sacramento River to SR3 Ag
		0.1	**0.02**		**0.95**	**0.88**	**HSU3D66_C303**
62		0.1	0.02	Ag			Colusa Basin Drain to SR3 Ag
63		0.1	0.02	Refuge			Colusa Basin Drain to SR3 Ag
		0.2	**0.04**		**0.95**	**0.76 (0.88)**	**HSU3C305_C303**
28	4	0.1	0.02	Ag			Sacramento River to SR4 Ag
		0.1	**0.02**		**0.97**	**0.88**	**HSU4D30_C14**
30	5	0.1	0.02	Ag			Tarr Ditch SR5 Ag (55% is used inside the model area)
		0.1	**0.02**		**0.96**	**0.88**	**HSU5C35_C26**
31		0.1	0.02	Ag			Miocene and Wilenor Canals SR5 Ag
33		0.1	0.02	Ag			Oroville-Wyandotte ID through Forbestown Ditch SR5 Ag
37		0.1	0.02	Ag			Feather River to SR5 Ag (replaced by Thermalito)
39		0.1	0.02	Ag			Feather River to SR5 Ag
35		0.1	0.02	Ag			Bangor Canal SR5 Ag (Miners Ranch Canal)
		0.4	**0.08**		**0.96**	**0.52 (0.88)**	**HSU5C77_C26**
38		0.03	0.02	M&I			Feather River to Thermalito ID SR5 M&I
40		0.03	0.01	M&I			Feather River to Yuba City SR5 M&I
32		0.03	0.02	M&I			Palermo Canal from Oroville Dam SR5 M&I
43		0.03	0.01	M&I			Yuba River to SR5 M&I
		0.12	**0.06**		**1**	**0.82 (1)**	**T61_Ext: Yuba and T61_Int: Yuba**
36		0.1	0.02	Ag			Thermalito Afterbay to SR5 Ag
44		0.1	0.02	Ag			Bear River to Camp Far West ID North Side SR5 Ag
		0.2	**0.04**		**0.96**	**0.76 (0.88)**	**HSU5C80_C26**
42		0.1	0.02	Ag			Yuba River to SR5 Ag
	6				**0.96**	**0.88**	**HSU5C83_C26**
64		0.1	0.02	Ag			Knights Landing Ridge Cut diversions (Baseflow) SR3 Ag
65		0.1	0.02	Ag			Sacramento R Rt Bk btwn Knights Landing & Sacramento to SR6 Ag
		0.2	**0.04**		**0.93**	**0.76**	**HSU6C314_C17**
66		0.03	0.01	M&I			Sacramento River to West Sacramento SR6 M&I
72		0.03	0.02	M&I			Putah South Canal SR6 M&I

89		0.05	0.02	M&I			Delta to North Bay Aqueduct to SR6 M&I
		0.11	**0.05**		**1**	**0.84**	**T14_ERes: Napa-Solano, T14_Ind: Napa-Solano and T14_IRes: Napa-Solano**
69		0.1	0.02	Ag			Cache Creek to SR6 Ag
					0.93	**0.88**	**HSU6C16_C17**
70		0.1	0.02	Ag			Yolo Bypass to SR6 Ag
71		0.03	0.02	Ag			Putah South Canal SR6 Ag
74		0.1	0.02	Ag			Putah Creek riparian diversions SR6 Ag
88		0.1	0.02	Ag			Delta to North Bay Aqueduct to SR6 Ag
		0.33	**0.08**		**0.93**	**0.59**	**HSU6C21_C17**
41	7	0.1	0.02	Ag			Feather River to SR7 Ag
					0.93	**0.88**	**HSU7D42_C34**
45		0.1	0.02	Ag			Bear River to Camp Far West ID South Side SR7 Ag
46		0.1	0.02	Ag			Bear River to South Sutter WD SR7 Ag
47		0.1	0.02	Ag			Bear River Canal to South Sutter WD SR7 Ag
		0.3	**0.06**		**0.93**	**0.64 (0.88)**	**HSU7C33_C34**
67		0.1	0.02	Ag			Sacramento R Lt Bk btwn Knights Landing & Sacramento to SR7 Ag
					0.93	**0.88**	**HSU7C67_C34 (Include diversions from Butte Creek & Little Chico)**
76	8	0.05	0.01	M&I			Folsom Lake to SR7 M&I
80		0.03	0.01	M&I			American R to Carmichael WD SR7 M&I
81		0.03	0.01	M&I			American R LB to City of Sacramento SR7 M&I
68		0.03	0.01	M&I			Sacramento River Left Bank to City of Sacramento SR8 M&I
78		0.05	0.01	M&I			Folsom South Canal to SR8 M&I
		0.19	**0.05**		**1**	**0.76 (1)**	**T4_Ext: Sacramento and T4_Int: Sacramento**
78		0.05	0.01	M&I			Folsom South Canal to SR8 M&I
					1	**0.94 (1)**	**T43_Ext: CVPM8 and T43_Int:CVPM8**
75		0.1	0.02	Ag			American River to North Fork and Natomas Ditches to SR7 Ag*
77		0.1	0.02	Ag			Folsom South Canal to SR8 Ag
		0.2	**0.04**		**0.92**	**0.76 (0.88)**	**HSU8C173_C36**
82		0.1	0.02	Ag			Cosumnes R riparian to SR8 Ag
					0.92	**0.88**	**HSU8C37_C36**
83		0.1	0.02	Ag			Mokelumne R to SR8 AgS
84		0.1	0.02	Ag			Mokelumne R to SR8 Ag
		0.2	**0.04**		**0.92**	**0.76 (0.88)**	**HSU8D98_C36**

86	9	0.1	0.02	Ag			Delta to SR9 Ag
					1	**0.88 (0.93)**	**HSU9D507_C68**
171		0.05	0.02	Ag			Delta Mendota Canal to Subregion 9 Ag
					1	**0.93**	**HSU9D521_C68 and HSU9D515_C68**
128	10	0.15	0.03	Ag			San Joaquin R riparian (Fremont Ford to Vernalis) SR10 Ag
					0.9	**0.82**	**HSU10C10_C84**
173		0.05	0.01	M&I			Delta-Mendota Canal to SR10 M&I
185		0.05	0.01	M&I			O'Neill Forebay to SR10 M&I
188		0.05	0.01	M&I			San Luis Canal to SR10 M&I
172		0.05	0.02	Ag			Delta Mendota Canal to Subregion 10 Ag
174		0.05	0.02	Refuge			Delta-Mendota Canal to SR10 Refuges (Ag)
					0.9	**0.93**	**HSU10C30_C84**
177		0.16	0.02	Ag			Mendota Pool to SR10 Ag
178		0.16	0.02	Refuge			Mendota Pool to SR10 Refuges (Ag)
					0.9	**0.82**	**HSU10D731_C84**
184		0.1	0.02	Ag			O'Neill Forebay to SR10 Ag
186		0.1	0.02	Refuge			O'Neill Forebay to SR10 Refuges (Ag)
					0.9	**0.88**	**HSUD803_C84 (IN CALVIN as CA Aqueduct, Harvey Bank Pumping Station, should confirm this)**
187		0.05	0.02	Ag			San Luis Canal to SR10 Ag
189		0.05	0.02	Refuge			San Luis Canal to SR10 Refuges (Ag)
					0.9	**0.93**	**HSU10C85_C84**
94	11	0.15	0.03	Ag			Stanislaus R to South San Joaquin Canal to SR11 Ag
96		0.15	0.03	Ag			Stanislaus R to Oakdale Canal to SR11 Ag
		0.3	**0.06**		**0.8**	**0.64 (0.82)**	**HSU11D16_C172**
95		0.05	0.01	M&I			Stanislaus R to South San Joaquin Canal to SR11 M&I
97		0.05	0.01	M&I			Stanislaus R to Oakdale Canal to SR11 M&I
99		0.05	0.01	M&I			Stanislaus R riparian to SR11 M&I
102		0.05	0.01	M&I			Modesto Canal to SR11 M&I
104		0.05	0.01	M&I			Tuolumne R RB riparian to SR11 M&I
		0.25	**0.05**		**1**	**0.7 (1)**	**T45_Ext:CVPM11 and T45_Int:CVPM11**
98		0.15	0.03	Ag			Stanislaus R riparian to SR11 Ag
					0.88	**0.82**	**HSU11D672_C172**
101		0.15	0.03	Ag			Modesto Canal to SR11 Ag
					0.88	**0.82**	**HSU11D662_C172**
103		0.15	0.03	Ag			Tuolumne R RB riparian to SR11 Ag
					0.88	**0.82**	**HSU11D664_C172**

129		0.15	0.03	Ag			San Joaquin R riparian (Fremont Ford to Vernalis) SR11 Ag
					0.88	**0.82**	**HSU11D689_C172**
105	12	0.15	0.03	Ag			Tuolumne R LB riparian to SR12 Ag
					0.9	**0.82**	**HSU12D664_C45**
106		0.05	0.01	M&I			Tuolumne R LB riparian to SR12 M&I
113		0.05	0.01	M&I			Merced R Right Bank riparian to SR12 M&I
111		0.05	0.01	M&I			Merced R to Merced ID Northside Canal to SR12 M&I
109		0.05	0.01	M&I			Turlock Canal to SR12 M&I
		0.2	**0.04**		**1**	**0.76 (1)**	**T66_Ext:CVPM12 & T66_Int:CVPM12**
108		0.15	0.03	Ag			Turlock Canal to SR12 Ag
					0.9	**0.82**	**HSU12D662_C45**
110		0.15	0.03	Ag			Merced R to Merced ID Northside Canal to SR12 Ag
					0.9	**0.82**	**HSU12D645_C45**
112		0.15	0.03	Ag			Merced R Right Bank riparian to SR12 Ag
					0.9	**0.82**	**HSU12D649_C45**
130		0.15	0.03	Ag			San Joaquin R riparian (Fremont Ford to Vernalis) SR12 Ag
					0.9	**0.82**	**HSU12D699_C45**
115	13	0.05	0.01	M&I			Merced R Left Bank riparian to SR12 M&I
117		0.05	0.01	M&I			Merced R to Merced ID Main Canal to SR12 M&I
125		0.05	0.01	M&I			San Joaquin R riparian (Friant to Gravelly Ford) SR13 M&I
				AG	**0.9**	**0.94**	**HSU13D606_C46**
211		0.05	0.01	M&I			Madera Canal to SR13 M&I
114		0.15	0.03	Ag			Merced R Left Bank riparian to SR12 Ag
					0.9	**0.82**	**HSU13D649_C46**
116		0.15	0.03	Ag			Merced R to Merced ID Main Canal to SR12 Ag
					0.9	**0.82**	**HSU13D645_C46**
118		0.15	0.03	Ag			Madera Canal to Chowchilla WD SR13 Ag
121		0.15	0.03	Ag			Madera Canal to Madera ID SR13 Ag
210		0.05	0.02	Ag			Madera Canal to SR13 Ag
		0.2	**0.05**		**0.9**	**0.75 (0.88)**	**HSU13C72_C46**
119		0.15	0.03	Ag			Chowchilla R riparian SR13 Ag
					0.9	**0.82**	**HSU13D634_C46**
122		0.15	0.03	Ag			Fresno R riparian SR13 Ag
					0.9	**0.82**	**HSU13D624_C46**
124		0.15	0.03	Ag			San Joaquin R riparian (Friant to Gravelly Ford) SR13 Ag

131		0.15	0.03	Ag			San Joaquin R riparian (Fremont Ford to Vernalis) SR13 Ag
					0.9	**0.82**	**HSU13D694_C46**
175		0.05	0.02	Ag			Delta-Mendota Canal to SR13 Ag
179		0.16	0.02	Ag			Mendota Pool to SR13 Ag
		0.21	**0.04**		**0.9**	**0.75 (0.88)**	**HSU13D731_C46**
180	14	0.16	0.02	Ag			Mendota Pool to SR14 Ag
					0.9	**0.82**	**HSU14D608_C91**
190		0.05	0.02	Ag			San Luis Canal to SR14 Ag
192		0.05	0.02	Refuge			San Luis Canal to SR14 Refuges (Ag)
					0.9	**0.93**	**HSU14C92_C91**
191		0.05	0.01	M&I			San Luis Canal to SR14 M&I
					1	**0.94**	**D750_Ext:CVPM14**
138	15	0.16	0.04	Ag			Kings R Main Stem to SR15 Ag
140		0.16	0.04	Ag			Kings R North Fork to SR15 Ag
142		0.16	0.04	Ag			Kings R South Fork to SR15 Ag
144		0.16	0.04	Ag			Kings R Fresno Slough to SR15 Ag
					0.84	**0.8**	**HSU15C52_C90**
181		0.16	0.02	Ag			Mendota Pool to SR15 Ag
183		0.16	0.02	Refuge			Mendota Pool to SR15 Refuges (Ag)
					0.84	**0.82**	**HSU15D608_C90**
193		0.05	0.02	Ag			San Luis Canal to SR15 Ag
195		0.05	0.02	Refuge			San Luis Canal to SR15 Refuges (Ag)
					0.84	**0.93**	**HSU15C75_C90 (CALVIN as CA Aqueduct, name for State is CA Aqueduct and Fed operation refers to San Luis Canal)**
212		0.05	0.02	Ag			Friant-Kern Canal to SR15 Ag
					0.84	**0.93**	**HSU15C49_C90**
126	16	0.15	0.03	Ag			San Joaquin R riparian (Friant to Gravelly Ford) SR16 Ag
					0.8	**0.82**	**HSU16D606_C50**
132		0.12	0.03	Ag			Kings R to Fresno ID SR16 Ag
					0.8	**0.85**	**HSU16C53_C50**
213		0.05	0.02	Ag			Friant-Kern Canal to SR16 Ag
					0.8	**0.93**	**HSU16C49_C50**
127		0.05	0.01	M&I			San Joaquin R riparian (Friant to Gravelly Ford) SR16 M&I
215		0.05	0.01	M&I			Friant-Kern Canal to SR16 M&I
		0.1	**0.02**		**1**	**0.88 (1)**	**T24_Ext: City of Fresno and T24_Int: City of Fresno**

134	17	0.16	0.04	Ag			Kings R to Condolidated ID SR17 Ag
136		0.16	0.04	Ag			Kings R to Alta ID SR17 Ag
					0.9	**0.8**	**HSU17C53_C55**
216		0.05	0.02	Ag			Friant-Kern Canal to SR17 Ag
					0.9	**0.93**	**HSU17C76_C55**
146	18	0.14	0.03	Ag			Kaweah R Partition A to SR18 Ag
148		0.14	0.03	Ag			Kaweah R Partition B to SR18 Ag
150		0.14	0.03	Ag			Kaweah R Partition C to SR18 Ag
152		0.14	0.03	Ag			Kaweah R Partition D to SR18 Ag
154		0.14	0.03	Ag			Kaweah R to Corcoran ID SR18 Ag
					0.9	**0.83**	**HSU18C56_C60**
156		0.14	0.03	Ag			Tule R riparian to SR18 Ag
					0.9	**0.83**	**HSU18C58_C60**
196		0.05	0.02	Ag			**California Aqueduct to SR18 Ag**
219		0.05	0.02	Ag			Friant-Kern Canal to SR18 Ag
					0.9	**0.93**	**HSU18C688_C60**
237		0	0.02	Ag			**Cross-Valley Canal to SR18 Ag**
221		0.05	0.01	M&I			Friant-Kern Canal to SR18 M&I
					1	**0.94 (1)**	**C688_T51 (New supply for 2100 from FKC to CVPM18)**
158	19	0.07	0.01	Ag			Kern R to SR19 Ag
					0.9	**0.92**	**HSU19C73_C100**
197		0.05	0.02	Ag			California Aqueduct to SR19 Ag
200		0.05	0.02	Refuge			California Aqueduct to SR19 Refuges (Ag)
					0.9	**0.93**	**HSU19D847_C100 and HSU19D850_C100**
222		0.05	0.02	Ag			Friant-Kern Canal to SR19 Ag
224		0.05	0.02	Refuge			Friant-Kern Canal to SR19 Refuges (Ag)
					0.9	**0.93**	**HSU19C62_C100**
199		0.05	0.01	M&I			**California Aqueduct to SR19 M&I**
239		0.05	0.02	Refuge			Cross-Valley Canal to SR19 Refuges (Ag)
					0.9	**0.93**	**HSU19C74_C100**
160	20	0.13	0.03	Ag			Kern R to SR20 Ag
					0.9	**0.84**	**HSU20C65_C63**
201		0.05	0.02	Ag			**California Aqueduct to SR20 Ag**
225		0.05	0.02	Ag			Friant-Kern Canal to SR20 Ag
					0.9	**0.93**	**HSU20C64_C63**
240		0.05	0.02	Ag			Cross-Valley Canal to SR20 Ag
					0.9	**0.93**	**HSU20C74_C63**

161		0.05	0.01	M&I			Kern R to SR20 M&I
227		0.05	0.01	M&I			Friant-Kern Canal to SR20 M&I
		0.1	**0.02**		**1**	**0.88**	**T53_Int:CVPM20 and T53_Ext:CVPM20**
163	21	0.08	0.02	Ag			Kern R to SR21A Ag
165		0.08	0.02	Ag			Kern River to Subregion 21B Ag
168		0.08	0.02	Ag			Kern River to Subregion 21C Ag
					0.8	**0.9**	**HSU21C65_C66**
202		0.05	0.02	Ag			California Aqueduct to SR21 Ag
228		0.05	0.02	Ag			Friant-Kern Canal to SR21 Ag
					0.8	**0.93**	**HSU21C689_C66**
242		0.05	0.02	Ag			Cross-Valley Canal to SR21 Ag
					0.8	**0.93**	**HSU21C74_C66**
204		0.05	0.01	M&I			California Aqueduct to SR21 M&I
					1	**0.94 (1)**	**T28_Int:Bakersfield and T28_Ext:Bakersfield**

Appendix C: Annual Average Historical External Inflow Components by Decade

Tables below show annual average flow components of ”External Inflows” to groundwater by decades for each subregion. These are computed from budgets from a historical land use C2VSIM run.

Subregion 1 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-200	12	0	73	0	0	6	162
1932-1941	-208	14	0	75	0	0	23	137
1942-1951	-248	17	0	86	0	0	27	134
1952-1961	-256	21	0	86	0	0	29	153
1962-1971	-234	17	0	85	0	0	30	130
1972-1981	-248	17	0	88	0	0	30	129
1982-1991	-244	17	0	89	0	0	31	125
1992-2001	-189	14	0	82	0	0	33	101
2002-2009	-173	14	0	88	0	0	34	85
Annual Average (1922-1951)	**-218**	**14**	**0**	**78**	**0**	**0**	**18**	**146**
Annual Average (1952-2009)	**-226**	**17**	**0**	**86**	**0**	**0**	**31**	**121**

Subregion 2 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-182	5	0	80	0	0	-29	145
1932-1941	-130	6	0	127	0	0	-45	121
1942-1951	-127	9	0	137	0	0	-39	98
1952-1961	-71	11	0	141	0	0	-30	129
1962-1971	-12	12	0	141	0	0	-18	129
1972-1981	-4	13	0	142	0	0	-18	155
1982-1991	-10	14	0	144	0	0	-10	156
1992-2001	43	13	0	142	0	0	-24	175
2002-2009	37	14	0	148	0	0	-24	158
Annual Average (1922-1951)	**-149**	**7**	**0**	**114**	**0**	**0**	**-38**	**122**
Annual Average (1952-2009)	**-5**	**13**	**0**	**142**	**0**	**0**	**-21**	**149**

Subregion 3 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-141	24	0	41	1	0	21	93

1932-1941	-143	15	0	34	0	0	26	68
1942-1951	-177	30	0	46	0	0	20	68
1952-1961	-188	44	0	40	0	0	-17	79
1962-1971	-172	41	0	40	0	0	-35	76
1972-1981	-145	48	0	53	1	0	-49	92
1982-1991	-165	50	0	60	1	0	-85	128
1992-2001	-97	43	0	61	3	0	-28	107
2002-2009	-107	49	0	69	2	0	-29	126
Annual Average (1922-1951)	**-153**	**22**	**0**	**41**	**0**	**0**	**23**	**76**
Annual Average (1952-2009)	**-147**	**46**	**0**	**53**	**1**	**0**	**-40**	**100**

Subregion 4 - Annual Average flows (taf/yr)

Years	**Streamflow Exchange**	**Diversion Losses**	**Lake Exchange**	**Boundary Inflow**	**Subsidence**	**Tile Drain Outflow**	**Interbasin Inflow**	**Deep Percolation from Precip.**
1922-1931	-280	42	0	0	0	0	57	64
1932-1941	-296	46	0	0	0	0	43	85
1942-1951	-440	82	0	0	0	0	18	90
1952-1961	-444	96	0	0	0	0	17	117
1962-1971	-348	90	0	0	0	0	35	118
1972-1981	-250	89	0	0	1	0	65	113
1982-1991	-243	77	0	0	2	0	99	111
1992-2001	-112	75	0	0	5	0	64	128
2002-2009	-159	83	0	0	2	0	53	134
Annual Average (1922-1951)	**-335**	**55**	**0**	**0**	**0**	**0**	**41**	**78**
Annual Average (1952-2009)	**-266**	**85**	**0**	**0**	**2**	**0**	**55**	**120**

Subregion 5 - Annual Average flows (taf/yr)

Years	**Streamflow Exchange**	**Diversion Losses**	**Lake Exchange**	**Boundary Inflow**	**Subsidence**	**Tile Drain Outflow**	**Interbasin Inflow**	**Deep Percolation from Precip.**
1922-1931	-163	62	0	15	0	0	-22	110
1932-1941	-193	69	0	15	0	0	-28	130
1942-1951	-284	95	0	18	0	0	-5	116
1952-1961	-234	110	0	18	0	0	8	142
1962-1971	-187	122	0	17	0	0	5	158
1972-1981	-148	127	0	18	0	0	-1	160
1982-1991	-155	124	0	20	0	0	-12	176
1992-2001	-67	134	0	19	0	0	-8	208
2002-2009	-111	155	0	19	0	0	-9	216
Annual Average (1922-1951)	**-212**	**74**	**0**	**16**	**0**	**0**	**-19**	**116**
Annual Average (1952-2009)	**-153**	**127**	**0**	**19**	**0**	**0**	**-3**	**176**

Subregion 6 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-68	13	0	23	5	0	-45	82
1932-1941	6	12	0	23	4	0	-43	87
1942-1951	-5	19	0	27	3	0	-32	72
1952-1961	95	20	0	23	11	0	-4	112
1962-1971	128	22	0	23	6	0	-5	137
1972-1981	104	26	0	26	8	0	-9	131
1982-1991	37	26	0	28	0	0	-24	136
1992-2001	63	29	0	27	1	0	-48	136
2002-2009	83	31	0	32	0	0	-46	127
Annual Average (1922-1951)	**-26**	**14**	**0**	**24**	**4**	**0**	**-41**	**81**
Annual Average (1952-2009)	**85**	**26**	**0**	**26**	**5**	**0**	**-22**	**129**

Subregion 7 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-9	17	0	30	0	0	-4	58
1932-1941	7	21	0	62	0	0	7	65
1942-1951	-2	26	0	85	0	0	-7	60
1952-1961	11	30	0	88	0	0	-11	64
1962-1971	19	39	0	82	0	0	-22	64
1972-1981	11	45	0	84	0	0	-27	59
1982-1991	18	41	0	89	0	0	-8	58
1992-2001	34	41	0	86	0	0	12	62
2002-2009	42	43	0	86	0	0	18	58
Annual Average (1922-1951)	**-2**	**21**	**0**	**58**	**0**	**0**	**-1**	**61**
Annual Average (1952-2009)	**22**	**39**	**0**	**86**	**0**	**0**	**-7**	**61**

Subregion 8 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	17	9	0	94	0	0	-6	85
1932-1941	70	11	0	99	0	0	24	94
1942-1951	60	12	0	116	0	0	48	93
1952-1961	60	12	0	119	0	0	88	118
1962-1971	80	14	0	109	0	0	136	136
1972-1981	74	13	0	114	0	0	152	151
1982-1991	81	13	0	123	0	0	165	165
1992-2001	100	13	0	114	0	0	188	152

2002-2009	89	14	0	119	0	0	213	116
Annual Average (1922-1951)	**47**	**10**	**0**	**102**	**0**	**0**	**21**	**91**
Annual Average (1952-2009)	**81**	**13**	**0**	**116**	**0**	**0**	**154**	**140**

Subregion 9 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-117	0	0	9	0	0	63	71
1932-1941	-55	0	0	11	0	0	46	111
1942-1951	-39	0	0	13	0	0	27	75
1952-1961	-1	5	0	15	0	0	-23	96
1962-1971	44	10	0	12	0	0	-56	74
1972-1981	63	18	0	16	0	0	-78	70
1982-1991	57	20	0	19	0	0	-75	71
1992-2001	73	18	0	23	0	0	-112	144
2002-2009	85	20	0	20	0	0	-131	94
Annual Average (1922-1951)	**-72**	**0**	**0**	**11**	**0**	**0**	**47**	**83**
Annual Average (1952-2009)	**51**	**15**	**0**	**17**	**0**	**0**	**-76**	**93**

Subregion 10 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-116	69	0	22	37	16	-32	93
1932-1941	-106	80	0	28	32	22	-36	87
1942-1951	-129	100	0	29	52	27	-53	81
1952-1961	-129	151	0	28	44	30	-88	92
1962-1971	-138	186	0	29	22	38	-154	115
1972-1981	-137	198	0	31	29	40	-140	123
1982-1991	-134	189	0	31	54	39	-98	110
1992-2001	-102	173	0	38	64	32	-9	133
2002-2009	-107	182	0	32	50	31	-32	142
Annual Average (1922-1951)	**-116**	**82**	**0**	**26**	**38**	**21**	**-41**	**87**
Annual Average (1952-2009)	**-125**	**179**	**0**	**31**	**45**	**35**	**-88**	**118**

Subregion 11 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-204	121	0	18	0	0	-34	85
1932-1941	-218	146	0	18	0	0	-55	68
1942-1951	-232	160	0	19	0	0	-53	61

1952-1961	-198	166	0	18	0	0	-54	68
1962-1971	-155	179	0	18	0	0	-61	73
1972-1981	-122	174	0	18	0	0	-58	84
1982-1991	-141	164	0	18	0	0	-89	101
1992-2001	-117	157	0	18	0	0	-114	112
2002-2009	-102	153	0	16	0	0	-112	107
Annual Average (1922-1951)	**-218**	**141**	**0**	**18**	**0**	**0**	**-47**	**71**
Annual Average (1952-2009)	**-142**	**166**	**0**	**18**	**0**	**0**	**-80**	**90**

Subregion 12 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-129	94	0	3	0	0	-5	62
1932-1941	-132	106	0	2	0	0	-11	60
1942-1951	-158	121	0	3	0	0	-22	46
1952-1961	-147	119	0	3	0	0	-11	55
1962-1971	-130	130	0	2	0	0	9	62
1972-1981	-122	137	0	2	0	0	17	71
1982-1991	-119	126	0	2	0	0	13	79
1992-2001	-95	135	0	2	0	0	-2	86
2002-2009	-93	131	0	2	0	0	4	75
Annual Average (1922-1951)	**-139**	**107**	**0**	**2**	**0**	**0**	**-12**	**56**
Annual Average (1952-2009)	**-119**	**130**	**0**	**2**	**0**	**0**	**4**	**71**

Subregion 13 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-102	95	0	12	1	0	28	101
1932-1941	-6	112	0	15	0	0	48	125
1942-1951	-60	130	0	13	3	0	69	111
1952-1961	-37	134	0	13	12	0	81	154
1962-1971	-9	151	0	14	13	0	90	201
1972-1981	-25	153	0	13	20	0	94	218
1982-1991	-14	142	0	14	14	0	93	226
1992-2001	44	155	0	16	9	0	81	217
2002-2009	1	138	0	12	13	0	101	187
Annual Average (1922-1951)	**-58**	**112**	**0**	**13**	**1**	**0**	**47**	**111**
Annual Average (1952-2009)	**-7**	**145**	**0**	**14**	**13**	**0**	**89**	**200**

Subregion 14 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	0	0	0	11	125	0	-31	101
1932-1941	0	0	0	18	68	1	21	24
1942-1951	0	0	0	16	187	2	25	18
1952-1961	0	0	0	13	281	2	56	16
1962-1971	0	12	0	16	202	2	152	17
1972-1981	0	97	0	27	22	2	131	52
1982-1991	0	108	0	25	19	2	136	84
1992-2001	0	92	0	36	19	1	107	74
2002-2009	0	80	0	24	36	1	93	89
Annual Average (1922-1951)	**0**	**0**	**0**	**15**	**122**	**1**	**6**	**49**
Annual Average (1952-2009)	**0**	**63**	**0**	**23**	**102**	**2**	**111**	**53**

Subregion 15 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-331	523	-108	2	55	0	239	50
1932-1941	-350	577	-61	6	7	0	205	52
1942-1951	-383	450	-68	3	64	0	257	52
1952-1961	-240	425	-51	3	142	0	360	84
1962-1971	-117	452	-27	4	149	0	327	119
1972-1981	-49	443	-16	5	93	0	252	129
1982-1991	-187	583	-48	4	38	0	201	134
1992-2001	-63	492	-9	5	27	0	288	129
2002-2009	-47	498	-33	4	25	0	295	108
Annual Average (1922-1951)	**-356**	**525**	**-79**	**4**	**39**	**0**	**230**	**51**
Annual Average (1952-2009)	**-122**	**478**	**-31**	**4**	**82**	**0**	**288**	**117**

Subregion 16 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	7	26	0	4	0	0	-46	71
1932-1941	13	51	0	10	0	0	-57	54
1942-1951	10	48	0	6	0	0	-85	44
1952-1961	11	59	0	6	0	0	-110	67
1962-1971	14	77	0	7	0	0	-131	97
1972-1981	15	67	0	9	0	0	-139	95
1982-1991	13	66	0	10	0	0	-148	110
1992-2001	17	74	0	12	0	0	-171	153

2002-2009	14	68	0	9	0	0	-191	142
Annual Average (1922-1951)	**10**	**42**	**0**	**7**	**0**	**0**	**-61**	**56**
Annual Average (1952-2009)	**14**	**68**	**0**	**9**	**0**	**0**	**-146**	**109**

Subregion 17 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	3	23	0	1	1	0	-45	59
1932-1941	-31	66	0	4	-1	0	-74	136
1942-1951	-53	55	0	3	0	0	-81	84
1952-1961	-36	68	0	3	1	0	-106	101
1962-1971	-25	88	0	3	0	0	-96	127
1972-1981	-13	80	0	5	0	0	-48	133
1982-1991	-12	69	0	6	0	0	-3	129
1992-2001	-8	86	0	7	0	0	5	170
2002-2009	-2	64	0	4	0	0	20	123
Annual Average (1922-1951)	**-27**	**48**	**0**	**3**	**0**	**0**	**-66**	**93**
Annual Average (1952-2009)	**-17**	**76**	**0**	**5**	**0**	**0**	**-41**	**130**

Subregion 18 - Annual Average flows (taf/yr)

Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-12	148	0	18	61	0	-92	62
1932-1941	-24	271	0	26	18	0	-63	78
1942-1951	-32	203	0	22	62	0	-87	65
1952-1961	-23	251	0	21	93	0	-166	100
1962-1971	-30	268	0	23	104	0	-199	134
1972-1981	-31	275	0	26	110	0	-193	137
1982-1991	-80	300	0	26	47	0	-205	133
1992-2001	-160	350	0	27	9	0	-329	239
2002-2009	-174	324	0	23	7	0	-353	160
Annual Average (1922-1951)	**-24**	**207**	**0**	**22**	**45**	**0**	**-79**	**69**
Annual Average (1952-2009)	**-79**	**292**	**0**	**24**	**64**	**0**	**-235**	**149**

Subregion 19 - Annual Average flows (taf/yr)								
Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	-220	364	0	3	49	0	33	98
1932-1941	-234	415	0	5	17	0	5	29
1942-1951	-223	354	0	3	23	0	29	27
1952-1961	-126	278	0	4	58	0	81	37
1962-1971	-105	425	0	4	76	0	97	48
1972-1981	-64	325	0	5	58	0	101	47
1982-1991	-179	516	0	4	27	0	44	34
1992-2001	-55	298	0	5	36	0	76	33
2002-2009	19	155	0	4	47	0	102	32
Annual Average (1922-1951)	**-228**	**381**	**0**	**4**	**29**	**0**	**21**	**52**
Annual Average (1952-2009)	**-90**	**338**	**0**	**4**	**51**	**0**	**83**	**39**

Subregion 20 - Annual Average flows (taf/yr)								
Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	23	5	0	26	25	0	-55	43
1932-1941	29	37	0	56	10	0	-39	27
1942-1951	24	24	0	59	26	0	-77	29
1952-1961	24	28	0	48	48	0	-146	60
1962-1971	30	29	0	42	68	0	-194	89
1972-1981	27	30	0	54	77	0	-161	91
1982-1991	28	35	0	57	63	0	-106	85
1992-2001	27	38	0	66	41	0	-57	80
2002-2009	23	31	0	47	55	0	-50	89
Annual Average (1922-1951)	**25**	**22**	**0**	**48**	**19**	**0**	**-55**	**33**
Annual Average (1952-2009)	**27**	**32**	**0**	**52**	**59**	**0**	**-121**	**81**

Subregion 21 - Annual Average flows (taf/yr)								
Years	Streamflow Exchange	Diversion Losses	Lake Exchange	Boundary Inflow	Subsidence	Tile Drain Outflow	Interbasin Inflow	Deep Percolation from Precip.
1922-1931	5	18	-21	41	73	0	0	140
1932-1941	48	17	-16	47	37	0	1	34
1942-1951	51	15	-12	72	70	0	19	29
1952-1961	89	16	-3	40	58	0	47	29
1962-1971	139	21	1	39	41	0	89	26
1972-1981	118	31	2	53	40	0	79	28
1982-1991	95	32	0	63	25	0	83	35
1992-2001	129	34	2	88	14	0	47	49

2002-2009	114	29	2	77	18	0	44	69
Annual Average (1922-1951)	**33**	**17**	**-16**	**54**	**59**	**0**	**6**	**69**
Annual Average (1952-2009)	**113**	**27**	**1**	**59**	**34**	**0**	**65**	**38**

Appendix D: Comparison CALVIN Terms C2VSIM, CVHM and CVGSM

Tables below compare CALVIN Terms extracted from the DWR C2VSIM and USGS CVHM groundwater models, with CVGSM, the Central Valley model that precedes C2VSIM, on which CALVIN was originally based. Old CALVIN values represent Terms used in the original version of CALVIN. These differ from CVGSM values as a result of calibration efforts to make sure mass balance and water budgets were representative of known systems operations. Chou, 2012 details calculation or extraction of terms from the USGS CVHM model.

Table D.1 Fraction of non-consumptive use applied water to SW (Term 1a)

Subregion	C2VSIM	CVHM	Old CALVIN	CVGSM
1	0.72	0.01	0.56	0.55
2	0	0.02	0.23	0.31
3	0.4	0.03	0.22	0.4
4	0.01	0.04	0.82	0.88
5	0.28	0.03	0.26	0.41
6	0.02	0.03	0	0.63
7	0	0.02	0.45	0.58
8	0.07	0.02	0.79	0.86
9	0	0.04	0.3	0.26
10	0.06	0.05	0.74	0.79
11	0.06	0.03	0	0.35
12	0.06	0.04	0.62	0.78
13	0.03	0.03	0.66	0.75
14	0	0.08	0	0
15	0	0.06	0.6	0.7
16	0.16	0.02	0.69	0.87
17	0	0.03	0.39	0.58
18	0	0.04	0	0.01
19	0	0.03	0	0
20	0.18	0.03	0.01	0.41
21	0	0.04	0	0.06

Table D.2 Fraction of non-consumptive use applied water to GW (Term 1b)

Subregion	C2VSIM	CVHM	Old CALVIN	CVGSM
1	0.28	0.99	0.44	0.45
2	1	0.98	0.77	0.69
3	0.6	0.97	0.78	0.6

4	0.99	0.96	0.18	0.12
5	0.72	0.97	0.74	0.59
6	0.98	0.97	1	0.37
7	1	0.98	0.55	0.42
8	0.93	0.98	0.21	0.14
9	1	0.96	0.7	0.74
10	0.94	0.95	0.26	0.21
11	0.94	0.97	1	0.65
12	0.94	0.96	0.38	0.22
13	0.97	0.97	0.34	0.25
14	1	0.92	1	1
15	1	0.94	0.4	0.3
16	0.84	0.98	0.31	0.13
17	1	0.97	0.61	0.42
18	1	0.96	1	0.99
19	1	0.97	1	1
20	0.82	0.97	0.99	0.59
21	1	0.96	1	0.94

Table D.3 Central Valley amplitude for Internal Re-use (Term 2)

Subregion	C2VSIM	CVHM	Old CALVIN	CVGSM
1	1	1	1	1.32
2	1	1	1	1.26
3	1.086	1	1.05	1.28
4	1.001	1	1.13	1.21
5	1.049	1	1.06	1.283
6	1.001	1	1.32	1.08
7	1	1	1.08	1.3
8	1.003	1	1.1	1.23
9	1	1	1.1	1.21
10	1.003	1	1.05	1.33
11	1.005	1	1.04	1.272
12	1.004	1	1.1	1.18
13	1.002	1	1.1	1.18
14	1	1	1	1.22
15	1	1	1.05	1.21
16	1.015	1	1.1	1.18
17	1	1	1.1	1.17
18	1	1	1	1.25

19	1	1	1	1.21
20	1.014	1	1.07	1.17
21	1	1	1	1.25

Table D.4 Central Valley amplitude for AG return flow of applied water (Term 3)

Subregion	C2VSIM	CVHM	Old CALVIN	CVGSM
1	0.47	0.26	0.32	0.39
2	0.14	0.27	0.26	0.29
3	0.2	0.17	0.28	0.35
4	0.14	0.21	0.21	0.35
5	0.21	0.2	0.283	0.37
6	0.06	0.23	0.08	0.28
7	0.25	0.23	0.3	0.45
8	0.12	0.25	0.23	0.33
9	0.09	0.22	0.21	0.21
10	0.2	0.21	0.33	0.4
11	0.22	0.23	0.272	0.43
12	0.16	0.24	0.18	0.34
13	0.12	0.21	0.18	0.27
14	0.18	0.13	0.22	0.26
15	0.12	0.24	0.21	0.27
16	0.28	0.19	0.18	0.45
17	0.13	0.2	0.17	0.27
18	0.18	0.21	0.25	0.31
19	0.03	0.23	0.21	0.29
20	0.1	0.19	0.17	0.3
21	0.1	0.19	0.25	0.32

Table D.5 Annual Average Net External Inflows in the Central Valley (Term 4)

Subregion	C2VSIM	CVHM	CVGSM
1	28	7	2
2	177	406	403
3	-9	31	9
4	-96	23	261
5	67	64	144
6	180	453	367
7	168	186	278
8	402	686	747

9	85	446	14
10	72	30	296
11	-1	20	-159
12	49	58	155
13	344	564	863
14	278	260	309
15	594	1117	1161
16	51	-9	280
17	96	198	360
18	263	564	484
19	368	410	162
20	101	21	220
21	290	-64	387
Sacramento	**1002**	**2302**	**2225**
San Joaquin	**464**	**672**	**1155**
Tulare	**2041**	**2497**	**3363**
Central Valley Total	**3507**	**5471**	**6743**

Table D.6 Maximum Storage Constraint (part Term 5)

Subregion	C2VSIM	CVHM	CVGSM
1	38,510	19,543	5,448
2	136,757	33,133	24,162
3	133,958	22,782	22,127
4	61,622	15,730	15,362
5	92,020	23,850	24,399
6	175,719	34,350	22,864
7	58,484	12,190	12,270
8	193,433	31,153	32,842
9	139,752	81,528	23,395
10	91,920	20,844	29,250
11	59,302	10,704	15,543
12	43,510	16,651	13,919
13	142,508	48,168	47,484
14	181,001	32,789	65,235
15	313,759	38,000	90,978
16	64,915	27,274	11,650
17	98,836	31,370	13,942
18	322,480	58,956	59,544
19	147,060	28,006	68,266
20	141,457	20,229	40,814

21	351,327	58,804	81,622
Sacramento	**1,030,255**	**274,259**	**182,869**
San Joaquin	**337,240**	**96,367**	**106,196**
Tulare	**1,620,835**	**295,428**	**432,051**
Central Valley Total	**2,988,330**	**666,054**	**721,116**

Table D.7 Groundwater Overdraft Allowable in CALVIN: Initial – Ending Storage extracted from the groundwater models (part Term 5)

Subregion	C2VSIM	CVHM	Old CALVIN
1	-990	3,045	128
2	-882	3,077	601
3	939	-773	-200
4	220	-1,257	-231
5	656	-311	991
6	-307	-3,457	1,871
7	5,330	1,032	-2,143
8	7,836	1,595	6,090
9	-362	-11,323	-2,730
10	3,155	251	-1,264
11	592	289	2,201
12	1,737	-723	966
13	9,656	10,756	-26
14	6,831	9,495	5,312
15	2,977	12,555	79
16	257	9,435	6,359
17	3,561	9,142	306
18	-11,063	20,349	6,828
19	13,526	7,256	-2
20	11,937	6,654	-773
21	27,903	5,611	4,007
Sacramento	**12,440**	**-8,372**	**4,377**
San Joaquin	**15,140**	**10,573**	**1,877**
Tulare	**55,929**	**80,497**	**22,116**
Central Valley Total	**83,509**	**82,698**	**28,370**

Table B.8 Central Valley Pumping Capacity (Term 7)

Note: Minimum Pumping is zero for all models

Subregion	C2VSIM	CVHM	Old CALVIN	CVGSM
1	7	2	21	19
2	93	355	153	146
3	176	4	171	163
4	109	2	110	105
5	240	25	226	215
6	86	182	148	141
7	121	74	96	87
8	186	474	208	198
9	44	90	74	67
10	185	8	198	188
11	65	23	52	47
12	87	19	81	73
13	226	524	291	277
14	221	215	333	317
15	335	1067	408	388
16	62	32	61	55
17	153	275	152	145
18	238	571	349	332
19	214	471	171	163
20	125	162	108	103
21	266	113	228	217
Sacramento	**1062**	**1208**	**1207**	**1141**
San Joaquin	**563**	**574**	**622**	**585**
Tulare	**1614**	**2906**	**1810**	**1720**
Central Valley Total	**3239**	**4688**	**3639**	**3446**

Table D.9 Representative Depth to Groundwater (Term 8)

Subregion	C2VSIM (2003)	DWR Average Measured Well data (2000)	CVHM	CVGSM
1	175	71.5	153	130
2	144	41.5	43	120
3	104	28	63	100
4	17	16	-	60
5	35	27.5	14	75
6	64	24.5	57	70

7	95	40.5	19	95
8	148	91.5	17	110
9	30	24.5	43	80
10	80	46.5	73	60
11	54	45.5	22	75
12	48	68	42	90
13	108	75	113	125
14	373	197.5	176	350
15	73	116	36	210
16	59	57	123	130
17	145	34	80	130
18	180	80	186	200
19	407	139	165	310
20	429	238	366	310
21	592	191	250	310

Appendix E: Comparison Recharge Terms Updated Base Case CALVIN and C2VSIM with Base Case CALVIN allocations

This appendix compares recharge components for the C2VSIM simulation with Updated Base Case CALVIN surface water diversions and pumping with inputs used in the Updated Base Case CALVIN.

Table E-1. Stream Exchange, Diversion Losses & Artificial Recharge, Deep Percolation from Precipitation and Irrigation Return Flows CALVIN vs. C2VSIM with CALVIN Deliveries

	Annual Average Stream Exchange (taf/yr)		**Diversion Losses & Artificial Recharge (taf/yr)**		**Annual Average Deep Percolation from Precipitation (taf/yr)**		**Annual Average Deep Percolation from Irrigation Return Flow (taf/yr)**	
Subregion	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Deliveries**	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Deliveries**	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Deliveries**	**Updated Base Case CALVIN**	**C2VSIM with Base Case CALVIN Deliveries**
1	-233	-139	16	7	136	117	74	1
2	-16	20	10	18	133	113	123	44
3	-160	-114	36	52	87	61	158	23
4	-294	-232	75	106	100	67	123	192
5	-166	-103	101	131	143	135	225	106
6	90	108	20	43	108	32	71	92
7	9	36	31	58	61	76	103	55
8	64	105	12	21	120	-33	83	168
9	46	137	8	50	83	34	121	1
10	-126	-77	139	203	101	130	322	144
11	-148	-137	158	100	77	206	264	205
12	-132	-96	119	129	62	165	212	168
13	-14	56	164	118	162	-27	312	260
14	0	0	32	345	45	-91	230	142
15	-137	-149	557	860	89	-222	272	440
16	12	-28	147	210	78	85	91	217
17	-23	1	154	79	110	67	125	83
18	-55	-446	575	1072	102	363	459	453
19	-105	37	383	136	46	-107	51	147
20	26	24	27	89	61	29	84	148
21	112	140	23	53	45	45	124	141
Sacramento	**-661**	**-182**	**309**	**486**	**971**	**603**	**1081**	**681**
San Joaquin	**-419**	**-254**	**580**	**550**	**402**	**474**	**1110**	**777**
Tulare	**-169**	**-422**	**1898**	**2844**	**576**	**168**	**1436**	**1773**
Central Valley Total	**-1249**	**-858**	**2787**	**3880**	**1949**	**1245**	**3627**	**3231**

Table E-2. Boundary Inflows, Inter-basin Inflow and Flow from Subsided interbeds CALVIN vs. C2VSIM with Base Case CALVIN Deliveries

Subregion	Annual Average Boundary Inflows (taf/yr)		Annual Average Inter-basin Inflow (taf/yr)		Annual Average Subsidence (taf/yr)	
	Updated Base Case CALVIN	C2VSIM with Base Case CALVIN Deliveries	Updated Base Case CALVIN	C2VSIM with Base Case CALVIN Deliveries	Updated Base Case CALVIN	C2VSIM with Base Case CALVIN Deliveries
1	83	84	25	24	0	0
2	130	139	-27	-28	0	0
3	45	48	-18	44	1	4
4	0	0	49	-33	1	1
5	17	18	-8	16	0	0
6	25	26	-24	-56	5	10
7	74	84	-10	16	0	0
8	110	113	89	192	0	0
9	14	14	-16	-32	0	0
10	28	29	-84	-62	41	27
11	0	18	-59	-97	0	0
12	0	2	-1	-90	0	0
13	0	13	72	218	9	9
14	0	20	71	166	128	36
15	-53	4	263	165	78	38
16	8	8	-104	-317	0	0
17	4	4	-63	105	0	0
18	23	23	-146	-379	70	43
19	4	4	55	190	43	51
20	49	50	-110	-31	46	17
21	51	56	46	-9	49	0
Sacramento	**498**	**526**	**60**	**141**	**7**	**16**
San Joaquin	**28**	**63**	**-72**	**-31**	**50**	**35**
Tulare	**86**	**168**	**12**	**-110**	**414**	**185**
Central Valley Total	**612**	**758**	**0**	**0**	**471**	**236**

Table E-3. Lake Exchange CALVIN vs. C2VSIM with Base Case CALVIN Deliveries

Subregion	Annual Average Lake Exchange (taf/yr)	
	CALVIN	C2VSIM
15	-53	-74
21	-7	1

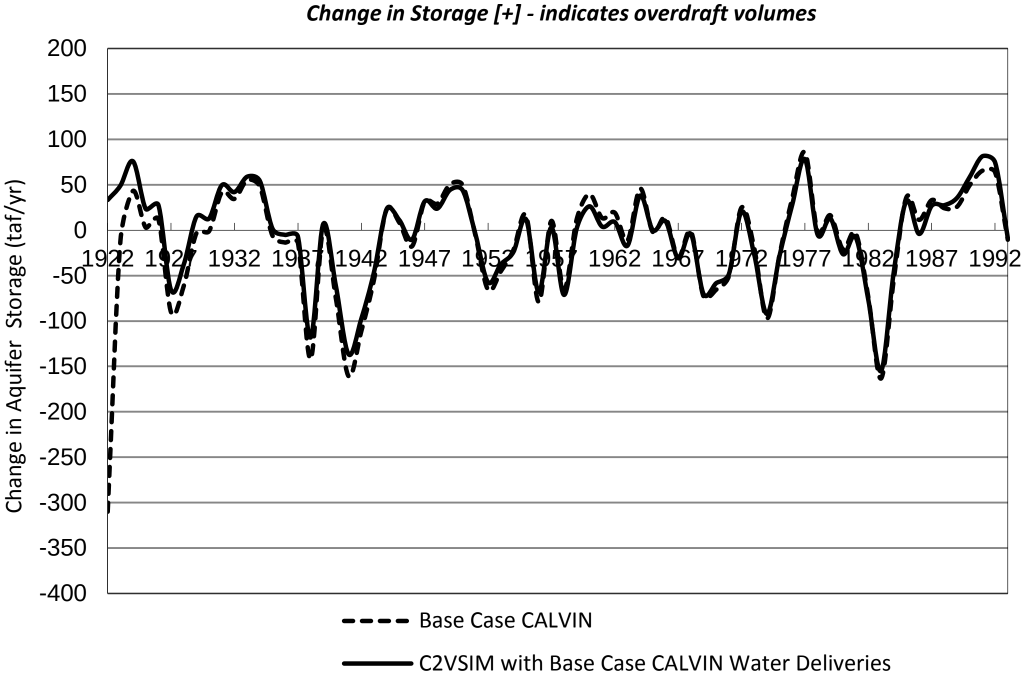
Table E-4. Tile Drain Outflows CALVIN vs. C2VSIM with Base Case CALVIN Deliveries

Subregion	Tile Drain Outflows (taf/yr)	
	Updated Base Case CALVIN	C2VSIM
10	-30	-17
14	-1	0

Appendix F: Graphs of estimated Overdraft C2VSIM vs. CALVIN over 72-years for Base Case CALVIN

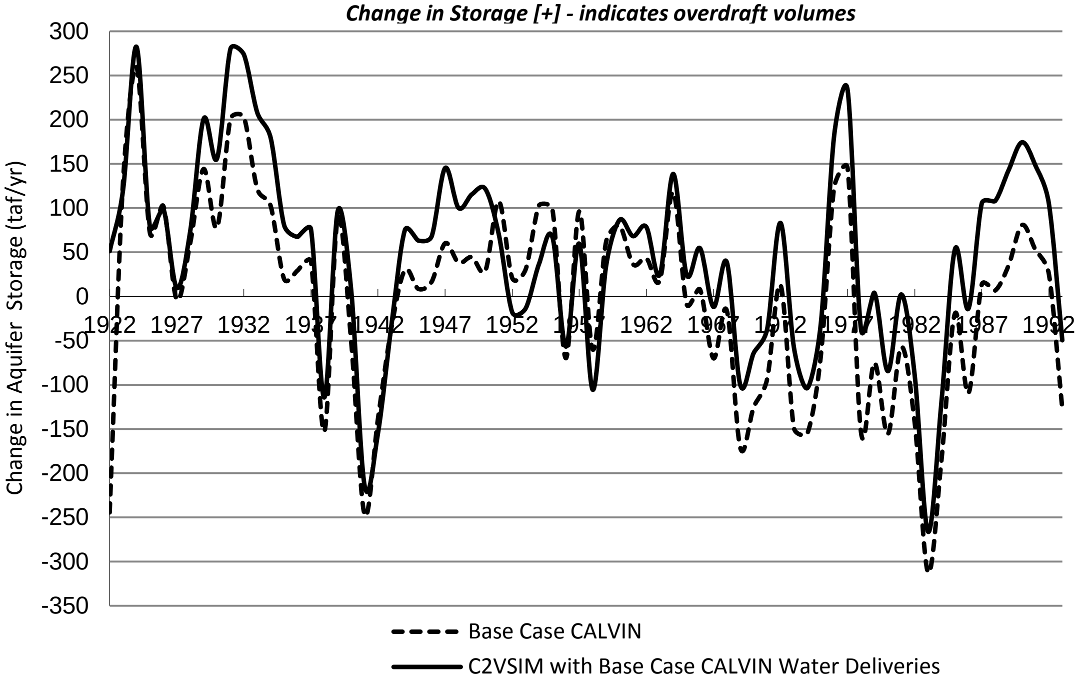
This Appendix accompanies Chapter Four sections, the graphs below show annual differences between change in storage estimated in CALVIN and C2VSIM for Base Case.

Subregion 1



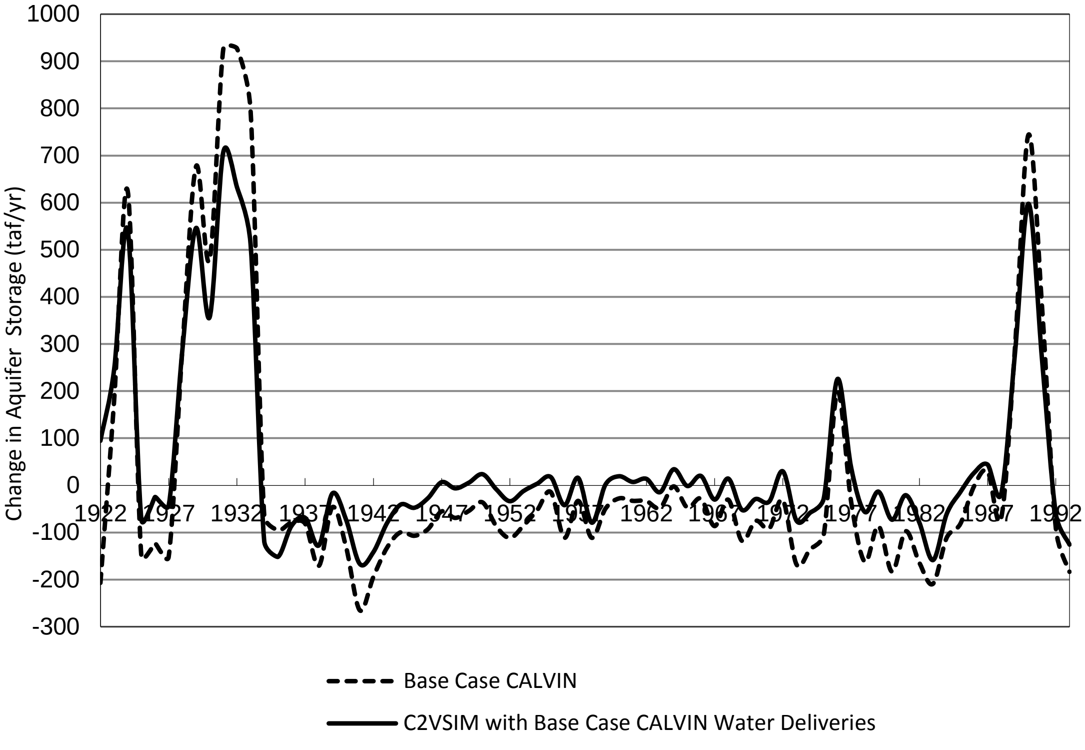
Subregion 2

Change in Storage [+] - indicates overdraft volumes



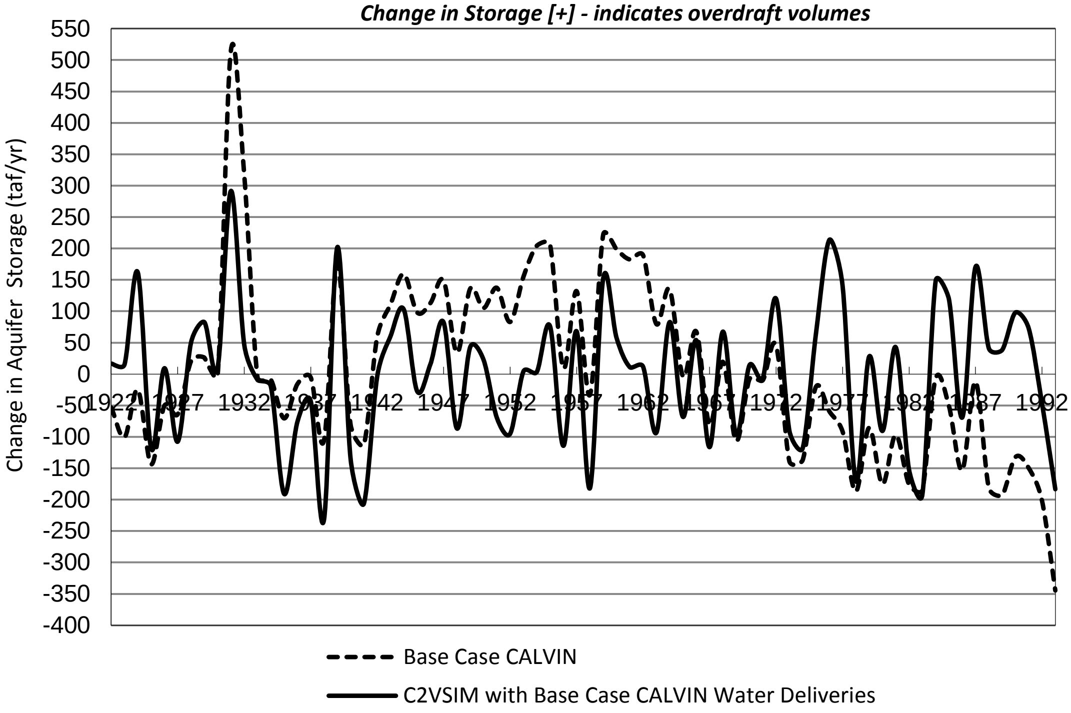
Subregion 3

Change in Storage [+] - indicates overdraft volumes



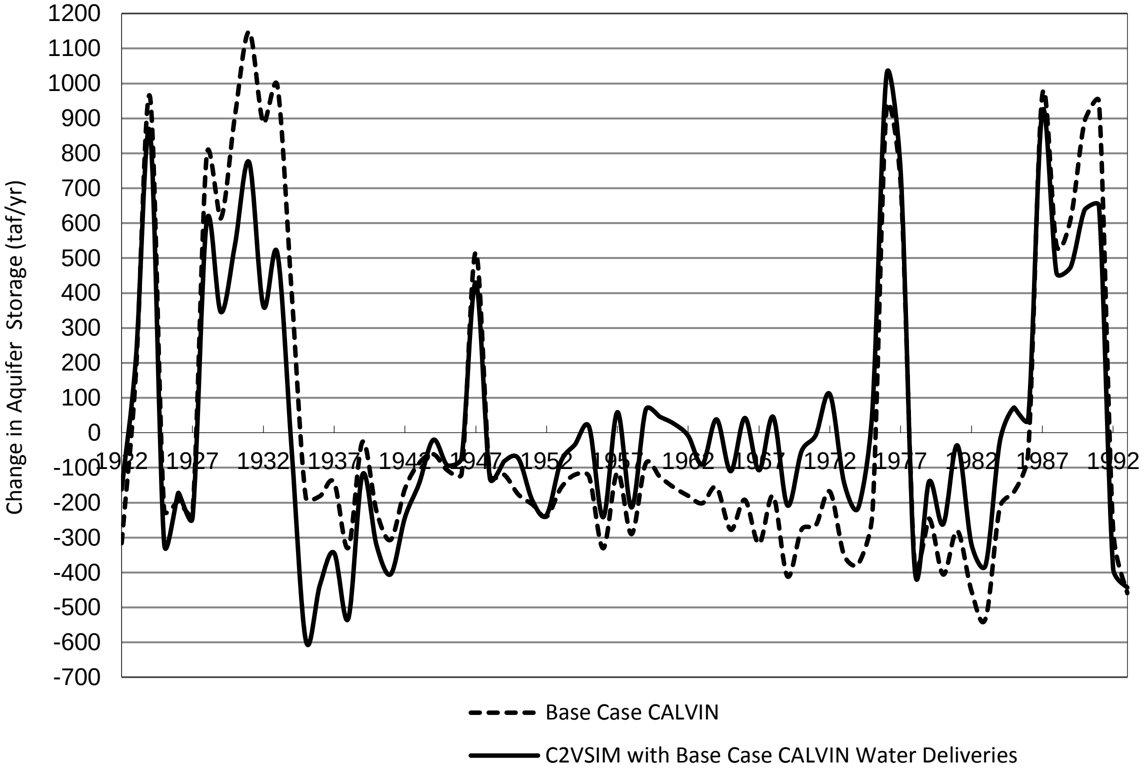
Subregion 4

Change in Storage [+] - indicates overdraft volumes

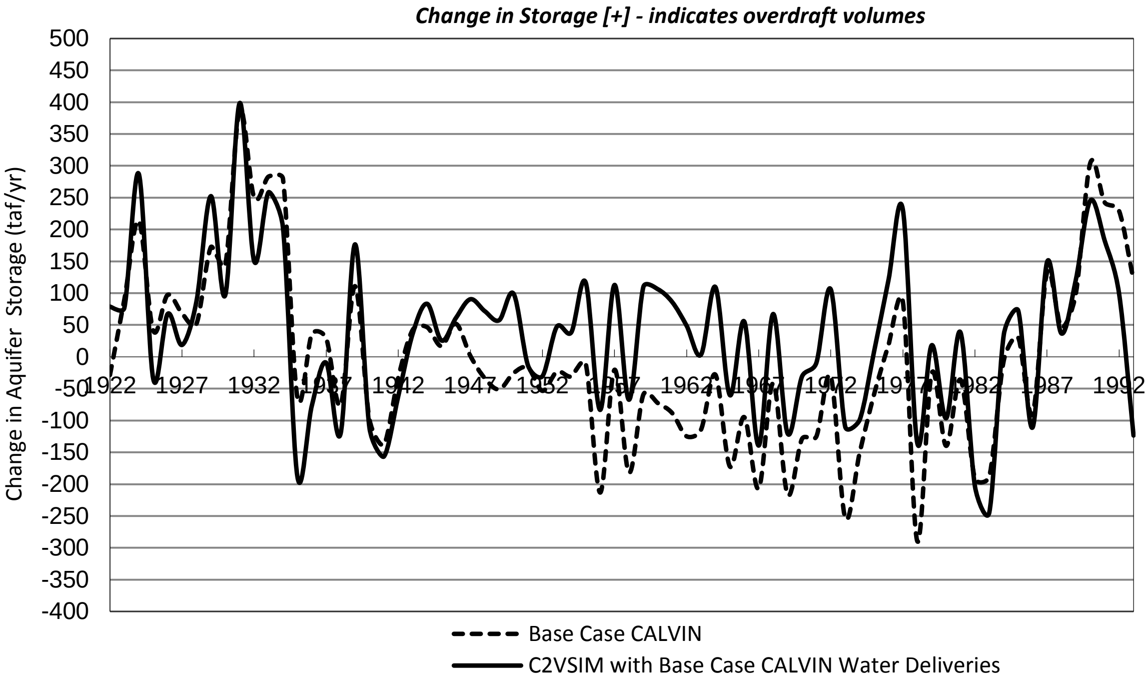


Subregion 5

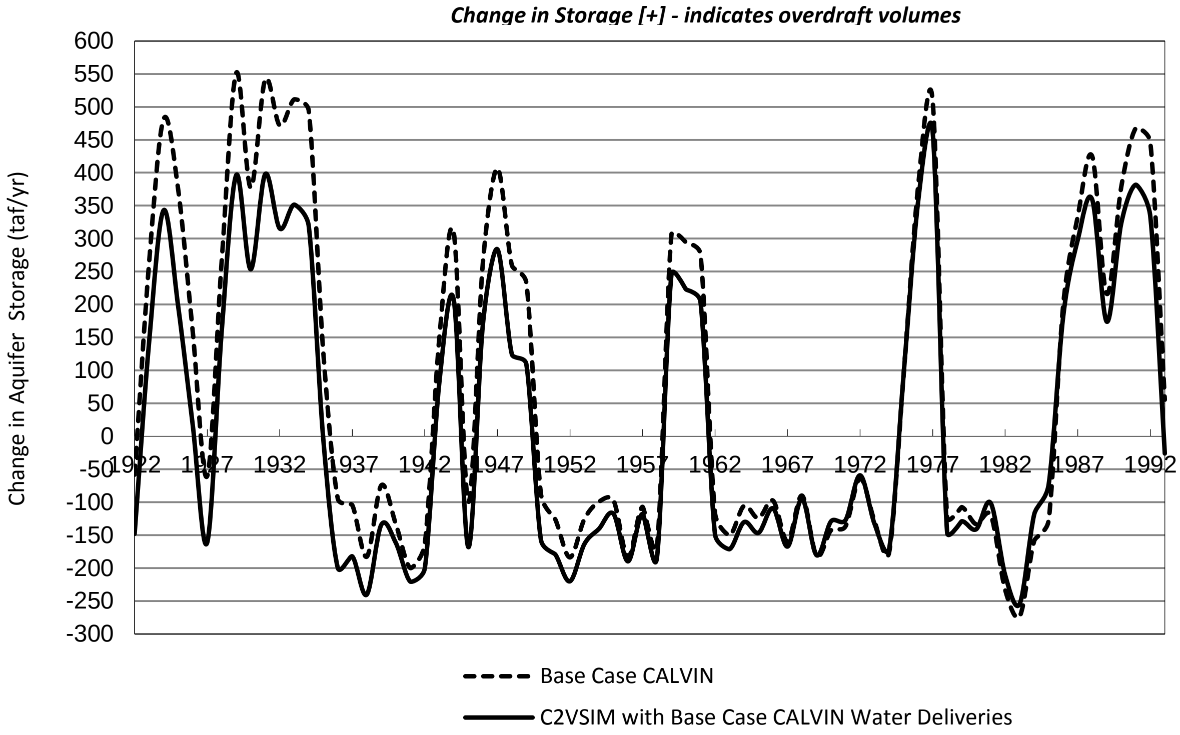
Change in Storage [+] - indicates overdraft volumes



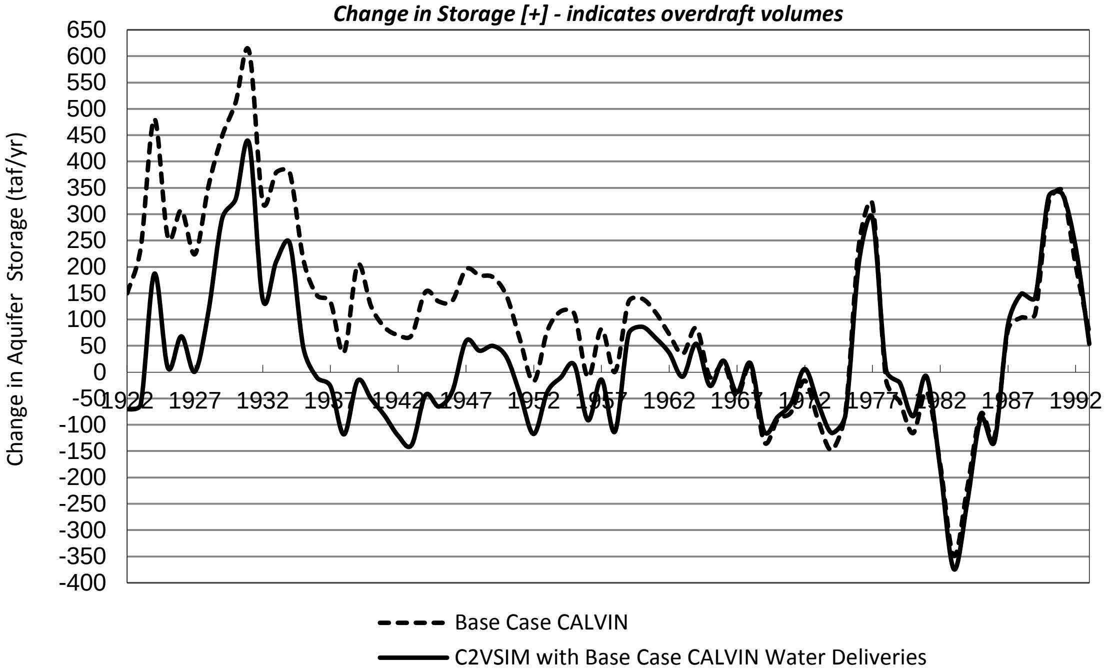
Subregion 6



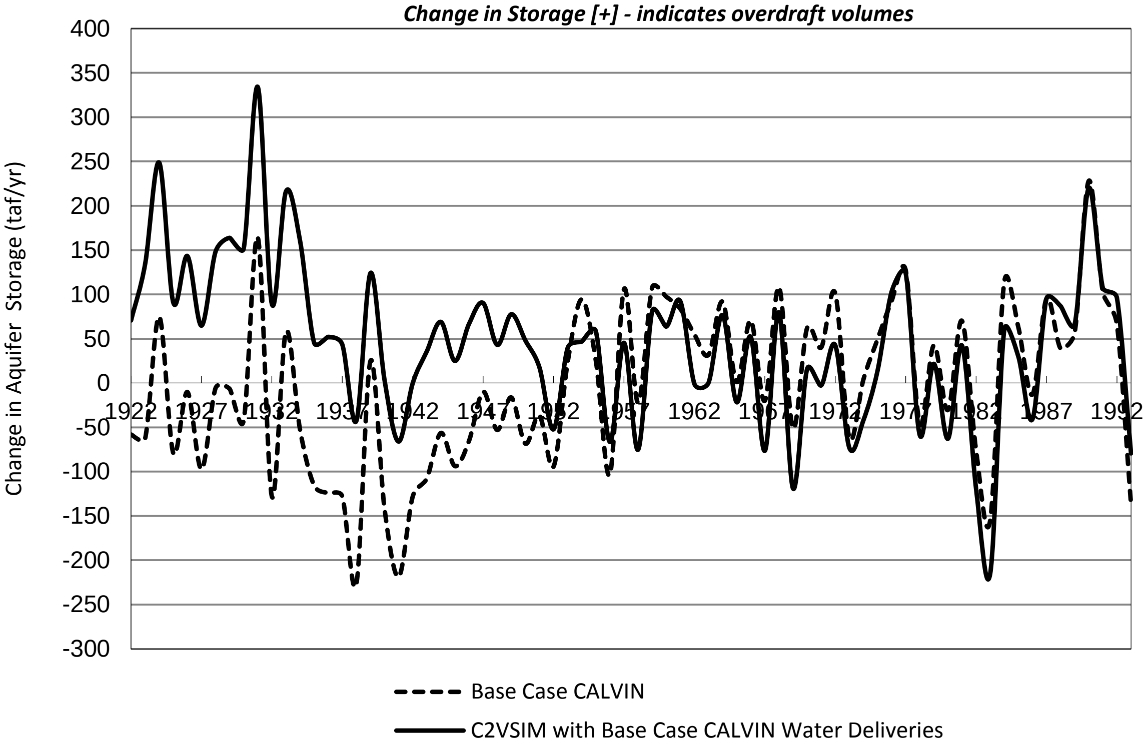
Subregion 7



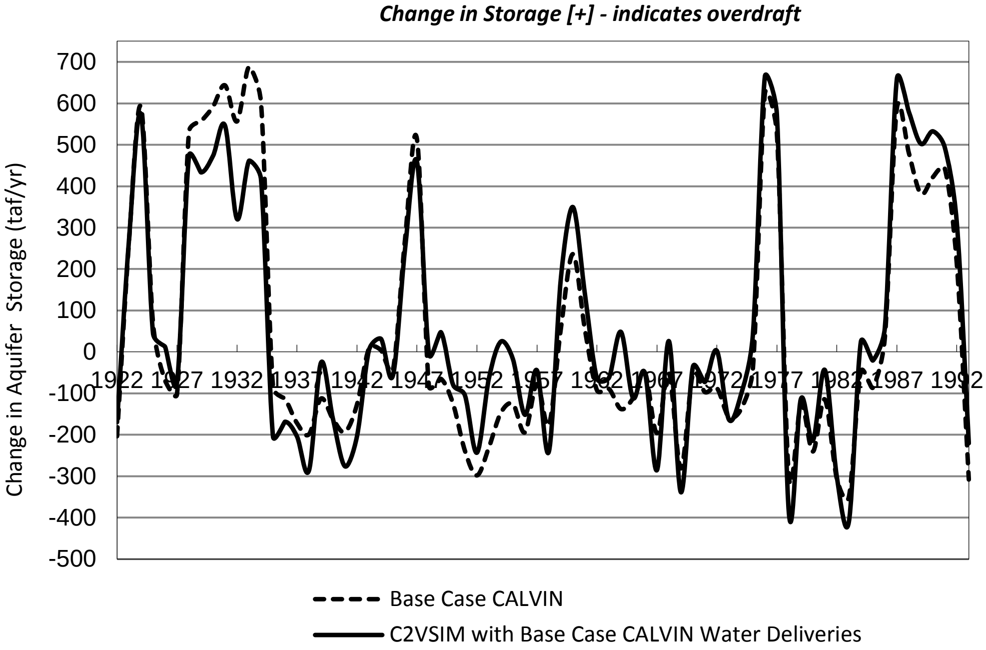
Subregion 8



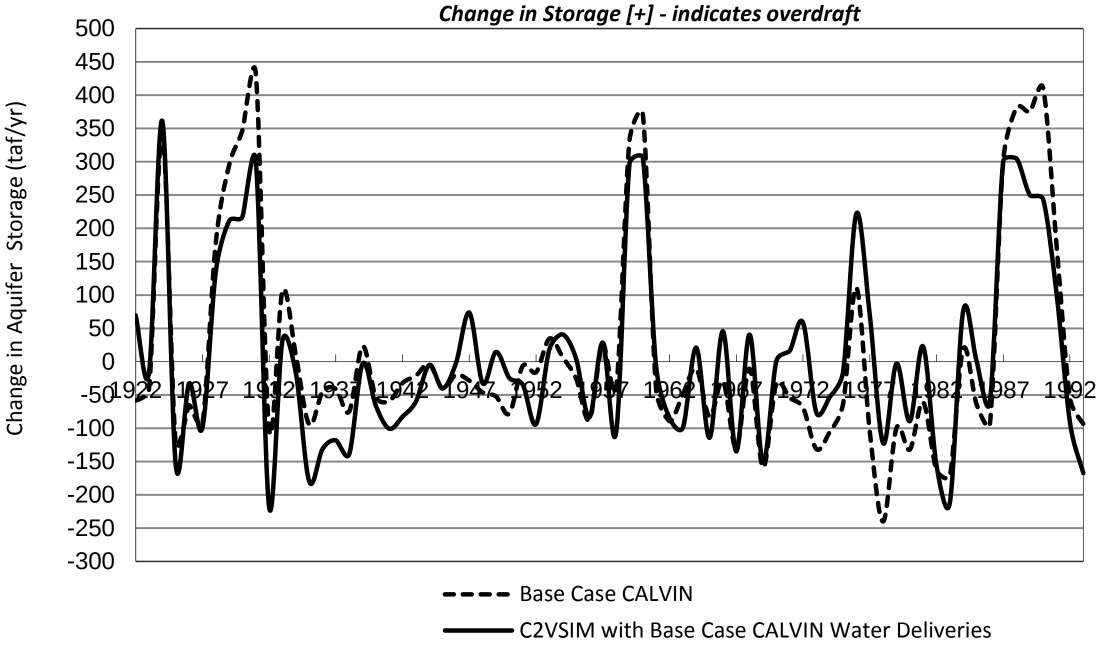
Subregion 9



Subregion 10

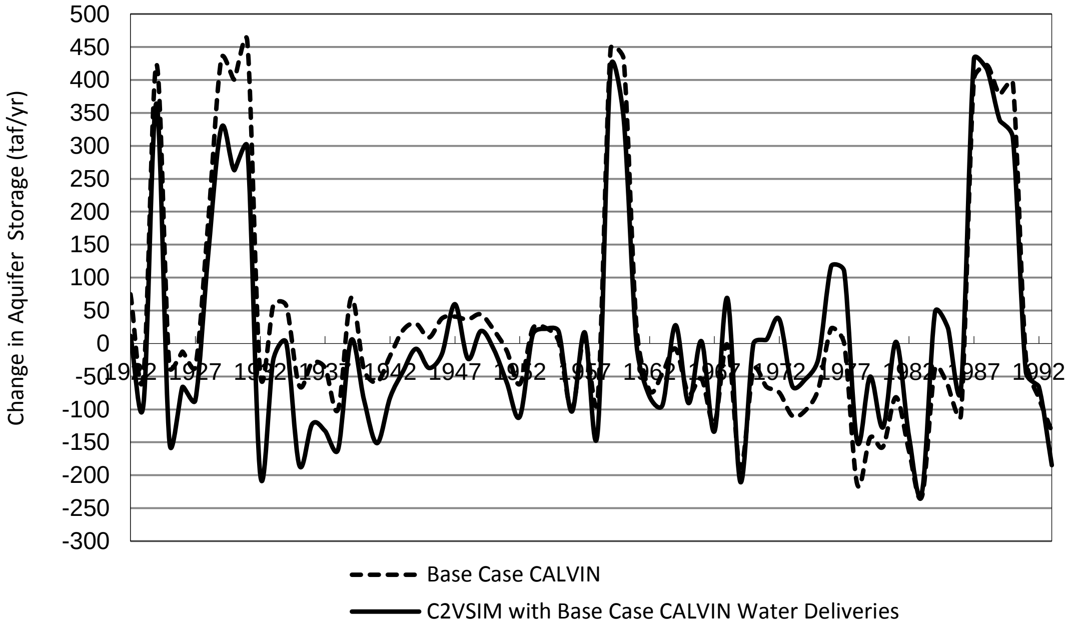


Subregion 11



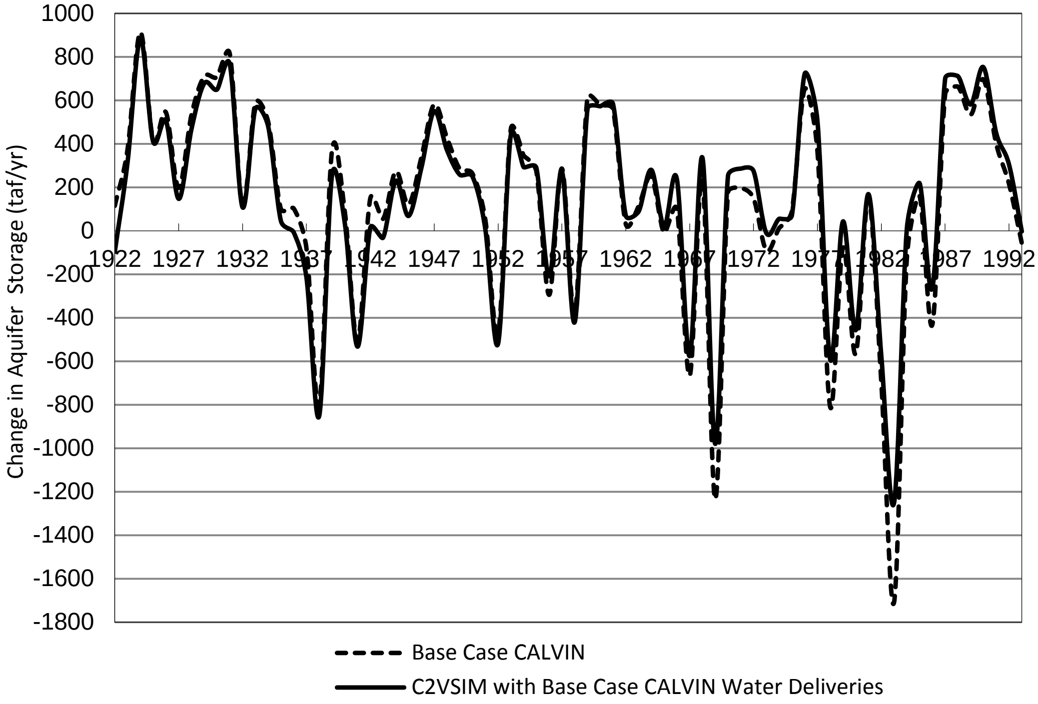
Subregion 12

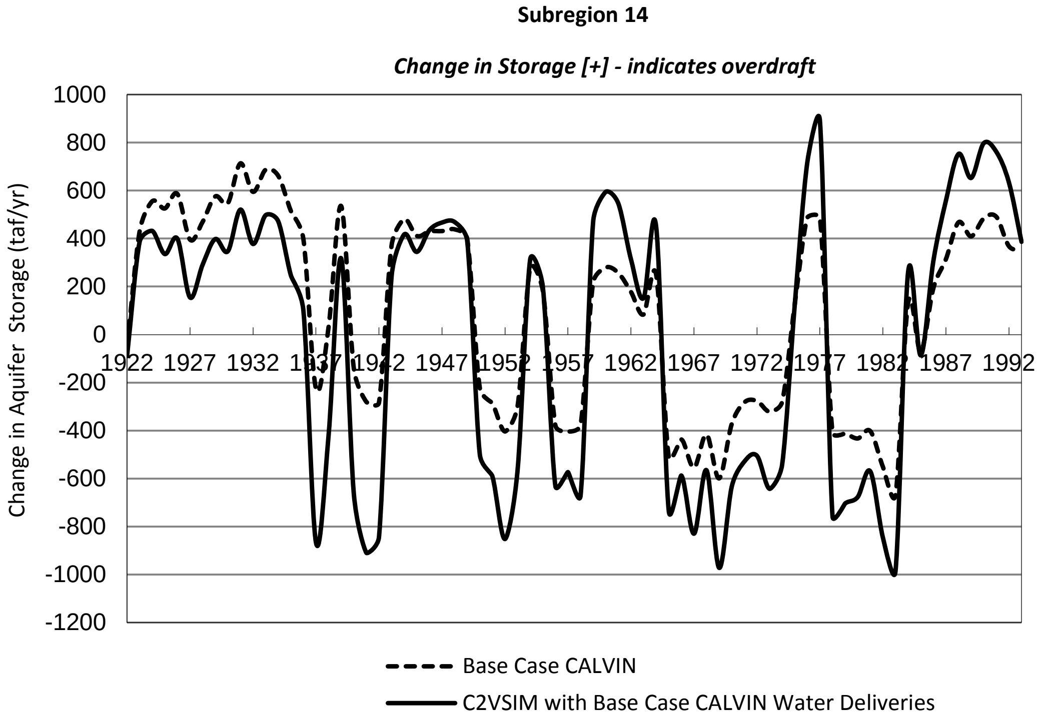
Change in Storage [+] - indicates overdraft volumes



Subregion 13

Change in Storage [+] - indicates overdraft





Subregion 14

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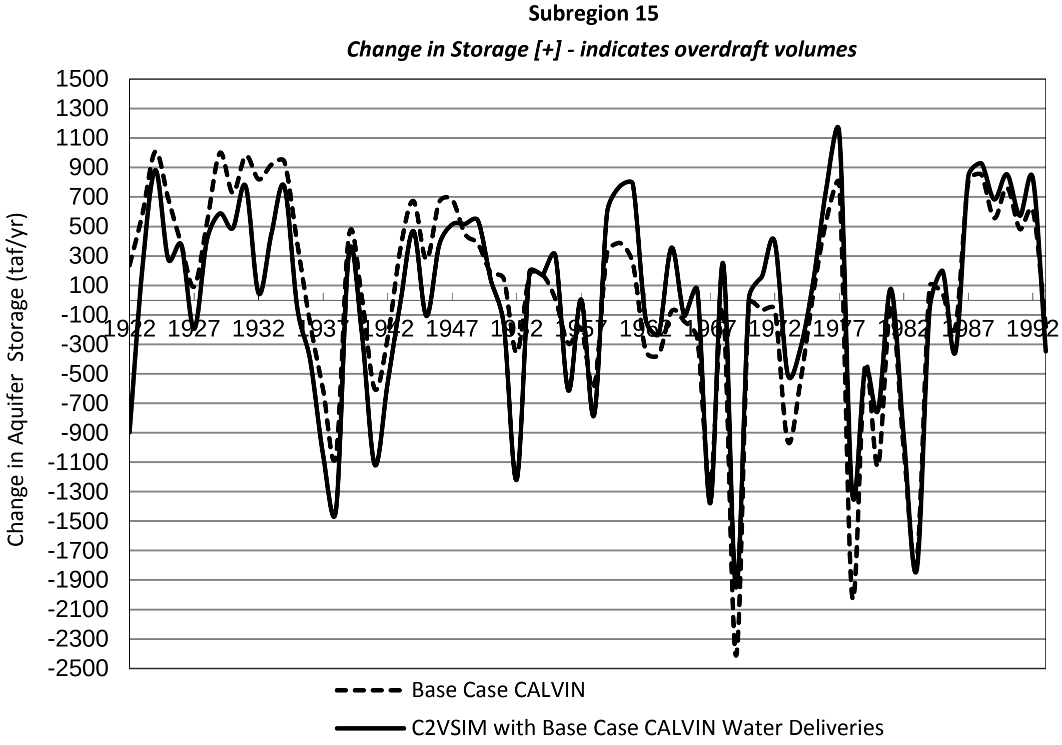
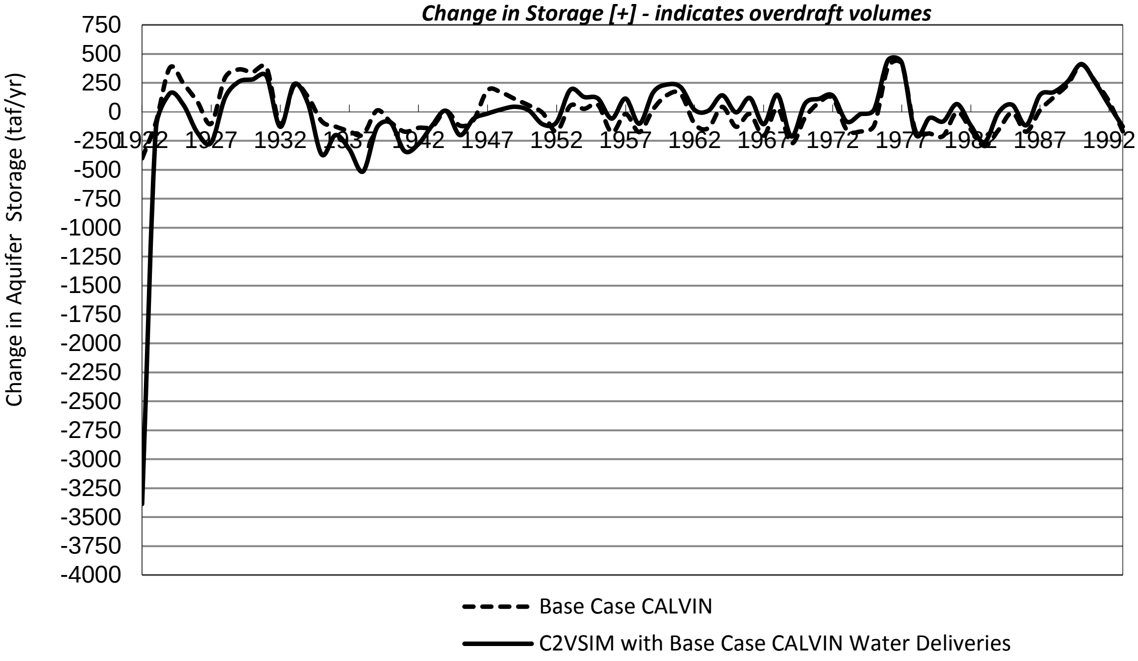


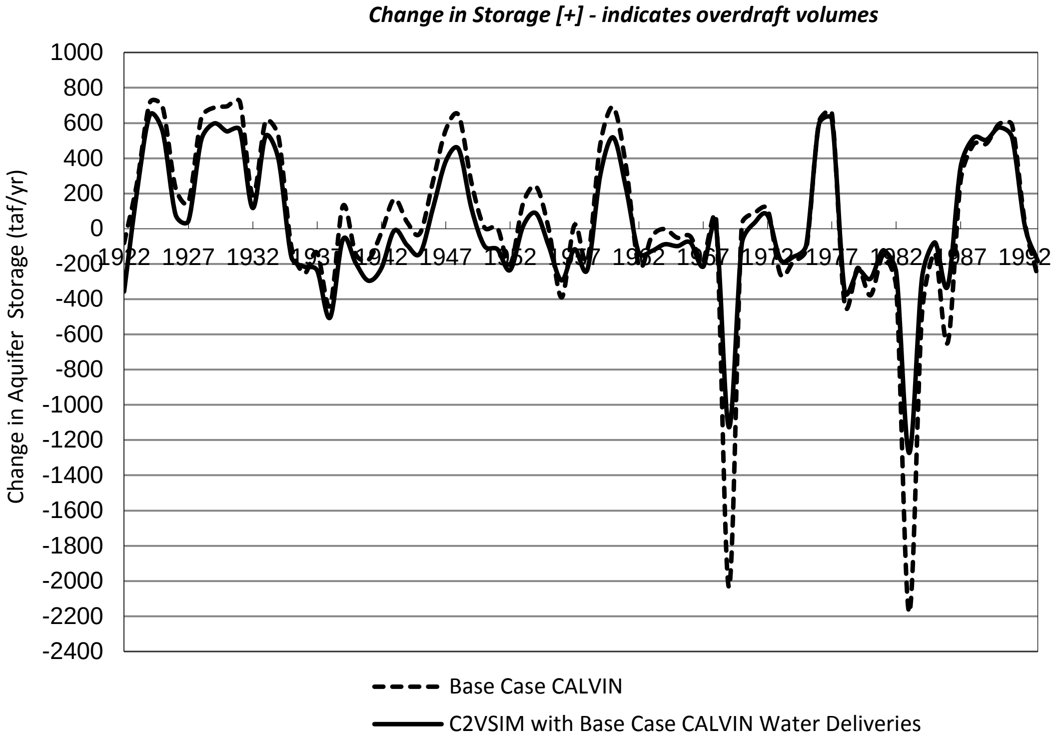
Subregion 15

Change in Storage [+] - indicates overdraft volumes

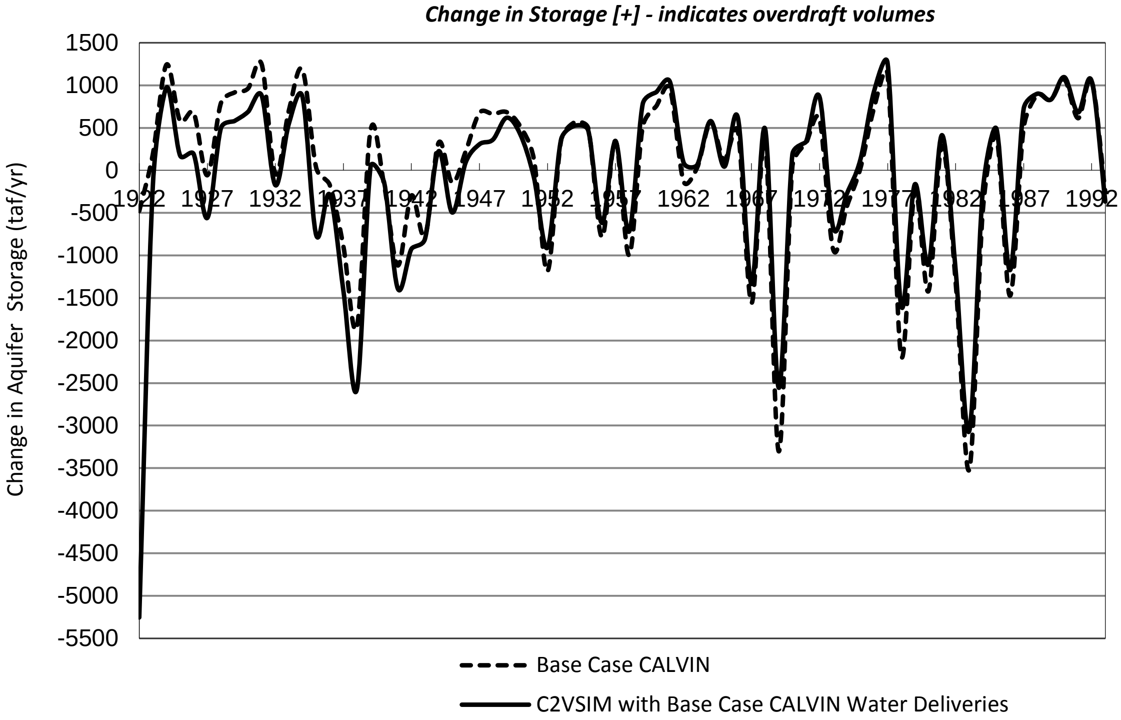
Subregion 16



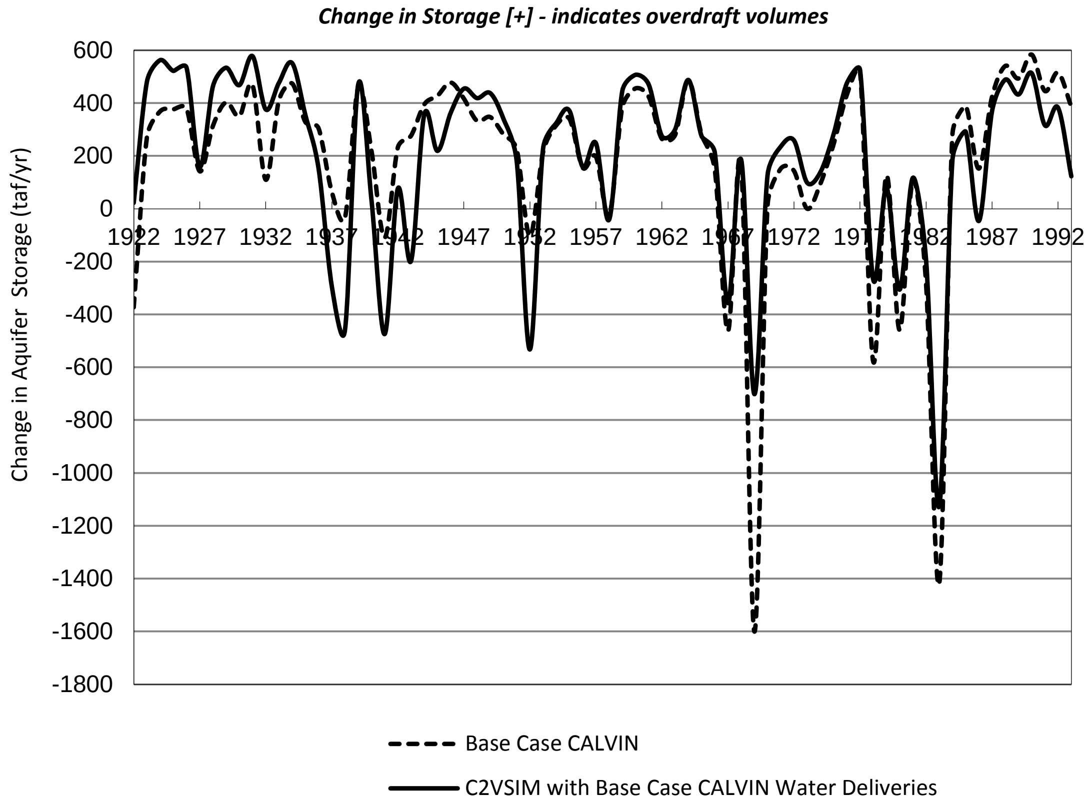
Subregion 17



Subregion 18

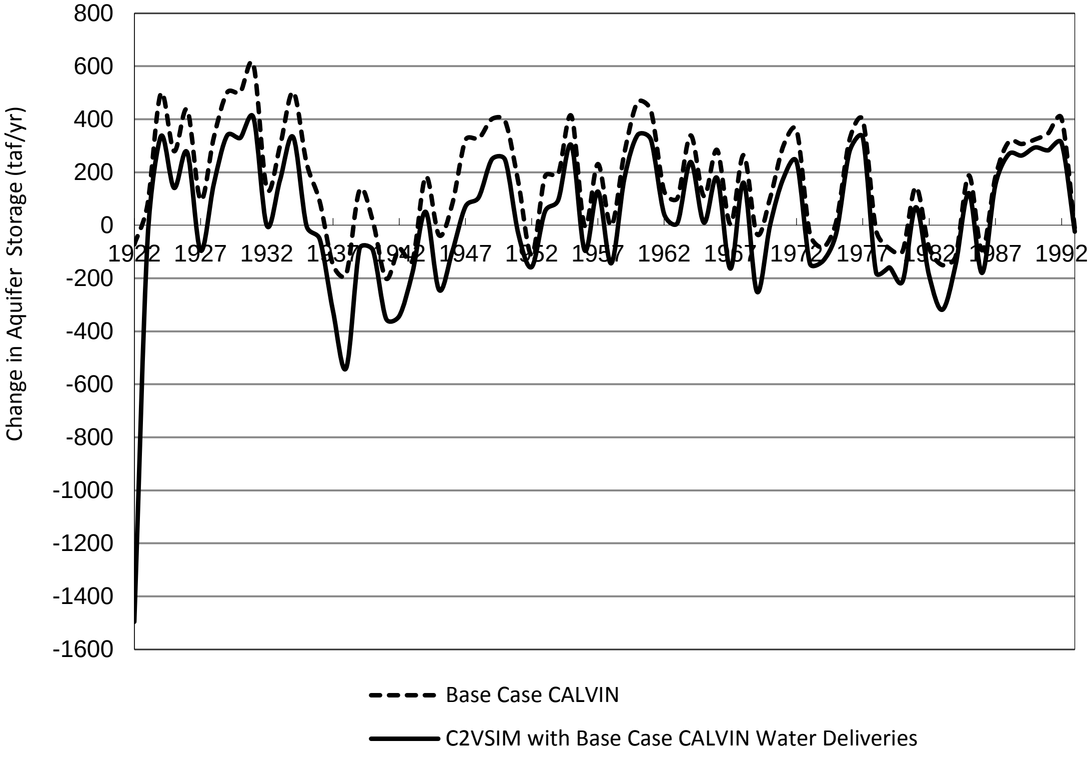


Subregion 19



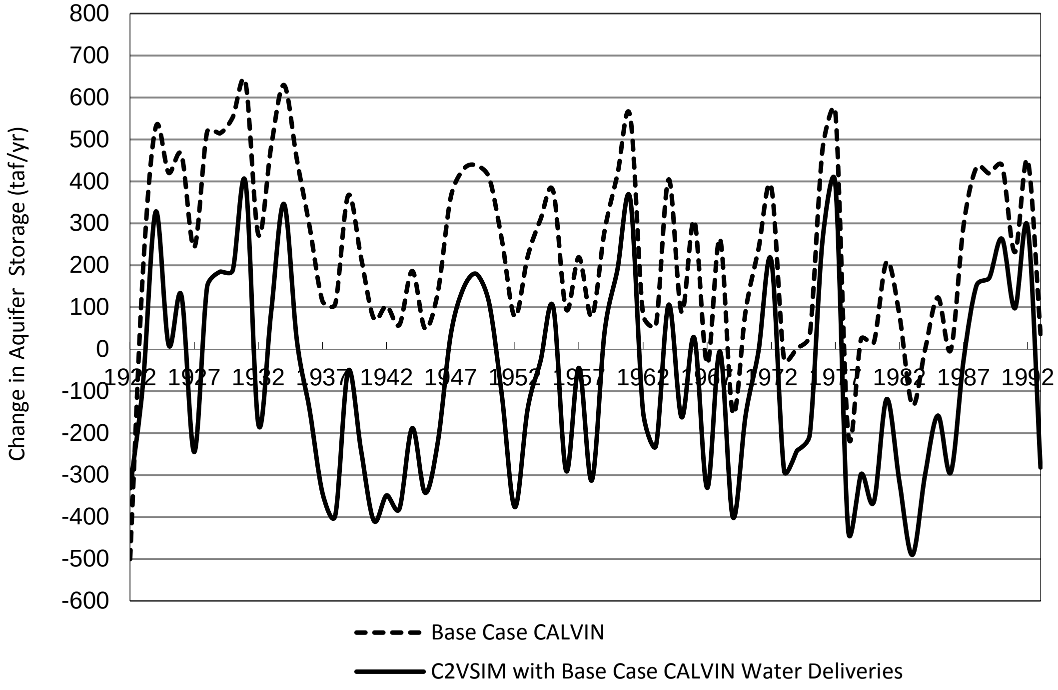
Subregion 20

Change in Storage [+] - indicates overdraft volumes



Subregion 21

Change in Storage [+] - indicates overdraft volumes

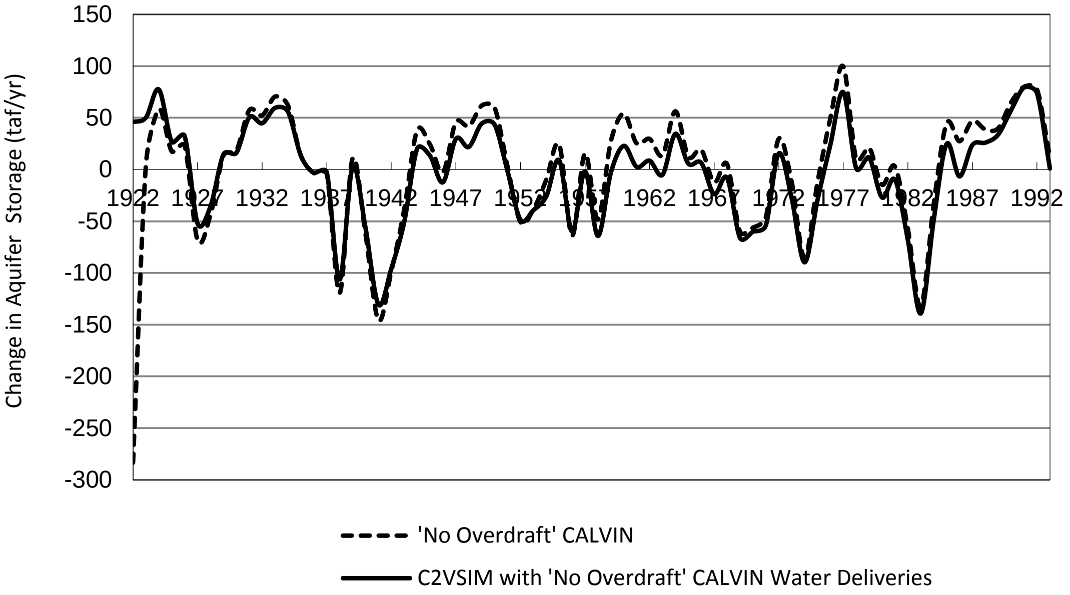


Appendix G: Graphs of estimated Overdraft C2VSIM vs. CALVIN over 72-years for 'No Overdraft' CALVIN

This Appendix accompanies Chapter Four sections, the graphs below show annual differences between change in storage estimated in CALVIN and C2VSIM for 'No Overdraft' case.

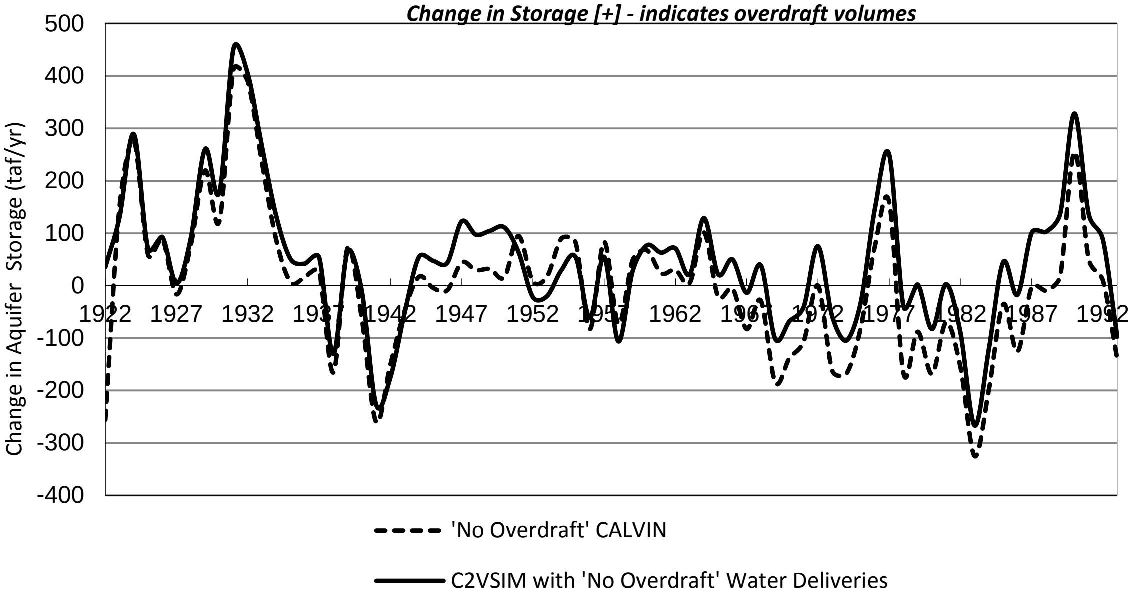
Subregion 1

Change in Storage ([+] - indicates overdraft volumes)



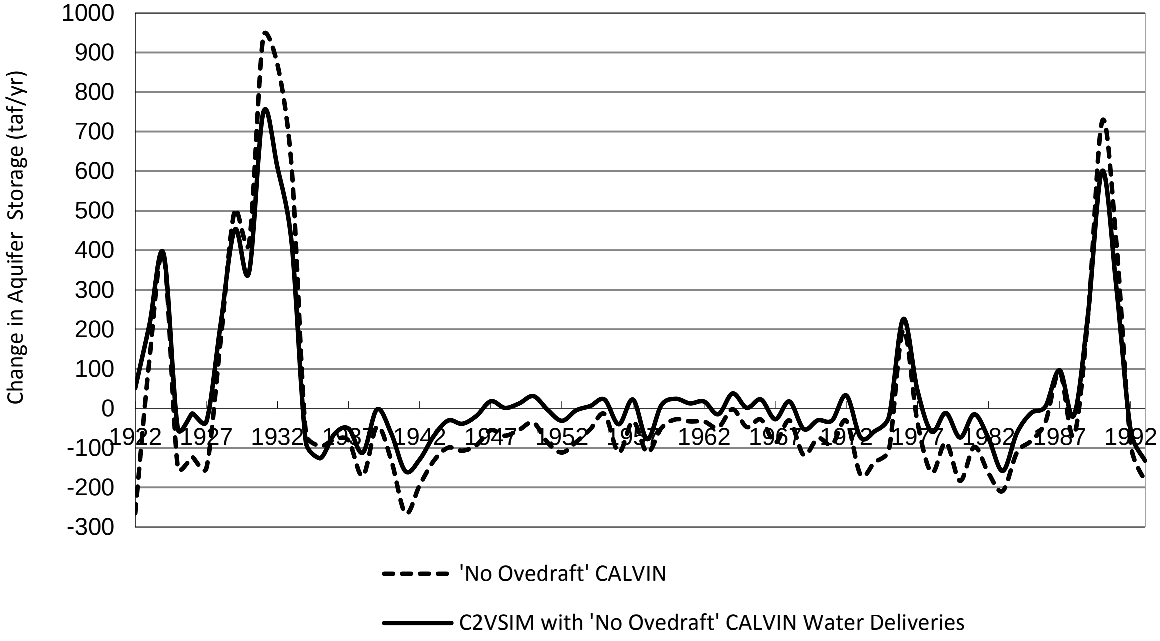
Subregion 2

Change in Storage [+] - indicates overdraft volumes



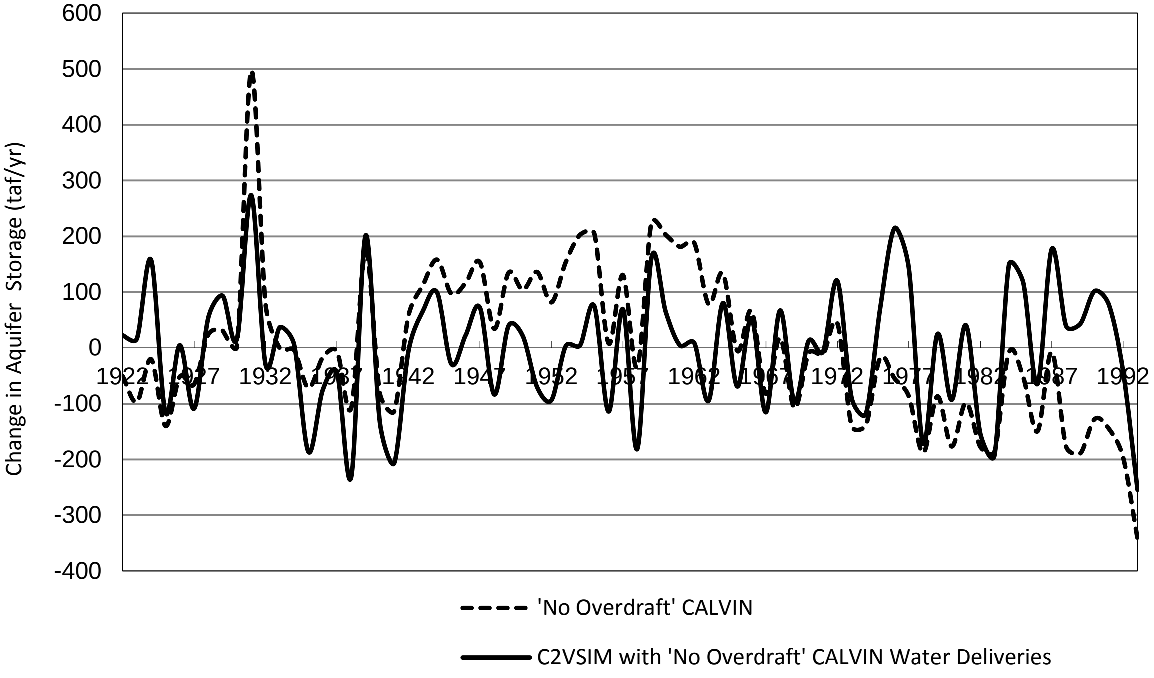
Subregion 3

Change in Storage [+] - indicates overdraft volumes



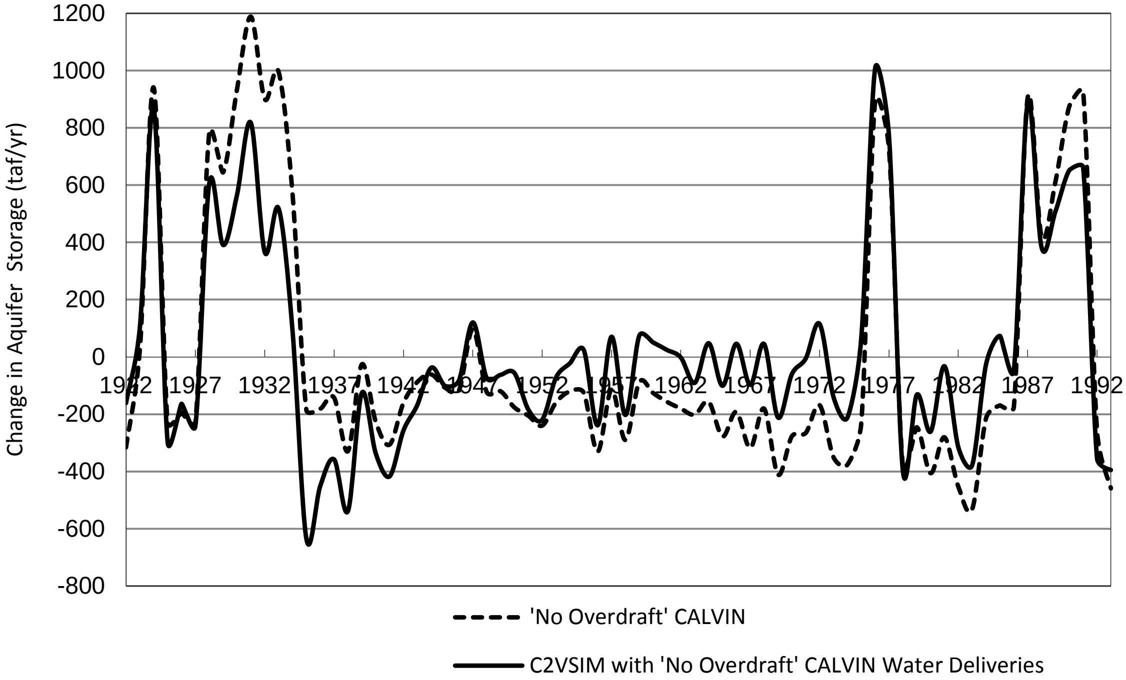
Subregion 4

Change in Storage [+] - indicates overdraft volumes



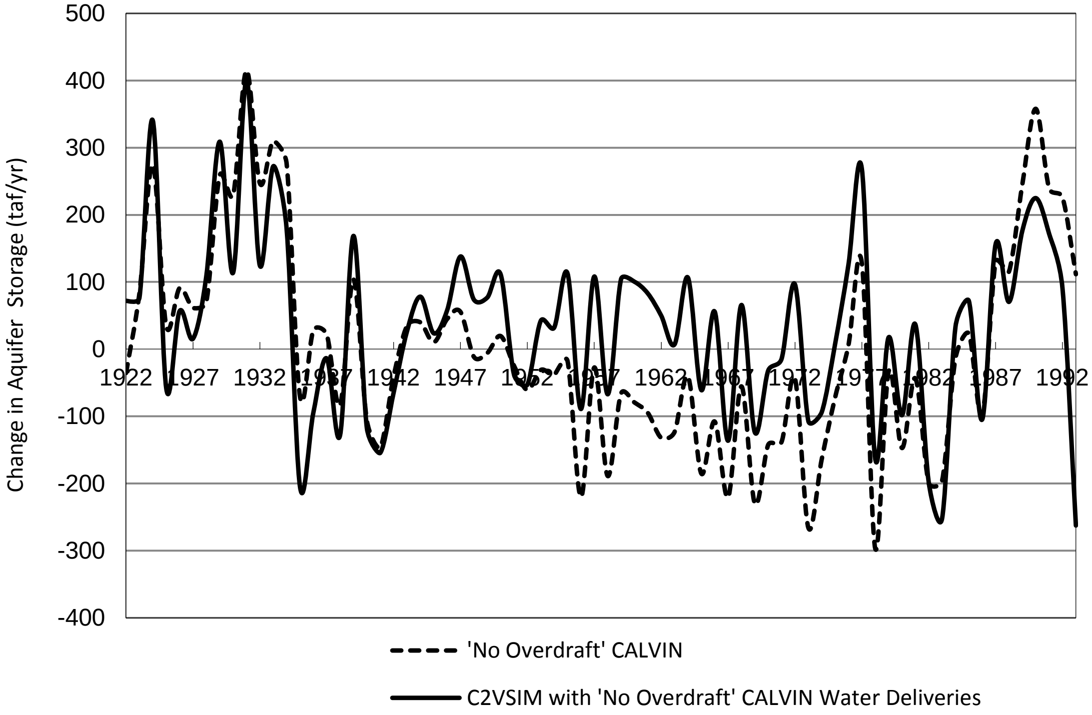
Subregion 5

Change in Storage [+] - indicates overdraft volumes



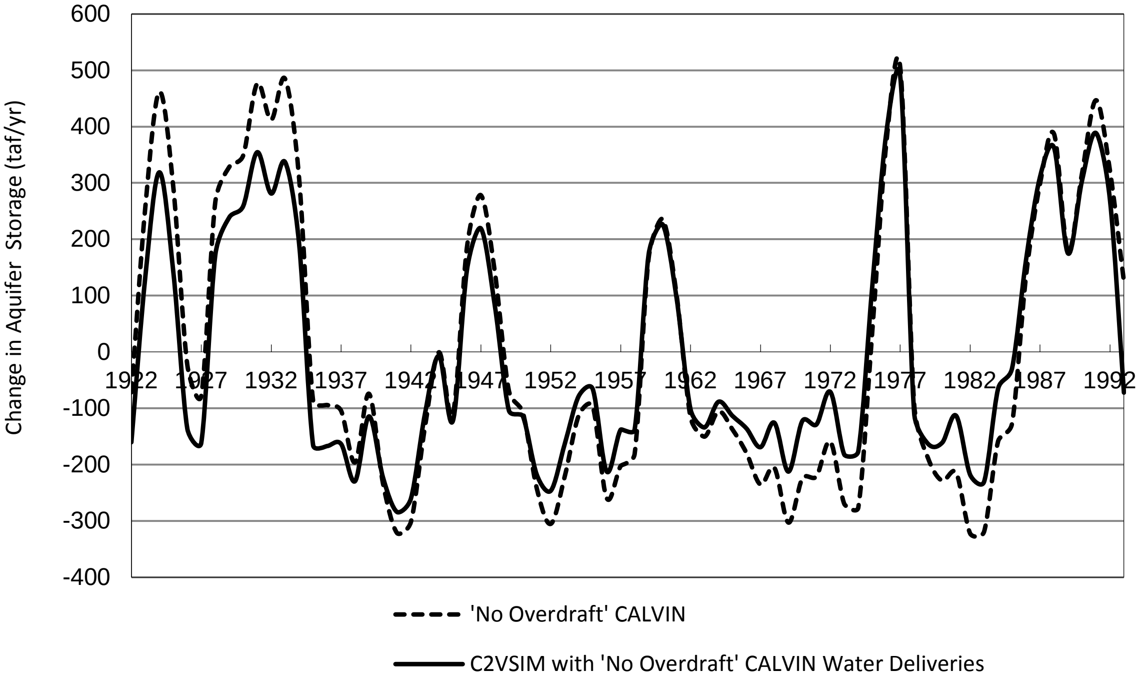
Subregion 6

Change in Storage [+] - indicates overdraft volumes



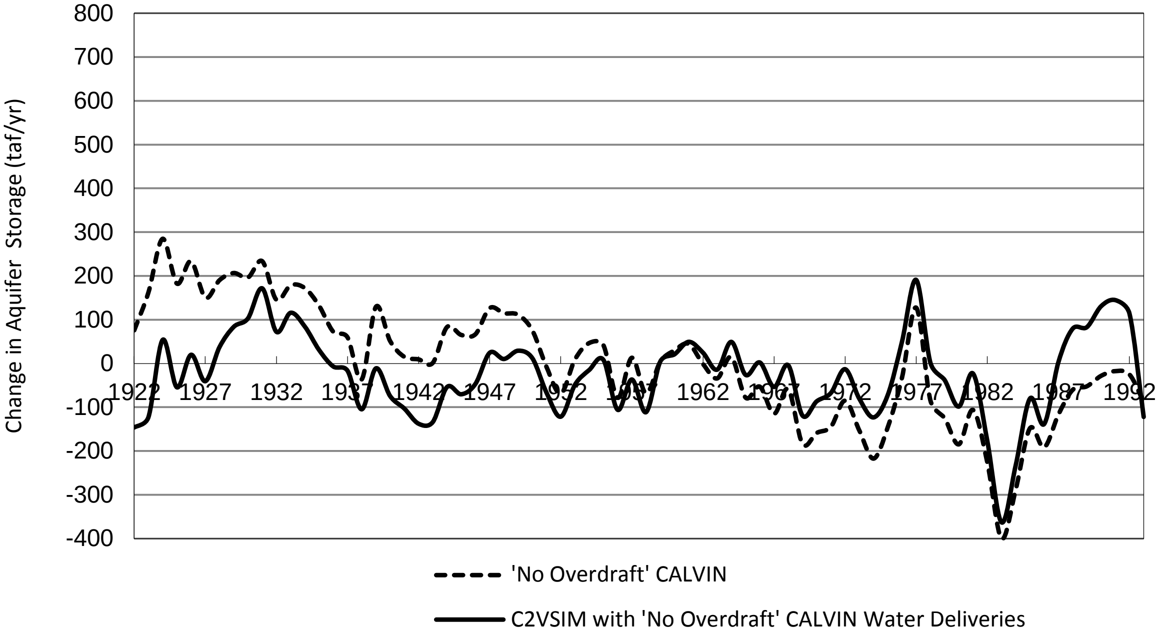
Subregion 7

Change in Storage [+] - indicates overdraft volumes



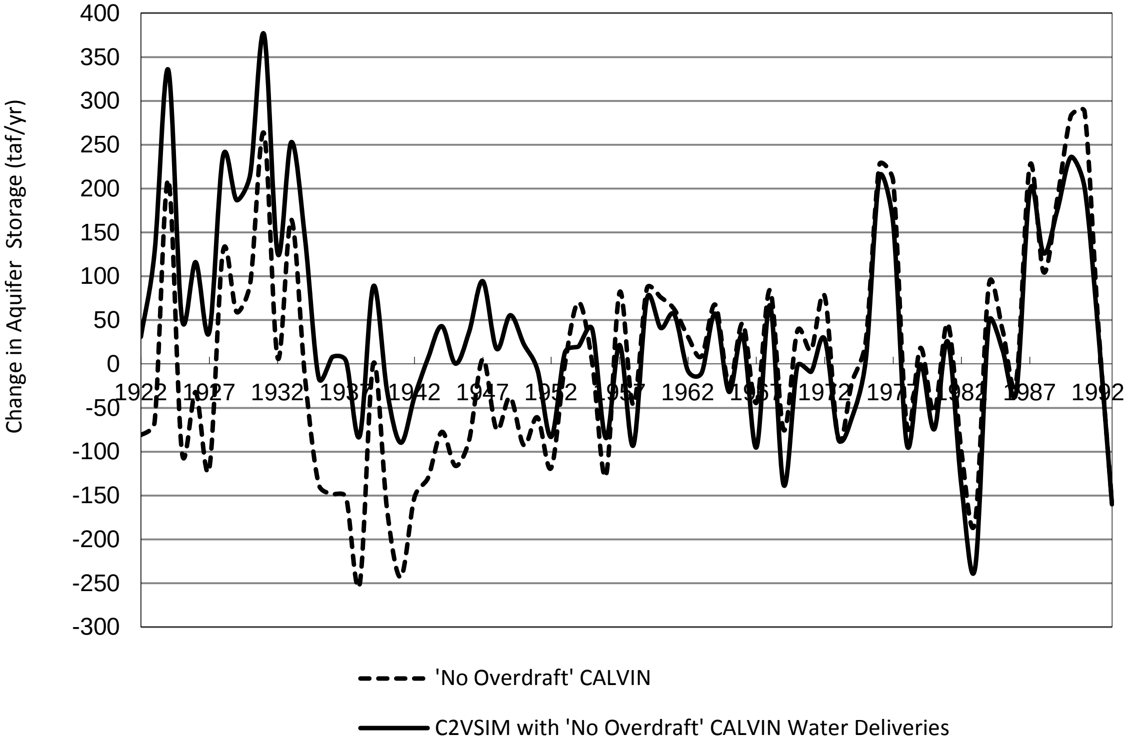
Subregion 8

Change in Storage [+] - indicates overdraft volumes



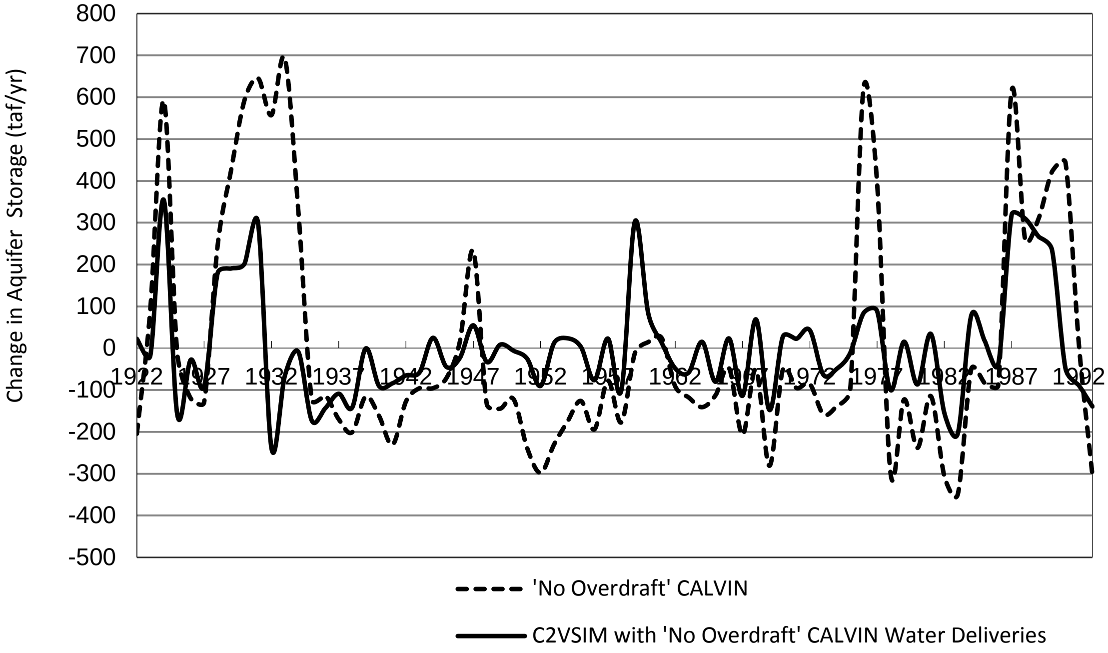
Subregion 9

Change in Storage [+] - indicates overdraft volumes



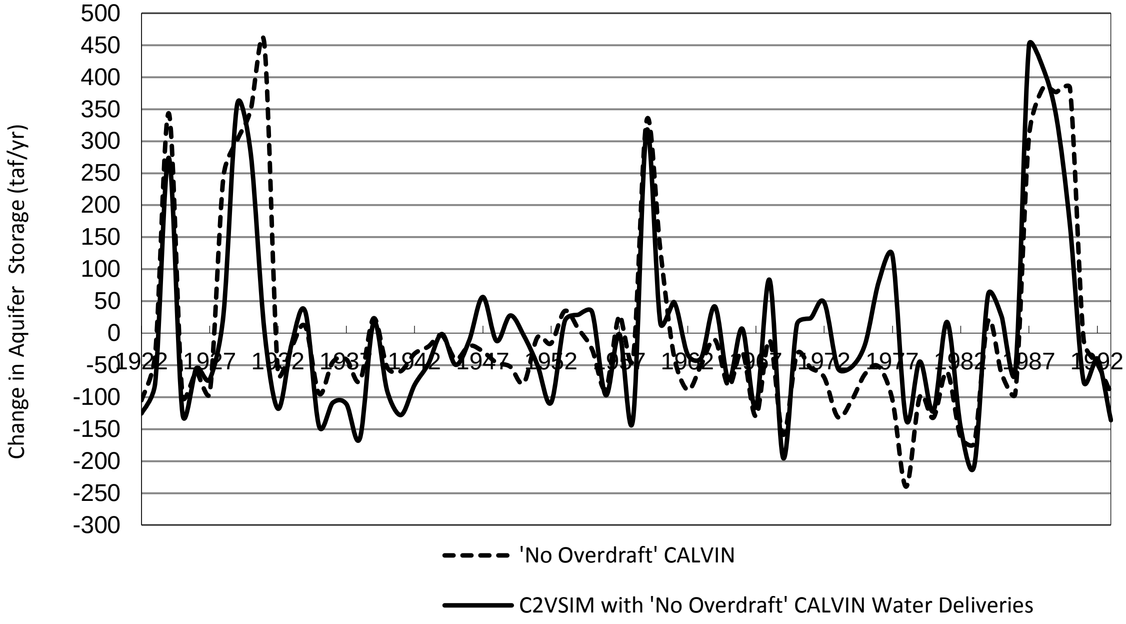
Subregion 10

Change in Storage [+] - indicates overdraft volumes



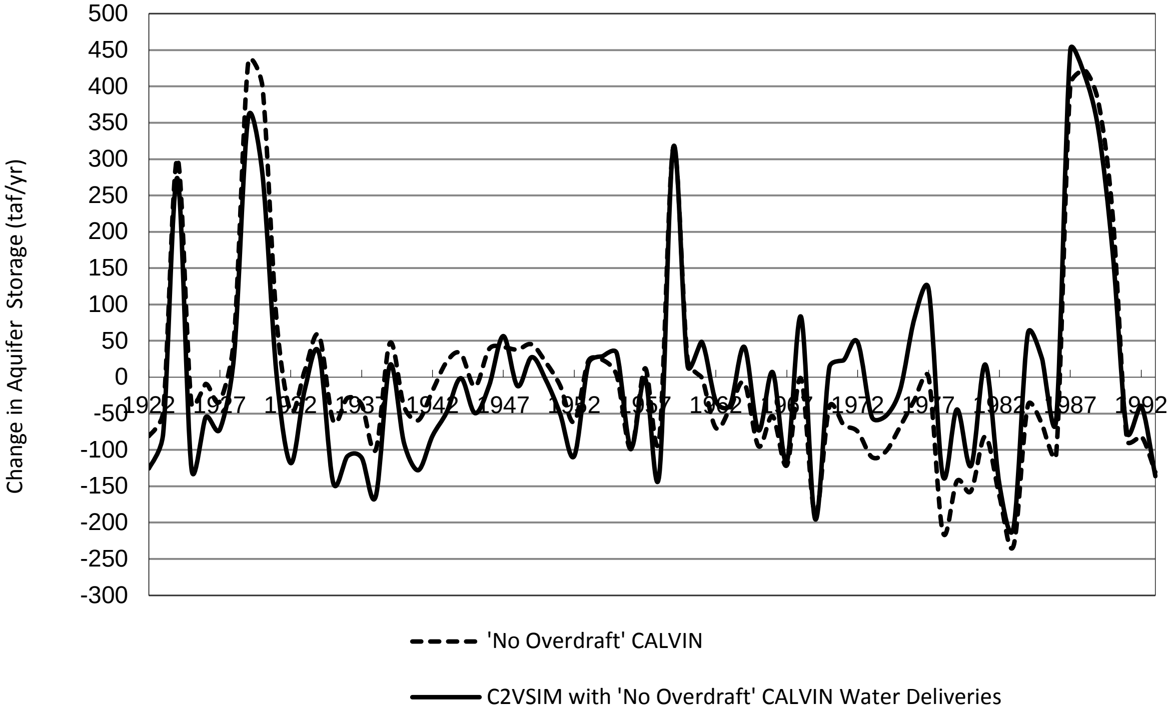
Subregion 11

Change in Storage [+] - indicates overdraft volumes



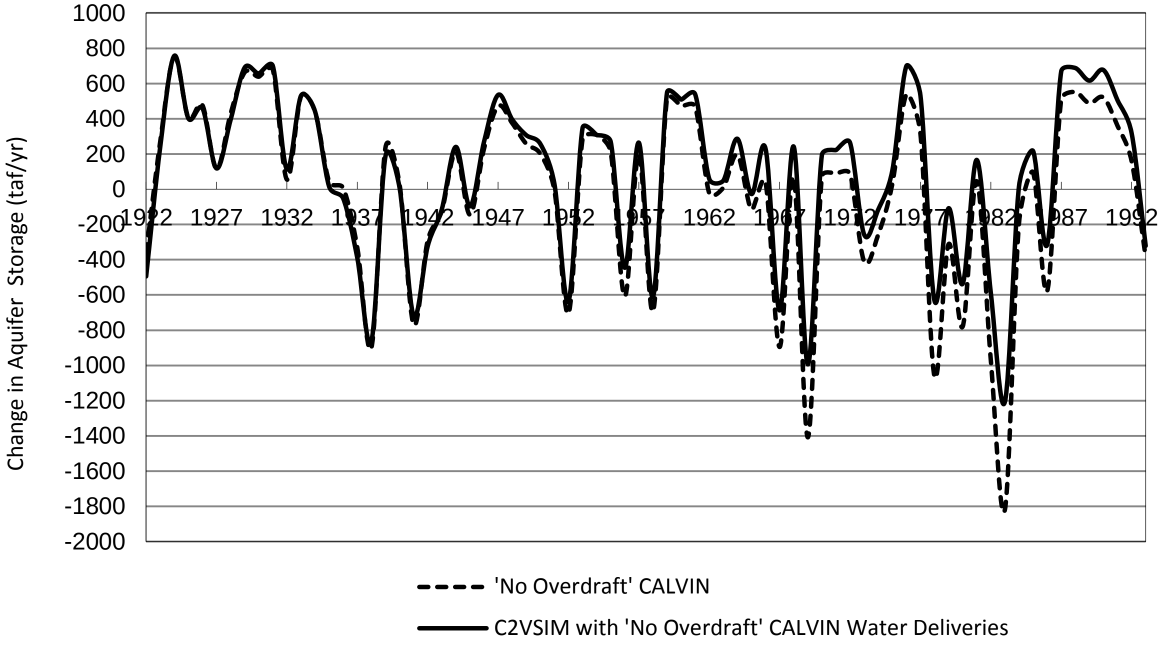
Subregion 12

Change in Storage [+] - indicates overdraft volumes



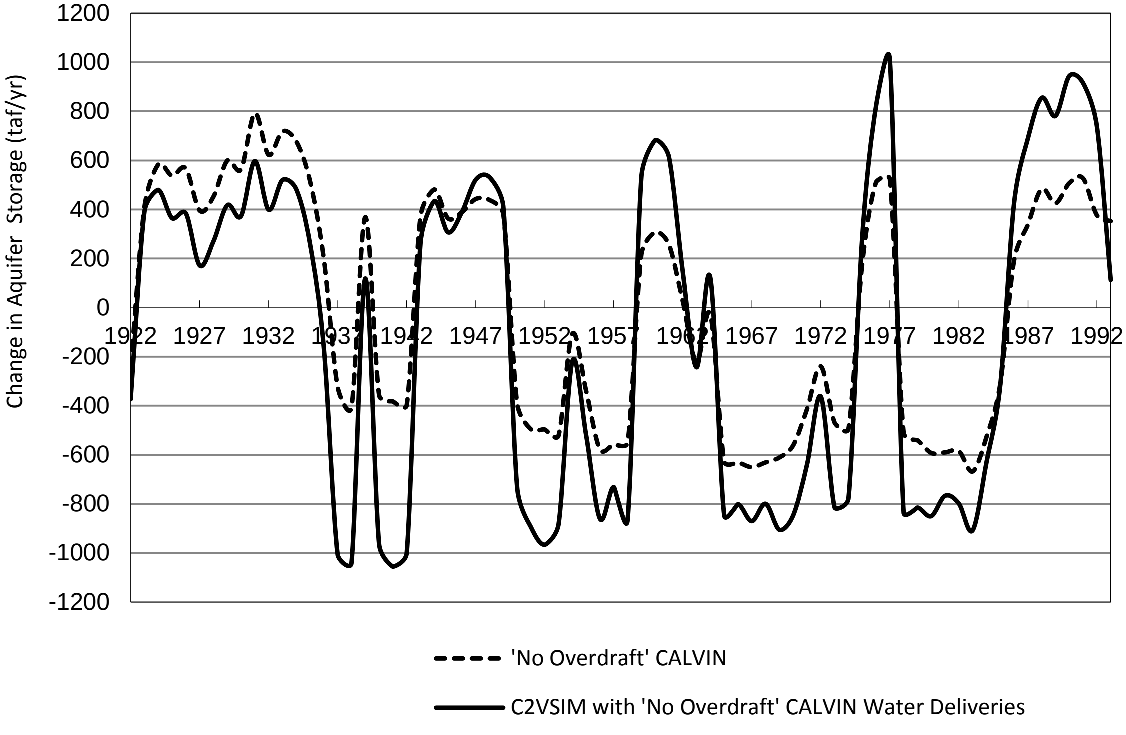
Subregion 13

Change in Storage [+] - indicates overdraft volumes



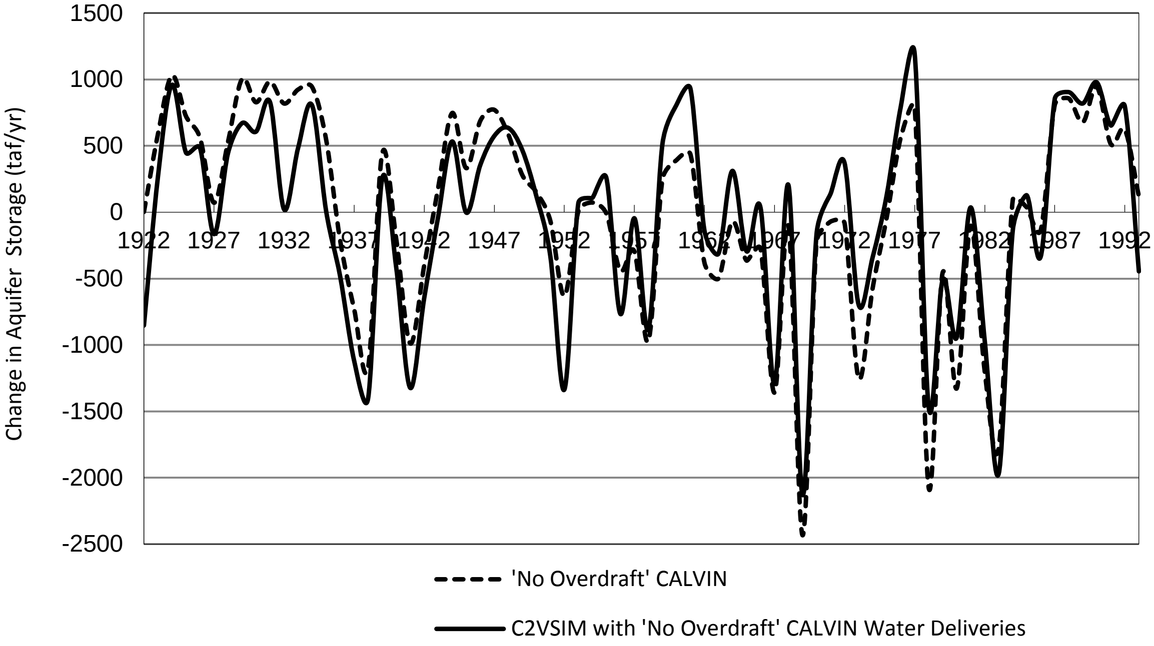
Subregion 14

Change in Storage [+] - indicates overdraft volumes



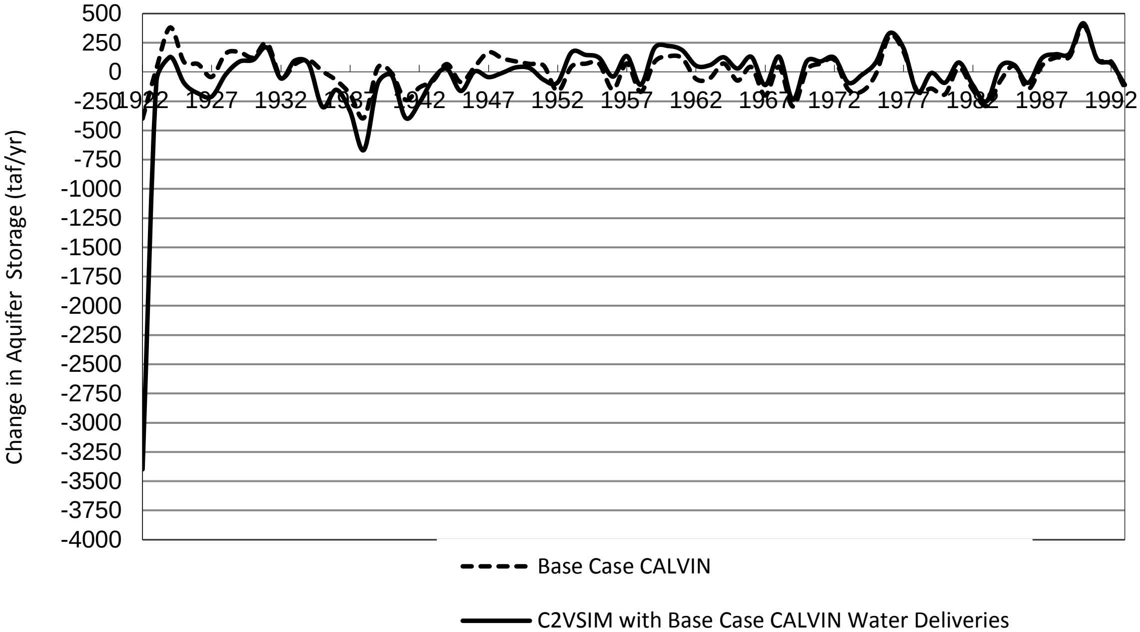
Subregion 15

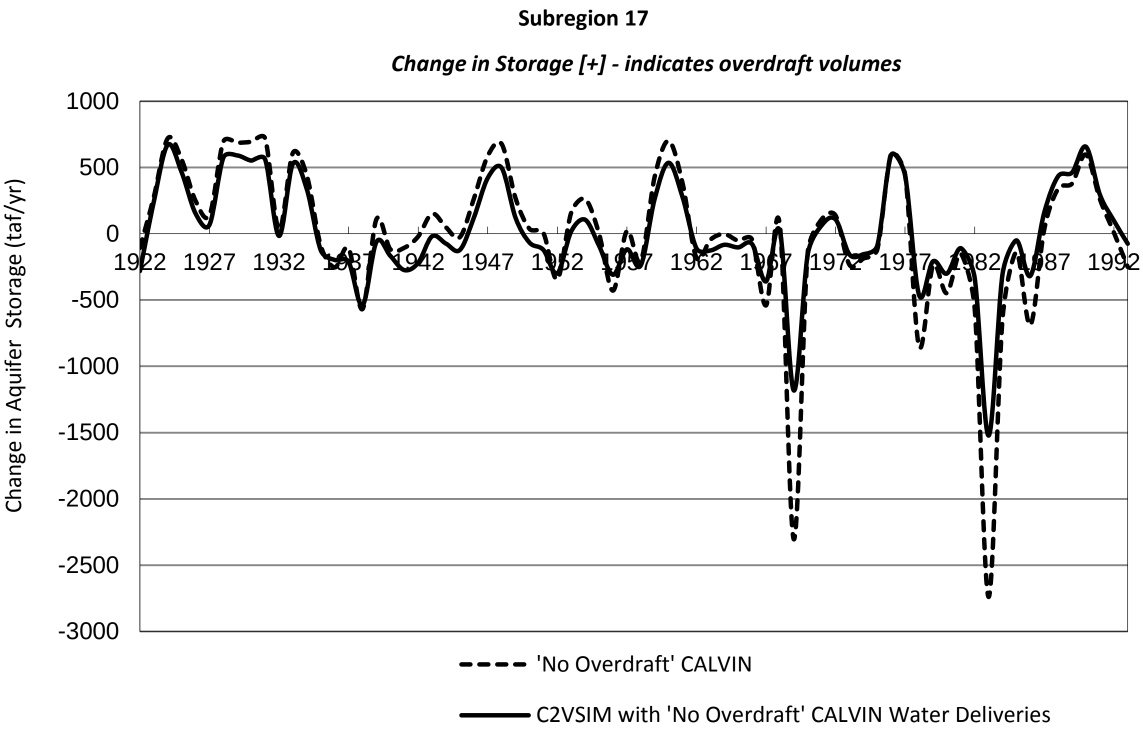
Change in Storage [+] - indicates overdraft volumes

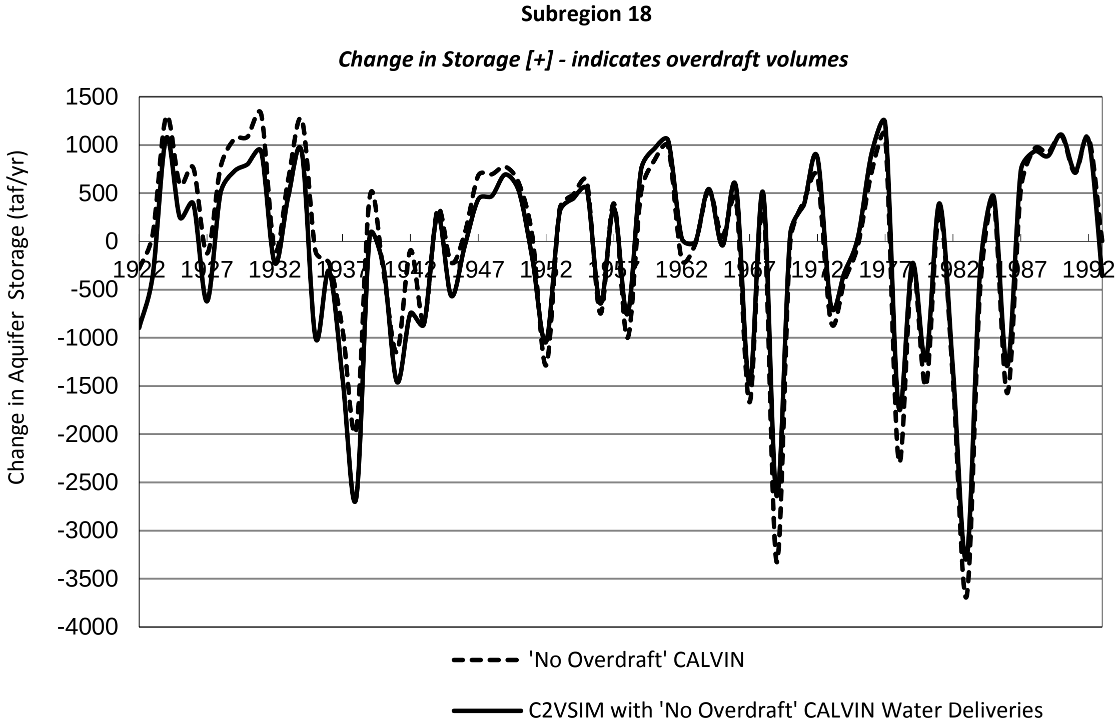


Subregion 16

Change in Storage [+] - indicates overdraft volumes

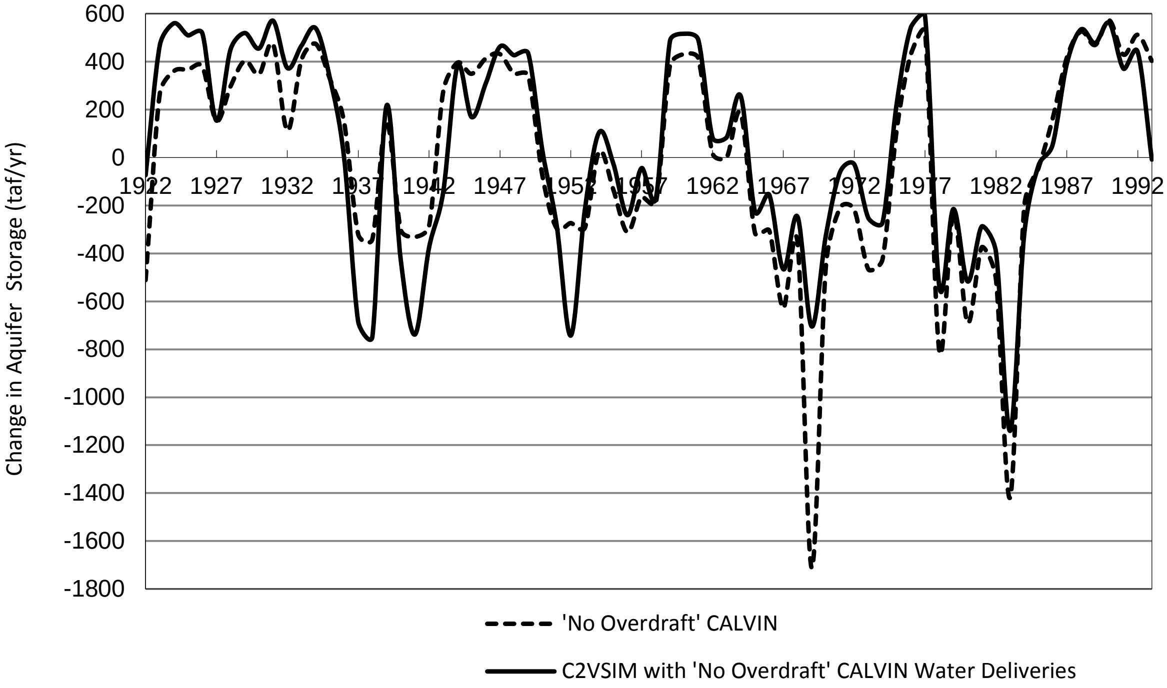



Subregion 17
Change in Storage [+] - indicates overdraft volumes
Change in Aquifer Storage (taf/yr)
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
1922
1927
1932
1937
1942
1947
1952
1957
1962
1967
1972
1977
1982
1987
1992
'No Overdraft' CALVIN
C2VSIM with 'No Overdraft' CALVIN Water Deliveries


Subregion 18
Change in Storage [+] - indicates overdraft volumes
Change in Aquifer Storage (taf/yr)
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
1922
1927
1932
1937
1942
1947
1952
1957
1962
1967
1972
1977
1982
1987
1992
'No Overdraft' CALVIN
C2VSIM with 'No Overdraft' CALVIN Water Deliveries

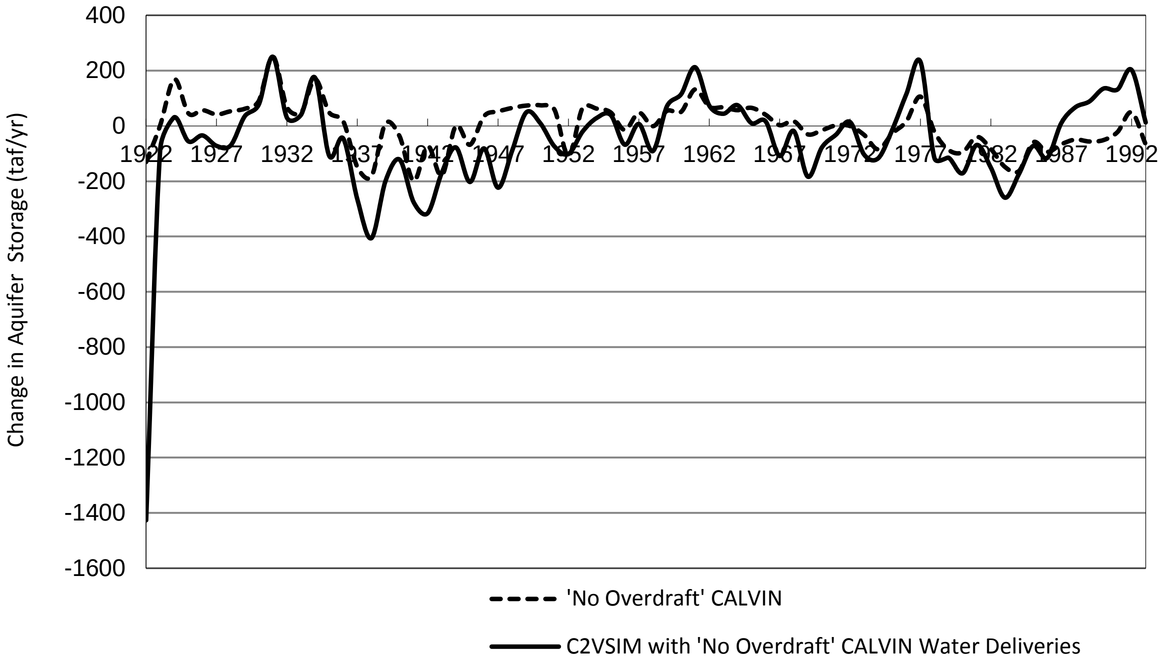
Subregion 19

Change in Storage [+] - indicates overdraft volumes



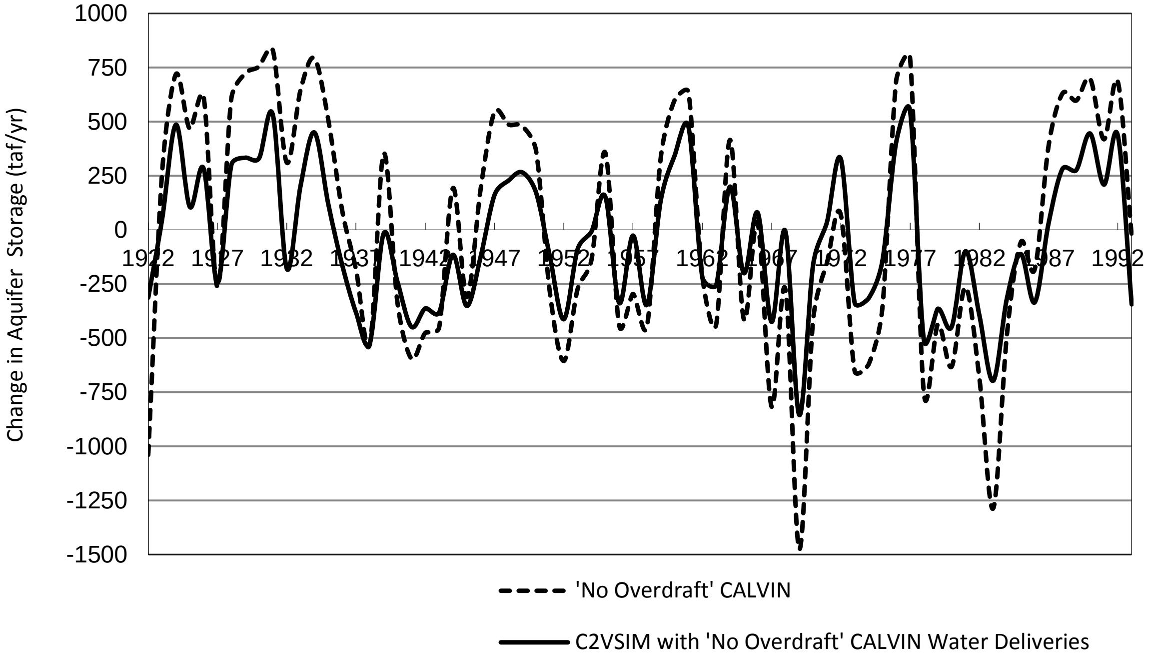
Subregion 20

Change in Storage [+] - indicates overdraft volumes



Subregion 21

Change in Storage [+] - indicates overdraft volumes



Appendix H: Comparison by subregion C2VSIM with Base Case and "No Overdraft" CALVIN water deliveries

Sections below detail for each subregion water budget analysis and water table elevation plots for C2VSIM simulations with CALVIN Base Case and "No Overdraft" case water allocations. Results of ground water heads at each node in feet above mean sea level are reported in the results folder CVGWheadall.OUT file, for the end of each month for the three aquifer layers. Post processing for getting weighted average heads for each subregion was performed as shown in **Error! Reference source not found.**. Nodes that dry up during the simulation are assigned a value that is too large ~ 20,000 feet.

Reported water budget are from C2VSIM run with 2005 land use and optimized CALVIN water deliveries for Base and 'No Overdraft' cases. These are compared with historical C2VSIM run; groundwater in the current updated CALVIN model is based on C2VSIM with historical land use some adjustments were made per calibration process in Chapter 3.

1. Surbregion 1 - Water Budget Analysis

Table H-1. Ground-water water budget analysis Subregion 1

	Annual Average Water Budget Analysis (taf/yr)		
Subregion 1	**Base Case CALVIN**	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	117.3	113.2	141.8
3. Diversion Losses	7.3	5.2	15.8
4. Boundary Inflow	84.4	84.4	89.4
5. Inter-basin Inflow	23.7	23.8	33.6
Total Recharge	***232.8***	***226.5***	***280.6***
OUTFLOW			
6. Stream Exchange	139.4	129.6	215.2
7. Subsidence	0.001	0.001	0.003
Total Discharge	***139.4***	***129.6***	***215.2***
8. Pumping	88.6	93.4	51.1
Change in Storage ([+] - indicates overdraft volumes)	-4.9	-3.5	-14.2

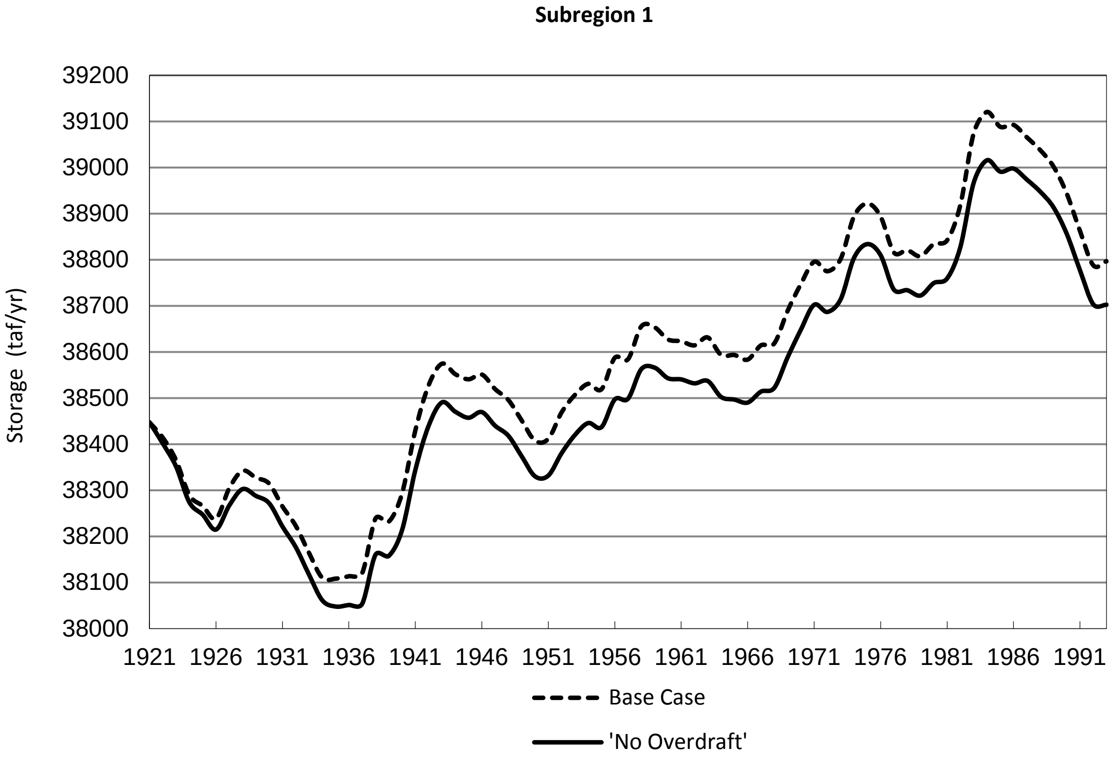


Figure H-1. Effect of ground water development for subregion 1- groundwater storage

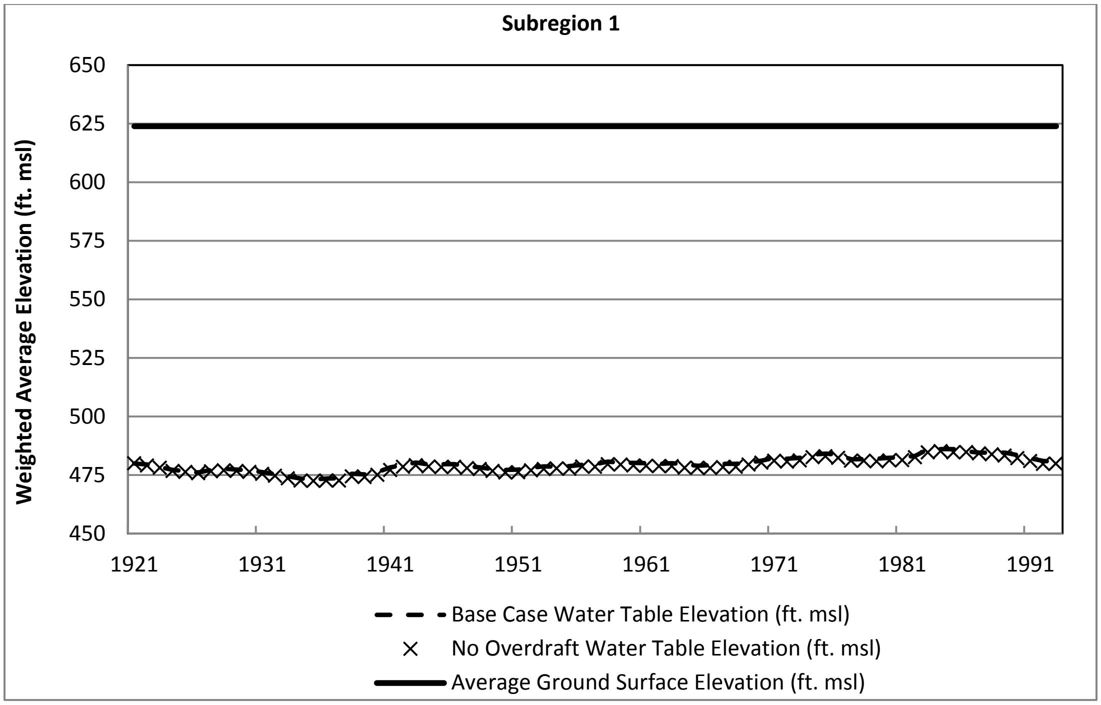


Figure H-2. Effect of ground water development for subregion 1- Water Table Elevation

2. Subregion 2 - Water Budget Analysis

Table H-2. Ground-water water budget analysis subregion 2

Subregion 2	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	**No Overdraft CALVIN Scenario**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	156.6	148.7	209.8
2. Diversion Losses	18.2	17.4	13.9
3. Boundary Inflow	138.9	138.9	149.2
4. Stream Exchange	19.8	21.5	22.2
5. Subsidence	0.01	0.01	0.0013
Total Recharge	***333.5***	***326.5***	***395.2***
OUTFLOW			
6. Inter-basin Inflow	27.7	26.1	19.7
Total Discharge	***27.7***	***26.1***	***19.7***
7. Pumping	*352.1*	*347.2*	362.8
Change in Storage ([+] - indicates overdraft volumes)	46.3	46.8	-12.7

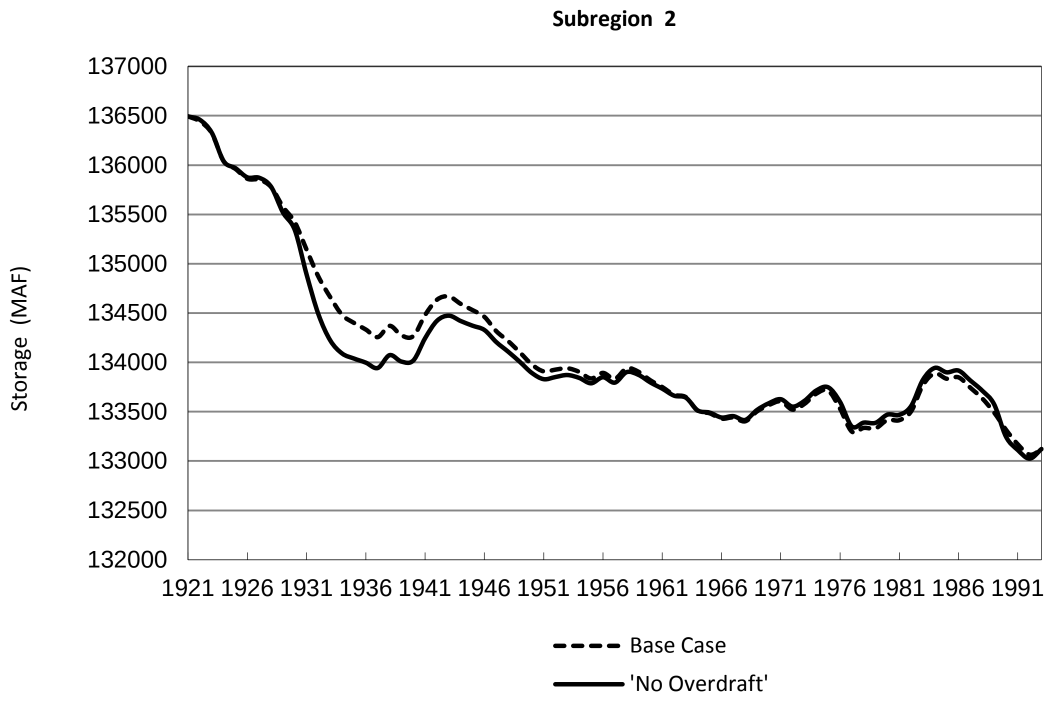


Figure H-3. Effect of ground water development for subregion 2-groundwater storage

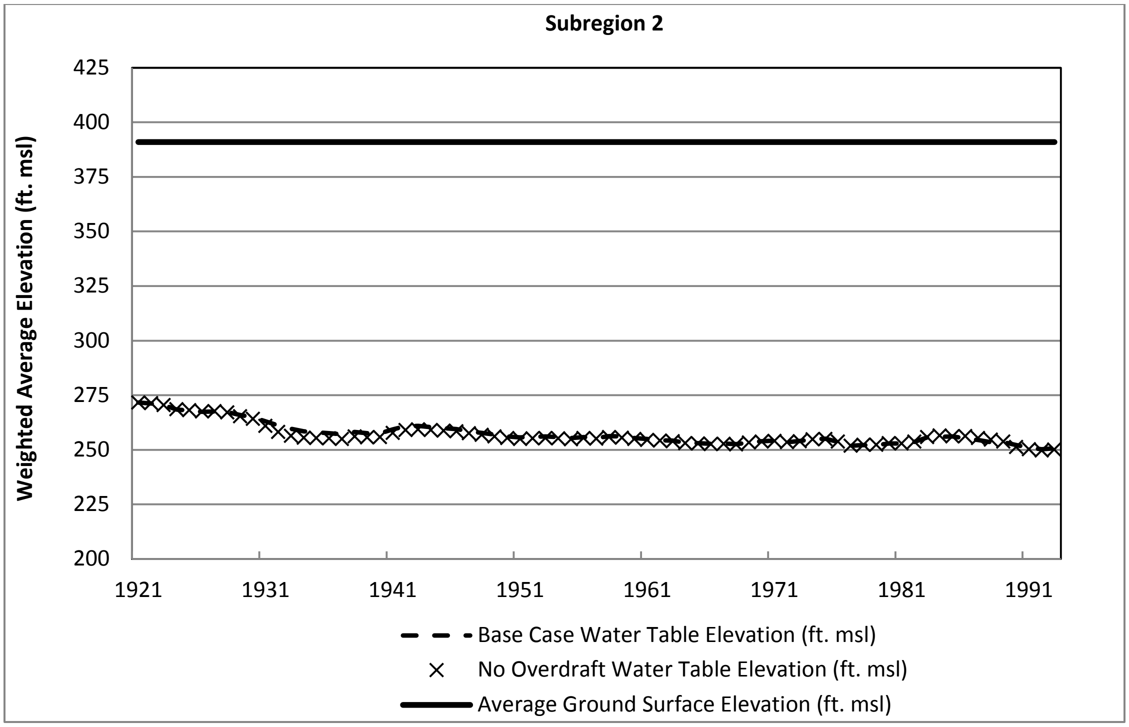


Figure H-4. Effect of ground water development for subregion 2- Water Table Elevations

3. Subregion 3 - Water Budget

Table H-3. Ground-water water budget analysis Subregion 3

Subregion 3	Annual Average Water Budget Analysis (taf/yr) Base Case CALVIN	No Overdraft CALVIN Scenario	Historical 1980-2009
INFLOW			
1. Precipation + Irrigation Return Flow	84.3	84.2	225
2. Diversion Losses	51.5	52.2	49.6
3. Boundary Inflow	47.4	47.4	64.6
4. Subsidence	3.8	3.1	1.9
5. Inter-basin Inflow	43.7	35.4	0
Total Recharge	***230.7***	***222.2***	***341.2***
OUTFLOW			
6. Stream Exchange	113.4	116.8	129.9
7. Inter-basin Inflow	0.0	0.0	51.4
Total Discharge	***113.4***	***116.8***	***181.3***
8. Pumping	160.9	147.8	173.4
Change in Storage ([+] - indicates overdraft volumes)	43.6	42.5	13.5

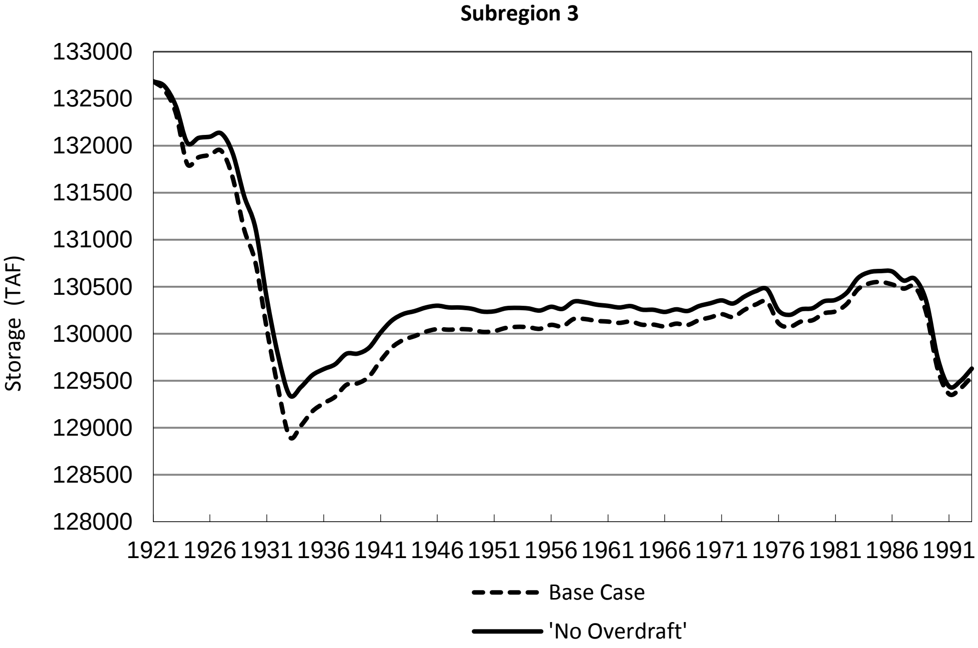


Figure H-5. Effect of ground water development for subregion 3- groundwater storage

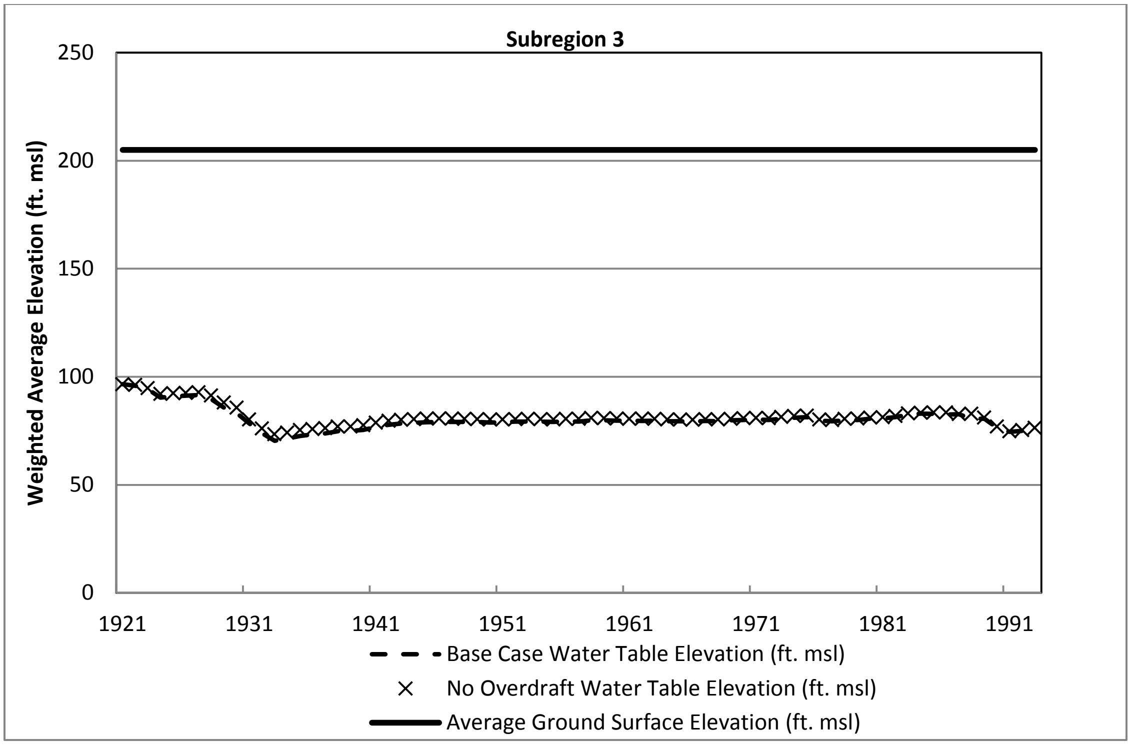


Figure H-6. Effect of ground water development for subregion 3- Water Table Elevations

4. Subregion 4 - Water Budgets Analysis

Table H-4. Ground-water water budget analysis Subregion 4

Subregion 4	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	258.4	246.5	141.8
3. Diversion Losses	105.0	103.9	15.8
4. Boundary Inflow	0.0	0.0	89.4
5. Inter-basin Inflow	0.9	0.6	33.6
Total Recharge	***364.2***	***351.0***	***280.6***
OUTFLOW			
6. Stream Exchange	229.6	231.8	215.2
7. Subsidence	32.9	23.0	0.003
Total Discharge	***262.5***	***254.8***	***215.2***
8. Pumping	99.4	94.1	51.1
Change in Storage ([+] - indicates overdraft volumes)	-2.3	-2.0	-14.2

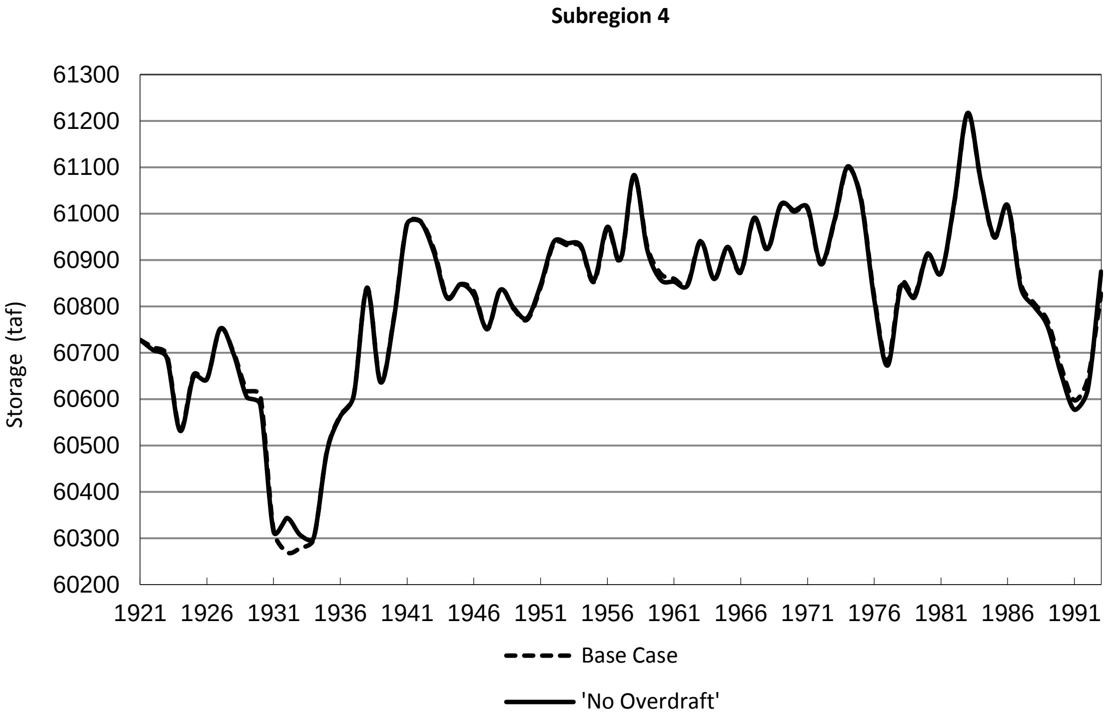


Figure H-7. Effect of ground water development for Subregion 4- groundwater storage

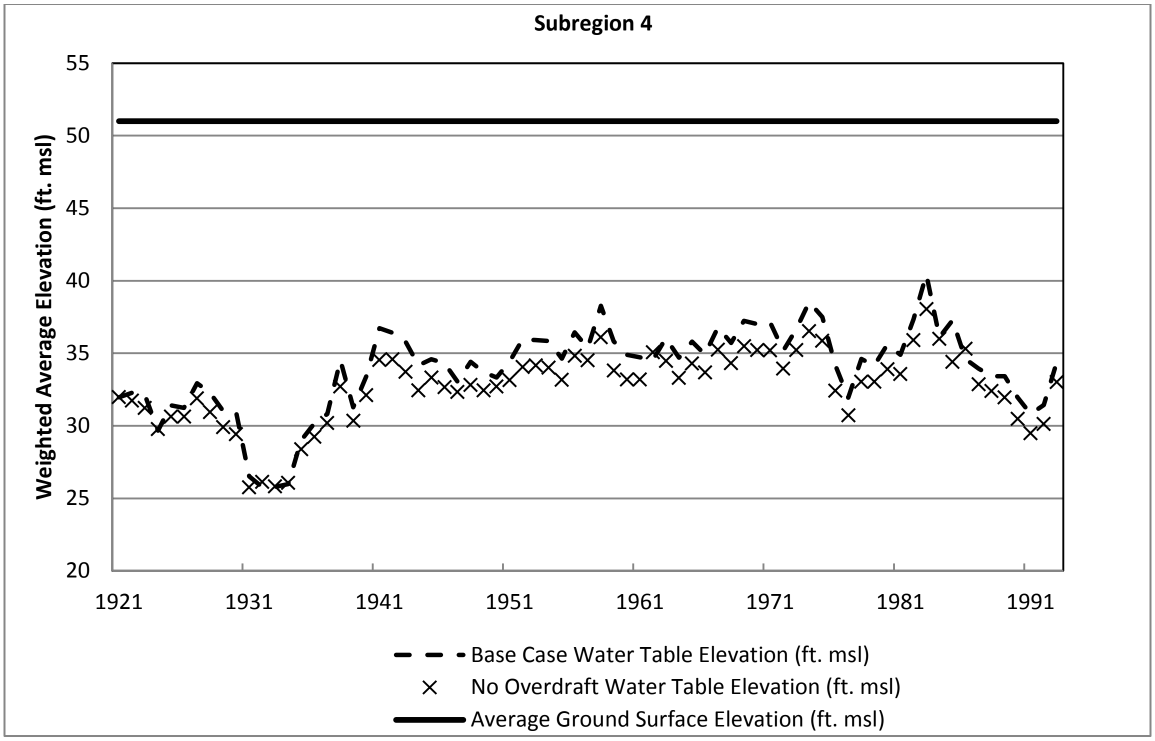


Figure H-8. Effect of ground water development for Subregion 4- Water Table Elevations

5. Subregion 5 - Water Budgets

Table H-5. Ground-water water budget analysis Subregion 5

Subregion 5	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flows	240.5	237.5	380
3. Diversion Losses	130.3	130.6	141.1
4. Boundary Inflow	17.8	17.8	20
6. Inter-basin Inflow	15.5	18.5	0
Total Recharge	***404.0***	***404.3***	***541.1***
OUTFLOW			
6. Stream Exchange	101.9	109.5	115.9
7. Inter-basin Inflow	0.0	0.0	9.5
5. Subsidence	0.001	0.003	0.00
Total Discharge	***101.9***	***109.5***	***125.4***
9. Pumping	320.6	311.5	425.1
Change in Storage ([+] - indicates overdraft volumes)	18.5	16.7	9.4

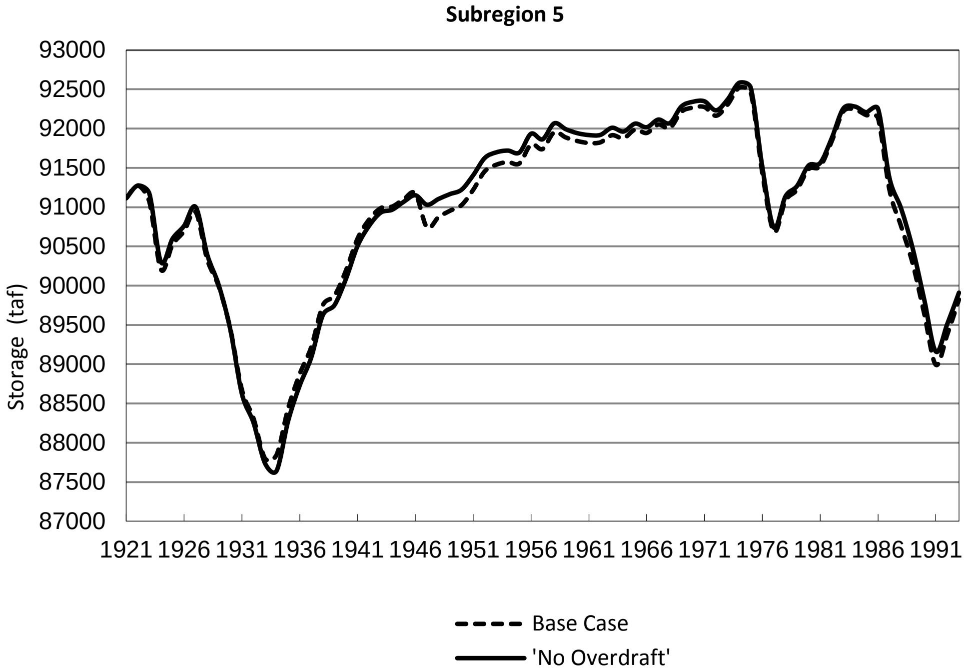


Figure H-9. Effect of ground water development for subregion 5- groundwater storage

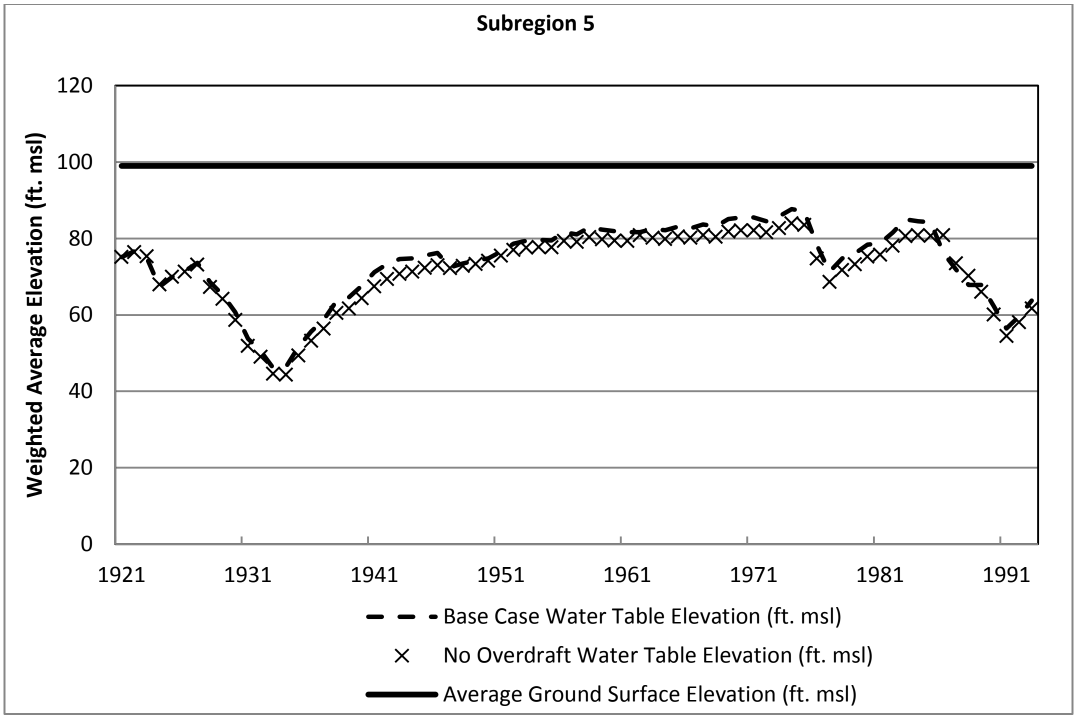


Figure H-10. Effect of ground water development for Subregion 5- Water Table Elevations

6. Subregion 6 - Water Budgets under Base Case CALVIN

Table H-6. Ground-water water budget analysis Subregion 6

	Annual Average Water Budget Analysis (taf/yr)		
Subregion 6	**Base Case CALVIN**	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flows	123.0	120.9	175.3
3. Diversion Losses	42.7	42.2	29.7
4. Boundary Inflow	25.6	25.6	29.8
5. Subsidence	10.4	10.6	0.5
6. Stream Exchange	107.3	100.8	62.8
Total Recharge	***309.0***	***300.2***	***298.2***
OUTFLOW			
7. Inter-basin Inflow	56.4	44.7	38.9
Total Discharge	***56.4***	***44.7***	***38.9***
8. Pumping	287.2	290.4	254.9

Change in Storage ([+] - indicates overdraft volumes)	34.6	34.9	-4.4

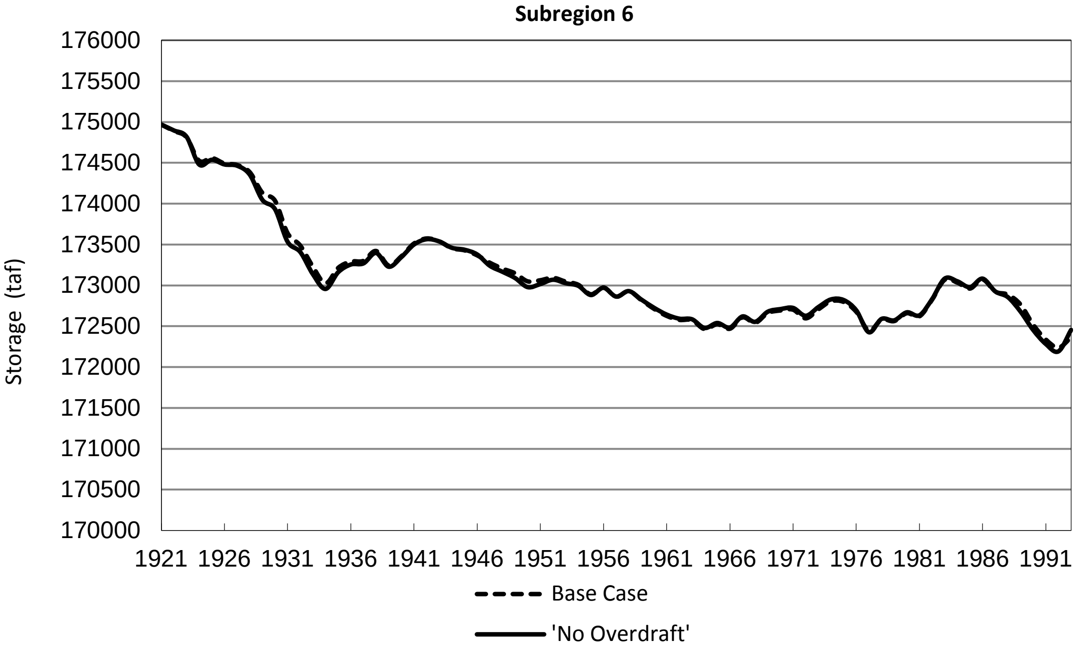


Figure H-11. Effect of ground water development for subregion 6- groundwater storage

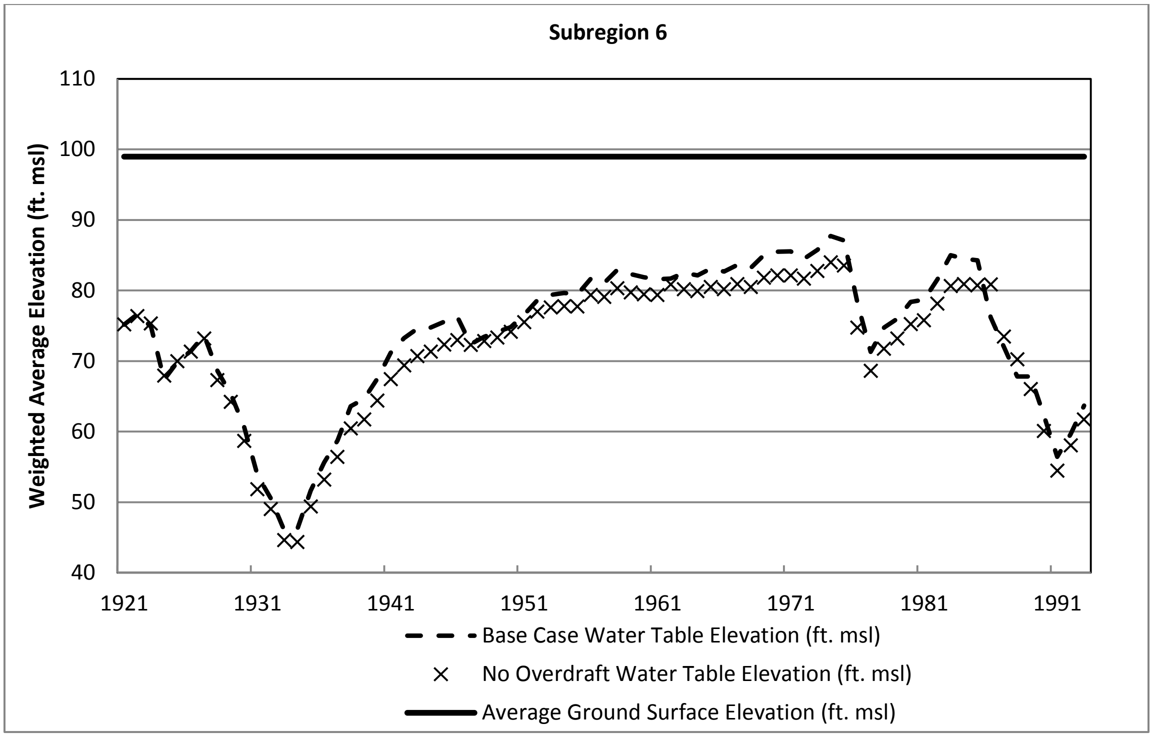


Figure H-12. Effect of ground water development for subregion 6- Water Table Elevations

7. Subregion 7 - Water Budgets

Table H-7. Ground-water water budget analysis Subregion 7

	Annual Average Water Budget Analysis (taf/yr)		
Subregion 7	**Base Case CALVIN**	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flows	130.9	112.7	149.8
2. Diversion Losses	58.1	60.6	43.5
3. Boundary Inflow	83.7	83.7	89.5
4. Interbasin Inflow	15.5	0.0	5
5. Stream Exchange	35.5	21.7	43.5
6. Subsidence	0.0	0.0	0.02
Total Recharge	***323.7***	***278.7***	***331.4***
OUTFLOW			
7. Subsidence	0.0004	0.008	0
8. Interbasin Inflow	0.0	8.88	
Total Discharge	***0.0***	***8.8877***	***0***
9. Pumping	339.7	264.6434944	395.1
Change in Storage ([+] - indicates overdraft volumes)	16.1	-5.2	63.7

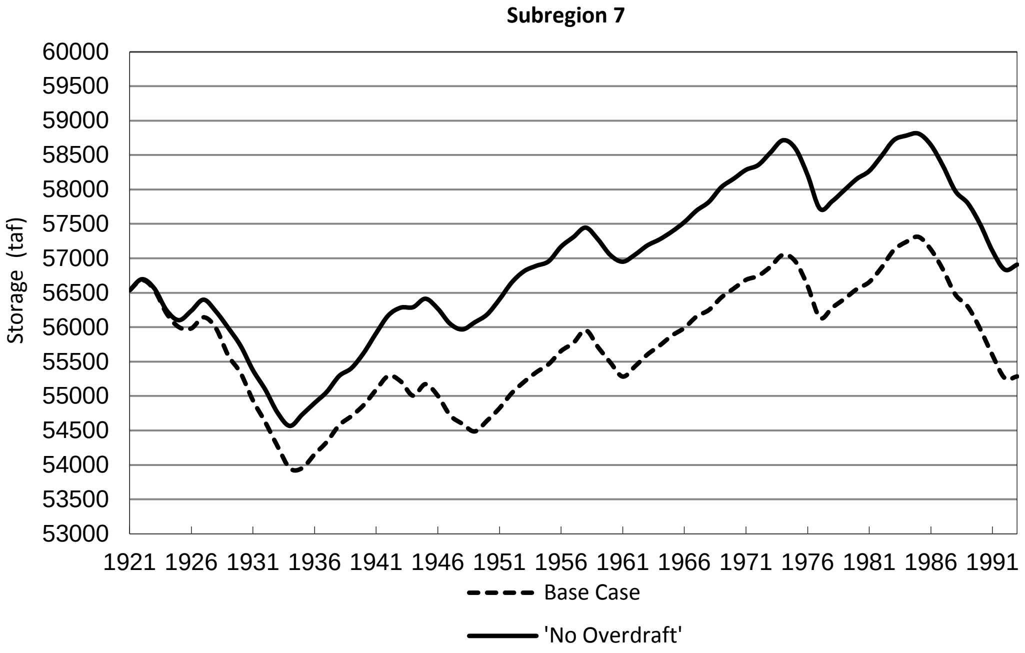


Figure H-13. Effect of ground water development for subregion 7- groundwater storage

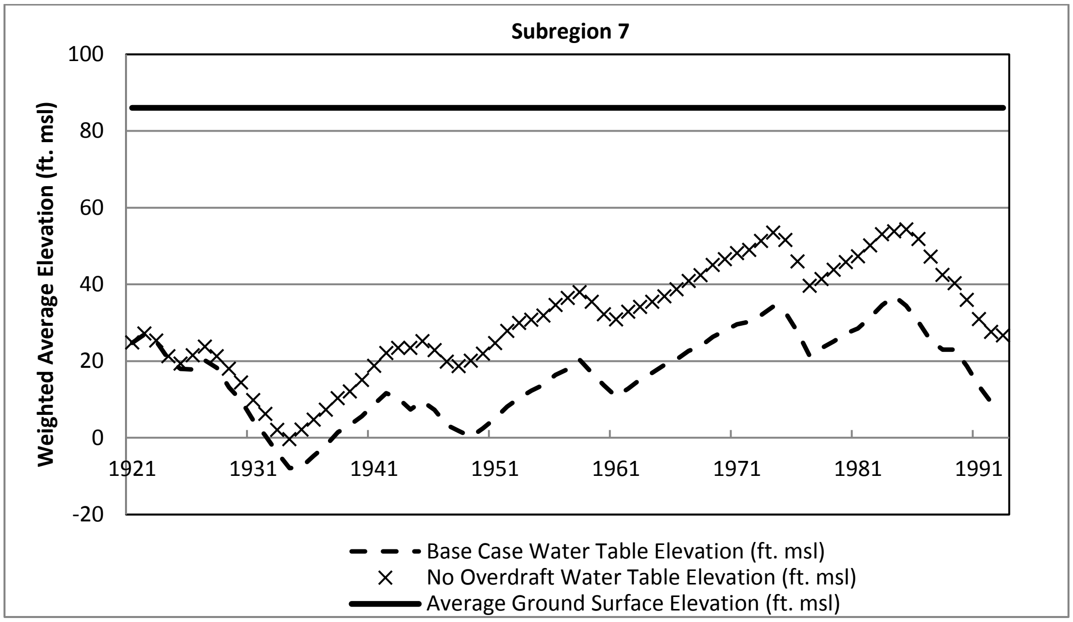


Figure H-14. Effect of ground water development for Subregion 7- Water Table Elevations

8. Subregion 8 - Water Budgets Analysis

Table H-8. Ground-water water budget analysis subregion 8

Subregion 8	Annual Average Water Budget Analysis (taf/yr) Base Case CALVIN	No Overdraft CALVIN	Historical 1980-2009
INFLOW			
1. Precipitation + Irrigation Return Flow	134.1	97.5	227.7
2. Diversion Losses	21.4	23.1	13.8
3. Boundary Inflow	112.8	112.8	122.2
4. Interbasin Inflow	190.7	162.7	191.9
5. Stream Exchange	104.8	96.1	93
6. Subsidence	0.0	0.0	0.03
Total Recharge	***563.8***	***492.1***	***648.5***
7. Subsidence	0.002	0.024	0
Total Discharge	***0.002***	***0.024***	***0***
8. Pumping	581.5	467.8	761.1
Change in Storage ([+] - indicates overdraft volumes)	17.7	-24.4	-112.6

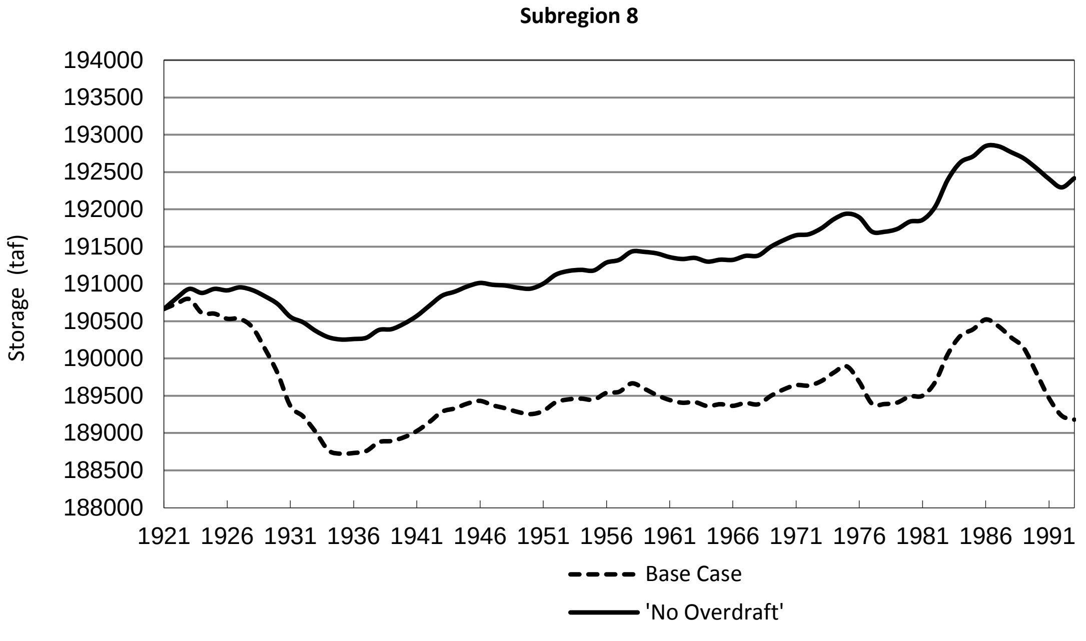


Figure H-15. Effect of ground water development for subregion 8- groundwater storage

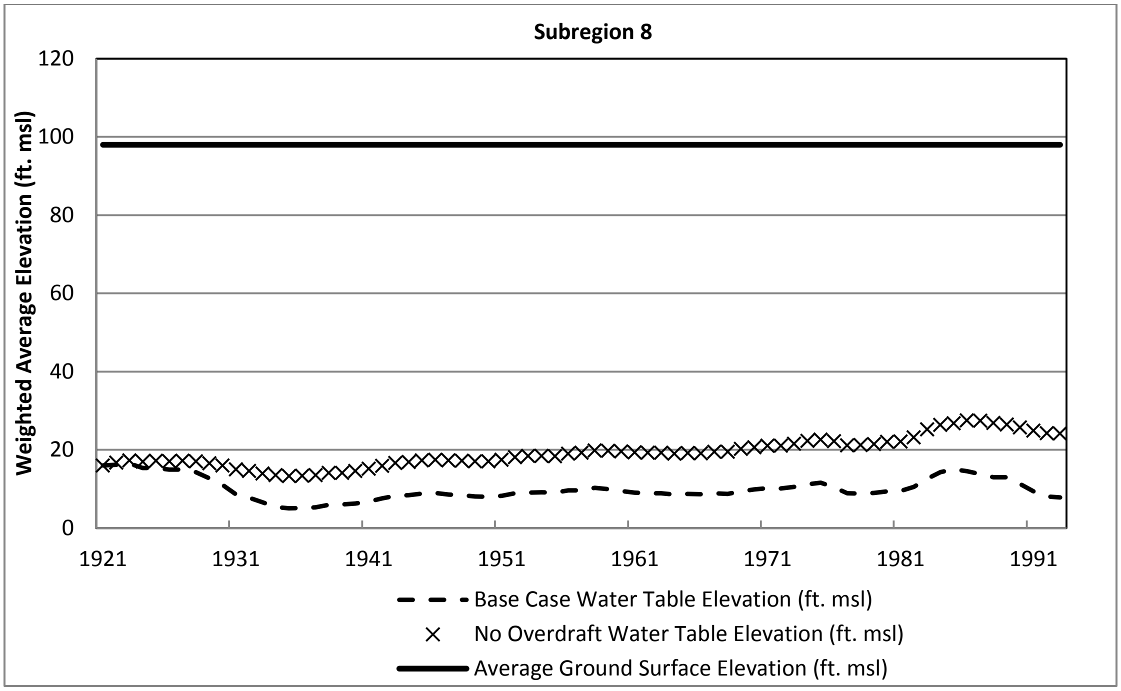


Figure H-16. Effect of ground water development for subregion 8- Water Table Elevations

9. Subregion 9 - Water Budgets Analysis

Table H-9. Ground-water water budget analysis Subregion 9

Subregion 9	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	33.9	32.5	131.2
2. Diversion Losses	49.4	54.1	19.8
3. Boundary Inflow	14.3	14.3	21.1
4. Stream Exchange	136.4	105.8	73.1
5. Subsidence	0.4	0.5	0.01
6. Inter-basin Inflow	0.0	2.9	0
Total Recharge	***234.4***	***210.1***	***245.1***
OUTFLOW			
7. Interbasin Inflow	31.7	0.0	105.2
Total Discharge	***31.7***	***0.0***	***105.2***
8. Pumping	247.7	249.1	134.8

Change in Storage ([+] - indicates overdraft volumes)	45.0	39.0	-5.2

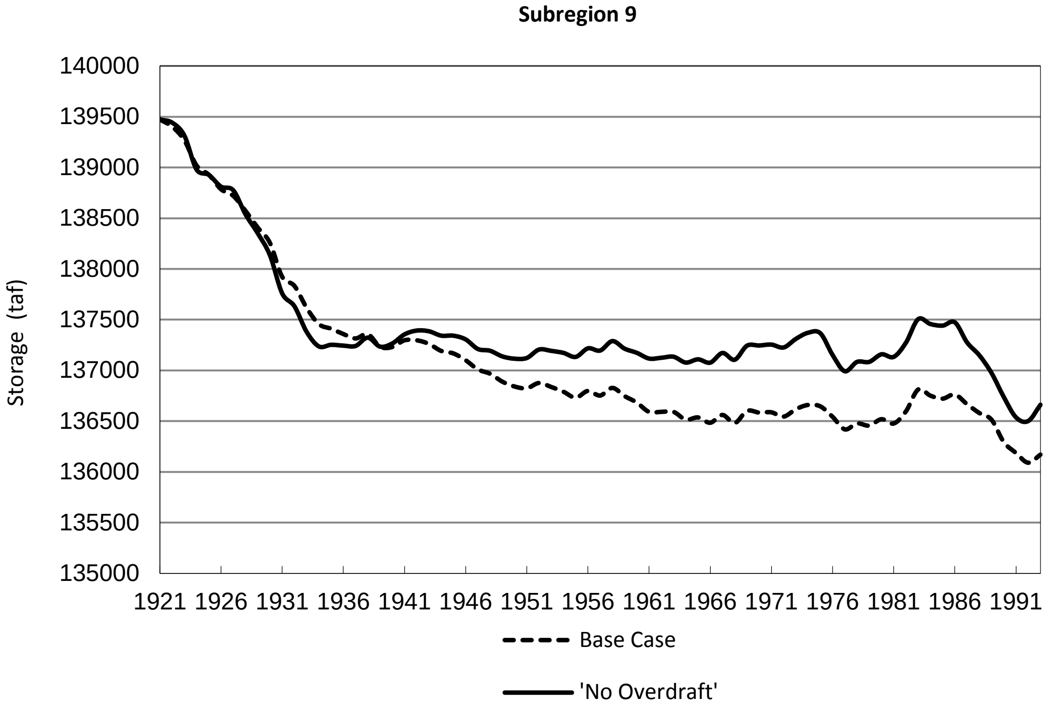


Figure H-17. Effect of ground water development for subregion 9- groundwater storage

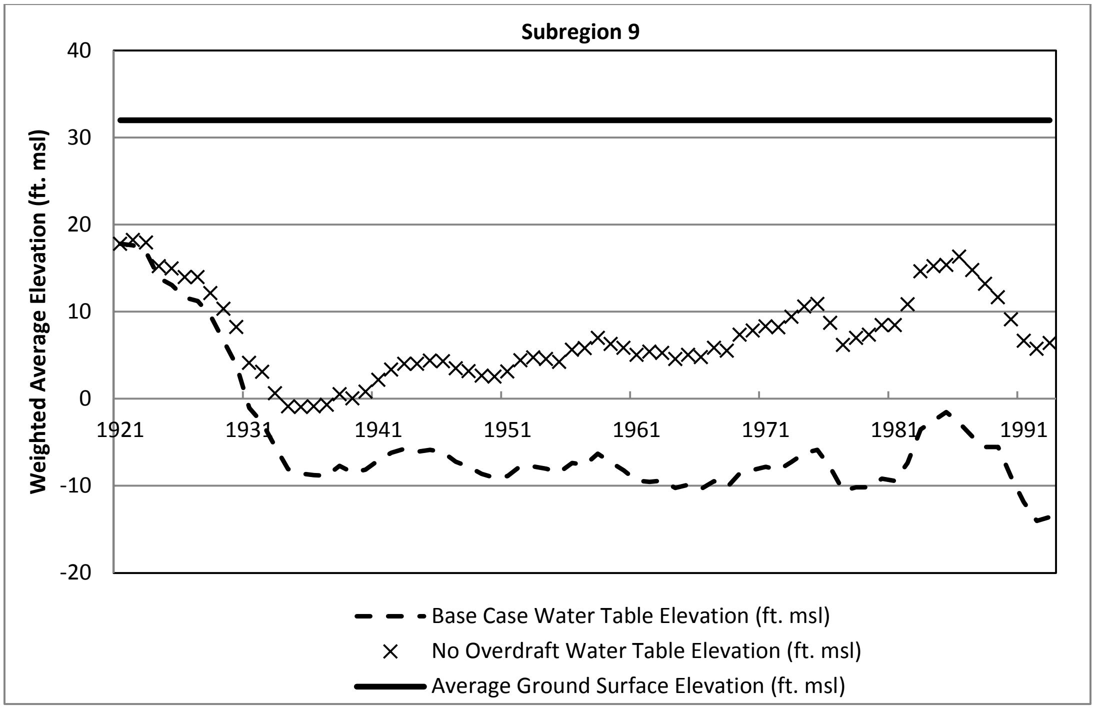


Figure H-18. Effect of ground water development for subregion 9- Water Table Elevations

10. Subregion 10 - Water Budgets Analysis

Table H-10. Ground-water water budget analysis subregion 10

	Annual Average Water Budget Analysis (taf/yr)		
Subregion 10	**Base Case CALVIN**	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	272.9	270.2	300.5
2. Diversion Losses	201.8	218.5	189.9
3. Boundary Inflow	29.1	29.1	34.8
4. Subsidence	26.5	18.9	55.034
Total Recharge	***530.2***	***536.7***	***580.3***
5. Stream Exchange	76.4	93.7	120.6
6. Interbasin Inflow	61.9	65.0	54.2
7. Tile Drain Outflow	16.9	21.5	35.7
Total Discharge	***155.2***	***180.1***	***210.6***
8. Pumping	432.8	388.4	415
Change in Storage ([+] - indicates overdraft volumes)	57.8	31.8	45.3

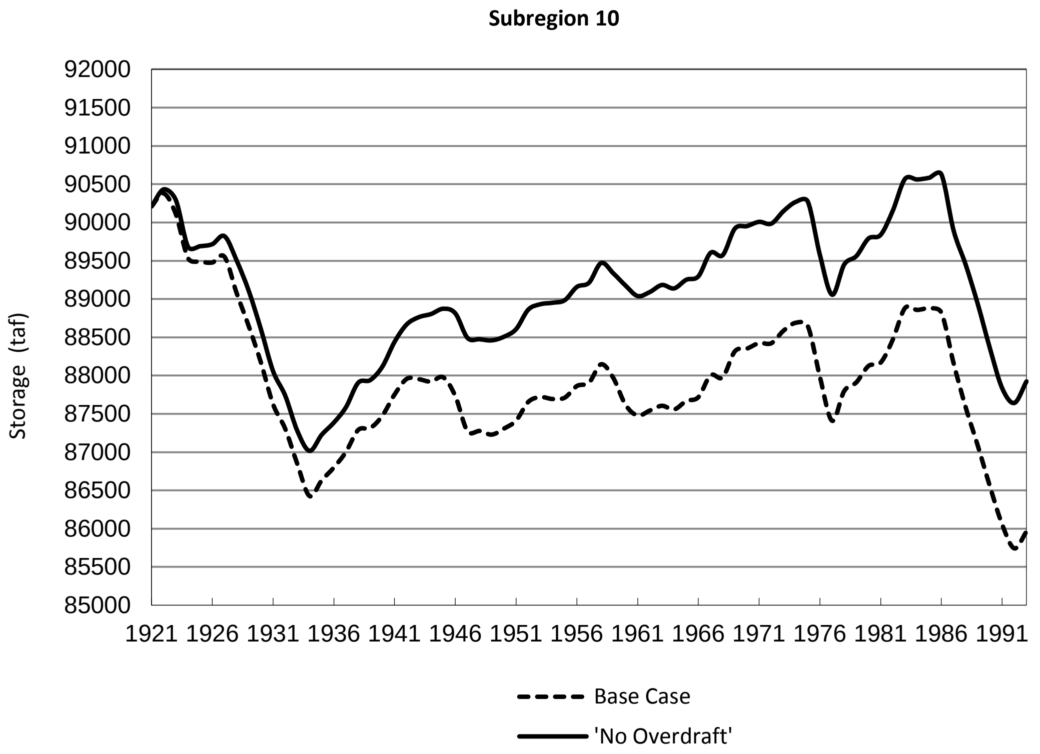


Figure H-19. Effect of ground water development for subregion 10- groundwater storage

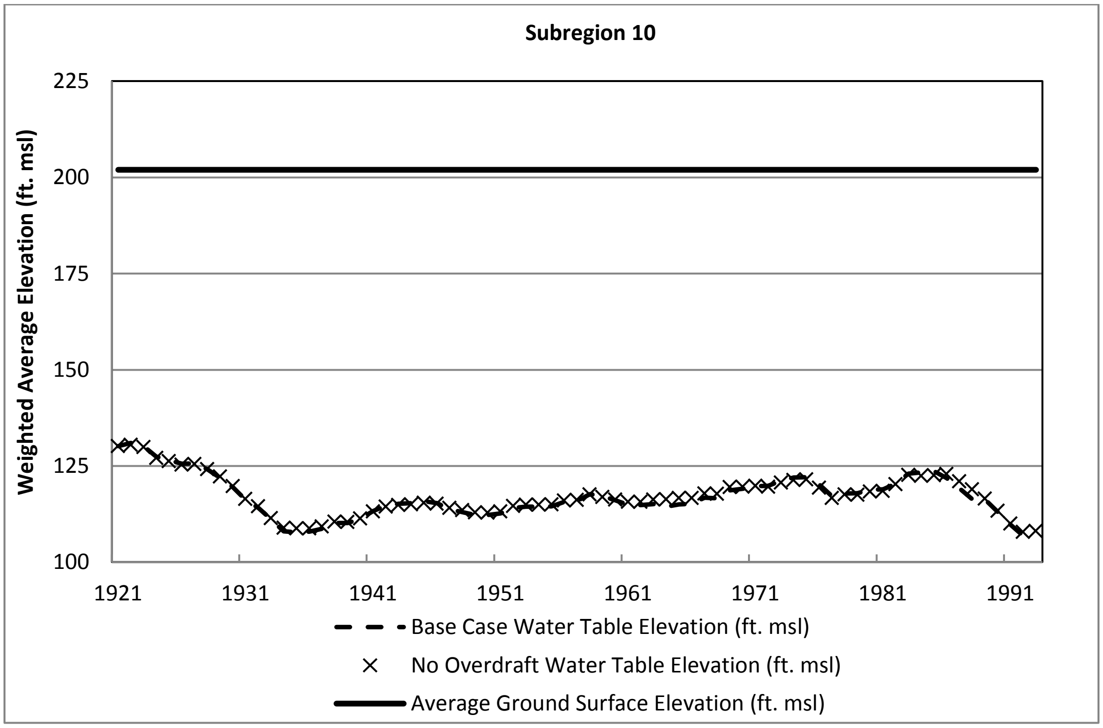


Figure H-20. Effect of ground water development for subregion 10- Water Table Elevations

11. Subregion 11 - Water Budgets Analysis

Table H-11. Ground-water water budget analysis subregion 11

	Annual Average Water Budget Analysis (taf/yr)		
Subregion 11	**Base Case CALVIN**	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	410.2	408.0	218.7
2. Diversion Losses	99.5	101.9	166.5
3. Boundary Inflow	17.9	17.9	18.2
4. Subsidence	0.0	0.0	0.017
Total Recharge	***527.6***	***527.8***	***403.5***
OUTFLOW			
5. Stream Exchange	136.8	159.6	127.6
6. Interbasin Inflow	96.1	80.1	106.5
7. Subsidence	0.000	0.002	0
Total Discharge	***232.9***	***239.7***	***234.1***
7. Pumping	300.2	290.0	177.9
Change in Storage ([+] - indicates overdraft volumes)	5.6	2.0	8.5

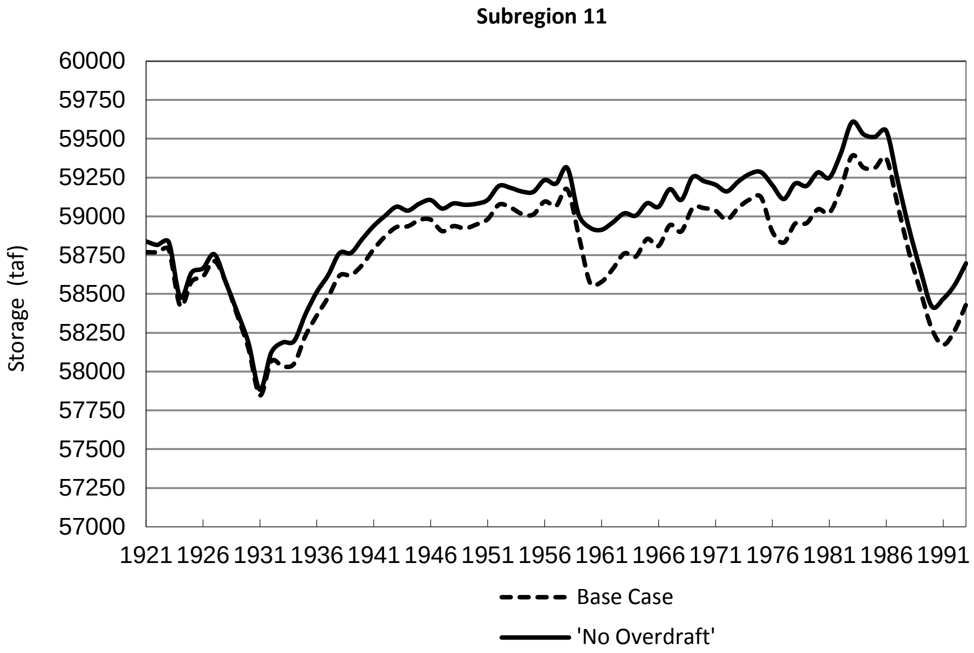


Figure H-21. Effect of ground water development for subregion 11- groundwater storage

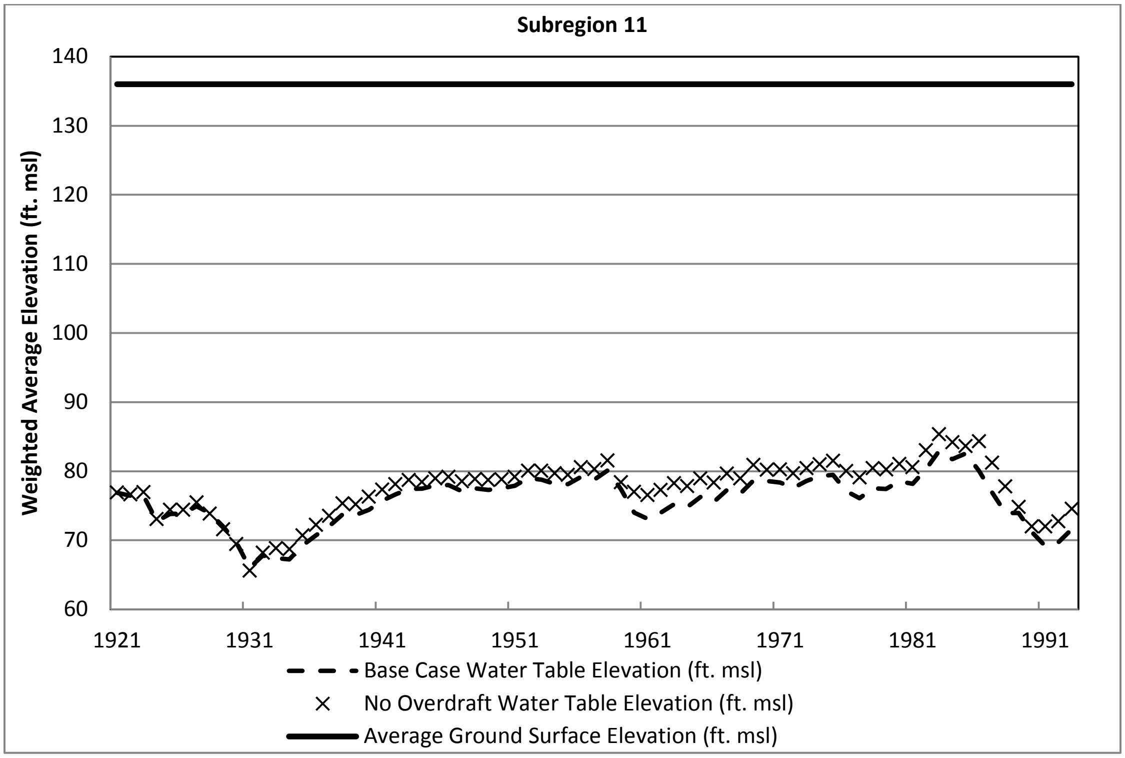


Figure H-22. Effect of ground water development for subregion 11- Water Table Elevations

12. Subregion 12 - Water Budgets Analysis

Table H-12. Ground-water water budget analysis subregion 12

Subregion 12	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	331.5	328.5	143.5
2. Diversion Losses	128.4	132.4	137.2
3. Boundary Inflow	2.5	2.5	2.5
4. Subsidence	0.0	0.0	0.033
5. Inter-basin Inflow	0.0	0.0	5.107
Total Recharge	***462.4***	***463.4***	***288.4***
OUTFLOW			
6. Stream Exchange	96.0	109.8	108.2
7. Inter-basin Inflow	89.6	95.1	0
8. Subsidence	0.003	0.003	0
Total Discharge	***185.6***	***204.9***	***108.2***
9. Pumping	282.4	257.7	205.1
Change in Storage ([+] - indicates overdraft volumes)	5.5	-0.7	25

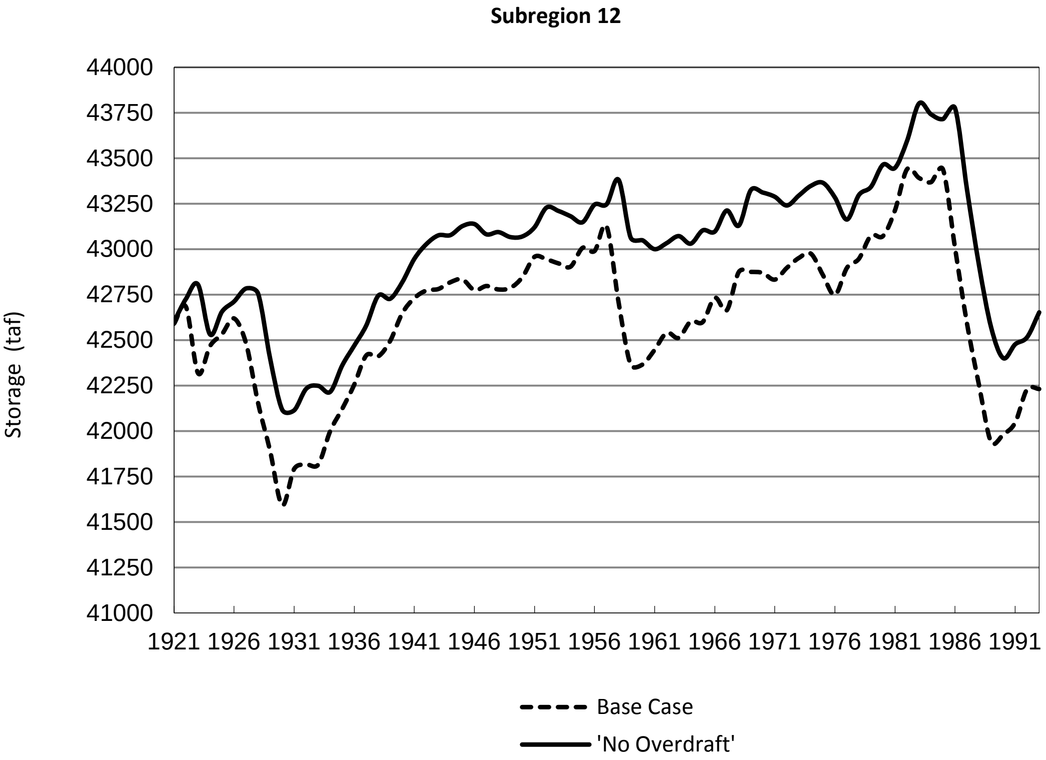


Figure H-23. Effect of ground water development for subregion 12- groundwater storage

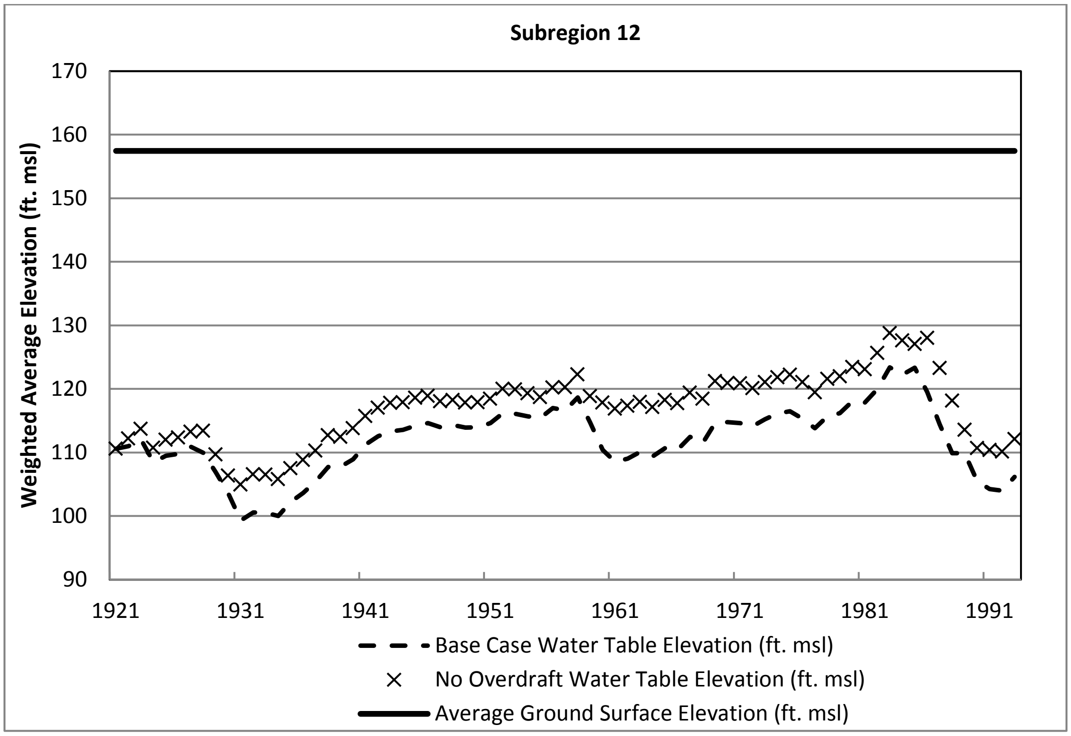


Figure H-24. Effect of ground water development for subregion 12- Water Table Elevations

13. Subregion 13 - Water Budgets Analysis

Table H-13. Ground-water water budget analysis subregion 13

Subregion 13	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	No Overdraft CALVIN	Historical 1980-2009
INFLOW			
1. Precipitation + Irrigation Return Flow	231.7	197.1	362.9
2. Diversion Losses + Artificial Recharge	117.4	128.6	156.3
3. Boundary Inflow	13.4	13.4	14.4
4. Subsidence	8.8	4.9	11.3
5. Inter-basin Inflow	216.7	215.8	93.7
6. Stream Exchange	56.5	33.3	11.5
Total Recharge	***644.4***	***593.1***	***638.7***
Total Discharge	***0.0***	***0.0***	***0***
7. Pumping	791.3	686.8	788.9
Change in Storage ([+] - indicates overdraft volumes)	146.9	93.7	150.2

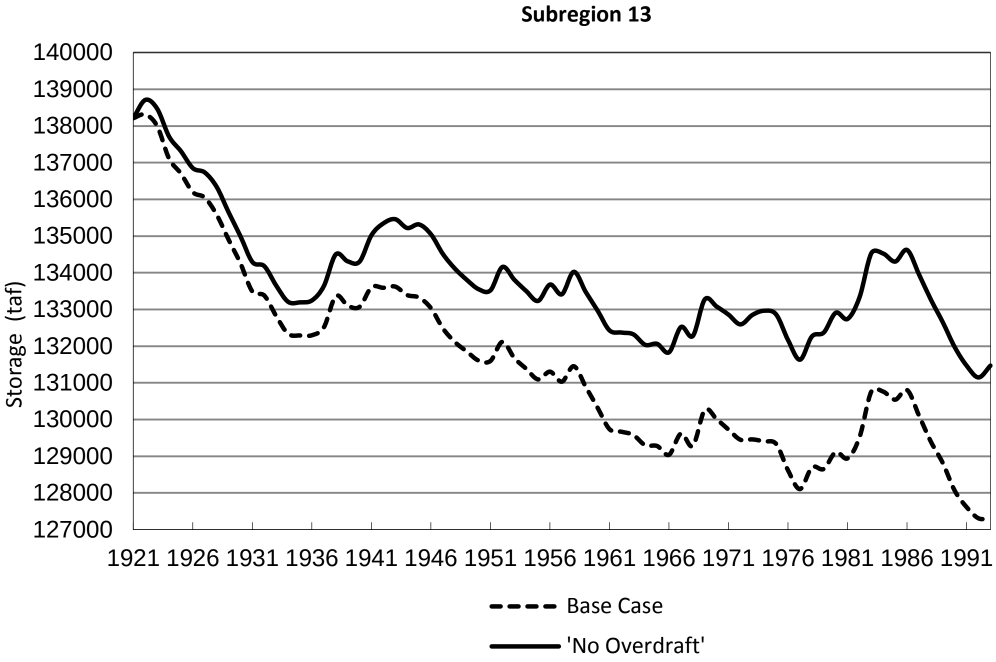


Figure H-25. Effect of ground water development for subregion 13- groundwater storage

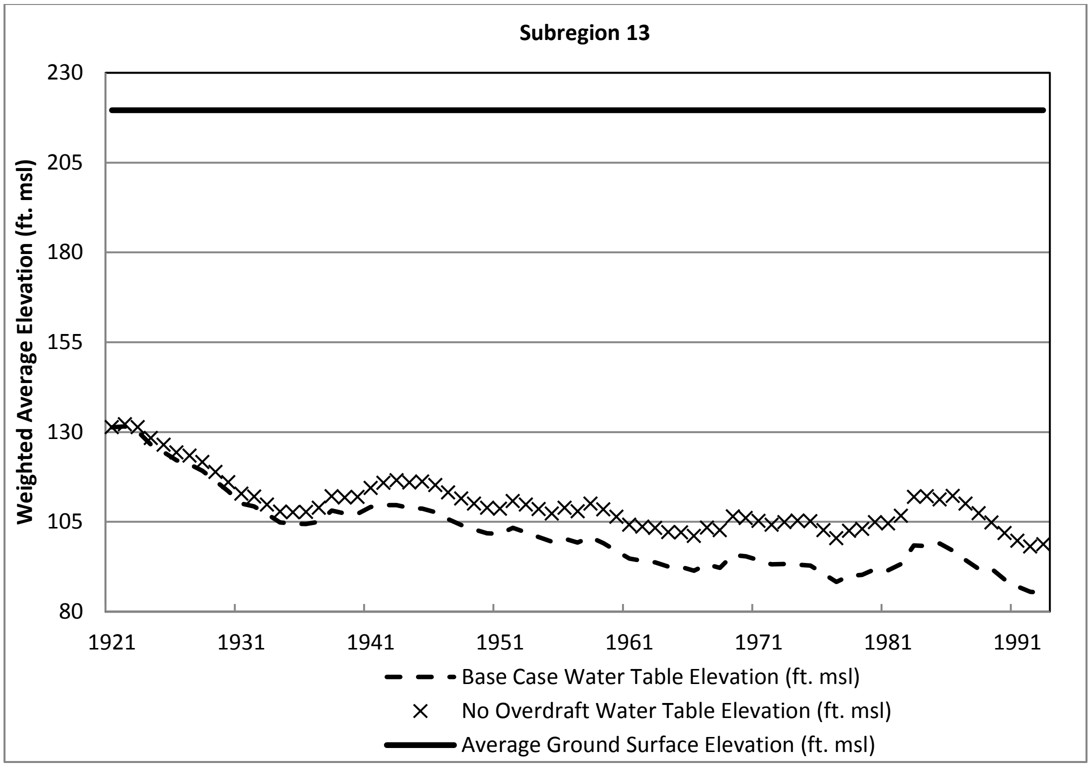


Figure H-26. Effect of ground water development for subregion 13- Water Table Elevations

14. Subregion 14 - Water Budgets Analysis

Table H-14. Ground-water water budget analysis subregion 14

	Annual Average Water Budget Analysis (taf/yr)		
Subregion 14	**Base Case CALVIN**	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	51.3	50.5	145.2
2. Diversion Losses	345.2	413.6	99.9
3. Boundary Inflow	19.6	19.6	29.7
4. Subsidence	36.1	31.5	1.4
5. Inter-basin Inflow	165.3	99.1	120.9
6. Stream Exchange	0.0	0.0	0
Total Recharge	***617.5***	***614.4***	***397***
Total Discharge	***0.0***	***0.0***	***0***
7. Pumping	593.0	498.2	515.6
Change in Storage ([+] - indicates overdraft volumes)	-24.5	-116.2	118.6

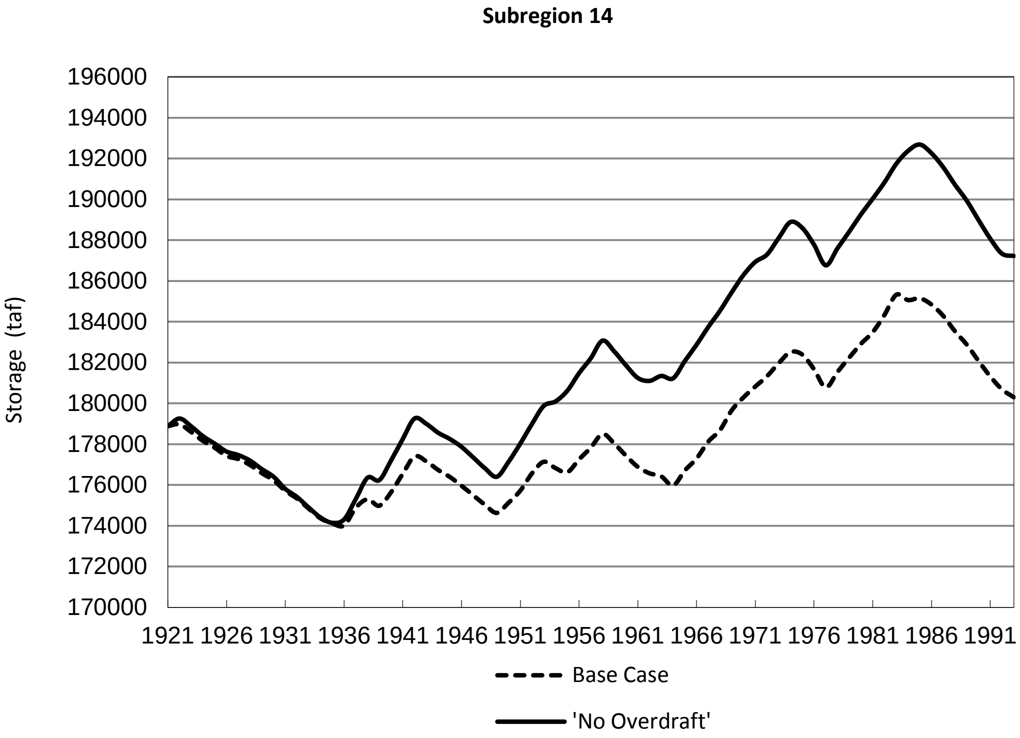


Figure H-27. Effect of ground water development for subregion 14- groundwater storage

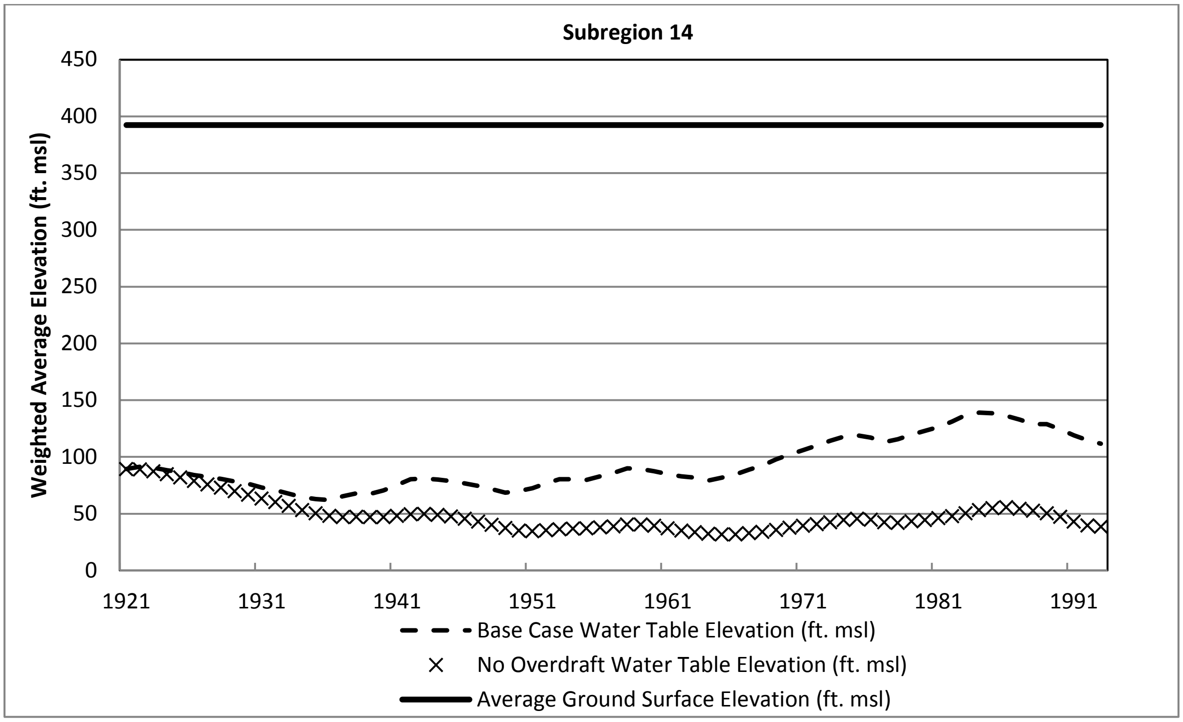


Figure H-28. Effect of ground water development for subregion 14 - Water Table Elevations

15. Subregion 15 - Water Budgets Analysis

Table H-15 Ground-water water budget analysis Subregion 15

Subregion 15	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	216.6	211.3	335.8
2. Diversion Losses + Artificial Recharge	856.1	836.3	627.6
3. Boundary Inflow	3.8	3.8	4.5
4. Subsidence	37.5	36.8	31.6
5. Inter-basin Inflow	164.0	210.2	263.2
Total Recharge	***1278.0***	***1298.5***	***1262.7***
OUTFLOW			
6. Lake Exchange	73.0	63.2	30.9
7. Stream Exchange	148.1	162.6	104.1
Total Discharge	***221.1***	***225.8***	***135***
8. Pumping	1049.5	1045.7	1170.5
Change in Storage ([+] - indicates overdraft volumes)	-7.3	-27.0	42.8

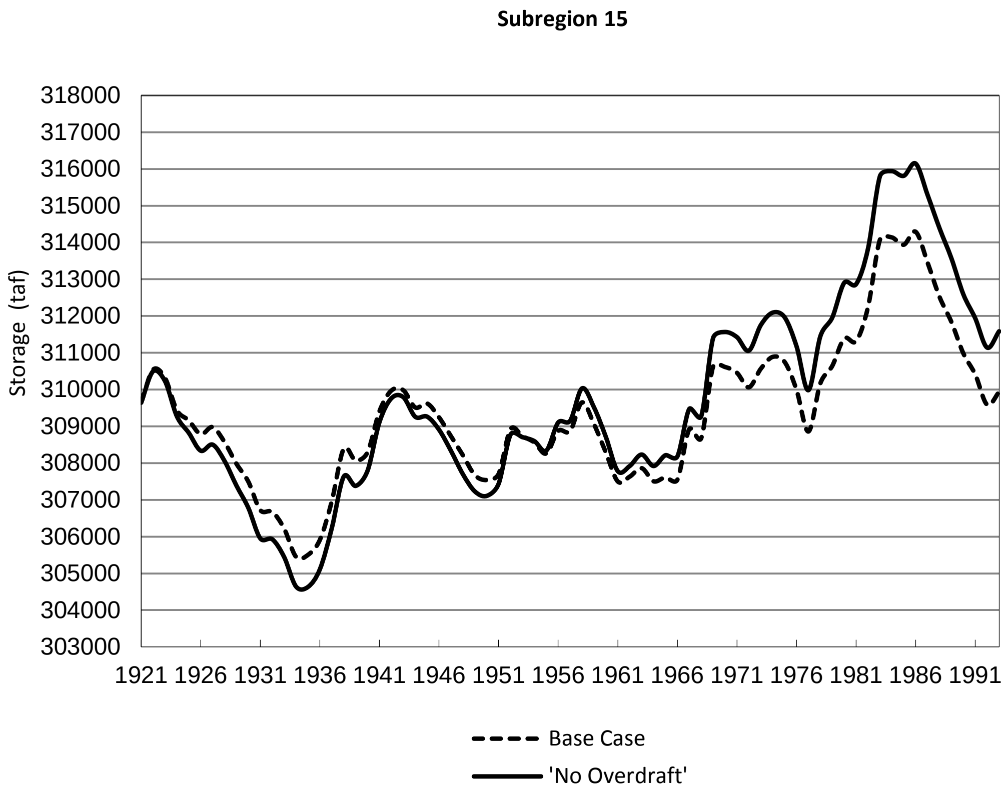


Figure H-29. Effect of ground water development for subregion 15 – groundwater storage

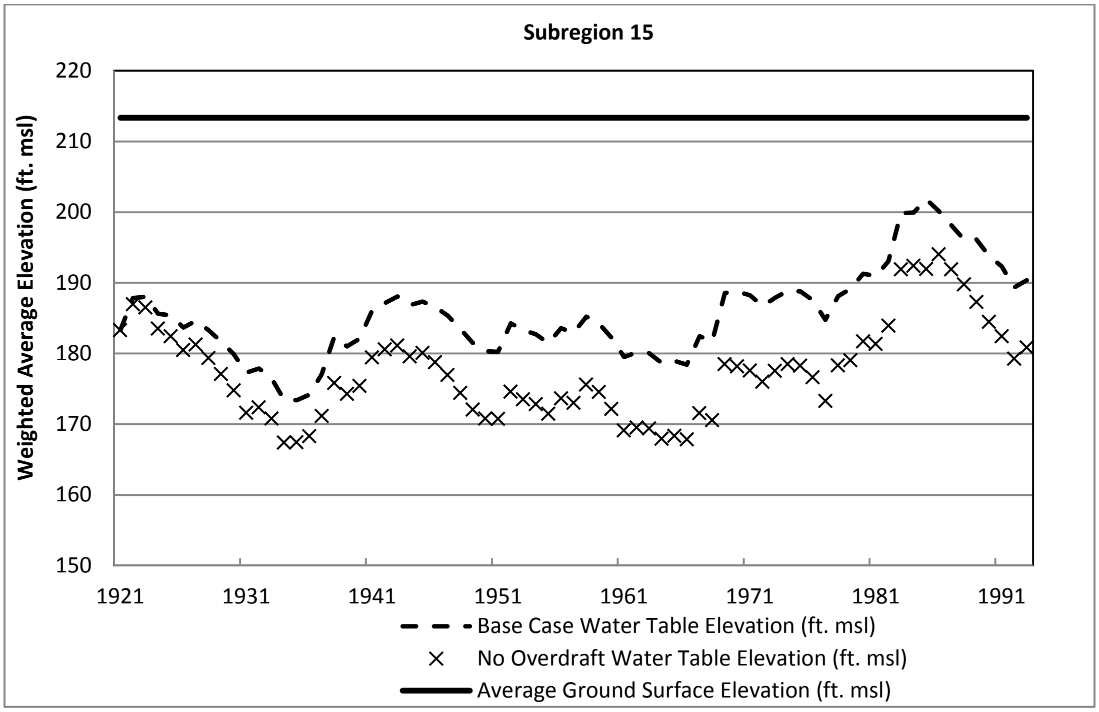


Figure H-30. Effect of ground water development for subregion 15 - Water Table Elevations

16. Subregion 16 - Water Budgets Analysis

Table H-16. Ground-water water budget analysis subregion 16

Subregion 16	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	301.9	322.3	229.8
2. Diversion Losses + Artificial Recharge	167.6	216.9	97.6
3. Boundary Inflow	8.0	8.0	10.6
4. Subsidence	0.0	0.0	0.1
5. Stream Exchange	0.0	0.0	15.0
Total Recharge	***477.5***	***547.2***	***353.1***
OUTFLOW			
6. Inter-basin Inflow	315.7	323.6	171.6
7. Stream Exchange	27.3	37.4	0.0
8. Subsidence	0.1	0.1	0.0
Total Discharge	***343.1***	***361.1***	***171.6***
9. Pumping	138.3	137.2	185.2
Change in Storage ([+] - indicates overdraft volumes)	3.9	-49.0	3.7

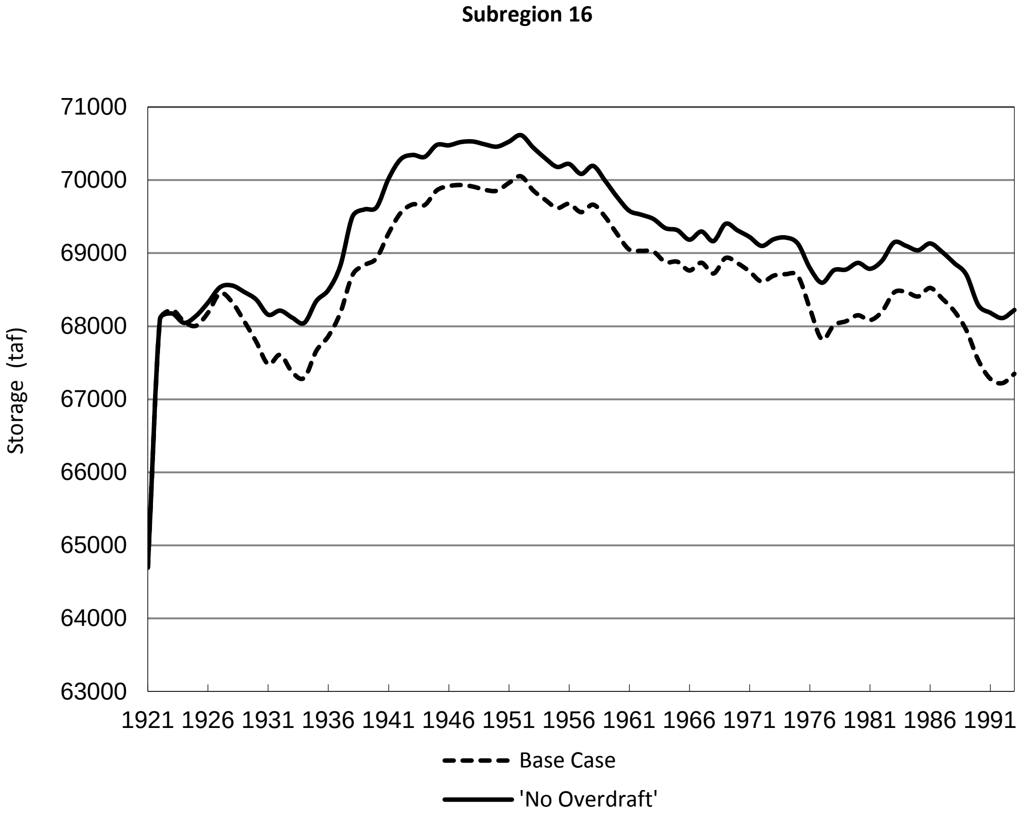


Figure H-31. Effect of ground water development for subregion 16 – groundwater storage

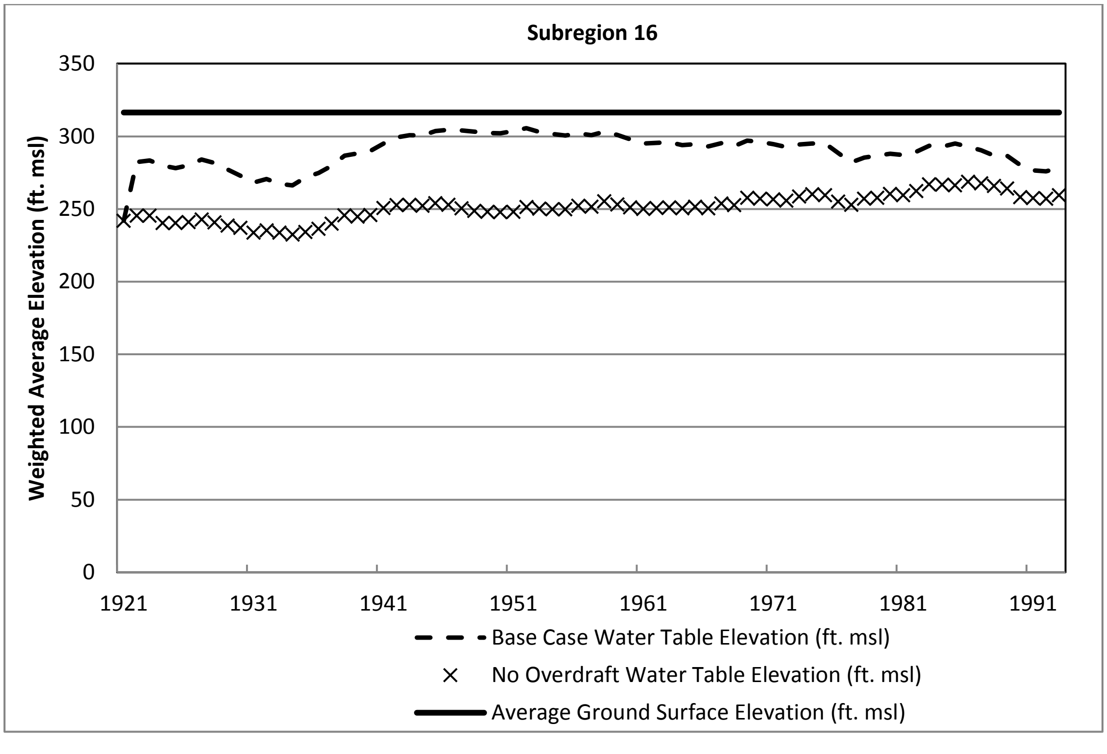


Figure H-32. Effect of ground water development for subregion 16 - Water Table Elevations

17. Subregion 17 - Water Budgets Analysis

Table H-17. Ground-water water budget analysis subregion 17

	Annual Average Water Budget Analysis (taf/yr)		
Subregion 17	**Base Case CALVIN**	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	149.2	143.0	228.1
2. Diversion Losses + Artificial Recharge	78.3	94.6	101.7
3. Boundary Inflow	4.1	4.1	6.1
4. Subsidence	0.0	0.0	0.1
5. Stream Exchange	0.0	0.0	0
6. Inter-basin Inflow	105.0	95.3	4.4
Total Recharge	***336.7***	***337.0***	***336***
OUTFLOW			
7. Stream Exchange	0.4	4.3	8.5
8. Subsidence	0.0	0.1	0
Total Discharge	***0.4***	***4.4***	***8.5***
9. Pumping	356.1	341.4	383
Change in Storage ([+] - indicates overdraft volumes)	19.0	8.8	55.5

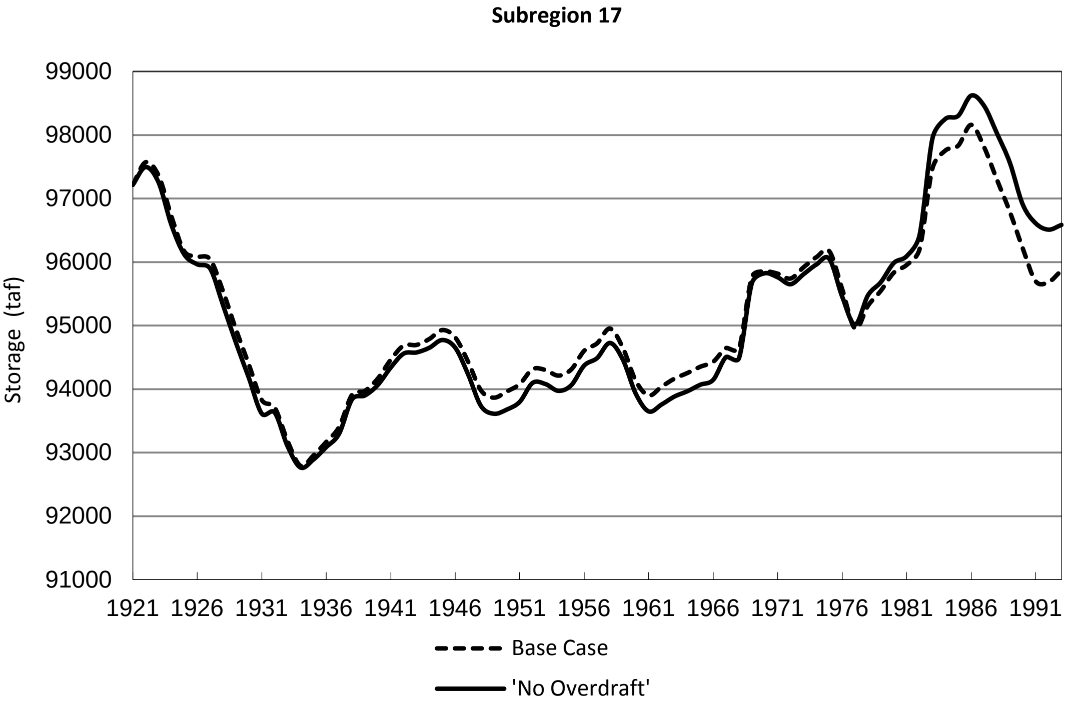


Figure H-33. Effect of ground water development for subregion 17 – groundwater storage

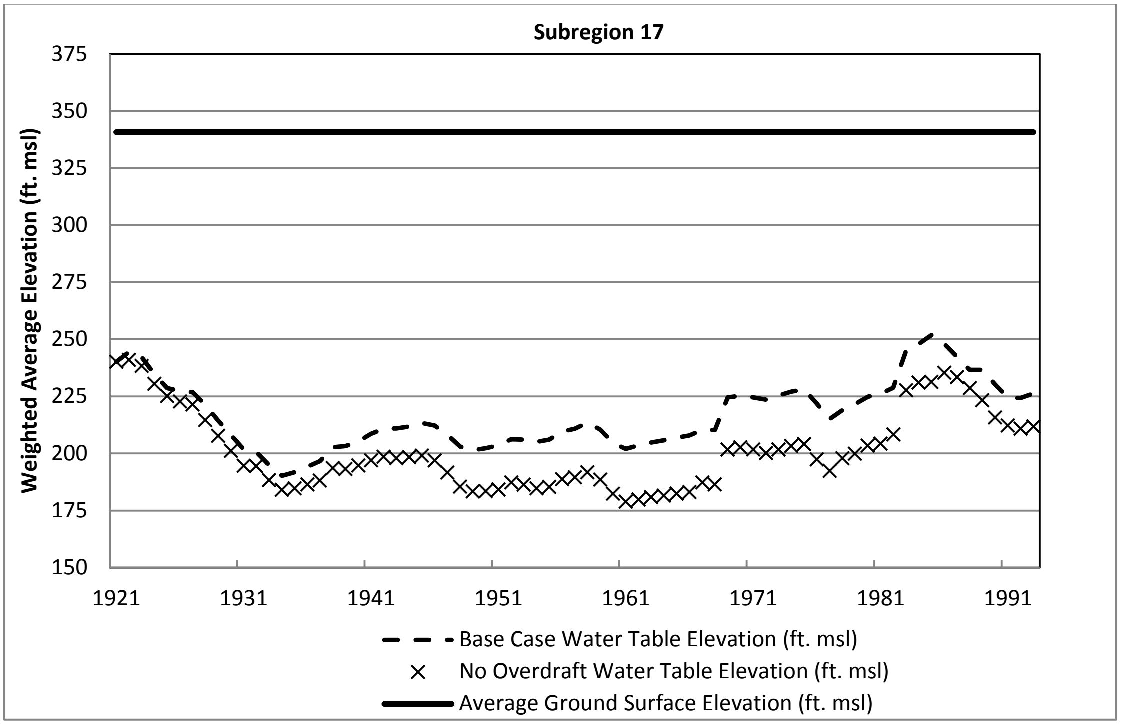


Figure H-34. Effect of ground water development for subregion 17 - Water Table Elevations

18. Subregion 18 - Water Budgets Analysis

Table H-18. Ground-water water budget analysis Subregion 18

Subregion 18	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	No Overdraft CALVIN	Historical 1980-2009
INFLOW			
1. Precipitation + Irrigation Return Flow	812.3	708.1	354.6
2. Diversion Losses + Artificial Recharge	1012.6	836.0	510.5
3. Boundary Inflow	23.4	23.4	26.6
4. Subsidence	42.7	42.8	24.5
Total Recharge	***1891.0***	***1610.3***	***916.2***
OUTFLOW			
5. Stream Exchange	442.9	276.8	135.1
6. Inter-basin Inflow	377.1	284.5	294.5
Total Discharge	***820.0***	***561.3***	***429.6***
7. Pumping	1020.8	985.3	484.6
Change in Storage ([+] - indicates overdraft volumes)	-50.2	-63.7	-1.9

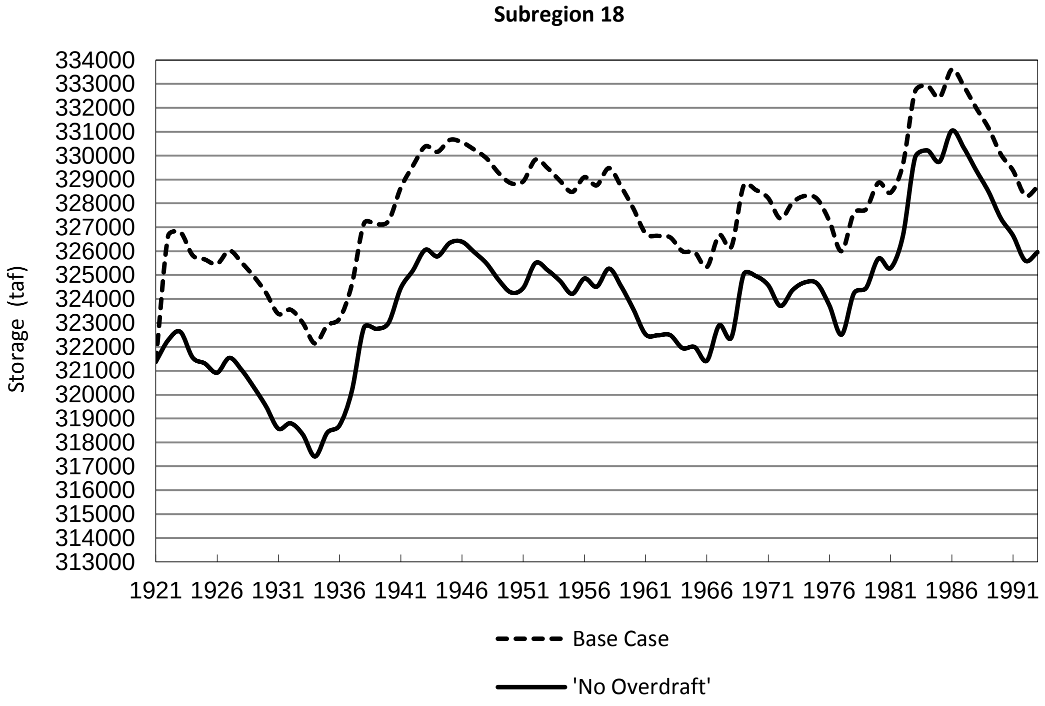


Figure H-35. Effect of ground water development for subregion 18 – groundwater storage

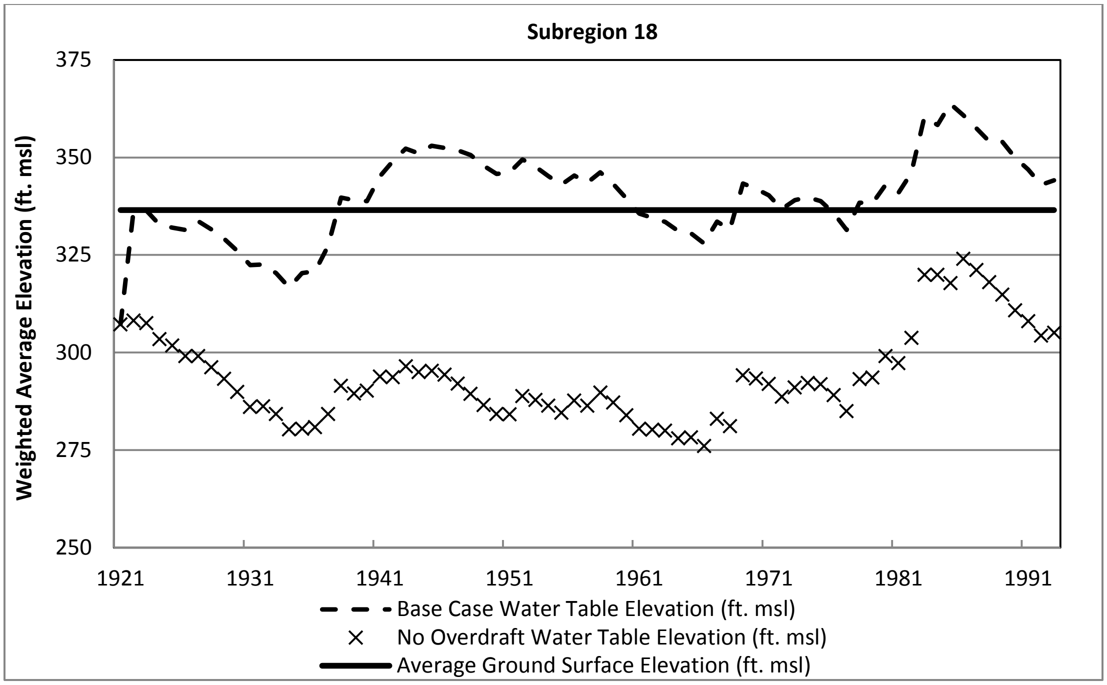


Figure H-36. Effect of ground water development for subregion 18 - Water Table Elevations

19. Subregion 19 - Water Budgets Analysis

Table H-19. Ground-water water budget analysis subregion 19

	Annual Average Water Budget Analysis (taf/yr)		
Subregion 19	**Base Case CALVIN**	**No Overdraft CALVIN**	**Historical 1980-2009**
INFLOW			
1. Precipitation + Irrigation Return Flow	39.7	39.9	51.8
2. Diversion Losses + Artificial Recharge	135.1	178.5	420.1
3. Boundary Inflow	4.1	4.1	4.8
4. Subsidence	50.4	15.8	37.0
5. Stream Exchange	36.2	29.5	0.0
6. Inter-basin Inflow	188.8	152.1	76.4
Total Recharge	***454.2***	***419.9***	***590.1***
OUTFLOW			
7. Stream Exchange	0.0	0.0	85.8
Total Discharge	***0.0***	***0.0***	***85.8***
8. Pumping	653.8	467.9	698.6

Change in Storage ([+] - indicates overdraft volumes)	199.6	48.0	194.3

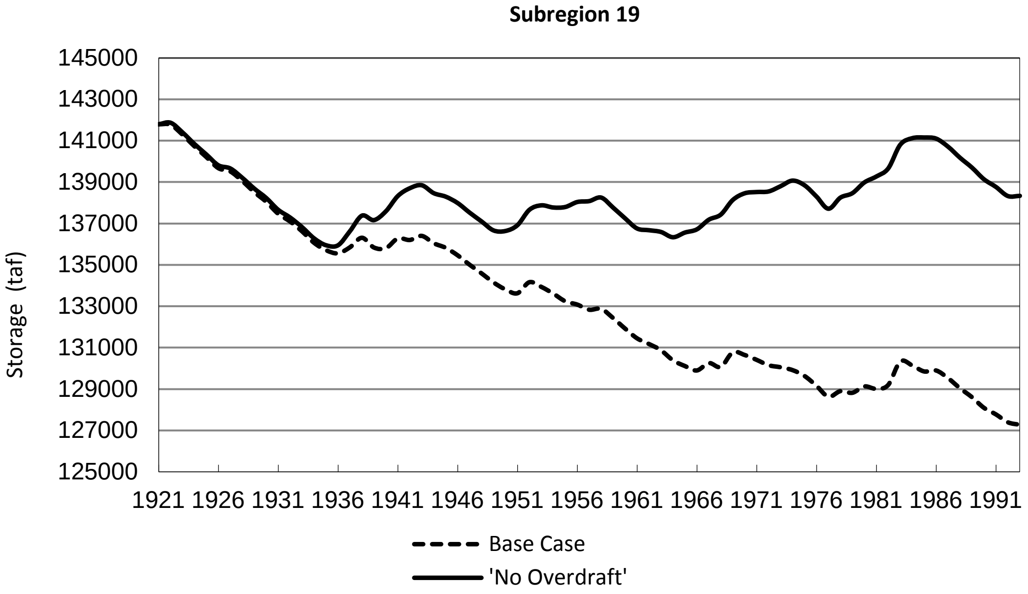


Figure H-37. Effect of ground water development for subregion 19 – groundwater storage

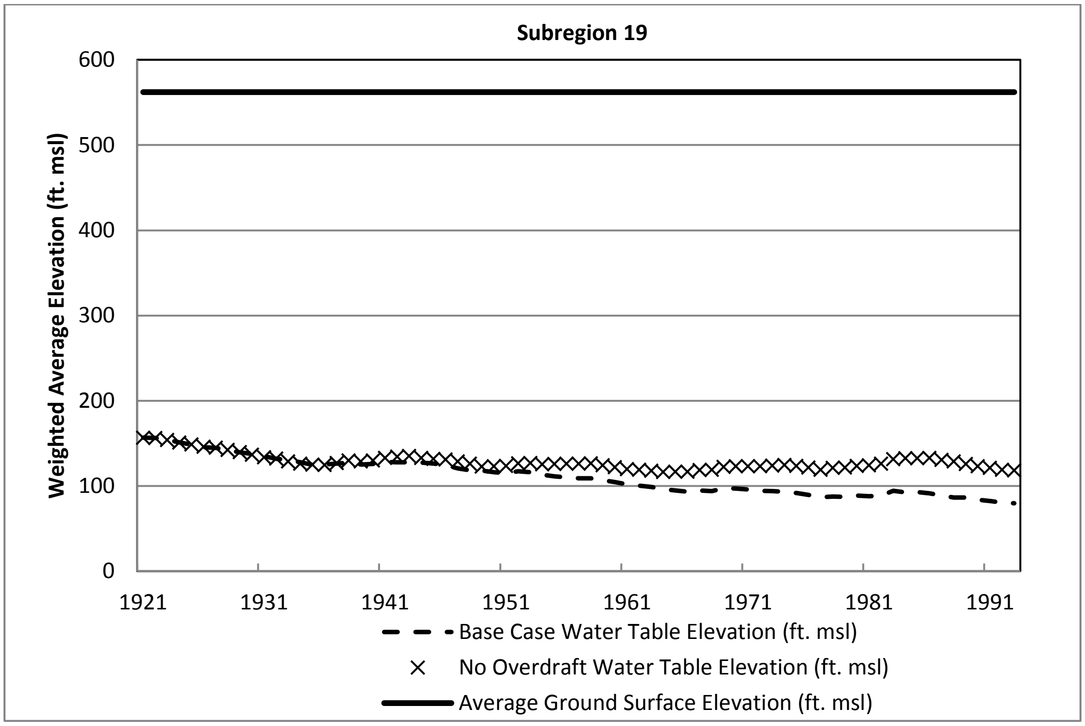


Figure H-38. Effect of ground water development for subregion 19 - Water Table Elevations

20. Subregion 20 - Water Budgets Analysis

Table H-20. Ground-water water budget analysis subregion 20

Subregion 20	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	No Overdraft CALVIN	Historical 1980-2009
INFLOW			
1. Precipitation + Irrigatio Return Flow	176.8	175.5	81.7
2. Diversion Losses + Artificial Recharge	75.4	108.4	104.3
3. Boundary Inflow	49.4	49.4	60.0
4. Subsidence	17.0	0.0	53.8
5. Stream Exchange	24.1	23.9	27.7
Total Recharge	***342.7***	***357.2***	***327.5***
OUTFLOW			
6. Inter-basin Inflow	30.7	117.0	79.6
7. Subsidence	0.0	1.1	0.0
Total Discharge	**30.7**	**118.1**	**79.6**
8. Pumping	346.5	181.0	469.3
Change in Storage ([+] - indicates overdraft volumes)	34.5	-58.1	221.4

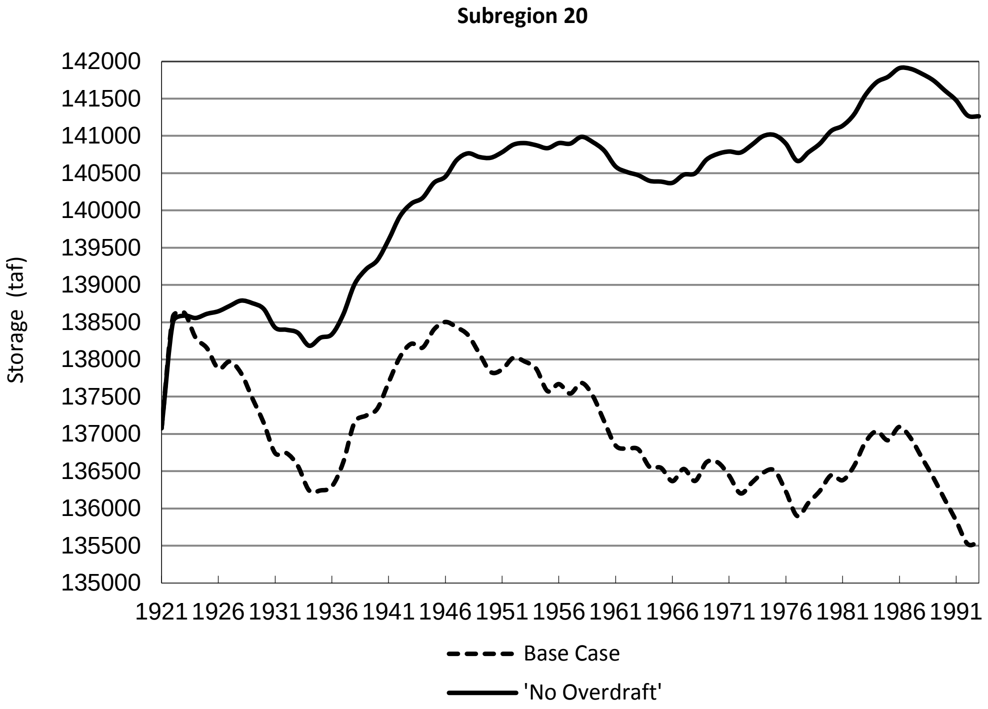


Figure H-39. Effect of ground water development for subregion 20 – groundwater storage

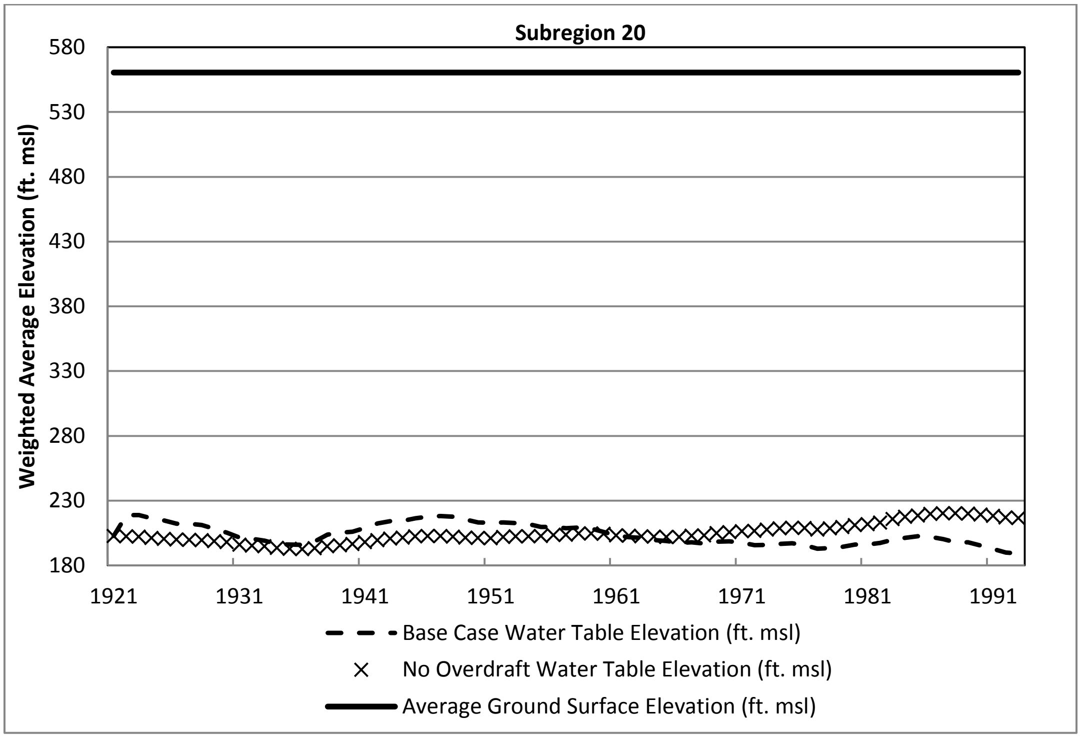


Figure H-40. Effect of ground water development for subregion 20 - Water Table Elevations

21. Subregion 21 - Water Budgets Analysis

Table H-21. Ground-water water budget analysis subregion 21

Subregion 21	Annual Average Water Budget Analysis (taf/yr)		
	Base Case CALVIN	No Overdraft CALVIN	Historical 1980-2009
INFLOW			
1. Precipitation + Irrigation Return Flow	185.4	185.3	92.4
2. Diversion Losses + Artificial Recharge	52.8	65.1	256.1
3. Boundary Inflow	55.3	55.3	78.0
4. Subsidence	0.0	0.2	20.1
5. Stream Exchange	139.3	131.8	115.2
6. Lake Exchange	1.0	1.0	1.6
7. Inter-basin Inflow	0.0	52.3	60.9
Total Recharge	***433.8***	***490.9***	***561.8***
OUTFLOW			
8. Inter-basin Inflow	8.8	0.0	0.0
Total Discharge	***8.8***	***0.0***	***0.0***
9. Pumping	348.1	445.2	1025.2
Change in Storage ([+] - indicates overdraft volumes)	-76.9	-45.7	463.4

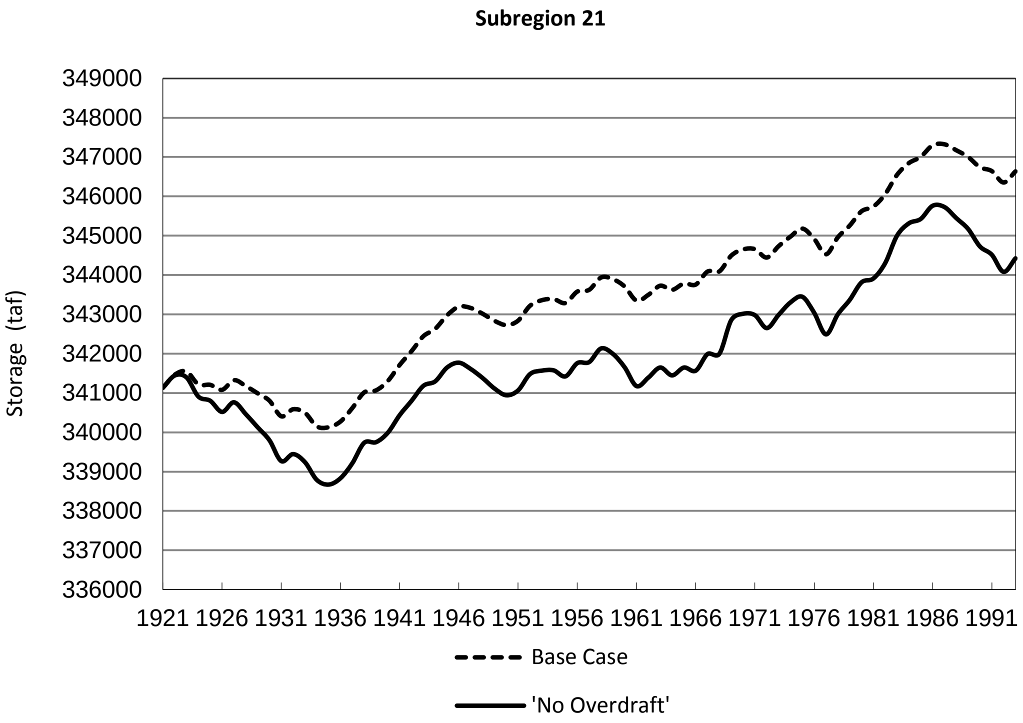


Figure H-41. Effect of ground water development for subregion 21 – groundwater storage

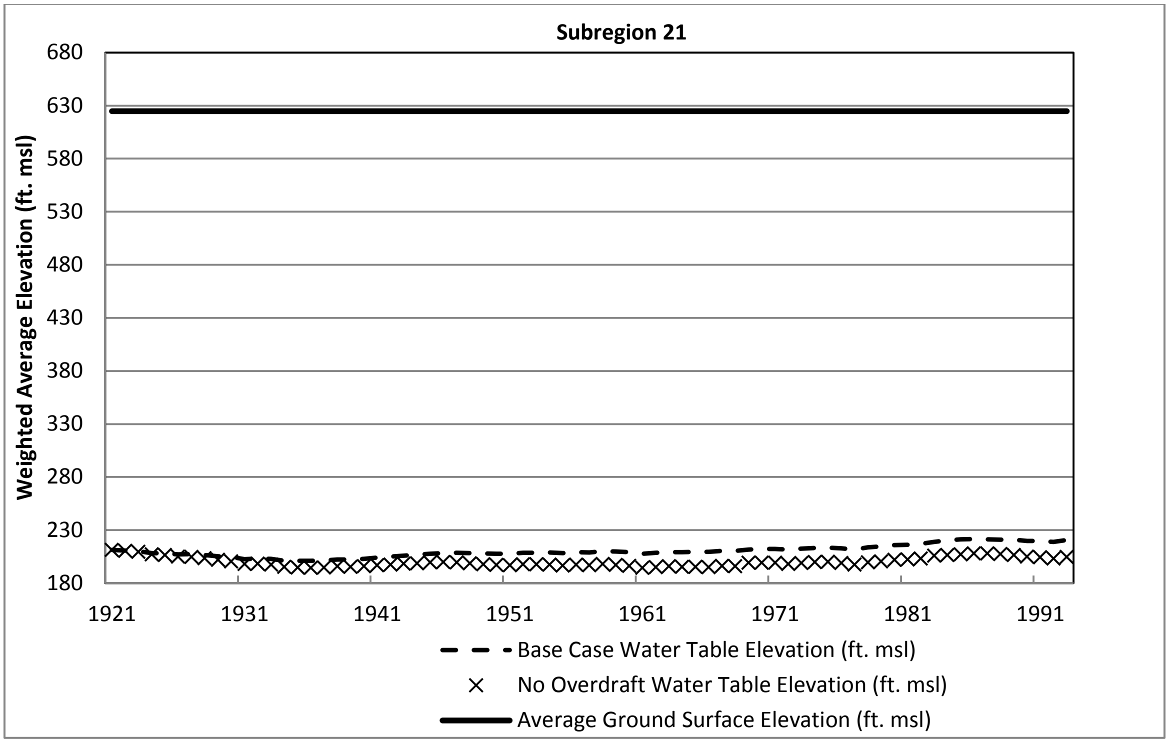


Figure H-42. Effect of ground water development for subregion 21 - Water Table Elevations