DROUGHT ANALYSES OF THE CALIFONIA CENTRAL VALLEY SURFACE-GROUNDWATER-CONVEYANCE SYSTEM

PIER PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Drought analysis of the California Central Valley surface-groundwater-conveyance system is the final report for the project, Development and Application of a California Basin Water-Energy Model (contract number 500-02-004, work authorization number MR-05-05A) conducted by Lawrence Berkeley National Laboratory and the University of California, Berkeley in collaboration with the California DEpartment of Water Resources.

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Abstract

A series of drought simulations were performed using the California Department of Water Resources codes and historical datasets representing a range of droughts from mild to severe for time periods lasting up to 60 years. Land use, agricultural cropping patterns, and water demand were held fixed at the 1973-2003 mean and water supply decreased by *effective* amounts ranging between 25 and 50 percent for the Central Valley, representing light to severe drought types. An examination of the impacts include four sub-basins, the Sacramento Basin, the San Joaquin Basin, the Tulare Basin, and the Eastside Drainage. Model output results suggest the greatest impacts are at the San Joaquin and Tulare Basins, regions that are heavily irrigated. Surface diversions decrease by as much as 42 percent in these regions. Stream-to-aquifer flows reversed and aquifer storage dropped. Most significant was the decline in groundwater head for the severe drought cases, where results suggest the water table is unlikely to recovery within the foreseeable future. However, the overall response to such droughts is not as severe as anticipated and the northern Central Valley may act as groundwater insurance to sustain California during extended dry periods.

Keyword: California, surface-groundwater model, drought scenarios

Executive Summary

Introduction

During the last 150 years, California has been in a slightly above average wet regime, with at least 11 short-duration drought periods. At the same time, California Central Valley agriculture has expanded over most of the Valley floor, and includes a system of managed irrigation and water conveyance that assumes climatically stationary conditions for model development and planning. The 1929-1934 drought has traditionally been the benchmark event used for designing storage capacity and yield of large California reservoirs. However, the California Department of Water Resources (CDWR) and other water agencies have begun to evaluate new approaches for managing water resources in response to the changing climate (CDWR 2006).

Purpose

The purpose of this study is to perform a series of exercises on the CDWR Integrated Water Flow Model (IWFM) under a range of changes in water delivery. These new studies provide insight into water availability outcomes during stress periods, and provide model evaluations with observations.

Project Objectives

The objectives of this study are to quantify the impacts of long-term droughts - an analogue for climate change related snowpack reduction - on water storage and to illustrate the potential for surface and subsurface storage to limit the adverse impacts of drought and snowpack reduction on water supply. This includes how groundwater pumping compensates for reductions in surface inflow, the extent in which the water table is reduced, and how, when, and if this system recovers or reaches a new equilibrium. In the next section, we provide details on our approach for simulating persistent droughts in the California Central Valley.

Project Outcomes

Model output results suggest the greatest impacts are at the San Joaquin and Tulare Basins, regions that are heavily irrigated. Surface diversions decrease by as much as 42 percent in these regions. Stream-to-aquifer flows are reversed and aquifer storage drops. Most significant is the decline in groundwater head for the severe drought cases, where results suggest the water table is unlikely to recovery within the foreseeable future. However, the overall response to such droughts is not as severe as anticipated and the northern Central Valley aquifer in particular may provide a form of drought insurance during extended dry periods.

Conclusions

Global warming and long-term drought is likely to deplete aquifers, increase electricity demand (cooling and pumping) and decrease hydropower generation. This study is intended to illustrate the impacts of climatic events on water storage, and suggests water management techniques to counter some of these adverse impacts. C2VSIM and all water allocation models are only partially verified. Many empirical parameters are tuned. Total groundwater pumping is not known and groundwater processes lack sufficient physical descriptions. Pumping is based on a limited available demand record. Demand is fixed and agriculture does not shift with change in supply.

1.0 Introduction

The western United States has experienced periods of long drought conditions since the last glacial epoch 11,000 years ago. The period between 900 and 1400 A.D. was a time when severe long duration droughts occurred in the western U.S. This Medieval mega-drought period was followed by a less severe drought period that was coincident with the Little Ice Age cooling period. Samples from sediments, tree rings, and tree stumps, combined with isotope dating analysis have been used to reconstruct these naturally occurring droughts that lasted 50 to more than 100 years (Stine 1994; Herweijer et al. 2006; Cook et al 2007). Indeed, two epic drought periods; one lasting from approximately 900 to 1100, and the second lasting from about 1200 to 1350, contributed to the decline and disappearance of the Anasazi people, a culture that relied on irrigated agriculture to support its population. Drought is also seen as a contributing factor in the failure of European colonies in South Carolina and North Carolina in the 1500s.

During the last 150 years, California has been in a slightly above average wet regime, with at least 11 short-duration drought periods (Ingram et al. 1996; Cook et al. 2004). At the same time, California Central Valley agriculture has expanded over most of the Valley floor, and includes a system of managed irrigation and water conveyance that assumes climatically stationary conditions for model development and planning. The 1929-1934 drought has traditionally been the benchmark event used for designing storage capacity and yield of large California reservoirs. However, the California Department of Water Resources (CDWR) and other water agencies have begun to evaluate new approaches for managing water resources in response to the changing climate (CDWR 2006).

The goals of this study are to quantify the impacts of long-term droughts - an analogue for climate change related snowpack reduction - on water storage, and to illustrate the potential for surface and subsurface storage to limit the adverse impacts of drought and snowpack reduction on water supply. This includes how groundwater pumping compensates for reductions in surface inflow, the extent in which the water table is reduced, and how, when, and if this system recovers or reaches a new equilibrium. In the next section, we provide details on our approach for simulating persistent droughts in the California Central Valley. This is followed by the results and discussion section, then our summary and conclusions.

2.0 Approach

Analysis of California Central Valley impacts of sustained droughts are based in this study on a series of specified reductions in surface flows corresponding to historical 30% (below average), 50% (dry), and 70% (critically dry) effective reduction, for periods ranging from 10 to 60 years, and applied to the CDWR's California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM). This simplified methodology represents a means to evaluate the impacts of reductions in net surface flow from reservoirs and Central Valley precipitation. The CDWR is addressing global climate change in the California Water Plan, Bulletin 160, (CDWR 2005a). Specified drought scenarios act as an analogue to projected reductions in snowpack surface flows. Rather than focus on causes of global climate change, which are being addressed by other agencies and research institutions, the CDWR Water Plan looks at potential impacts of climate change on water resources in California and strategies for adapting to these changes.

2.1 Model Descriptions

The CDWR water flow and allocation models, the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) and the California Simulation model (CALSIM) were used for this study.

California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM)

The *C2VSIM* model was developed as an application of the CDWR's Integrated Water Flow Model (IWFM: CDWR 2005b, 2005c, 2006). IWFM simulates land-surface processes, surface water flow and groundwater flow. The land-surface module computes infiltration and runoff from net precipitation; consumptive use by native vegetation, irrigated crops and urban areas; surface water diversion and application; groundwater pumping and application; infiltration and return flow from irrigation; and recharge. Surface water flow is simulated as a function of flow from upstream reaches, tributaries and lakes; surface runoff; agricultural and urban return flows; diversions and bypasses; and exchanges with the groundwater flow system. Horizontal and vertical groundwater flow are simulated using the Galerkin finite element method and a quasi-threedimensional approach utilizing the depth-integrated groundwater flow equation for horizontal flows in each aquifer layer and leakage terms for vertical flow between aquifer layers. To the extent that is practical, IWFM directly incorporates readily available historical and spatial data sets, including precipitation, the Natural Resource Conservation Service (NRCS) runoff curve number, surface water inflows and diversions, land use and crop acreages.

The *C2VSIM II* model simulates land surface processes, groundwater flow and surface water flow in the alluvial portion of the Central Valley (Fig. 1) using a monthly time step. *C2VSIM II* covers an area of approximately 7,722 km^2 (20,000 $mile^2$), and incorporates 1392 nodes forming 1393 elements and 3 layers, 431 stream nodes delineating 74 stream reaches with 97 surface water diversion points, 2 lakes, and 8 bypass canals (Fig. 1a). Surface water inflows are specified for 35 gauged streams and simulated for ungauged small watersheds. The model area is divided into 21 sub-regions (Fig. 1b), where each sub-region is treated as a 'virtual farm' for allocating groundwater and surface water to meet water demands in the land-surface process. *C2VSIM II* was calibrated to match observed groundwater heads and surface water flows from October 1975 through September 1999. The calibrated model used here is the basis for the groundwater flow, and is a component of *CALSIM II*.

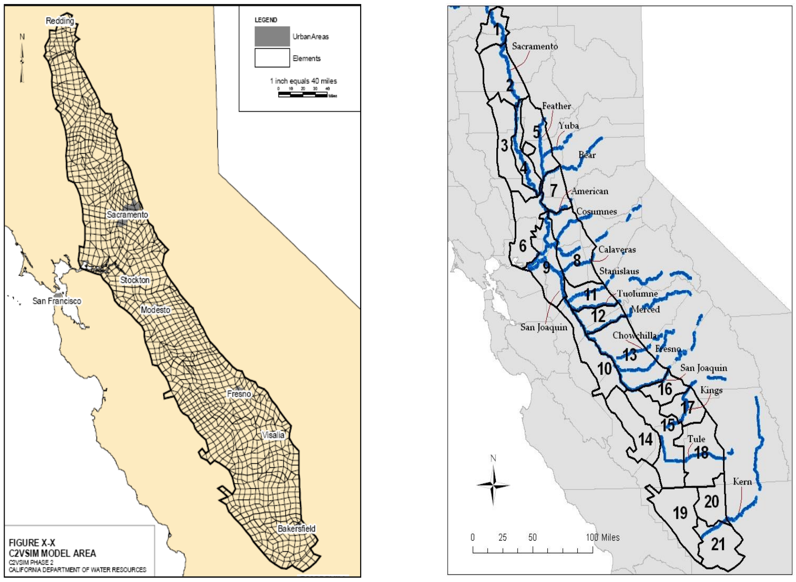


Figure 1. *C2VSIM II* fine grid and sub-basins.

The model was run with a monthly time step from October 1972 to September 2003. Regional-scale parameter values were calibrated using the PEST parameter estimation program (Doherty, 2005) to match semi-annual groundwater head observations at 121 locations and monthly surface water flow observations at 9 locations from October 1975 to September 1999, and average monthly stream-aquifer interaction values at 65 locations.

California Simulation Model version II (CALSIM II)

The *CALSIM* model (Draper et al. 2004) is a general-purpose, network flow, reservoir and river basin water resources simulation model developed jointly by the California Department of Water Resources and the U.S. Bureau of Reclamation. It is used for evaluating operational alternatives of large, complex river basins. *CALSIM* integrates a simulation language for flexible operational criteria specification, a mixed integer linear programming solver for efficient water allocation decisions, and graphics capabilities for ease of use. A linear objective function describes the priority in which water is routed through the system and the constraints set the physical and operational limitations toward meeting the objective. *CALSIM* maximizes the objective function in each time period to obtain an optimal solution that satisfies all constraints.

CALSIM was originally designed, and has been successfully implemented as a planning model of the State Water Project (SWP) and Central Valley Project (CVP) system to examine the range of options to improve supply reliability. The second generation version used here calculates the reservoir operations and time dependent rimflow into the Central Valley (CV) on monthly timesteps, providing the needed boundary conditions to *C2VSIM II*.

2.2 Drought Scenarios

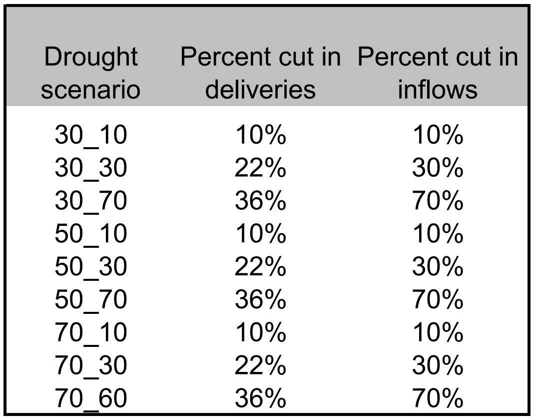
Drought scenarios are defined here as constructed surface flow reductions representing scenarios with *reductions* from 30% to 70%, for periods ranging from 10 years to 60 years, with a 10-year spin-up and a 30-year recovery. The *C2VSIM II* boundary forcing was generated using the *CALSIM II* model and historical flow observations of Central Valley rim flows based on the specified reductions corresponding to each scenario. The notation for the set of twelve scenarios is given in Table 1.

Specified Scenarios	**10 years**	**20 Years**	**30 years**	**60 years**
30% reduction	30_10	30_20	30_30	30_60
50% reduction	50_10	50_20	50_30	50_60
70% reduction	70_10	70_20	70_30	70_60

Table 1. Drought scenario notation.

The methodology used to create hypothetical drought scenarios consisted of selecting anomalous hydrologic dry years (in terms of reservoir inflow) from the historic record and appending them to create specified droughts.

The remainder of this report refers to the three drought intensity levels as light (30%), moderate (50%), and severe (70%), noting that the reductions in deliveries are lower than the reductions in reservoir inflows. The specified drought scenarios, reservoir inflows and deliveries are represented in Table 2.



Drought scenario	Percent cut in deliveries	Percent cut in inflows
30_10	10%	10%
30_30	22%	30%
30_70	36%	70%
50_10	10%	10%
50_30	22%	30%
50_70	36%	70%
70_10	10%	10%
70_30	22%	30%
70_60	36%	70%

Table 2. Percent cut in deliveries and releases.

3.0 Results and Discussion

Stream to groundwater flow, water table height, and groundwater volumetric storage change in response to drought scenarios are dynamically interrelated, along with the change in pumping under the fixed 1973-2003 set of demands, land use, and population. Here we discuss the drought responses for four major hydrologic regions: Sacramento, Eastside, San Joaquin, and Tulare, and for the entire Central Valley, with a detailed focus on three drought scenarios, the 30-year moderate drought, the 60-year light drought, and the 60-year severe drought. The appendix provides more detail on the full set of scenarios.

3.1 Surface Diversions

The above defined droughts all begin with the same ten year base period, during which surface diversions across the Central Valley average 10.65 million acre feet (maf) per year. After the 10-year base period, surface diversions in the Central Valley fall 36% during the severe drought scenario. During the moderate drought scenario, surface diversions fall 22% and during the light drought scenario diversions fall 10% (Table 3).

	Base Period (maf/y)	**Severe drought Impact** maf/y	**Moderate drought Impact** maf/y	**Light drought impact** maf/y
Central Valley	10.65	-3.78	-2.32	-1.07
Change (%)		-36%	-22%	-10%

Table 3. Impact of Droughts on Surface Diversions on the Central Valley

The impacts of the droughts are modeled separately for four different regions in the Central Valley, including the Sacramento Basin, Eastside, the San Joaquin Basin, and the Tulare Basin.[1] The regions differ in size and it is easiest to compare impacts across regions on a per acre foot basis (acre feet per acre per year in each region).[2] On regional a per acre basis, it is apparent

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[1] The Delta is also included as a separate region in the model but the impacts of the drought on that region are very minor and are not included in this report.

[2] The Central Valley region includes 12.8 million total acres and 6.8 million crop acres. In this study, per acre impacts are measured using total acres. A per acre measure based on cropland would be roughly the size of the measure based on total acres.

that drought scenario impacts are concentrated in the San Joaquin and Tulare Basins. In the severe 60-year drought scenario the Tulare and San Joaquin Basins experience a 0.41 and 0.42 foot per year decline in surface deliveries, compared to the base period (Table 4). In the moderate 30-year and light 60-year drought scenarios, deliveries to the San Joaquin declines about 0.2 and 0.13 feet per year from base year levels. Deliveries to the Tulare basin decline 0.36 and 0.14 feet per year respectively, during the moderate and light drought scenarios (Table 4). The Sacramento Basin and Eastside regions experience comparatively small changes in surface diversions during droughts. Sacramento Basin diversions decline 0.22 feet per year in the severe drought, but only change by a slight amount (0.04 to 0.07 feet) for other the two drought scenarios. Eastside diversions are virtually the same during all drought scenarios.

	Base Period	Severe drought Impact	Moderate drought Impact	Light drought impact
	(af/a/year	af/a/y	af/a/y	af/a/y
Sacramento	1.04	-0.22	-0.04	0.07
Eastside	0.01	-0.01	-0.01	-0.01
San Joaquin	0.97	-0.42	-0.20	-0.13
Tulare	0.58	-0.41	-0.36	-0.24
Central Valley	0.83	-0.30	-0.18	-0.08
Change (%)		-36%	-22%	-10%

Table 4. Surface Diversions in Base and Drought Periods on five sub-regions

3.2 Groundwater Pumping

Farmers in the Central Valley increase groundwater pumping during drought periods to make up for the decline in surface water deliveries. To maintain irrigation levels in the entire Central Valley during droughts, groundwater pumping is increased by 74% in the severe drought, 51% in the moderate drought, and 27% in the light drought scenario (Table 5).

Interestingly, drought period groundwater pumping more than offsets declines in surface diversions. For example, Central Valley groundwater pumping increases 0.36 feet per year in the severe drought, when surface diversions declined only 0.3 feet per year. In most regions, groundwater pumping goes up between 0.05 and 0.15 feet per year more than irrigation diversions go down. The extra groundwater pumping is needed to make up for dryer climate conditions experienced during drought years. Indeed, groundwater pumping impacts may indicate drought severity better than surface diversion impacts in most regions. For example, Eastside groundwater pumping is increased by 0.12 feet per year in the severe drought scenario and 0.1 and 0.07 feet per year in the moderate and light drought scenarios, while surface diversions remain close to the base period levels (Table 5).

	Base Period (af/a/year	Severe drought Impact af/a/y	Moderate drought Impact af/a/y	Light drought impact af/a/y
Sacramento	0.17	0.10	0.03	0.00
Eastside	0.42	0.12	0.10	0.07
San Joaquin	0.40	0.51	0.29	0.21
Tulare	0.85	0.58	0.46	0.22
Central Valley	0.49	0.36	0.25	0.13
Change (%)		74%	51%	27%

Table 5. Impact of drought on groundwater pumping

3.3 Stream-to-Aquifer Flows

In normal years, the San Joaquin and Sacramento Rivers are “gaining rivers”, meaning that their flow is increased by movement of water from aquifers that are adjacent to rivers. The flow of water from this groundwater source is decreased during droughts, as groundwater levels in these regions decline. And in the severe drought, ground flows to the San Joaquin River may become reversed with the aquifer drawing water from the river. During moderate and light droughts, the San Joaquin River continues to draw aquifer water, but the amount is diminished (Table 6). Alternatively, in normal years the Eastside and Tulare Rivers are “losing rivers” such that they give up flows to replenish aquifers. In drought years, stream-to-aquifer flows diminish, due to a loss of stream-to-aquifer connectivity or to a relative decline in stream levels compared to groundwater levels.

Sacramento and San Joaquin stream-to-aquifer flows are larger than Eastside and Tulare flows, and tend to dominate the Central Valley averages. These flows help to maintain drought groundwater levels and represent a source of natural recharge in the Sacramento and San Joaquin Basins. However, the storage benefit of this drought period stream-to-groundwater (relative) flow must be balanced against the corresponding loss of streamflow to the Sacramento and San Joaquin Rivers.

	Base Period af/a/y	Severe drought Impact af/a/y	Moderate drought Impact af/a/y	Light drought impact af/a/y
Sacramento	-0.44	0.14	0.01	-0.07
Eastside	0.13	-0.06	-0.06	-0.05
San Joaquin	-0.17	0.21	0.06	0.02
Tulare	0.08	-0.02	0.03	0.01
Central Valley	-0.18	0.07	0.02	-0.02
Change (%)		-38%	-10%	13%

Table 6. Impact of drought on stream to aquifer flows

3.4 Aquifer Recharge

In normal years the Central Valley aquifers are recharged with excess surface irrigation deliveries and rainwater percolation. In the base period for example, the Central Valley groundwater recharge is 0.76 feet per year compared to groundwater pumping of 0.49 feet per year (Table 7). Excess recharge in normal years helps to maintain groundwater storage during droughts when there is a dramatic decline in recharge. Average recharge across the Central Valley drops 12%, during the light drought scenario, to as much as 41%, during the more severe drought scenario (Table 7).

Across regions, recharge varies in proportion to changes in surface deliveries and rainfall. In the severe drought scenario for example, the Sacramento, San Joaquin and Tulare regions register large declines in aquifer recharge and experience large declines in surface deliveries. The Sacramento and Eastside regions also experience the largest decline in rainfall totals during droughts. This variation in rainfall helps to explain the regional variation in recharge not explained by regional differences in surface deliveries.

	Base Period (af/a/y)	Severe drought Impact af/a/y	Moderate drought Impact af/a/y	Light drought impact af/a/y
Sacramento	0.73	-0.42	-0.32	-0.19
Eastside	0.24	-0.17	-0.17	-0.15
San Joaquin	0.89	-0.39	-0.28	-0.15
Tulare	0.77	-0.26	-0.19	-0.07
Central Valley	0.76	-0.31	-0.24	-0.12
Change (%)		-41%	-32%	-16%

Table 7. Impact of drought on aquifer recharge

3.5 Changes in Aquifer Storage

Changes in aquifer storage over time is the sum of aquifer withdrawals, including groundwater pumping, minus the aquifer inflows, including stream inflows and irrigation recharge. Changes in boundary flows have an additional, but very minor, impact on storage levels. During the base period (a mix of normal and above normal rainfall years), Central Valley storage increases by 0.16 feet per year. During the drought scenarios, Central Valley aquifer storage declines from 0.28 feet per year in the light drought scenario to 0.6 feet per year in the severe drought scenario (Table 8).

	Base Period (af/a/y)	Severe drought Impact af/a/y	Moderate drought Impact af/a/y	Light drought impact af/a/y
Sacramento	0.24	-0.35	-0.33	-0.26
Eastside	0.17	-0.39	-0.36	-0.30
San Joaquin	0.26	-0.67	-0.51	-0.32
Tulare	0.02	-0.84	-0.65	-0.28
Central Valley	0.16	-0.60	-0.48	-0.28

Table 8. Impact of drought on aquifer storage

3.6 Groundwater Levels

Central Valley groundwater levels adjust to changes in storage, rising during the base period and falling during the drought scenarios. During the base period, Central Valley groundwater levels rise 0.98 feet per year, with the Sacramento and San Joaquin Basins increasing by 1.52 feet per year and 1.07 feet per year, respectively, and the Tulare Basin increasing by only 0.11 feet per year. The Central Valley groundwater levels decline by 1.81 feet per year and 3.79 feet per year, respectively, during the light and severe drought scenarios, with substantial variation shown by region (Table 9).

	Base Period (af/a/y)	Severe drought Impact af/a/y	Light drought impact af/a/y
Sacramento	1.52	-2.09	-1.64
Eastside	1.07	-2.34	-1.80
San Joaquin	1.63	-5.12	-2.40
Tulare	0.11	-4.93	-1.65
Central Valley	0.98	-3.79	-1.81

Table 9. Impact drought on groundwater levels

The changes in groundwater level closely match changes in storage levels. In the simple case, assuming a bathtub model of the aquifer, absent confined layers, the annual change in storage (ft) divided by the change in groundwater depth (ft) of an aquifer equals the specific yield of the aquifer. That is, if storage declines by 1 foot and groundwater depth declines 6.25 feet, dividing one by the other results a "specific yield" of 0.16. In fact, the specific yield in the Central Valley is set to be close to 0.16 for all regions in *CV2SIM II*.

It is apparent that in general and on average, estimated groundwater levels equal the product of estimated storage times the inverse of specific yield in the model. This is indicated in Table 10, which shows changes in storage divided by changes in estimated groundwater level for different regions and time periods in the model. In most cases, the ratio of storage over groundwater is about .16, assumed specific yield in the model (Table 10). In the base period for example, the storage to groundwater level ratio is exactly .16. This indicates that groundwater levels during that period vary directly according to changes in storage divided by the specific yield. (Table 10). In other periods and regions, the storage to groundwater ratio varies from .16. In the San Joaquin Basin for example, the severe drought period storage to groundwater ratio is .13. This indicates that drought period groundwater levels in that region decline more rapidly that suggested by changes in storage and the assumed specific yield.

This is explained by the fact that groundwater wells in the San Joaquin Basin draw water from beneath the impermeable Corcoran Clay layer, In this case, changes in groundwater pressure are likely to be only loosely correlated with changes in aquifer storage.

	Base Period (ft/ft storage)	Severe drought Impact (ft/ft storage)	Light drought impact (ft/ft storage)
Sacramento	0.16	0.17	0.16
Eastside	0.16	0.17	0.17
San Joaquin	0.16	0.13	0.14
Tulare	0.16	0.17	0.17
Central Valley	0.16	0.16	0.15

Table 10. Simple model specific yield implied by changes in storage and groundwater.

Groundwater levels at the end of the severe drought drop 169 feet and levels at the end of the moderate drought fall 143 ft. Levels at the end of the light drought decline 50 ft. During the base period, groundwater levels rise 6.25 feet for every additional foot of storage added to the groundwater. During the drought periods, groundwater levels decline slightly more than 6.25 feet per storage feet on average.   Looking at this in more detail, it is apparent that groundwater levels in the Eastside and Tulare Basins decline less and levels in the San Joaquin Basin decline more than 6.25 feet per storage foot.

3.7 Groundwater Decline and Recovery

At the end the drought scenarios, groundwater levels across the Central Valley generally decline by less than 200 ft (Table 11). At the end of the severe 60-year drought scenario, Central Valley groundwater levels drop an average of 169 ft, groundwater levels fall 144 feet at the end of the moderate drought, and 50 feet at the end of the light drought. Groundwater levels in the San Joaquin and Tulare Basins drop more than the other basins due primarily to the compensating increase in pumping for these regions. The Tulare Basin experiences the largest decline, ranging from 92 feet in the light drought scenario to 289 feet in the severe drought scenario (Table 11).

	End Severe 60 year drought	Recovery		Moderate 30 year drought	Recovery		Light 60 year drought	Recovery	
	(feet)	(feet)	(%)	(feet)	(feet)	(%)	(feet)	(feet)	(%)
Sacramento	-34	25	74%	-27	13	48%	-7	9	129%
Eastside	-76	27	35%	-69	15	22%	-44	17	39%
San Joaquin	-209	78	37%	-157	61	38%	-46	39	85%
Tulare	-289	25	9%	-256	32	12%	-92	14	15%
All	-169	35	20%	-144	29	20%	-50	17	34%

Table 11. Groundwater drought decline and recovery

The model runs include a 30-year "recovery period" indicating how aquifers in the Central Valley respond to a return to normal rainfall and irrigation conditions. The Central Valley groundwater reaches 20% of the pre-drought levels after the severe and moderate droughts, and 34% of pre-drought levels after the light drought during this recovery period (Fig. 2). In general, groundwater levels recover most rapidly in the San Joaquin Basin, and less rapidly in the Tulare Basin and eastside region. The recovery rates suggest that the Tulare Basin would not achieve pre-drought groundwater levels for a very long period of time, if ever. Other regions experience more rapid rates of groundwater recovery. These regions would likely achieve pre-drought groundwater levels relatively rapidly after a drought.

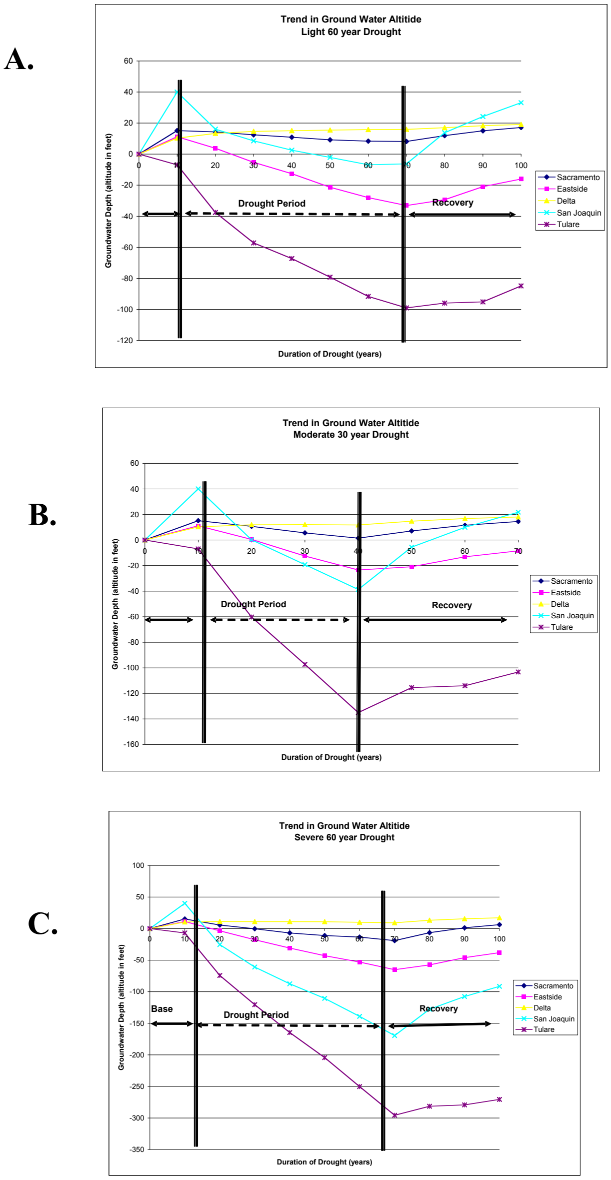

Figure 2. Groundwater trends before during and after A). a moderate 30-year drought , B) a slight 60 year drought, and C) a severe 60-year drought.

4.0 Summary and Conclusions

The impacts of global warming and long-term drought are likely to deplete aquifers, increase electricity demand (cooling and pumping) and decrease hydropower generation. This study is intended to illustrate the impacts of climatic events on water storage, and suggests water management techniques to counter some of these adverse impacts.

C2VSIM and all water allocation models are only partially verified. Many empirical parameters are tuned. Total groundwater pumping is not known and groundwater processes lack sufficient physical descriptions. Pumping is based on a limited available demand record. Demand is fixed and agriculture does not shift with change in supply.

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