IMPACTS OF POPULATION GROWTH AND CLIMATE CHANGE ON CALIFORNIA'S FUTURE WATER SUPPLIES

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ABSTRACT

CALVIN, an economic-engineering optimization model of California's water supply system, is used to assess the interaction of potential impacts of population growth and climate change on water supplies in California. CALVIN includes the state's surface and groundwater system and is driven by economic values for agricultural and urban water use. Future agricultural and urban demands are represented by water value functions estimated from separate agricultural and urban economic models. In addition, values for hydropower generation and flood damage reductions are being developed for CALVIN to represent these additional water management benefits. This allows CALVIN to re-operate statewide facilities and allocate water supplies to minimize economic losses to agricultural, urban, hydropower, and flooding sectors throughout the system for changes in climate or water demands. Methods for developing economic values of the different water functions and for adjusting hydrologic inputs for climate change in CALVIN are presented. Water supply impacts to agricultural and urban sectors are assessed for a range of population and climate scenarios.

INTRODUCTION

Concurrent with expected climatic changes in California over the next 50 to 100 years are likely increases in population. How these two dynamic forces may interact and affect future water supplies and the operation and management of California's water resource system at local, regional, and statewide scales, is the focus of this research project. Funded by the California Energy Commission (CEC), the study explores the potential for adaptation to impacts of climate change and population growth on the state's water resource system and the associated economic costs of these impacts. By studying both effects, the sensitivity of climate impacts to population assumptions can be evaluated.

Already, water supplies are strained in dry years in California creating substantial water scarcity and severe problems balancing urban, agricultural and

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environmental demands (California Department of Water Resources (DWR) 1998). Flooding in the Central Valley is an important water management concern with potential damages in the tens of billions of dollars (US Army Corps of Engineers (USACE) 2002). Reservoir flood reserve pools are an integral component of flood protection, while reservoir-based hydropower supplies significant amounts of the state's electric generation.

Consequences of global warming for California's climate include higher maximum temperatures, more intense precipitation, increasingly dry summers, and increased risk of drought (see Miller et al. (2001) for a review of climate change studies). Currently, California's water supplies, water infrastructure, and the management of water resources are finely tuned to historic runoff timing and magnitude, especially snowmelt-driven Sierra Nevada runoff. Investigations of California streamflow response to climate change indicate that runoff is likely to peak earlier in the season (Miller et al. 2001). However, the full extent of shifts in runoff timing and magnitude across the state are uncertain (Roos 2001).

This study examines a range of climate scenarios for California's water supplies, including two atmospheric general circulation model (GCM) scenarios and combinations of temperature and precipitation changes. Runoff changes are simulated by Miller et al. (2001) for representative headwater basins, forced by precipitation and temperature variables using coupled soil moisture accounting and snow accumulation/ablation models. Six watersheds capture a variety of altitude and location conditions to represent basin scale sensitivities to climate changes. Simulated runoff changes, and associated temperature and precipitation changes provide a set of monthly perturbation parameters to drive hydrologic changes for input to large-scale water resources system models such as CALVIN.

Long-term population growth depends on demographic changes and net migration, both difficult to forecast for California beyond 20 years. Official projections for 2040 span a low of 46.8 million to a high of 63.4 million, reflecting a large range of uncertainty (Johnson 1999). For this study, low and high population scenarios for 2100 are developed, along with their projected spatial footprints (see Landis 2000) to test the sensitivity of climate change impacts to population uncertainties and bookend a range of impacts to the state's water resources.

CALVIN MODELING APPROACH FOR CLIMATE CHANGE

Adaptation to changing climatic and water demand conditions will require system flexibility as well as physical changes to water management infrastructure in California (VanRheenen et al. 2001). The need to explore flexible operating and management policies that balance multiple water resource objectives and identify promising long-range system changes has motivated the choice of the CALVIN optimization model for this study. Economic optimization, in contrast with simulation models that require specifying operating rules a priori, allows the system to adapt operations and allocations within the physical capacities of infrastructure to maximize benefits (minimize costs) across hydropower generation, flood damage mitigation, agricultural and urban water supply. Economics is the compensatory tool to make such tradeoffs, with the exception of environmental demands that are represented as required flows.

CALVIN Model

CALVIN is an economic-engineering optimization model of California's water supply system, explicitly integrating the operation of water facilities, resources and water demands across the state's entire inter-tied surface and groundwater system from Trinity-Shasta in the north to the Mexico border in the south. The CALVIN model uses the US Army Corps of Engineers' HEC-PRM network flow with gains optimization solver to find water operations and allocations that maximize regional or statewide economic benefits (Jenkins et al. 2001).

Covering 92% of California's projected 2020 population and 88% of its estimated irrigated acreage in 2020, the CALVIN model contains roughly 1,200 spatial elements, including 51 surface reservoirs, 28 groundwater basins, 19 urban economic demand areas, 24 agricultural economic demand areas, 39 environmental flow locations, 113 surface and groundwater inflows, and numerous conveyance and other links representing the vast array of California's water management infrastructure (Jenkins et al. 2001). The model's schematic is available at http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/.

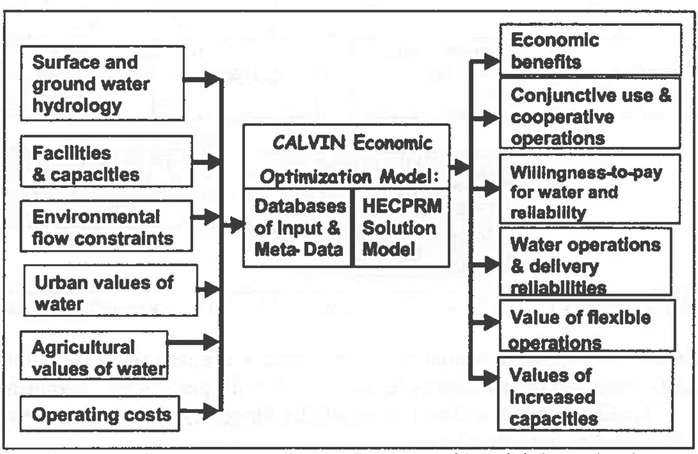

Figure 1. CALVIN Data Input, Output and Model Organization

The optimization is currently driven by economic values for agricultural and urban water use across the network system, subject to environmental flow constraints and flood storage operations. CALVIN is a data driven model as shown in Figure 1 that produces a variety of economic and water supply reliability information. For this study, enhancements to CALVIN include adding economic values for reservoir-based hydropower generation and damage costs for flooding along the Sacramento and San Joaquin River systems, as described below. The economic representation in CALVIN of these additional water resource management objectives allows us to more fully explore the potential for operational and policy changes along with infrastructure expansion to adapt to and mitigate impacts of climate change on water resources for California.

Modeling Approach for Climate Change

Figure 2 depicts the modeling approach, data flow, and linkages among modeling components of the CEC climate study. This paper addresses the shaded boxes and their linkages to the CALVIN model in Figure 2. Other CEC researchers are developing the modeling components shown by unshaded boxes.

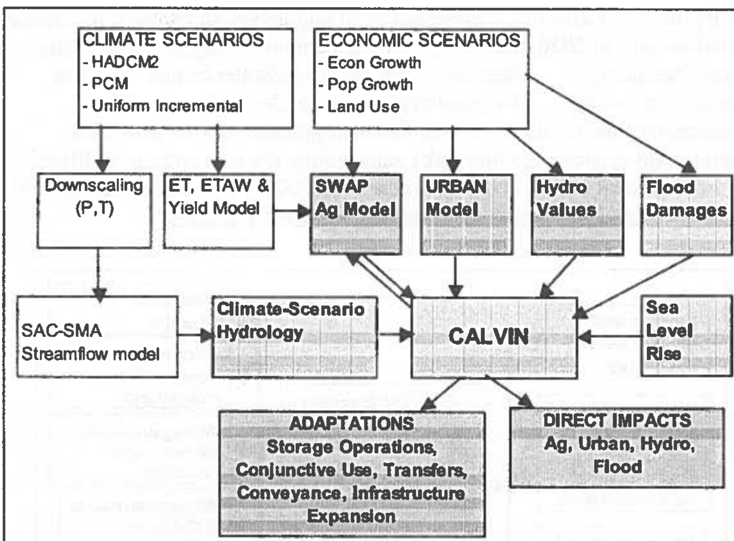

Figure 2. Model Linkages and Data Flow - CALVIN Climate Impacts Study

The climate and economic scenarios are combined to define a set of perturbations, including changes to temperature, precipitation, runoff, population, income and land use. These are then translated into spatially disaggregated inputs to drive the CALVIN model as described below.

Hydrology

CALVIN hydrology consists of rim inflows from outside the modeled system, net local stream accretions from within the modeled system, and net groundwater recharge (exclusive of agricultural and urban return flows) (see Technical Appendices, Jenkins et al. 2001). All three of these components are perturbed for climate change. The 38 rim inflow points are mapped to the six representative headwater climate change basins for which monthly runoff ratios are available from the National Weather Service Sacramento Soil Moisture Accounting Model (SAC-SMA) streamflow simulations (see Miller et al. 2001). The appropriate runoff ratios are then used to perturb the 1922-1993 monthly historic time series for each CALVIN inflow. Central Valley groundwater recharge and local accretions are perturbed using precipitation changes. Changes in the historic monthly volume of precipitation over each of 21 groundwater basins are partitioned into deep percolation and runoff using empirical relationships for each basin. The historical hydrologic time series of monthly groundwater inflows and local accretions for each basin are then adjusted accordingly. No attempt is made to adjust stream-aquifer gains. Adjustments to local accretions and groundwater recharge for land use changes are handled within CALVIN explicitly through return flows from deliveries to agricultural and urban demands within each basin.

Urban Demands

CALVIN uses economic water value functions to represent the demands of 19 urban areas included in the system. These value functions are developed from estimates of population, per capita use, sector water use breakdowns (residential, commercial/public, and industrial), industrial water production values, and monthly use patterns for each urban area, and estimates of seasonal residential price elasticities of demand in California (see Appendix B, Jenkins et al 2001). For the CEC study, spatially disaggregated urban land use and population changes for each urban area in CALVIN are computed from statewide projections developed for each economic scenario. Estimated changes in per capita use are based on location-specific population density and income effects using relationships derived from California Department of Water Resources urban water use forecasting data (DWR 1998). These estimates are then combined to develop new urban water value functions for each economic scenario studied. No attempt is made to adjust residential price elasticities or sector breakdowns. In some scenarios, new CALVIN urban demand areas are added in the Central Valley.

Agricultural Demands

The Statewide Agricultural Production model is used to develop agricultural water value functions for CALVIN (Appendix A, Jenkins et al. 2001). CALVIN includes 24 production areas. In the CEC study, climate effects on yield are estimated and used to adjust crop production functions. Land use changes from the economic scenarios are also input to the model along with shifts in commodity demand, to develop new agricultural water demand functions for each of the 24 areas consistent with a scenario's land use changes and urban demands.

Hydropower

Energy production models and estimates of the value of energy are combined to develop hydropower values as a function of month, storage level, and flow for the major reservoirs with variable head hydropower facilities in CALVIN. Fixed head hydropower facilities are represented more simply as monthly linear functions of flow. Seasonal variation in the price of electricity reflects winter vs. summer demand as it has historically affected electricity prices in California. Sensitivity to energy prices will be examined in the course of the study. An iterative solution technique in HEC-PRM is used to find an optimal network solution for CALVIN when variable-head hydropower is included.

Flooding

Flood damage data from the Sacramento-San Joaquin River Basin Comprehensive Study (USACE 2002) is used to derive monthly flow-damage functions along Central Valley river reaches with flood damage potential in CALVIN. The 2000 level-of-development data is scaled using spatially disaggregated population projections for the scenarios modeled in this study. Damage-discharge relationships for flood events are converted to monthly damage functions by relating data on flood peak flows with associated monthly flow volumes. While reservoir flood reserve pools are maintained in CALVIN at current levels based on historical hydrology, the addition of flood damage functions on downstream reaches will drive CALVIN to increase flood reserve pools if this is economically optimal with climate induced changes to runoff hydrology.

Sea Level Rise

Temperature rise is expected to raise sea level (Titus and Narayanan 1995). The effects of projected sea level rise on water quality in the San Francisco-Bay Delta and subsequent operational changes to maintain salinity levels below regulatory thresholds and legal requirements for Delta exports are estimated in this modeling component. The output will produce a modified monthly time series of required Delta outflows for input into CALVIN as part of adjusting environmental requirements for climate change. The higher expected outflows are likely to produce operational changes on the Sacramento and San Joaquin River systems in the process of adapting to changing climate conditions.

Model development and testing is currently under way to generate the various CALVIN inputs (disaggregated economic value functions for urban demand areas, agricultural production areas, hydropower facilities, and flood damage areas; sea level rise changes to required Delta outflows; perturbed climate hydrologic data) needed to model the economic and climate scenario in CALVIN.

MODIFYING CALIFORNIA'S HYDROLOGY FOR CLIMATE CHANGE

Twelve climate scenarios are investigated in this study (see Table 1), capturing a range of potential temperature and precipitation shifts anticipated for California. The two GCM scenarios represent a warmer, wet alternative (HadCM2 run 1, Johns et al. 1997) and a cooler, dry alternative (PCM run B06.06, Dia et al. 2001). Three different time slices from each GCM projection are considered, centered on 2020, 2060, and 2100. Uniform incremental scenarios span the range of anticipated temperature and precipitation uncertainty.

Estimated change in the historical 1922-1993 total average annual rim inflow volume of 28.2 maf in CALVIN under the various climate scenarios (Table 1) varies from a low of –25.5 % for the PCM 2080-2099 period (a loss of 7.1 maf/year of water supply) to a high of +76.5.% for the HadCM2 2080-2099 period (a gain of 21.6 maf/yr of water supply). More important perhaps, is the consistent seasonal shift in streamflow volume arising from temperature increases in all scenarios, including the cooler, dry PCM projections. The seasonal shift in timing and volume for each inflow point in CALVIN is more or less pronounced depending on the characteristics of the basin to which it is mapped, in particular the freezing elevation.

Table 1. CALVIN California Historic and Climate Perturbed Rim Inflows

Climate Scenario	Description	Change T °C	Change P %	Volume (maf/yr)	% Change Total	% Change Oct-Mar	% Change Apr-Sep
Historical	1922-1993	0	0	28.2	0	0	0
1	Uniform Incremental	1.5	0	28.6	1.1%	15.6%	-13.4%
2	"	1.5	9	32.4	14.6%	31.7%	-2.7%
3	"	3	0	28.5	0.9%	28.0%	-26.5%
4	"	3	18	36.2	28.1%	64.4%	-8.7%
5	"	5	0	27.9	-1.1%	37.1%	-39.7%
6	"	5	30	40.6	43.7%	103.8%	-17.0%
7	HadCM2[a] 2010-2039	1.4	22	38.5	36.4%	54.9%	17.6%
8	HadCM2[a] 2050-2079	2.4	32	41.3	46.4%	82.0%	10.4%
9	HadCM2[a] 2080-2099	3.3	62	49.8	76.5%	134.3%	18.1%
10	PCM[b] 2010-2039	0.5	-9	26.5	-6.2%	-6.7%	-5.7%
11	PCM[b] 2050-2079	1.5	-14	24.4	-13.6%	-3.8%	-23.5%
12	PCM[b] 2080-2099	2.4	-24	21.1	-25.5%	-14.2%	-36.9%

[a] Hadley (Johns et al., 1997); [b] Parallel Climate Model (Dai et al., 2001)

Rim inflows are the largest component of water supplies in CALVIN, followed by groundwater recharge from natural sources (7.8 maf/yr) and net local accretions (5.2 maf/yr). Work is under way to finalize estimated changes in natural deep percolation to groundwater (1.7 maf/year in CALVIN for the Central Valley) and runoff contributions to local accretions for CALVIN from precipitation changes under each climate scenario.

CALIFORNIA'S WATER DEMANDS UNDER POPULATION GROWTH

Future economic scenarios are considered for 2020, 2060, and 2100. The 2020 scenario is the baseline condition for CALVIN, developed from California Department of Water Resources (DWR) Bulletin 160-98 projections for 2020 (DWR 1998; Jenkins et al. 2001). For later years, two population trajectories are considered: a High Scenario with high population growth combined with low income growth (reduction in historic rate to 1% growth in per capita income), and a Low Scenario with lower population growth stabilizing in 2060 combined with high income growth (continuation of historic 2% growth in per capita income). These bracket the anticipated population uncertainty for the purpose of measuring climate change impacts in this study.

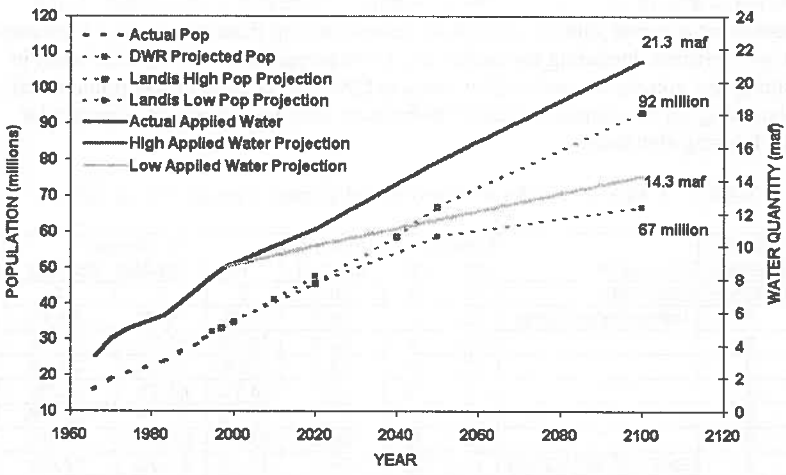

Figure 3. California Projected Population and Urban Water Use Ranges

Key parameters to estimate urban water demands across the CALVIN model for each of these periods, and the associated effects on agricultural land and production, are: total population, where that population occurs, how densely it is arranged, and income levels. Figure 3 shows the range of population projections and associated water use estimates for the 2100 period considered in this study. Table 2 compares DWR population and water use data for 1995 and projected for 2020 across the 10 hydrologic regions of California with this study's 2100 High and Low economic scenarios. Projected increases in population-driven water demands for 2100 range from 8 to 11.3 maf/yr, or 1.8 to 2.3 times current (1995) levels estimated by DWR.

Table 2. California Population and Water Use - Economic Scenarios

Hydrologic Region	M&I Urban Water Use (maf/yr)				Population (millions)		
	DWR 1995	DWR 2020	2100 L	2100 H	DWR 2020	2100 L	2100 H
Central Coast	0.3	0.4	0.7	0.9	1.9	3.2	4.7
Colorado River	0.4	0.7	0.9	1.2	1.1	3.2	5.0
N. Coast	0.2	0.2	0.3	0.3	0.8	1.3	1.8
N. Lahontan	0.0	0.1	0.0	0.0	0.1	0.1	0.1
S. Coast	4.3	5.5	7.4	8.7	24.3	31.3	42.8
San Francisco	1.3	1.3	1.9	2.2	7.0	9.7	12.3
San Joaquin	0.6	1.0	1.1	1.2	3.0	3.8	5.6
S. Lahontan	0.2	0.6	1.3	1.7	2.0	3.8	5.8
Sacramento R.	0.8	1.1	1.7	2.0	3.8	5.5	7.7
Tulare Lake	0.7	1.1	1.5	1.9	3.3	5.0	7.4
TOTAL CA	8.8	12.0	16.7	20.1	47.5	66.9	93.1

ASSESSING WATER SUPPLY IMPACTS

The list of climate-economic scenarios for CALVIN modeling that will be assessed in this study is given in Table 3. Outputs produced by CALVIN, shown in Figures 1 and 2, will be assessed for each case. These include direct water resource-related economic and reliability impacts on urban and agricultural water supplies across the system, on hydropower generation and on flood protection.

Table 3. CALVIN Climate Impacts Modeling Runs

Run	Period	Economic Scenario Population	Income	Urban Demand	Climate Scenario #	Rim Inflows (maf)
0	2020	47 million	Base	12 maf	Historical	28.2
1	2100	93 million	Low	20.1 maf	4	36.2
2	2100	67 million	High	16.7 maf	4	36.2
3	2100	93 million	Low	20.1 maf	5	27.9
4	2100	93 million	Low	20.1 maf	12	21.1
5	2100	93 million	Low	20.1 maf	9	49.8
6	2060	67 million	Low	14.3 maf	11	24.4
7	2060	67 million	Low	14.3 maf	8	41.3
8	2100	93 million	Low	20.1 maf	2	32.4
9	2100	93 million	Low	20.1 maf	3	28.5
10	2100	93 million	Low	20.1 maf	6	40.6
11	2100	93 million	Low	20.1 maf	1	28.6
12	2020	47 million	Base	12 maf	7	38.5
13	2020	47 million	Base	12maf	10	26.5

In addition, changes in facility operation and usage, and allocations across the system taken by CALVIN in balancing competing water resources management objectives under these scenarios will be examined for promising adaptations to climate change and opportunities for expanding infrastructure across the range of uncertain climatic conditions and population projections anticipated for California.

REFERENCES

DWR (Dept. of Water Resources) (1998) *California Water Plan Update: Bulletin 160-98, Vol. 1 and 2.* California Dept. of Water Resources, Sacramento, CA.

Dai, A., Meehl, G. A., Washington, W. M., Wigley, T. M. L., et al. (2001) "Ensemble simulation of 21st century climate changes: Business as usual vs. CO_2 stabilization." *Bulletin of the American Meteorological Society.* 82: 2377-2388.

Jenkins, M. W., Draper, A. J., Lund, J. R., Howitt, R. E., et al. (2001) *Improving California Water Management: Optimizing Value and Flexibility.* Center for Environmental and Water Resources Engineering Report #01-1, University of California, Davis, CA. http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/

Johns, T. C., Carnell, R. E., Crossley, J. F., Gregory, J. M., et al. (1997) "The Second Hadley Centre Coupled Ocean-Atmospherie GCM: Model Description, Spinup and Validation." *Climate Dynamics* 13:103-134.

Johnson, H. (1999) "How Many Californians?" *California Counts, Population Trends and Profiles.* Vol.1, No. 1, October 1999. Public Policy Institute of California, San Francisco, CA.

Landis, J. D. (2000) *Raising the Roof, California's Housing Development Projections and Constraints, 1997-2020.* Prepared for the California Dept. of Housing and Community Development by the University of California, Berkeley, Institute of Urban and Regional Development.

Miller, N. L., Bashford, K. E., and Strem, E. (2001) *Climate Change Sensitivity Study of California Hydrology.* A report to the California Energy Commission, LBNL Technical Report No. 49110, Berkeley, CA, November, 2001.

Roos, M. (2001) *Suggested Research on the Effect of Global Climate Change on California Water Resources.* A report to the California Energy Commission's Public Interest Energy Research Program (PEIR), Sacramento. Draft 9/28/2001.

Titus, J. G. and Narayanan, V. K. (1995) *The Probability of Sea Level Rise.* U.S. EPA, EPA 230-R-95-008, September, 1995, Washington, D.C.

USACE (2002) "Commonly Asked Questions - Economics." Sacramento and San Joaquin River Basins Comprehensive Study Web Page: http://www.compstudy.org/news_info/CAQs/economics.asp

VanRheenen, N. T., Wood, A. W., Palmer, R. N., Payne, J. T., Lettenmaier, D. P. (2001) "The Effects of Climate Change on Water Management Strategies and Demands in the Central Valley of California." *Proceedings World Water and Environmental Resources Congress, May 20-24, 2001, Orlando, FL.* CD-ROM, ASCE, Reston, VA.