Climate Change, Agriculture, and Sustainable Management of Water Resources in the Sacramento River Basin

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I. Introduction

Growing water needs and climate change are posing a threat to water resources in many parts of the world. California is a prominent example of the phenomenon. Declining river flows and falling groundwater tables are of serious concern in the state. These trends in river flows are quite evident for the Sacramento River (see Figure 1). This is the largest river in California, starting from southern Oregon, past Shasta Dam, through Sacramento and the Delta, flowing into the San Francisco Bay. Its primary tributaries are the Pit, the Feather, and the American Rivers, which are included in the 27000 square mile Sacramento River basin. This area covers the largest watershed system in the western part of United States, with 31% of California's total surface water runoff coming from Sacramento River (Mount). Over 2.8 million people live in the Sacramento River basin and it also supports a very productive agriculture (Wikipedia).

Though there is variation across the state, water usage in California is dominated by agriculture - after accounting for environmental flow needs. This is particularly true for the Sacramento River basin (See Figure 2). Furthermore, both agricultural and urban surface water diversions, as well as groundwater extracted annually, have been showing increasing trends since 1920 (Northern California Water Association 2014). Consistent with such trends, predictions made by Domagalski et al. (2000) indicate that in 2020, 8 percent of the Sacramento Valley water allocation will be for urban use. 39 percent for environmental flows, and 53 percent for agriculture.

Climate change may well have made a contribution to decreased average water availability in the Sacramento River basin over the last few decades and is also likely to do so in the future. According to Knowles and Cayan (2002) average temperature in California is predicted to increase by 2.1°C, causing higher runoff peaks earlier in the year and lower flows subsequently, with the latter appearing to dominate (see Figure 3), suggesting an overall annual decrease.

Any climate change induced alterations in river flow patterns may be expected to lead to new environmental flow requirements. Consequently, the trade-off between agriculture and urban water use and environment needs may be impacted. Decreasing trends in surface water availability are likely to increase the competition for water and the pressure on the state's groundwater resources. As a result, the sustainability of agricultural, residential, and industrial water use may be in danger. Realization of the dire consequences of inaction in the face of such trends prompted the enactment of the Sustainable Groundwater Management Act (SGMA) in 2014. This landmark legislation requires formation of local agencies to ensure long-term viability the state's groundwater supplies.

The overall objective of our paper is to investigate the potential role of efficient water use in achieving sustainability of water supply in the Sacramento River basin. Since agriculture is a major user of water in the basin, we carry out our analysis in the context of a model in which agricultural producer profits are maximized, subject to water and land availability, environmental flow requirements, and given urban water demand. Specifically, this model is used to:

1) Examine the possible implications of the Sustainable Groundwater Management Act (SGMA) on agriculture in the Sacramento River basin.

2) Analyze the trade-off between water use for environmental river flow and agriculture under alternative climate change scenarios.

3) Examine adaptation strategies to climate change, such as promotion of conservationist irrigation technologies and cropping pattern changes.

The paper is organized as follows. Section II reviews the relevant literature and indicates our contribution. Section III explains the hydrological and economics components of our model.

Section IV discusses the data and empirical procedures we use. Section V presents simulation results and their policy implications. Section VI presents some concluding remarks.

II. Literature review

Water resources management strategies for river basins all over the world have been studied extensively. For Elbe River Basin in Germany, scholars used change in net income methods to define loss functions for hydropower, fisheries industry, thermal power plants, irrigation, water supply utilities and boating tourism enterprises (Grossmann et al. 2011). In Brazil, nonlinear constant elasticity of substitution production functions were applied to Sao Francisco River Basin (Maneta et al. 2009). For India's Ganges Basin, Christian introduced cropped area as an endogenous decision variable in a hydro-economic optimization model (Siderius et al. 2016). For China, water quality decisions and water allocation decisions were coupled to estimate the additional cost of meeting water quality in the rivers in North Plain area (Davidsen et al. 2015). Methodologies that generate decision information to individual farmers or farmer associations, regarding long-term field irrigation technology choices and crop pattern planning and short-term water allocation among crops under specific hydrologic scenarios were applied in Chile's Maipo River Basin (Cai and Rosegrant 2004). The model applied in Zayandeh-Rood water resource system in Iran considered and integrated reservoir and aquifer carry-over, river-aquifer interaction and water quality with stakeholders' socio-economic indices of production, net income and labor force employment to evaluate the socio-economic and environmental value of conjunctive water management (Daneshmand et al. 2014).

In the United States, most research on economics of surface water resources has been done for California. Water scarcity has always a problem in this state. For California's water supply system, a study estimated the economic benefits of flexible operations, user willingness to pay for the additional water, and economic opportunity costs of environmental flows (Marion et al. 2004). Droughts happen frequently in California. Not surprisingly, there is research evaluating desirability of potential water transfers under drought conditions (Howitt et al. 2012).

Hydro-economic research has also been conducted for many river basins in the United States. There exists a risk-based economic model which integrates biophysical and economic components for maximizing producers' utility, and provides corresponding land and water allocation strategies as well as expectation and variability of profit for salinity-affected farms in south central Utah (Kim and Kaluarachchi 2015). Research has been done for Central Valley, San Francisco Bay Metropolitan area, and Southern California that uses historical hydrologic record to maximize the economic values of agricultural and urban water use in the presence of environmental constraints (Draper et al. 2003). For the Upper Rio Grande Basin of North America, research about the impacts of water conservation on water withdrawals has been conducted (Ward and Pulido-Velazquez 2008). A proposal to protect the endangered Rio Grande silvery minnow using minimum instream flows has been evaluated (Ward and Booker 2003). Huber-Lee et al. (2003) is probably the most comprehensive existing hydro-economic study of the Sacramento River basin. It does not, however, carry out an assessment of improved water use efficiency or cropping pattern changes to help achieve sustainable water uses in the basin. Also, as the Sustainable Groundwater Management Act (SGMA), which represents California's first statewide law for this purpose, was just adopted in 2014, another contribution of our paper is to analyze the impact of implementing the new policy on agriculture in Sacramento River Basin.

III. Methodology

The conceptual framework developed for this paper is divided into two parts. The first part is used to carry out a hydrological analysis of the flow of Sacramento River. The second part presents an integrated hydro-economics model to analyze the impact of climate change and water management policy on agriculture in the Sacramento River basin.

i. Hydrological Analysis

Rivers are an important component of the hydrologic cycle. There exist a large number of methodologies to study river flows. The Flow Duration Curve (FDC) has been a popular technique in use since 1915 (Searcy 1959). It is a statistical method to characterize a river's ability to provide flows of different magnitudes. The flow duration curve is a graph that shows the relationship between river flow and exceedance probability. Exceedance probability is probability that the water flow in the river is likely to equal or exceed some specified amount in a certain period. The FDC is used to set up the river flow requirements for regulations, policies, and the amount of water in the river for specific use. Keeping the FDC within the 25th and 75th percentiles for 50% of the time has been recommended as the best flow amount for a river to support ecosystem health (Mathews and Richter 2007). A recommendation like this may be used to formulate the environmental flow constraint in our economic optimization model.

To be specific, exceedance probability can be calculated as follows:

$$p = 100 * \left[\frac{m}{n+1}\right] * 100\%$$

$p = probability\ that\ a\ given\ flow\ will\ be\ equaled\ or\ exceeded\ (\%\ of\ time)$

$n = total\ number\ of\ days\ for\ period\ of\ record$

$m = assigned\ rank\ number$

After ranking river flow discharge amount by magnitude from the largest amount to the smallest amount, one assigns the rank number m to each discharge in the period of record from 1 to *n*. Figure 4 shows an example of the DFC for Butte County. From year 1980 to 2015, Sacramento River flow in Butte County segment was at least 200 cf/s for 50% of time. If we set the environmental flow requirement as 25th percentile for 50% of the time, then the constraint for environmental flow will be 50 cf/s.

ii. Economic Analysis

Economic analysis is carried out with an integrated model which combines hydrologic and economic components. The objective of this model is to maximize the net present value of annual benefits from agriculture, subject to available land and water constraints. Total surface water constraint is considered as the average annual flow in Sacramento River. Annual groundwater usage is restricted to the recharge amount for implementing the goal of sustainable groundwater management. Surface and groundwater amounts thus made available for annual consumptive use are then used as a constraint in the economic model. Agricultural profits are computed using crop specific per acre production functions that make yields depend on water and temperature as well as irrigation technology. Net benefits from water use in the urban sector are based on current demand and projected increases. For purposes of simplification, we treat this urban water usage as an exogenous variable. Several crops are grown using water and other inputs, including technology for application of water, such as gravity, sprinkler, or drip irrigation. Choice variables in the agricultural sector are surface water, groundwater, and irrigation technology used for each crop, and land devoted to each crop.

The optimization problem is stated as follows:

$$\underset{SW_{ij},\, GW_{ij},\, Ld_{ij}}{Max} \quad \sum_{ij} P_{ij} * Y_{ij} - \sum_{i} (C_{ijsw} - C_{ijgw} - C_{ij})$$

$$s.t.: \sum_{ij} Ld_{ij} \leq \ TLd$$

$$\sum_{ij} SW_{ij} + \sum_{i} EF_i + \sum_{i} UW_{si} \leq TSW$$

$$\sum_{ij} GW_{ij} + \sum_{i} UW_{gi} \leq SGW$$

where :

i: number of counties in Sacramento River Basin

j: number of crop planted in each county

P_{ij}: *price of* j_{th}*crop in* i_{th}*county*

Y_{ij}: *yield of* j_{th}*crop in* i_{th}*county*

C_{isw}: *total cost of surface water withdral for agriculture in* i_{th}*county*

C_{igw}: *total cost of groundwater water for agriculture in* i_{th} *county*

C_i: *total other cost for agriculture in* i_{th}*county*

Ld_{ij}: *land use of* j_{th}*crop in* i_{th}*county*

TLd: *total land available for agriculture in Sacramento River Basin*

SW_{ij}: *agricultual water use from surface water for* j_{th}*crop in* i_{th}*county*

EF_i: *environmental flow requirements of river flow located in* i_{th}*county*

TW: *total water available in Sacramento River*

GW_{ij}: *agricultual water use from groundwater for* j_{th}*crop in* i_{th}*county*

SGW: goal of sustainable groundwater management set up by California Department of Water Resources

UW_{si}: *urban water use from surface water in* i_{th}*county*

UW_{gi}: *urban water use from groundwater in* i_{th}*county*

The crop production function we use is quadratic in water and temperature (Mendelsohn and Dinar 2003) and incorporates a water use efficiency parameter that is irrigation technology dependent. We estimate it for major crops cultivated in the region, for example, the top 10 crops planted in 2012 were corn for grain and forage, alfalfa, wheat, wine grape, processing tomato, safflower, asparagus, almond, rice, oats shown in Table 1 (Leinfelder-Miles).

Our production function may be stated in general form as:

$$Y_{ij} = f\left(X_{ijm}, SW_{ij}, GW_{ij}, Ld_{ij}, Z_{ij}, T_{ijn}\right)$$

Where

Y_{ij}: *output measured by yield of* j_{th}*crop in* i_{th}*county*

X_{ijm} :i_{th} *input, including labor and capital used to produce* j_{th}*crop in* i_{th}*county*

SW_{ij}: *agricultual water use from surface water for* j_{th}*crop in* i_{th}*county*

GW_{ij}: *agricultual water use from groundwater for* j_{th}*crop in* i_{th}*county*

Ld_{ij}: *land use of* j_{th}*crop in* i_{th}*county*

Z_{ij}: *the climate change variable set as temperature for* j_{th}*crop in* i_{th}*county*

T_{ijn}: m_{th}*water use efficiency parameter for* j_{th}*crop in* i_{th}*county, including gravity, sprinkler, and drip*

Climate change is modeled via scenarios for projected temperature and precipitation in the region, which impact river flows as well as crop productivity. Our predictions of Sacramento River flows under alternative climate change scenarios (going up to the year 2099) are based on Knowles and Cayan (Knowles and Cayan 2002). Temperature will be made to increase step-wise from 0.6°C to 2.1°C in the period 2020-2099. The entire time period will be divided into three segments. From 2020 to 2019, temperature will increase by 0.6°C. In this time period, the river flow will not be impacted much, so there is unlikely to be any discernable difference from prevailing conditions. In the second period (2050-2069), temperature will increase by 1.6°C, which will cause river flow to reduce 10% of the historical annual flow volume. In the last segment 2080-2099, temperature will increase 2.1°C, and Sacramento River Basin will be greatly impacted by climate change. There will be a loss of 4.4 km^3 of flow in the Sacramento River, which is about 20% of historical annual flow volume. Based on these climate scenarios, the amount of surface water constraint in the model, (TSW) will change accordingly from 0% to 20%.

IV. Data and Empirical Procedures

Data used for computations with our model includes river flow discharge, groundwater level, agricultural yields, and agricultural inputs, including land, water, climate conditions, labor and capital from nine counties covered by Sacramento River basin shown in Figure 5 (Hanak et al. March 2014). Top crops grown in the basin are listed in Table 1. Total land under crops is decreasing according to historical data collected from USDA shown in Table 2.

V. Simulation Results

VI. Conclusions

VII. References

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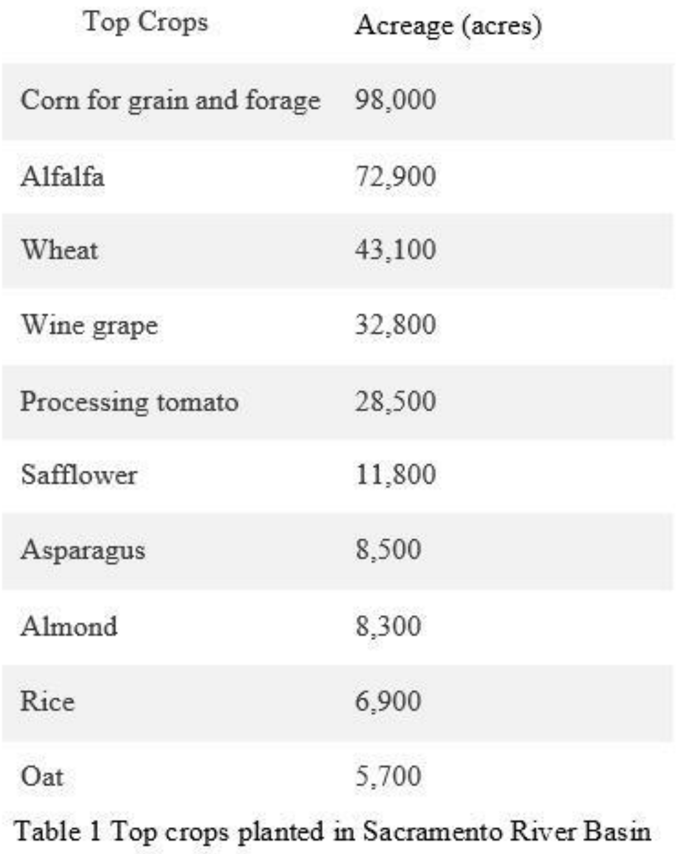
Table 1

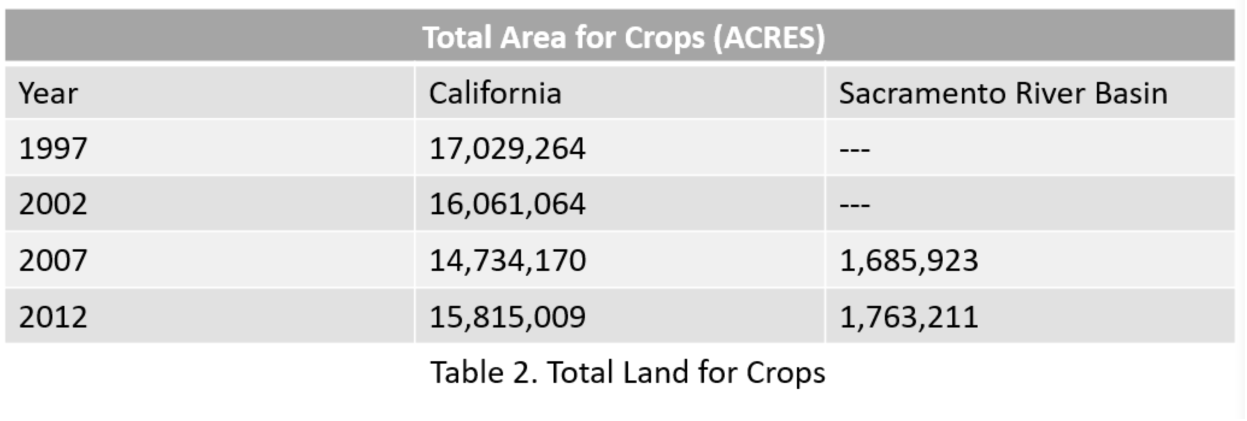


Top Crops	Acreage (acres)
Corn for grain and forage	98,000
Alfalfa	72,900
Wheat	43,100
Wine grape	32,800
Processing tomato	28,500
Safflower	11,800
Asparagus	8,500
Almond	8,300
Rice	6,900
Oat	5,700

Table 1 Top crops planted in Sacramento River Basin

Source: Leinfelder-Miles, Michelle. 'Welcome to the SJC and Delta Field Crops Page'. [http://ucanr.edu/sites/deltacrops/]

Table 2



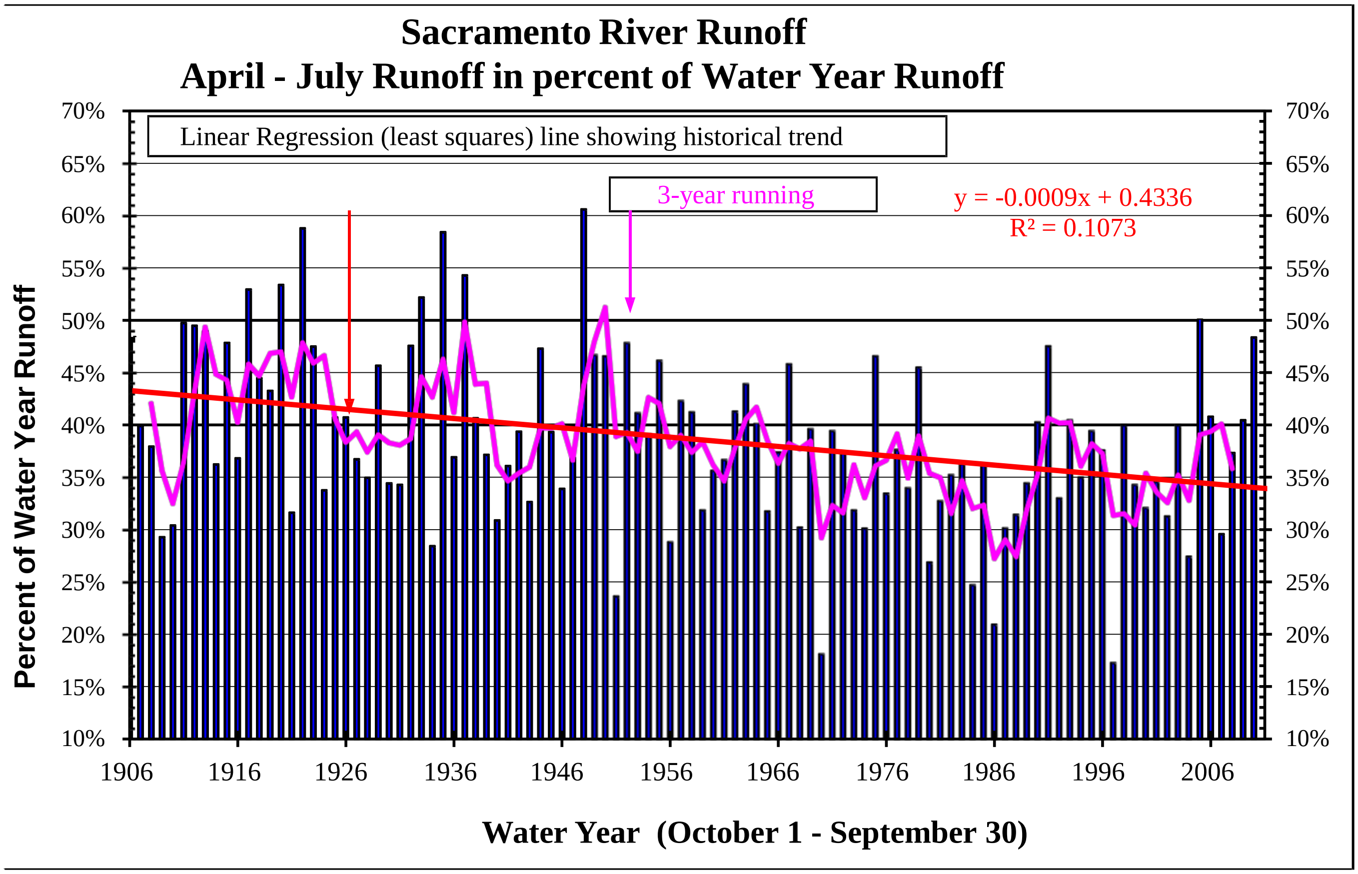
Total Area for Crops (ACRES)		
Year	California	Sacramento River Basin
1997	17,029,264	---
2002	16,061,064	---
2007	14,734,170	1,685,923
2012	15,815,009	1,763,211

Table 2. Total Land for Crops

Source: Census of Agriculture 1997-2012, United States Department of Agriculture.

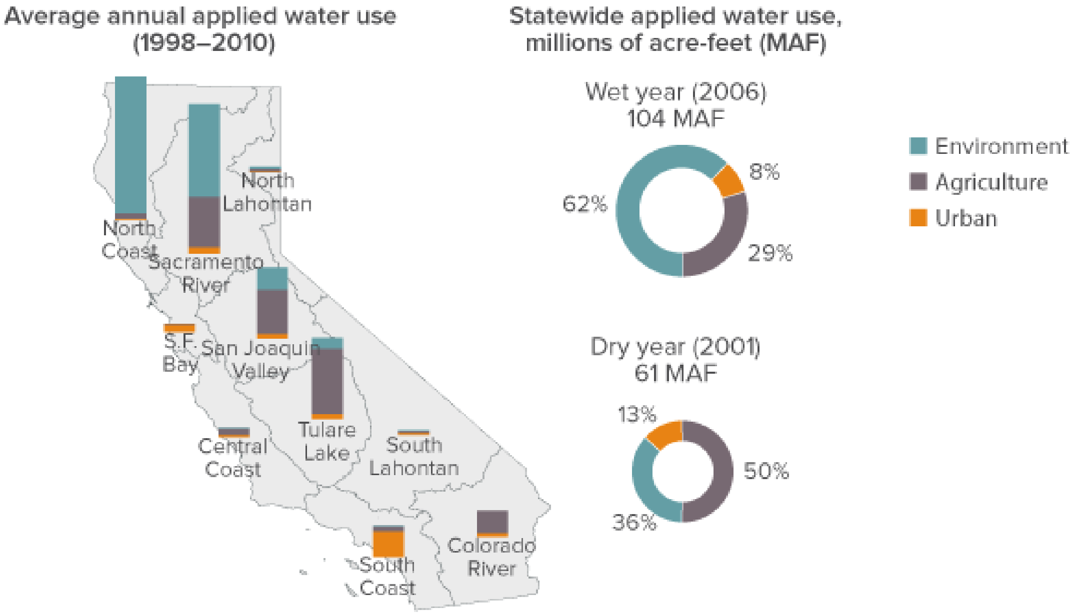
[https://www.agcensus.usda.gov/Publications/]

Figure 1



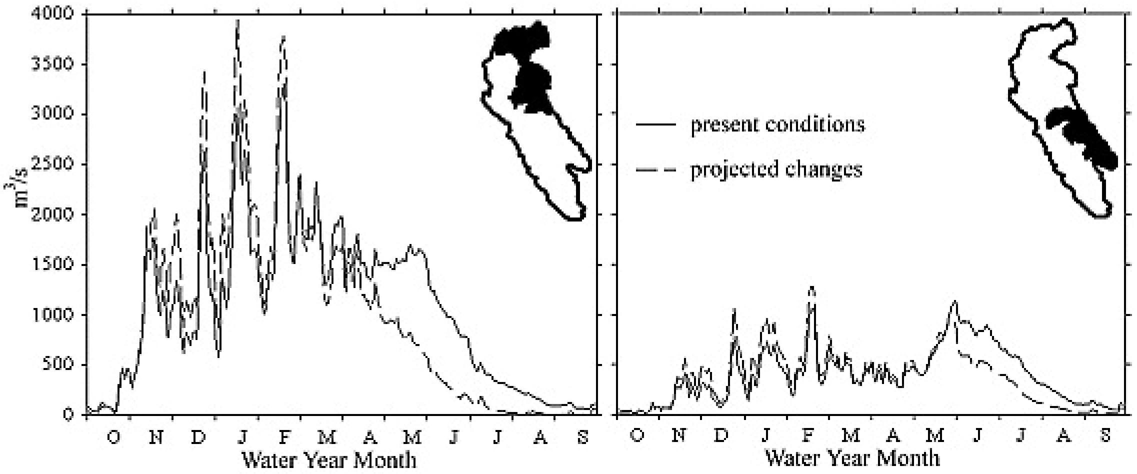
Source: Roos, Maury. 2012. "Snowpack and Snowmelt Changes." In, edited by California Department of Water Resources, 5.

Figure 2



Source: Department of Water Resources (2013). *California Water Plan Update* (Bulletin 160-13). [http://www.ppic.org/main/publication_show.asp?i=1108]

Figure 3



Projected mean annual hydrographs of northern and southern headwater regions for 2090, compared to present conditions.

Source: Knowles, Noah, and Daniel R. Cayan. 2002. 'Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary', *Geophysical Research Letters*, 29: 38-1-38-4

Figure 4

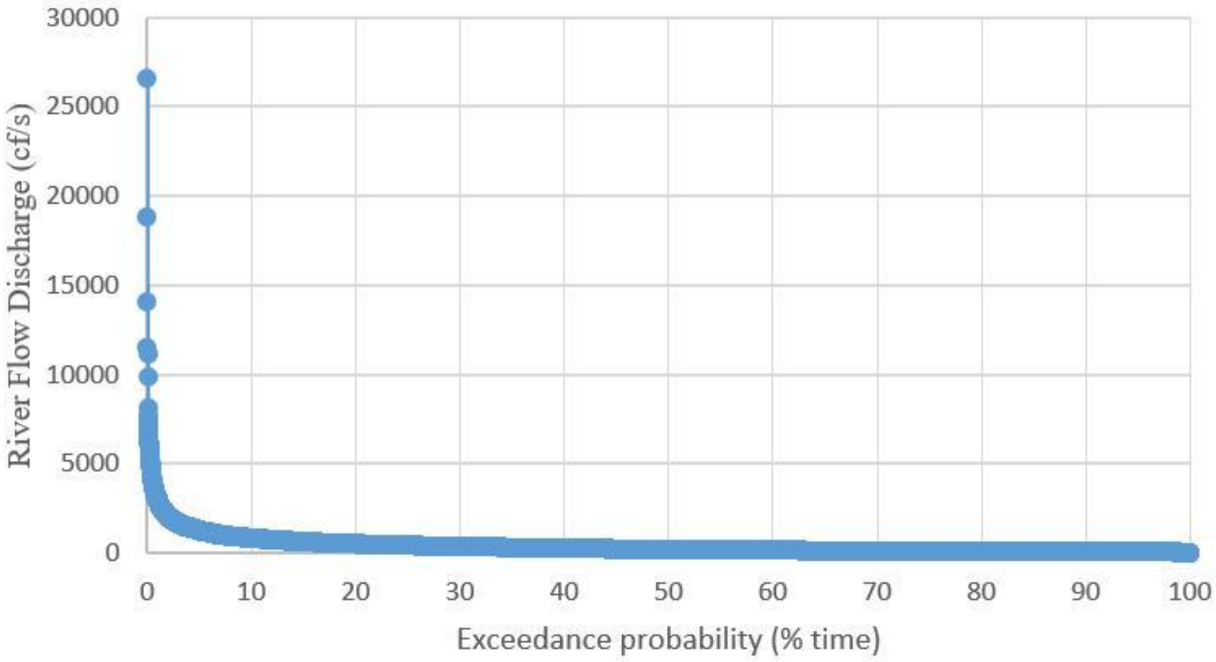


Figure 4. FDC for Station 11390000 Butte C NR Chico, CA (Year1980-2015)

Source: Daily streamflow data from USGS Water Resources

[https://waterdata.usgs.gov/ca/nwis/rt]

Figure 5

California Hydrologic Regions and Counties

Source: Hanak, Ellen, Brian Gray, Jay Lund, David Mitchell, Caitrin Chappelle, Andrew Fahlund, Katrina Jessoe, Josué Medellín-Azuara, Dean Misczynski, James Nachbaur, and Robyn Suddeth. March 2014. 'Paying for Water in California', Public Policy Institue of California: 81.