Applied Economic Perspectives and Policy (2016) volume 38, number 3, pp. 521–545.
doi:10.1093/aepp/ppw013
Advance Access publication on 13 July 2016.

Submitted Article

Drought Index Insurance for the Central Valley Project in California

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Submitted 20 August 2015; accepted 11 May 2016.

Abstract *A multi-year drought has taken a severe toll on the agricultural economy of California's Central Valley. Index insurance is an instrument with the potential to protect water users from economic losses due to periodic water shortages. An index insurance product based on the Sacramento Index and adapted to the Central Valley Project water supply is proposed. To address the potential for intertemporal adverse selection, three product designs are suggested: (1) "early bird" insurance; (2) variable premium insurance; and (3) variable deductible insurance. The performance of the designs are assessed using loss functions from the Westlands Water District in the San Joaquin Valley.*

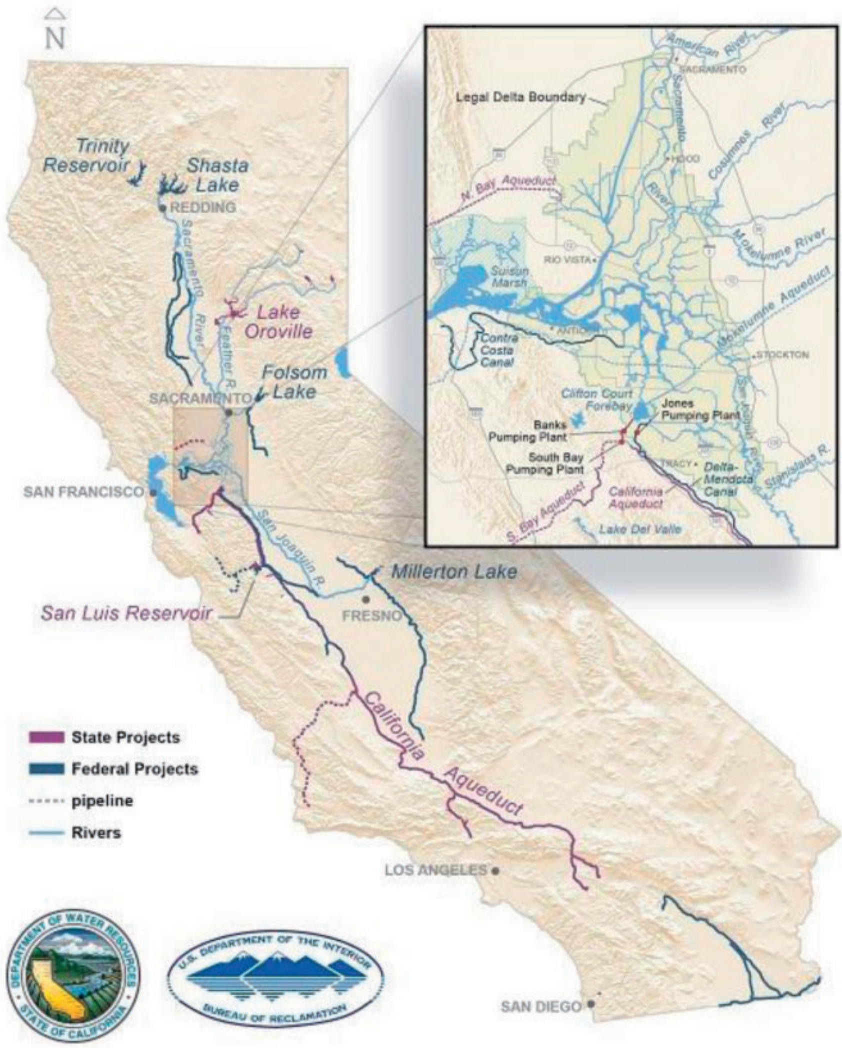
Key words: Intertemporal adverse selection, irrigated agriculture, Sacramento Index, water supply.

JEL codes: Q14, Q15, Q54.

Introduction

For more than 50 years California's Central Valley has been one of the most productive agricultural regions of the world, despite receiving rather limited rainfall (Griffin and Anchukaitis 2014). This is due in large part to irrigation water provided through an extensive network of interconnected reservoirs, aquifers, rivers, and aqueducts that link the two major river systems in the Central Valley: the Sacramento River in the north, and the San Joaquin River in the south (see figure 1). Water users in most of California have access to a wide portfolio of water sources, including water transfers, surface storage, groundwater banking, and water marketing, all of which reduce the vulnerability of irrigated agriculture to water scarcity situations

Figure 1 Geographic extent and general location of SWP and CVP facilities in Central Valley in California



Source: California Department of Water Resources and United States Bureau of Reclamation (2014).

(Hanak et al. 2011; Mukherjee and Schwabe 2015). There are two surface water supply infrastructures (the largest in California) that store and convey water in the Sacramento–San Joaquin River Basin: the Central Valley Project (CVP), financed by the federal government, and the State Water Project (SWP), financed by the state of California.

Despite the continuous efforts to increase efficiency and water reliability, California remains vulnerable to water scarcity problems. Prior to the winter of 2015–2016, California experienced three years of severe drought (Howitt et al. 2014). In fact, a recent study based on paleoclimate reconstructions of drought and precipitation in Central and Southern California found that the period 2012–2014 was the most severe drought experienced in the region over the last 1,200 years (Griffin and Anchukaitis 2014). This drought caused the loss of billions of dollars and thousands of seasonal and part-time jobs (Howitt et al. 2014).

This study examines the potential for landowners and farmers who receive irrigation water from the CVP to use an index insurance product to protect themselves from the financial implications of reduced water allocations. Specifically, scenarios are considered where reduced water allocations force landowners to leave some land fallow and farmers to experience increased costs associated with pumping groundwater for irrigation.

Various Multiple Peril Crop Insurance (MPCI) products are available for many of the crops produced in the Central Valley. For crops insured under an irrigated practice, these MPCI products provide coverage for yield losses due to a failure of irrigation water supply. However, farmers can insure under an irrigated practice only the acreage that would be fully irrigated considering the expected water availability at the beginning of the crop season (when insurance commences). The expected water availability is based on water available in reservoirs, soil moisture levels, snow pack storage levels (if applicable), and precipitation that would normally be received during the crop season. To be covered by MPCI, any failure in irrigation water supply must be due to a naturally occurring event. Decreased water allocations due to a diversion of water for environmental reasons, compact compliance, or other non-naturally occurring causes are not covered (USDA Risk Management Agency 2015).

Farm-level MPCI that includes coverage for irrigation water shortages can be difficult to implement due to asymmetrically distributed information. Insured farmers' proprietary knowledge of irrigation practices used on the farm leave the insurer vulnerable to moral hazard and adverse selection. To address asymmetric information concerns, an index insurance product is proposed that would cover the risk of water shortages. The product is also explicitly designed to cover shortages due to the diversion of water for environmental purposes—a major source of water supply risk that is not covered by existing MPCI products.

Compared to MPCI, index insurance is less vulnerable to moral hazard and adverse selection, is less expensive to administer, and is easier to reinsure because contracts are more transparent (Miranda and Farrin 2012). Unlike MPCI, which makes payments based on actual losses experienced by the insured, index insurance indemnifies the insured based on the observed value of a specified index. Ideally, an index is a random variable that is objectively observable, reliably measurable, and highly correlated with the losses of the insured, and cannot be influenced by the actions of the insured (Miranda and Farrin 2012). Examples that are well documented in the literature include area-yield (or revenue) index insurance in which indemnities are paid based on a shortfall in area average yield (or revenue) (Miranda 1991; Skees, Black, and Barnett 1997; Mahul 1999; Coble and Barnett 2008) and weather index insurance (Martin, Barnett, and Coble 2001; Turvey 2001; Vedenov and Barnett 2004; Barnett and Mahul 2007; Collier, Skees and Barnett 2009; Collier, Barnett and Skees 2011; North, Turvey, and Osgood 2013; Ritter, Musshoff, and Odening 2014).With weather index insurance, indemnities are paid based on realizations of an underlying index measured over a pre-specified period of time at a particular point of measurement. The underlying index triggering the indemnity might be a weather parameter such as rainfall or temperature, but it may also be an indirect measure of weather conditions such as a hydrologic variable (e.g., river flows or snow pack), a satellite-measured vegetation index, or an El Niño-Southern Oscillation index. The principal challenge in designing index insurance is to find an index that fulfills the quality standards of the insurance industry (i.e., objectivity, reliability, and transparency), correlates well with the insured losses, and generates sufficient demand (Collier, Skees, and Barnett 2009). Underlying indices generally must be carefully selected or designed for each index insurance product (Vedenov and Barnett 2004).

Weather index insurance pilot projects have been implemented in many developing countries (Skees et al. 2001; Barnett and Mahul 2007; Bielza et al. 2008; Barnett, Barrett, and Skees 2008; Collier, Skees, and Barnett 2009; Mahul and Stutley 2010; Miranda and Farrin 2012) but are feasible in developed countries as well. Previous studies demonstrate the potential for weather index insurance to cover water supply risks using a rainfall index (Zeuli and Skees 2005; Buchholz and Musshoff 2014) or streamflow indices (Brown and Carriquiry 2007; Leiva and Skees 2008; Zeff and Characklis 2013). However, to our knowledge no previous studies have focused on using index insurance to protect against water supply risks in California's Central Valley.

One major disadvantage of index insurance is basis risk, which is variability in the relationship between the value of losses as measured by the index and the value of losses actually experienced by the insured. Due to basis risk, it is possible for the insured to suffer a loss and yet not receive an indemnity (Barnett 2004; Skees, Barnett, and Collier 2008; Collier, Skees, and Barnett 2009; Miranda and Farrin 2012). Likewise, it is possible for the insured to receive an indemnity when no loss has occurred.

In the Central Valley of California, water is supplied by both the CVP and the SWP. However, water deliveries from the CVP are more variable than those of the SWP (Mukherjee and Schwabe 2015). Therefore, our study focuses on the CVP. Initial construction of the CVP began in October 1937; today the CVP consists of 22 reservoirs that can store 11 million acre-feet of water. In an average year, 7 million acre-feet are delivered, which is used to irrigate more than 3 million acres of farmland and provides drinking water to nearly 2 million consumers (California Department of Water Resources 2015b). An index insurance product is proposed that is adapted to the CVP water supply and provides economic compensation to landowners and farmers in years of surface water shortages. The insurance can be used to reduce variability in income and/or costs.

Water Management in the Central Valley of California

Surface water in the Central Valley flows through a network of canals and reservoirs that allows water to be transported from the more humid north (Sacramento Valley) to the drier south (San Joaquin Valley), where most of the irrigation demand is located. Two pumping stations, the C.W. Bill Jones (Tracy) Pumping Plant, operated by the CVP, and the Banks Pumping Plant, operated by the SWP (see figure 1), pump and divert water from the confluence of the Sacramento and San Joaquin rivers to the San Joaquin Valley. This water redistribution from north to south affects the water ecosystem, and concerns have been raised about maintaining sufficient surface water flows to support endangered species. Consequently, regulations establish minimum required surface water flows throughout the year and limit the export of water from the Sacramento–San Joaquin Delta. Appendix A.1 presents the primary water management regulations along with the period of implementation. Since 2009, environmental measures have become more stringent, with the implementation of Biological Opinions proposed by the

U.S. Fish and Wildlife Service (U.S. Bureau of Reclamation 2008), and by the National Marine Fisheries Service (National Marine Fisheries Service 2009), which set new salinity and flow requirements.

Groundwater constitutes, on average, about one-third of statewide water use. In contrast to surface water, there are few places (mainly in urbanized areas of Southern California) where users must have permits to withdraw a specific quantity of water. Thus, the right to pump groundwater is currently available to most users overlying the aquifer (Hanak and Stryjewski 2012). However, this is likely to change over time. State legislation adopted in January 2015 requires that local groundwater agencies be established by June 30, 2017. These agencies must develop groundwater management plans by January 31, 2020 for basins in a critical overdraft condition and by January 31, 2022 for all others. The legislation gives these local agencies the power to restrict groundwater pumping, shut down wells, and impose fines and penalties on resistant landowners (Dooley 2015).

For drought management and environmental protection purposes, the California Department of Water Resources and the United States Bureau of Reclamation use several indices to estimate available surface water supply in the Sacramento Valley (Sacramento Valley 40-30-30 Index) and the San Joaquin Valley (San Joaquin Valley 60-20-20 Index). Since most of the water used in the Central Valley comes from the Sacramento River, the Sacramento Valley 40-30-30 Index (hereafter, the Sacramento Index) is the most widely used to assess drought status for the Central Valley.

Drought Index Insurance for the Central Valley Project in California

The underlying index used for a water supply index insurance product should be a measure used by water managers for the distribution of water among users, provided it meets the quality standards of the insurance provider. For the CVP, the Sacramento Index is the measure used for water planning and management.

The Sacramento Index was originally specified in the 1995 State Water Resources Control Board (SWRCB) Water Quality Control Plan. The index is measured on May 1 each year and determines the water year hydrologic type for the implementation of flow and water quality criteria contained in State Water Board Decision D-1641 and in Biological Opinions (BOs; see Appendix A.1). The hydrologic classification of a water year provides relative estimates of a basin's available water supply based on the amounts of rainfall, snowmelt runoff, and groundwater accretion rates. Water year types are classified as wet, above normal, below normal, dry, or critical (California State Water Resources Control Board 2000; see table 1).

The hydrologic year begins in October. As shown in equation (1), the Sacramento Index (Sacramento Valley 40-30-30 Index) in hydrologic year t is composed of three components, weighted as its name suggests (40%, 30%, and 30%):

$$SI_t = [0.4 * \ AprJul_t] + [0.3 * \ OctMar_t] + [0.3 * Min(10, \ (SI_{t-1}))] \tag{1}$$

where $AprJul_t$ is the May forecast of runoff for the period April through July in million acre-feet, $OctMar_t$ is the actual unimpaired runoff for the period

Table 1 Sacramento Valley 40-30-30 Index (Sacramento Index) Water Year Hydrologic Classifications

Water Year Type	Sacramento Index value
Wet	Equal to or greater than 9.2
Above Normal	Greater than 7.8, and less than 9.2
Below Normal	Greater than 6.5, and equal to or less than 7.8
Dry	Greater than 5.4, and equal to or less than 6.5
Critical	Equal to or less than 5.4

Source: California State Water Resources Control Board (2000).

October through March in million acre-feet, and SI_{t-1} is the Sacramento Index in hydrologic year *t*-1. A cap of 10.0 million acre-feet is put on SI_{t-1} to account for required flood control reservoir releases during wet years. The $OctMar_t$ runoff is the sum of unimpaired flow from October through March in hydrologic year *t* in million acre-feet at the following locations: the Sacramento River above Bend Bridge; the Feather River at Oroville; the Yuba River near Smartville; and the American River below Folsom Lake. The unimpaired runoff represents the natural water production of the river basin, unaltered by upstream diversions, storage, or export or import of water to or from other watersheds. The natural runoff at a gauge is reconstructed by removing the effects of these "impairments". Unimpaired runoff is reconstructed following a methodology that is reported in the "California Central Valley Unimpaired Flow Data" (California Department of Water Resources 2007). Forecasts of runoff between April and July in hydrologic year *t* are made based on observed precipitation, flows, and snow pack by the California Department of Water Resources. Preliminary forecasts are made in February, March, and April, with the final determination coming in May.

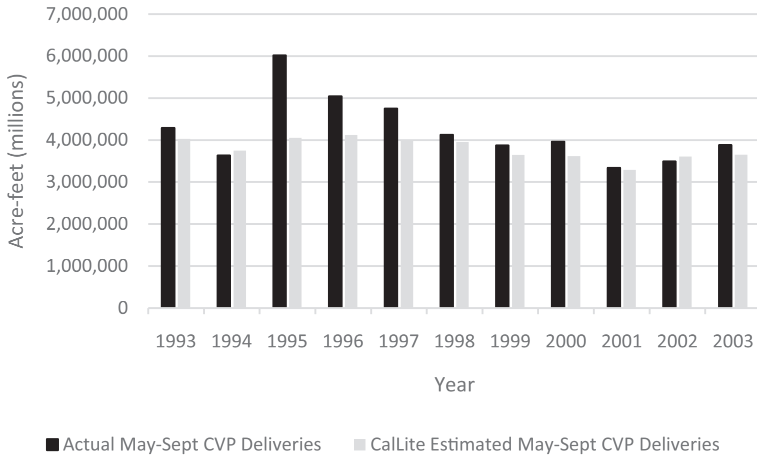
Potential for Intertemporal Adverse Selection

The Sacramento Index has an autoregressive component, which is the Sacramento Index of the previous hydrologic year (SI_{t-1}). If an insurance product based on the Sacramento Index is purchased at the beginning of the hydrologic year (October), both the policyholder and the insurer would have some information about the value that the Sacramento Index would take in the following May.[1] This autoregressive component must be addressed to avoid potential policyholders being more (less) likely to purchase the insurance product when the SI_{t-1} is low (high), suggesting that the Sacramento Index in the current year (SI_t) is also likely to be low (high).[2] To

[1]*Other examples of index insurance products with potential for intertemporal adverse selection include those with indices affected by the onset of El Niño conditions (GlobalAgRisk 2009) or those based on water reserves in a water supply system (Maestro et al. 2016).*

[2]*In an insurance context, adverse selection occurs when potential policyholders make insurance purchase decisions using information about their risk exposure that it not available (or, at least, not used) by the insurer. Adverse selection typically occurs cross-sectionally as the insurer inadvertently misclassifies the risk exposure of potential policyholders. Those whose risk exposure has been misclassified to their advantage (detriment) are more (less) likely to purchase insurance. However, adverse selection can also occur intertemporally if potential policyholders make purchase decisions using relevant information that is not used by the insurer.*

Figure 2. Actual and CalLite estimated CVP water deliveries for May through September irrigation period



address this potential for intertemporal adverse selection, the insurance sales closing date can be moved prior to the determination of SI_{t-1}. Alternatively, once SI_{t-1} is known, the premium rate or deductible may be made conditional on the value of SI_{t-1} (Luo, Skees, and Marchant 1994; Carriquiry and Osgood 2012; Ker and McGowan 2015; Osgood et al. 2008).

CalLite Estimates of Water Deliveries

Given the relatively recent changes in California water management regulations (the last changes were made in 2009), there are insufficient years of actual experience under the current regulatory regime to evaluate whether the Sacramento Index correlates well with actual CVP water deliveries. Therefore, a hydrologic model, known as CalLite, is used for estimating what would have happened in the past if the current regulatory regime had been in place. CalLite was developed by The California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Islam et al. 2011). CalLite can estimate monthly CVP water deliveries for the period 1922–2003 under different regulatory regimes. Additional information on CalLite can be found in Appendix A.2.

Data on actual monthly CVP water deliveries is available beginning in 1993 (United States Bureau of Reclamation 2015). The irrigation period is from May through September, so for each year between 1993 and 2003 the irrigation period actual deliveries were compared to the irrigation period CalLite estimated deliveries. Figure 2 clearly shows that the CalLite estimate of deliveries is generally lower than the actual CVP water deliveries for the irrigation period. But most of this difference occurs in years when the actual deliveries are unusually high (e.g., 1995–1997). What is relevant for the proposed insurance product is years when actual deliveries are less than expected. For the seven years when actual deliveries are less than the 11-year average of actual deliveries, the difference between the CalLite estimate and actual deliveries is quite small. Similarly, actual deliveries are clearly more variable than CalLite estimated deliveries over the 11-year period, but this difference goes away when one focuses only on the years when actual deliveries are less than the 11-year average. The correlation of the two series over the 11-year period is 0.79 (p-value $= 0.00$). For the seven years when actual deliveries were below the 11-year average, the correlation is 0.76 (p-value $=$ 0.02). For the three years when actual deliveries were less than 90% of the 11-year average, the correlation coefficient was 0.98 (p-value $= 0.06$). This suggests that the CalLite estimates are a good proxy for actual CVP water deliveries, especially in years when actual deliveries are low (which is what is relevant for the insurance product).

Data on the Sacramento Index is available from the California Department of Water Resources (2015a). No statistically significant time trend is observable in the Sacramento Index data from 1922 until 2003, which corresponds to the period for which CalLite can conduct water delivery estimates. The average value of the index over this period was 7.93, which is close to the threshold between *Above Normal* and *Below Normal* water year hydrologic classifications (see table 1).

The linear correlation between the Sacramento Index and CalLite estimated CVP annual irrigation period (May–September) water deliveries under the current regulatory regime for the period 1922–2003 is 0.87 (p value =0.00).[3] Linear and logarithmic models linking the Sacramento Index and CalLite estimated annual water deliveries in thousand acre-feet (TAF) were compared using the Box-Cox transformation, which makes the residual sums of squares directly comparable.[4] The double logarithmic model was selected because it had the smallest residual sum of squares:

$$\log CalLite\ Water\ deliveries_t = \underset{(0.048)}{7.34^{***}} + \log SI_t \times \underset{(0.023)}{0.38^{***}} \tag{2}$$

adjusted R^2 0.76.

In equation (2) the three asterisks denote statistical significance at the 1% level. Numbers inside parentheses represent the robust standard errors. Equation (2) means that if the Sacramento Index increases by 1%, estimated CVP water deliveries increase by 0.38%. The adjusted R^2 indicates that 76% of the variability in estimated water deliveries is explained by the Sacramento Index. However, equation (2) it is not sufficient to demonstrate the performance of an index insurance product based on the Sacramento Index because it does not account for how the level of water deliveries translates into economic losses. Thus, empirical analyses of the performance of the proposed index insurance product are presented later.

[3] *The current regulatory framework simulated in CalLite includes D-1641 and Biological Opinions.*

[4] *The procedure consists of dividing the observations on the dependent variable by their geometric mean and then regressing the transformed variables, leaving the right side of the equation unchanged. The residual sums of squares are then directly comparable. The specification with the smaller RSS therefore provides the better fit (Zarembka 1968; Spitzer 1984).*

Design and Rating of Sacramento Index Insurance

The proposed insurance product would provide a payout whenever environmental conditions (as measured by the Sacramento Index) fall below a threshold signaling that water users will not receive their full allocation of water. The payout increases as the Sacramento Index decreases (below the upper threshold). The rate at which the payout increases per unit change of the index is called the "tick" of the contract. The formula for the insurance payout or indemnity I_t in year t, is shown in equation (3):

$$I_t = \begin{cases} 0 & if \quad SI_t \geq U \\ D \times (U - SI_t) & if \quad SI_t \; < \; U \end{cases}, \tag{3}$$

where SI_t denotes the Sacramento Index in year t; U, the upper trigger of the contract, and D, the tick, are both choice variables selected by the purchaser. *Liability* is equal to $D \times U$, which is the maximum possible payout of the contract.

The actuarially fair premium P is given by the expected indemnity $E(I_t)$ and the actuarially fair premium rate in percentage terms is the actuarially fair premium (expected indemnity) divided by the liability.

To develop insurance designs that address the potential for intertemporal adverse selection, it is necessary to analytically determine the expected distribution of the Sacramento Index in year t conditional on the value of the Sacramento Index in year t-1. To do this, distributions were fit to each of the components of the Sacramento Index: $OctMar_t$ (actual unimpaired runoff for the period October through March in million acre-feet), $AprJul_t$ (May forecast of runoff for the period April through July in million acre-feet), and SI_{t-1} (Sacramento Index in hydrologic year t-1). Gamma, Lognormal, Normal, and Weibull distributions were compared using the Kolmogorov-Smirnov (K-S) test (Massey 1951). The K-S test measures how well the distribution fits the input data and how confident one can be that the data could have been produced by the distribution function. The (K-S) statistic is generally preferred over the chi-square statistic because it is not dependent on the set of midpoints used for the histogram (Palisade Corporation 2015). The Gamma distribution was the best fit for both $OctMar_t$ and $AprJul_t$ flows. For the lagged Sacramento Index (SI_{t-1}), the Lognormal distribution was the best fit, followed by the Gamma distribution. Since the Gamma distribution was also a valid fitting for SI_{t-1}, it was used for all the components, as shown in table 2. Summary statistics from the distribution fitting procedure can be found in appendix tables A1–A3.

For a given value of SI_{t-1}, stochastic simulation for the other two components was performed using @Risk 7 (Palisade Corporation 2015). The linear correlation between $OctMar_t$ and $AprJul_t$ was estimated to be 0.67 (p-value $=0.00$; see figure A1). The correlation between SI_{t-1} and $OctMar_t$ was not statistically significant (p value >0.10), nor was the correlation between SI_{t-1} and $AprJul_t$ ($p -$ value > 0.10), see figure A1. In order to better capture nonlinear dependencies that may exist at the relevant extremes of $OctMar_t$ and $AprJul_t$, copulas were used instead of linear correlations. A copula is a function that combines marginal distributions of variables into a specific multivariate distribution (Collier, Barnett, and Skees 2011). Five copula functions were tested

Table 2 Distributions Fitted to the Components of the Sacramento Index in the Period 1922–2014 and Sacramento Index Conditional Distributions for a Given Value *t* with Sacramento Index in Year t-1 Equal to 2, 4, 6, 8, and 10

Variable	Fitted Distribution Gamma (threshold θ, scale σ, shape α)	*p*-value Kolmogorov-Smirnov test	Expected value
Oct–Mar	Gamma (2.14, 3.50, 2.25)	>0.25	10.05
Apr–Jul	Gamma (1.44, 2.04, 2.49)	>0.5	6.5
SI	Gamma (1.75, 1.17, 5.24)	>0.25	7.88
SI | SI_{t-1} = 2	Gamma (1.69, 1.55, 2.92)	=0.15	6.22
SI | SI_{t-1} =4	Gamma (2.29, 1.55, 2.92)	=0.15	6.82
SI | SI_{t-1} =6	Gamma (2.89, 1.55, 2.92)	=0.15	7.42
SI | SI_{t-1} =8	Gamma (3.49, 1.55, 2.92)	=0.15	8.02
SI | SI_{t-1} =10	Gamma (4.09, 1.55, 2.92)	=0.15	8.62

using @Risk 7 (Palisade Corporation 2015): Gaussian and t copulas from the family of Elliptical copulas, and Gumbel, Clayton, and Frank copulas from the family of Archimedean copulas. Maximum likelihood estimation (MLE) was used to estimate the parameters of the copula functions. The Akaike Information Criterion (AIC) was used to choose among alternative model specifications. Although it does not provide any absolute measure of goodness-of-fit, AIC does identify that one copula is a better fit than the others (Palisade Corporation 2015). The best fit for the joint behavior of $OctMar_t$ and $AprJul_t$ was a Gumbel copula reflected about both axes (GumbelR) with $\theta = 2.127$ (see figure A1).

The conditional distributions of the Sacramento Index in year *t* for a Sacramento Index value in year *t*-1 equal to 2, 4, 6, 8, and 10 were fit using 5,000 draws from the distributions of $OctMar_t$ and $AprJul_t$ with the dependence between these variables modeled using a Gumbel copula as described above. Summary statistics from the distribution fitting procedure can be found in appendix tables A4–A8. Not surprisingly, the distributions shift to the right with increasing values of the Sacramento Index in year *t*-1.

Three alternative index insurance designs are proposed to address the potential for intertemporal adverse selection: (1) "early bird" insurance; (2) variable premium insurance; and (3) variable deductible insurance. Figure 3 shows the timeline of the insurance product purchase, payoff determination, and other important milestones such as the premium determination for the variable premium design and the deductible determination for the variable deductible design. Early bird insurance would require insurance to be purchased one year before the hydrologic season begins (i.e., October of the previous year). This design has a constant actuarially fair premium rate since no reliable information is yet available to inform expectations of the distribution of the Sacramento Index.

If the insurance product is instead purchased after SI_{t-1} has been determined, expectations of the distribution of SI_t can be conditioned on the value of the SI_{t-1}. As a consequence, two different designs are proposed to address the potential for intertemporal adverse selection: variable premium insurance utilizes a premium rate that is conditioned on the value of SI_{t-1}, and variable deductible insurance utilizes a deductible that is conditioned on the value of SI_{t-1}. The purchaser of an insurance product with the variable premium design would be concerned about protecting against

Figure 3 Timeline for proposed Central Valley Project index insurance designs

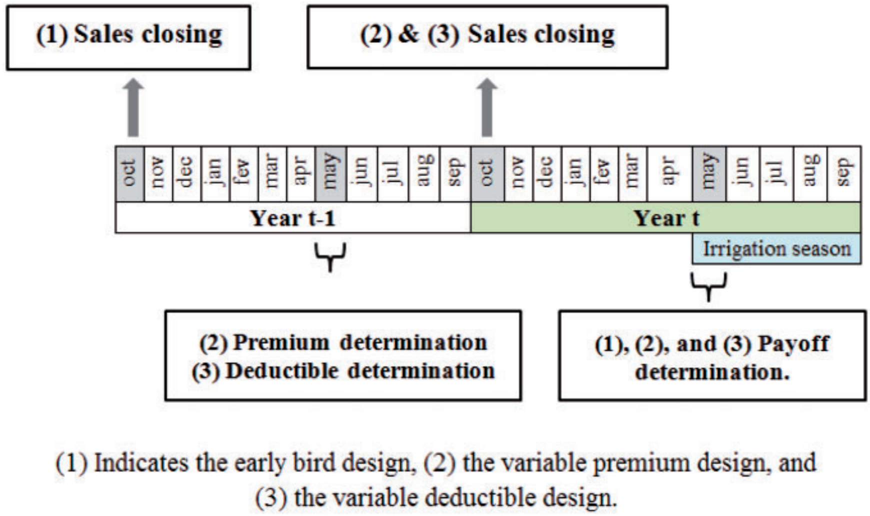


Table 3 Premium Rates for the Early Bird Contract Design Considering Different Sacramento Index Thresholds

Upper threshold	Premium rate (historic data)	Premium rate (Montecarlo simulation*)
6.4	6.08%	6.16%
7.2	10.13%	9.79%
7.6	12.37%	11.82%
7.8	13.45%	12.88%
8	14.53%	13.96%

Note: Asterisk * indicates 5,000 draws from Gamma (1.75, 1.17, 5.24). Premium Rates are calculated from historical data (1922–2014) and Monte Carlo simulation.

shortfalls in SI_t relative to an absolute upper threshold U (recognizing that the premium rate will vary with the level of SI_{t-1}). The purchaser of an insurance product with the variable deductible design would be concerned about protecting only against shortfalls in SI_t that could not have been anticipated given the value of SI_{t-1}.

For the early bird design, actuarially fair premium rates are shown in table 3. Several levels of the upper threshold are considered. An upper threshold equal to 8 (U = 8) corresponds to the expected value of the Sacramento Index. Put differently, U = 8 provides coverage equal to 100% of the expected value of the index. Lower values of the upper threshold would provide lower levels of coverage; U = 7.8, corresponding to the threshold between Below Normal and Above Normal water year hydrologic classifications (see table 1) provides 97% coverage; U = 7.6 provides 95% coverage, U = 7.2 provides 90% coverage, and U = 6.4 provides 80% coverage. Actuarially fair premium rates were calculated empirically using historical Sacramento Index data for the period 1922–2014. Premium rates were also calculated through Monte Carlo simulation. Five thousand realizations of the Sacramento Index were simulated using the gamma distribution fitted to the historic data (Gamma (1.75, 1.17, 5.24), see table 2). The premium rates obtained from each method were very similar (see table 3).

For both the variable premium and variable deductible designs, the upper threshold is established at U = 7.8 (to the threshold between Below Normal and Above Normal water year hydrologic classifications). For the variable premium design, actuarially fair premium rates are a decreasing function of SI_{t-1}. Because of the formula used to calculate the Sacramento Index (see equation 1), the actuarially fair premium rate remains constant for values of SI_{t-1} that are greater than or equal to 10. Equation (4) presents the equation for the actuarially fair premium rate based on the relationship between premium rates from their stochastic simulations at different levels of SI_{t-1}:

$$Premium\ rate\ (\%) = \begin{cases} \underset{(0.07)}{-2.485^{***}} \times SI_{t-1} + \underset{(0.42)}{31.334^{***}} & if\ SI_{t-1} < 10 \quad Adj\ R^2 = 0.99 \\ 7.76 & if\ SI_{t-1} > 10 \end{cases} \tag{4}$$

In equation (4), asterisks *** denote significance at the 1% level. Numbers inside parentheses represent the robust standard error.

For the variable deductible design, the premium rate remains constant but the deductible varies conditional on the value of SI_{t-1}. The variable conditional deductible would be calculated as shown in equation (5) as the difference between the maximum expected Sacramento Index in year t (that corresponds to the expected Sacramento Index in year t conditional on a Sacramento Index in t-1 greater than or equal to 10) and the expected Sacramento Index in year t conditional on the actual value of the Sacramento Index in year t-1:

$$Deductible = (E(SI_t)|SI_{t-1} \geq 10) - (E(SI_t)|SI_{t-1}). \tag{5}$$

The conditional deductible (as a percentage of the upper threshold U) varies as shown in equation (6) and the actuarially fair premium rate is constant at 7.76%:

$$Deductible\ (\%) = \begin{cases} -3.85 \times SI_{t-1} + 38.46 & if\ SI_{t-1} < 10 \quad Adj\ R^2 = 1 \\ 0 & if\ SI_{t-1} \geq 10 \end{cases}. \tag{6}$$

Index Insurance Performance for Westlands Water District Landowners and Farmers

The performance of the index insurance is tested by assuming that it is purchased by landowners or farmers who obtain irrigation water through the Westlands Water District (WWD).[5] The WWD is located in the San Joaquin Valley, in western parts of both Fresno and Kings counties and is

[5] *Drought conditions may also cause losses for a water supplier such as Westlands Water District (see Zeff and Charaklis 2013) but due to a lack of loss data for the water supplier, that scenario is not analyzed here.*

part of the San Luis Unit of the CVP. Much of the water supplied by the WWD is used for irrigation. There are likely other loss scenarios due to reduced water allocations that could be considered if sufficient data were available to estimate loss functions (e.g., switching from crops with higher expected returns but that require more water, to those with lower expected returns but that require less water).

The effectiveness of the index insurance in reducing income variability is tested using loss functions assuming the current water management regulatory regime. The effectiveness of the index insurance can be analyzed by comparing the standard deviation of net loss outcomes with and without the insurance contract (Collier, Skees, and Barnett 2009; Kellner and Musshoff 2011). In addition to the actuarially fair premium rate, premium loads of 10%, 20%, and 30% are considered.

Losses experienced due to water shortages are analyzed for both landowners and farmers. The loss function for landowners assumes that reduced water allocations cause land to be left fallow. The loss function for farmers assumes that a crop is planted but, due to a reduced surface water allocation, significantly higher costs are incurred to pump groundwater for irrigation.

Since data for individual landowners or farmers is not available, the analysis is conducted for all irrigated acreage in the WWD. For both the landowner and farmer analysis, the tick size is determined by minimizing the standard deviation of the net loss function, calculated by deducting from any indemnities received the actuarially-fair premium, as well as the estimated losses incurred from fallowed land or from pumping groundwater. Insufficient data are available to test the insurance performance out of sample; consequently, the hedging effectiveness of the index insurance design should be considered a best-case outcome.

Fallowed land is assumed to have no rental value for that year. Land acreage reports are available from 2000 to 2013 (Westlands Water District 2015). A negative correlation (-0.67) exists between the Sacramento Index and fallow land in the WWD for the period 2000–2013, confirming that fallow land increases in drought years. The loss in rental income on fallow land is measured considering the average annual cash rent per irrigated acre in California, obtained from the USDA (2015). These data exhibit a positive trend for the available period 1994–2008. As a consequence, the data series was detrended to the 2008 level for this analysis. Due to a lack of data after 2008, average annual cash rent per irrigated acre was considered to be constant from 2008 to 2013. Table 4 shows the hedging effectiveness of the proposed index insurance using a loss function based on annual cash rent losses for the period 2000–2013.

Compared to the no insurance scenario, all the insurance designs have a lower standard deviation of net losses. Furthermore, the maximum net loss is smaller for all of the insurance scenarios except for the variable deductible design with a 30% premium load. By comparing the different insurance designs, the early bird design is most effective in reducing cash rent variability, while the variable deductible design is the least effective.

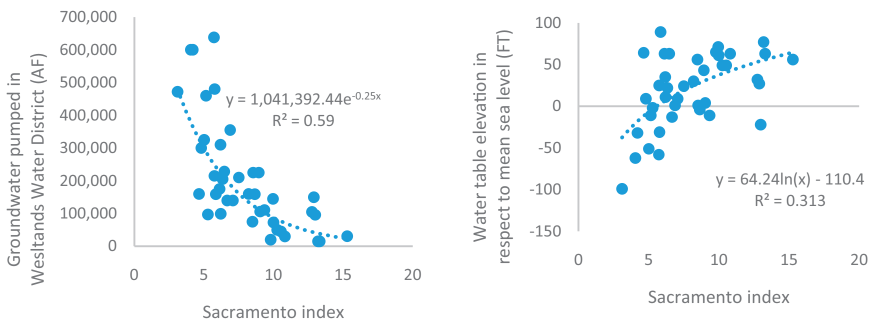
The performance of the index insurance can also be tested using a loss function based on costs incurred for pumping groundwater.[6] When needed,

[6] *The analysis presented here is based on the current situation with farmers generally having unrestricted rights to pump groundwater. In the future, as groundwater pumping restrictions authorized by recent*

Table 4 Hedging Effectiveness of the Index Insurance Schemes (Upper threshold U = 7.8) Proposed in Westlands Water District Using a Loss Function Based on Annual Cash Rent Losses (in millions $)

		With Insurance											
		(1) Early bird contract. Premium load:				(2) Variable premium. Premium load:				(3) Variable deductible. Premium load:			
In millions $	Without insurance	0%	10%	20%	30%	0%	10%	20%	30%	0%	10%	20%	30%
Tick	–	7.9				6.2				6.8			
Standard deviation	10.93	7.79	7.79	7.79	7.79	9.26	9.4	9.54	9.68	10.18	10.18	10.18	10.18
Maximum losses	56.25	48.22	49.02	49.81	50.61	52.68	53.58	54.48	55.37	55.26	55.66	56.05	56.45

Figure 4 Relationship between Sacramento Index and (left) groundwater pumped in acre-feet (AF) or (right) water table elevation in feet (FT), Westlands Water District, 1974-2013



farmers in the WWD pump groundwater to replace shortfalls in anticipated CVP surface water deliveries. Data on the depth of the groundwater table and the amount of groundwater pumped in the WWD are available for the years 1974–2013 (Westlands Water District 2014); these data are used to estimate a loss function. Groundwater pumping costs depend on the amount of water pumped and the vertical height lifted. Figure 4 (left) presents the relationship between the Sacramento Index and groundwater pumping in the WWD. The higher the Sacramento Index (the higher the availability of surface water), the less groundwater is pumped. In figure 4 (right), the relationship between the Sacramento Index and water table depth with respect to the sea level is shown. The higher the Sacramento Index, the higher is the water table (less energy is then needed to pump groundwater).

To estimate the costs of pumping groundwater, an energy intensity coefficient is used that estimates the kilowatt-hours (KwH) needed to pump one acre-foot of groundwater depending on the vertical height lifted (Fraenkel 1986). The energy intensity coefficient (e_{GW}) for self-supplied, untreated groundwater used by the agricultural and industrial sectors is shown in equation (7); it depends on a lift parameter (l), hydraulic head (h), and pump efficiency (ϵ)

state legislation take hold, farmers may wish to purchase the proposed index insurance to protect themselves against losses caused by seasonal pumping restrictions related to the value of the Sacramento Index.

Table 5. Hedging Effectiveness of the Index Insurance Schemes (Upper threshold U = 7.8) Proposed in Westlands Water District Using a Loss Function Based on Groundwater Pumping Costs (in millions $)

		With insurance											
		(1) Early bird contract. Premium load:				(2) Variable premium. Premium load:				(3) Variable deductible. Premium load:			
In millions $	Without insurance	0%	10%	20%	30%	0%	10%	20%	30%	0%	10%	20%	30%
Tick	–	16.8				15.2				20.6			
Standard deviation	30.5	20.68	20.68	20.68	20.68	23.57	23.91	24.26	24.62	26.12	26.12	26.12	26.12
Maximum pumping costs	114.65	96.76	98.44	100.13	101.82	100.08	101.76	103.45	105.14	110.94	112.14	113.35	114.55

$$e_{GW} = \frac{l * h}{\epsilon}, \tag{7}$$

where l is equal to 1.027KwH per 1 acre-foot of water per foot of depth, which is the theoretical energy required to lift a volume of water vertically from a well, assuming no friction and perfect pump efficiency, ϵ is established at 50%, considered an average pump efficiency in developed economies, and h is the water table depth in feet. The Westlands Water District average elevation is equal to 295 feet. The price of energy is assumed to be \$0.248/KwH (Pacific Gas & Electric Company 2014).

Based on these calculations, for the period 1974–2013 pumping costs for farmers in the Westlands Water District averaged \$31.4 million per year, and varied between \$1.7 and \$114.7 million, with a standard deviation of \$30.5 million. Pumping costs averaged \$140.40 per acre-foot and varied between \$104.90 and \$200.60 per acre-foot, with a standard deviation equal to \$22.10 per acre-foot.

Table 5 shows the hedging effectiveness of the proposed index insurance using a loss function based on groundwater pumping costs for the period 1974–2013. As with the previous loss function, each of the insurance designs reduces the standard deviation of net losses, even with a 30% premium load. For this loss function, each of the insurance designs also reduces the maximum net loss. Again, the early bird contract is the most effective in reducing the variability of pumping costs.

It is important to recall that the insurance payment is in no way dependent on how the landowner or grower decides to react to a reduced water allocation. For this reason, the proposed index insurance product does not affect marginal conditions for input (land or water) demands. The insurance payout is completely unrelated to whether or not the landowner actually fallows acreage, or whether or not the farmer actually pumps groundwater. The landowner is not required to plant to receive the insurance indemnity, nor is the farmer required to pump groundwater. For this reason, the insurance product should have no detrimental environmental impacts. This is in contrast to traditional multiple-peril crop insurance, which is tied directly to a farmer's production decisions and thus may affect marginal conditions for input (land or water) demands.

Conclusion

The California Central Valley is significantly exposed to water scarcity. An index insurance product adapted to the CVP is proposed as a means to provide landowners and farmers with protection against economic losses due to occasional reductions in surface water allocations.

The proposed index insurance is based on the Sacramento Index, one of the indicators used as a trigger in water management regulations. The Sacramento Index signals shortages in CVP water deliveries, including the effects of water diverted for environmental reasons. The implementation of the index insurance is straightforward, and its operating and administrative costs would be relatively small.

Due to changes in water regulations over time, the analysis could not be conducted using time series data on historical CVP water deliveries. Instead, a hydrologic model was used that simulates historical CVP water deliveries under an assumed regulatory regime. Reduced surface water deliveries were translated into monetary losses using two possible loss functions: one based on foregone rental revenue for landowners with fallow land, and one based on increased costs to farmers from groundwater pumping. Three different index insurance designs were considered along with four different premium rate structures. Premium rates are assumed to be actuarially fair, and loaded by 10%, 20%, or 30%.

Our results show that none of the proposed insurance designs completely offset losses arising from a reduction in surface water allocations. Index insurance would, however, reduce the losses, even when the insurance contains a 30% premium load. This study demonstrates the potential for using index insurance to decrease the variability of economic losses caused by shortages in CVP water allocations. The analysis with premium rate loads suggests a market opportunity for insurance suppliers. Further research could extend this analysis to other irrigation districts, as well as consider alternative index insurance designs.

Future research efforts could also examine whether the proposed insurance could provide risk reduction benefits to water market participants. In drought years the value of surface water increases. Thus, while holders of surface water rights may receive reduced allocations, the value of the surface water they receive on a per unit basis will be higher—which creates a sort of natural hedge for those who sell in water markets. Due to impacts on local economies or environmental conditions, the ability of water rights holders to export water out of a local area is sometimes limited by local, state, or federal authorities (Chaudry, Fairbanks, and Caldwell 2015). Such restrictions undermine the natural hedge and expose water sellers to greater revenue risk. The proposed index insurance could possibly be used by holders of water rights to compensate for the fact that water transfer restrictions have undermined the natural hedge in the value of annual water allocations.

Acknowledgments

This research was made possible by funding from the Mississippi Agricultural and Forestry Experiment Station and the National Research, Development and Innovation Plan, Office of the State Secretariat for Research, Development and Innovation, Ministry of Economy and Competitiveness, Spain, in the framework of the *Hydrological drought insurance for irrigation: an adaptation tool for climate change*, Project no. AGL2010-17634. The authors wish to thank Russ Freeman from Westlands Water District, Richard Howitt from the University of California, Davis for helpful comments, the California Department of Water Resources for sharing CalLite software, and anonymous reviewers for their useful comments.

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Appendices

A.1 Regulation Framework in Central Valley in California

Regulation and date of publication	Description and main regulatory constraints	Implementation
State Water Board Decision 1485 (D-1485). August 1978. (California State Water Resources Control Board 1978)	The D-1485 standards aim to protect the beneficial uses of the water of the Sacramento-San Joaquin Delta (Delta) and Suisun Marsh. The Racanelli Decision in 1986 overturned D-1485 because its use of *pre-project construction* conditions as a measure of flows needed to protect existing water rights in the Delta focused on water rights instead of beneficial uses.	1978–1986
Central Valley Project Improvement Act (CVPIA). October 1992 (United States Bureau of Reclamation 1992)	On October 30, 1992, Title 34 of Public Law 102-575, known as the CVPIA, was signed into law by the U.S. President. Title 34 mandates changes in management of the Central Valley Project, particularly for the protection, restoration, and enhancement of fish and wildlife. New regulations include 800,000 acre-feet of water dedicated to fish and wildlife annually (section 3406 (b)(2)), water transfer provisions (section 3405), and no new water contracts until fish and wildlife goals are achieved (section 3404).	1993–present
Bay-Delta Accord in 1994 (California Department of Water Resources 1994) and Bay-Delta Plan 1995.	Initiated a long-term planning process to improve the Delta and increase the reliability of its water supply, particularly for water quality standards. The accord also created the California Water Policy Council and Federal Ecosystem Directorate (CALFED). Bay-Delta Plan was superseded by Water Quality Control Plan in 2005.	1995–2005
State Water Board Decision 1641 (D-1641). 1999. (California State Water Resources Control Board 2000)	The primary purpose of this decision was to allocate responsibility for implementing the flow-dependent objectives of the 1995 Bay-Delta Plan (California Department of Water Resources 1994). D-1641 sets today's minimum outflow requirements for the Delta, delta cross channel operations, minimum river flows at Rio Vista, X2 requirements for salinity control, water temperature requirements, export restrictions through	1999–present

(continued)

Continued

Regulation and date of publication	Description and main regulatory constraints	Implementation
	the export-inflow ration and Vernalis criteria, and salinity standards at Emmaton, Jersey Point, Rock Slough, and Collinsville.	
Water Quality Control Plan (WQCP) for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. December 2006. (California State Water Resources Control Board 2006)	The Water Quality Control Plan (WQCP) supersedes the 1995 Bay-Delta Plan. WQCP is primarily a planning document that serves to identify the water quality objectives and the beneficial uses to be protected. Among other objectives, it defines Net Delta Outflow Index (NDOI) requirements and requirements for San Joaquin River flows at Vernalis.	2005–present
Biological Opinion FWS BO RPA. December 2008. (Bureau of Reclamation 2008)	The National Marine Fisheries Service (NMFS) provides Reasonable and Prudent Alternatives (RPA) of the U.S. Fish and Wildlife Service (FWS) to protect Delta Smelt; it also sets additional X2 salinity requirements (FWS Action 4), and flow restrictions at Old and Middle River (FWS Actions 1-3).	2009–present
Biological Opinion NMFS BO RPA and conference opinion on the long-term operations of the Central Valley Project and State Water Project. June 2009. (National Marine Fisheries Service 2009)	Sets minimum flow requirements below Whiskeytown Dam at Clear Creek (NMFS Action 1.1.1), additional closure of the delta cross channel gates during flushing flows in Oct–Dec (NMFS Action 4.1.2), limited CVP and SWP exports in April and May (NMFS 4.2.1), and minimum flow requirements below Goodwin Dam on the Stanislaus River (NMFS 3.1.3).	2009–present

A.2 CalLite Estimations

CalLite is an interactive screening model that simulates the hydrology of the Central Valley, reservoir operations, and delivery allocation decisions over an 82-year planning period (1922–2003; California Department of Water Resources and United States Bureau of Reclamation 2014). The software also allows the user to select different water management regulation regimes to test how these regulations affect the water supply system. Some of the Delta regulatory controls depend on the water year hydrologic classification (Wet, Above Normal, Below Normal, Dry and Critical), which is based on the Sacramento Index.

1993–2003 Estimations

To test the accuracy of CalLite in estimating historical water deliveries, actual monthly deliveries in the CVP during the period (1993–2003) were compared with estimated deliveries in CalLite (in CalLite the sum of water delivered to North of the Delta and South of the Delta are considered).

During the 1993–2003 period, the regulatory framework changed (see Appendix A.1). As a consequence, two regulatory frameworks are simulated. The actual deliveries in the period 1993–1998, were compared to deliveries estimated in CalLite using Central Valley Improvement Act (CVPIA) regulations that were in place at the time: flow regulations at Clear Creek and at the upper Sacramento River (consisting of the predetermined CVPIA 3406 (b) (2) flows). The actual deliveries in the period 1999–2003 are compared to deliveries estimated in CalLite under a regulatory regime that includes D-1641 regulations (see Appendix A.1). CalLite also allows for alternative climate change projections, alternative scenarios of sea level, alternative levels of water demands and several future management actions. For both scenarios, these variables were set at their base level.

A.3 Stochastic Simulation of Sacramento Index Conditioned on the Value of the Sacramento Index in Previous Year

Sacramento Index Components

Tables A1, A2, and A3 contain summary statistics from the Sacramento Index Components' distribution fitting. Figure A1 presents pairwise correlations among the Sacramento Index components.

Table A1 Summary Statistics from Oct.-Mar. Distribution Fitting

Oct.-Mar.	Entry data	Gamma (Threshold θ, Scale σ, Shape α) Gamma (2.14, 3.50, 2.25)
p-value K-S test		>0.25
Min.	2.49	2.145
Max.	22.75	∞
Mean	10.051	10.051
Mode	≈6.263	6.546
Median	8.4	8.918
Standard dev.	5.094	5.264
Asymmetry	0.7205	1.3316
Kurtosis	2.468	5.6598

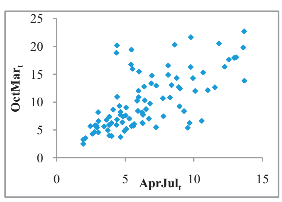
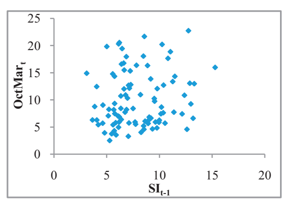
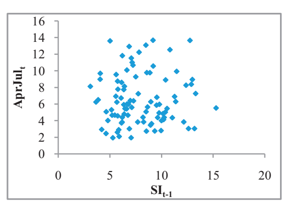
Table A2 Summary Statistics from Apr.-Jul. Distribution Fitting

Apr.-Jul.	**Entry data**	**Gamma (Threshold θ, Scale σ, Shape α) Gamma (1.44, 2.04, 2.49)**
p-value K-S test		>0.5
Min.	1.93	1.439
Max.	13.68	∞
Mean	6.505	6.505
Mode	≈4.383	4.467
Median	5.92	5.844
Standard dev.	3.059	3.212
Asymmetry	0.702	1.2683
Kurtosis	2.6858	5.4129

Table A3 Summary Statistics from Lagged Sacramento Index Distribution Fitting

SI_{t-1}	**Entry data**	**Gamma (Threshold θ, Scale σ, Shape α) Gamma (1.75, 1.17, 5.24)**
p value K-S test		>0.25
Min.	3.11	1.755
Max.	15.29	∞
Mean	7.884	7.884
Mode	≈6.200	6.715
Median	7.16	7.499
Standard dev.	2.634	2.677
Asymmetry	0.5411	0.8734
Kurtosis	2.6715	4.1442

Figure A1 Pairwise correlations between Sacramento Valley 40-30-30 Index components (1922–2014).

	$AprJul_t$	SI_{t-1}
$OctMar_t$	 Linear correlation= 0.67 p value=0.00 Copula fit: GumbleR (θ=2.127) AIC=-71.05	 Linear correlation= 0.15 p value=0.16
$AprJul_t$		 Linear correlation= 0.04 p value=0.71

Sacramento Index conditional distributions

Tables A4 to A8 contain summary statistics for the Sacramento Index conditional distributions. Distributions were fit using 5,000 draws from the simulated Sacramento Index components conditional on SI_{t-1} being equal to 2, 4, 6, 8, and 10 in tables A4, A5, A6, A7, and A8, respectively.

Table A4 Summary Statistics from SI_t | Si_{t-1}=2 Distribution Fitting

SI_t| SI_{t-1}=2	**Entry data**	**Gamma (Threshold θ, Scale σ, Shape α) Gamma (1.69, 1.55, 2.92)**
p-value K-S test		=0.15
Min.	1.885	1.689
Max.	22.41	∞
Mean	6.217	6.217
Mode	≈3.692	4.667
Median	5.755	5.712
Standard dev.	2.618	2.649
Asymmetry	1.0824	1.1702
Kurtosis	4.684	5.054

Table A5 Summary Statistics from SI_t| Si_{t-1}=4 Distribution Fitting

SI_t | Si_{t-1}=4	**Entry data**	**Gamma (Threshold θ, Scale σ, Shape α) Gamma (2.29, 1.55, 2.92)**
p-value K-S test		=0.15
Min.	2.485	2.289
Max.	23.01	∞
Mean	6.817	6.817
Mode	≈4.292	5.267
Median	6.355	6.312
Standard dev.	2.618	2.649
Asymmetry	1.0824	1.1702
Kurtosis	4.684	5.054

Table A6 Summary Statistics from SI_t | Si_{t-1}=6 Distribution Fitting

SI_t | Si_{t-1}=6	**Entry data**	**Gamma (Threshold θ, Scale σ, Shape α) Gamma (2.89, 1.55, 2.92)**
p-value K-S test		=0.15
Min.	3.085	2.889
Max.	23.61	∞
Mean	7.417	7.417
Mode	≈4.892	5.867
Median	6.955	6.912
Standard dev.	2.618	2.649
Asymmetry	1.0824	1.1702
Kurtosis	4.684	5.054

Table A7 Summary Statistics from SI_t | Si_{t-1}=8 Distribution Fitting

SI_t | Si_{t-1}=8	Entry data	Gamma (Threshold θ, Scale σ, Shape α) Gamma (3.49, 1.55, 2.92)
p-value K-S test		=0.15
Min.	3.685	3.489
Max.	24.21	∞
Mean	8.017	8.017
Mode	≈5.492	6.467
Median	7.555	7.512
Standard dev.	2.618	2.649
Asymmetry	1.0824	1.1702
Kurtosis	4.684	5.054

Table A8 Summary Statistics from SI_t | Si_{t-1}=10 Distribution Fitting

SI_t | Si_{t-1}=10	Entry data	Gamma (Threshold θ, Scale σ, Shape α) Gamma (4.09, 1.55, 2.92)
p-value K-S test		=0.15
Min.	4.285	4.089
Max.	24.81	∞
Mean	8.617	8.617
Mode	≈6.092	7.067
Median	8.155	8.112
Standard dev.	2.618	2.649
Asymmetry	1.0824	1.1702
Kurtosis	4.684	5.054

Appendix References

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