

# Using economic and other performance measures to evaluate a municipal drought plan

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## Abstract

This paper explores the welfare costs associated with drought plan transactions between a public municipal water agency, the El Dorado Irrigation District (EID) in California in the USA and its customers. The EID imposes a tiered pricing plan for municipal customers, which was analyzed as a discrete continuous choice (DCC) model by water users within a climate driven water evaluation and planning (WEAP) model of the EID water system. The DCC is subsequently used to estimate the compensating variation (CV) measure of the loss of consumer welfare in the case where a customer does not receive water that matches a preferred level of demand. In addition to monetized welfare loss, we look at other metrics of performance such as reservoir storage and hydropower generation. For the drought-of-record under full build-out, results show that the welfare loss to EID customers from the imposed drought plan is far less than if no drought plan were in place. This suggests that current consumption is well beyond essential needs and, without a drought plan, water shortages in the later period of a drought would generate a much greater welfare loss. Most of the cost associated with the drought plan is born by EID in the form of reduced revenues.

*Keywords:* Compensating variation; Drought management; Drought planning; Supply–demand modeling; Welfare measures

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## Introduction

Droughts cost money, estimated to be US\$6–8 billion annually, in lost global economic output (Wilhite, 2000). The 1988 drought, which is regarded as one of the most costly natural disasters in

doi: 10.2166/wp.2013.204

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the history of the USA, resulted in an estimated US\$40 billion in damage/costs (Ross & Lott, 2000). The managers of urban water systems must confront the challenge of anticipating when available water supplies may not be sufficient to meet typical water demands and how to implement policies to curtail these demands at the lowest loss of well-being. These policies have historically been ‘command-and-control’ (CAC) approaches such as rationing and use restrictions. This reflects a widespread reluctance to use price to ration water use, viewed as an essential commodity<sup>1</sup>. Yet a growing body of economic literature argues that this traditional CAC approach to municipal water conservation, through non-price policies such as conservation incentives, rationing, restrictions, prohibitions and enforcements on specific water uses is inefficient; using price to allocate water has the advantage of allowing users to self-select their level of use according to their need and willingness to pay (Brennan *et al.*, 2007; Mansur & Olmstead, 2007; Olmstead & Stavins, 2008).

In the USA, the vast majority of urban water systems are public rather than investor-owned entities and they report directly or indirectly to elected office holders. Unlike investor-owned utilities, which are common in the electricity sector, public water supply agencies do not have an objective of profit maximization. Instead, they aim to satisfy their customers’ needs for water supply at as low a cost as possible and they set prices to cover their costs rather than to earn a profit<sup>2</sup>. For many decades and long after this type of pricing was abandoned by electric utilities, many urban water utilities used some form of decreasing block pricing, in which larger users pay a lower price at the margin. In the past two decades, most urban water agencies have switched to flat-rate pricing (the same unit price is charged regardless of volume consumed) and, more recently, to increase block pricing (Agthe & Billings, 1987). With increasing block pricing (IBR) a higher unit price is charged for consumption beyond a certain level; thus there are at least two and perhaps more price tiers in the rate structure (Dahan & Nisan, 2007; Olmstead *et al.*, 2007; Schoengold & Zilberman, 2010).

This study explores the efficiency of a drought plan for a public water utility in California, the El Dorado Irrigation District (EID). EID serves an area in California’s Gold Country which was originally mainly agricultural, with most of the district’s supply used for irrigation. Over the last three decades, however, the urban population has grown to nearly 110,000 and the area has become a suburb of Sacramento, California’s Capital. EID is now primarily an urban water supply agency. For EID, like other public water agencies in California, but unlike investor-owned water agencies, there is no economic regulatory oversight. The district is governed by an elected board of directors. The directors have the freedom to exercise their own judgment in the choice of a rate structure. But, in practice there are political constraints on the directors because they are beholden to the electorate and any rate structure they adopt must be accepted as prudent, fair and reasonable.

Like other California urban water agencies with more than 3,000 connections or that deliver more than 3.7 million m<sup>3</sup> (MCM), EID is required under California’s Urban Water Management Planning Act (UWMP, Water Code 10610-10656) to submit an urban water management plan every 5 years to the California Department of Water Resources (DWR) which assesses future demand and supply over the next 20 years and identifies how the district would handle a drought involving either a

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<sup>1</sup> For example, while many electric utilities in the USA offer interruptible supply contracts to residential users at a reduced price, this is very rare among water utilities.

<sup>2</sup> In some cases, however, urban water agencies are required by a parent metropolitan government to generate a surplus that is turned over to the metropolitan parent.

single dry year or multiple dry years during that period. This reporting requirement has become a key motivator of drought planning for urban water agencies like EID.

Within the context of EID's self-determined pricing structure and environmental constraints, this study uses economic and other performance measures to assess the performance of EID's drought plan which includes a sophisticated set of drought actions combined with a tiered pricing structure. The drought plan includes *indices* that *trigger* drought stages which set in motion a package of *actions* by EID with the goal of reducing their customers' water demand. The EID's stated drought plan goals include:

*'defining water demand curtailments that can reasonably be accomplished in drought conditions, are financially sustainable, administratively appropriate, user-friendly and will perform well for all customers and stakeholders'* (Brown & Caldwell, 2008).

The expectation is that if customers are made aware of the level of demand curtailment required and if the anticipated levels are achieved, no further service reductions will occur. The premise is that the use of the drought plan will improve the outcome because it will avoid the imposition of abrupt water supply shortages and other system failures. This research evaluates whether economic measures of social welfare in the transaction between EID and its customers is improved when their drought plan is in place (White *et al.*, 2001; Rossi *et al.*, 2005, 2007).

The paper opens with a review of typical elements of a municipal drought plan, including indices, triggers and actions – characteristics of the EID plan. It then describes the EID water system and a brief description of the EID drought plan (Brown & Caldwell, 2008). Next, an EID water resources planning model is presented, along with a residential water demand model. From the fitted demand model, welfare evaluations can be performed to assess the welfare loss associated with price changes or limits on water use. Together, these components are used to estimate the potential activation of the drought plan and the resulting economic welfare implications. Recognizing secondary benefits of water savings to the district, other drought performance measures include, (1) reservoir storage, a proxy of recreational benefits; (2) the quantity of hydropower produced; and (3) a measure of environmental performance in terms of meeting in-stream flow requirements<sup>3</sup>.

### **Elements of a municipal drought plan: indices, triggers and actions**

Drought planning literature has evolved and expanded over the past several decades, from early efforts that define drought (Palmer, 1965), through the development of indices of drought as it emerges and develops (Dracup *et al.*, 1980; Garen, 1993; Heim, 2002; Strzepek *et al.*, 2010), up to the current literature which combines indices and triggers in order to initiate a drought management response (Wilhite, 1991; Shepherd, 1998; Steinemann & Cavalcanti, 2006). Unfortunately, the literature becomes sparse regarding actions to be taken once a drought is declared (Werick & Whipple, 1994; Wilhite *et al.*, 2000; White *et al.*, 2001). Evidence derived from a review of actual water utility drought

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<sup>3</sup> In-stream or environmental flow requirements are established at critical district diversion points on the South Fork of the American River. These are established during licensing of hydropower through the Federal Energy Regulatory Commission (FERC); or at the State level, to protect endangered species by the California State Water Resources Control Board.

preparedness plans suggests that standard system level metrics of performance such as water supply reliability, water storage, regulatory compliance, and so on, are commonly used to evaluate options (Brown & Caldwell, 2008; Corpus Christi, 2009). Drought plans serve the purpose of tying indices, triggers and actions together, to meet demand reduction goals.

Briefly, drought indices can assist in ascertaining whether drought conditions are in the offing or are already in place, but are insufficient for specifying an appropriate response once a drought has occurred (Heim, 2002; Palmer *et al.*, 2002). In the USA, the Palmer Index or PDSI (Palmer, 1965) and the Standardized Precipitation Index (McKee *et al.*, 1993) are well known and widely used drought indices (Dracup *et al.*, 1980; Alley, 1984; Guttman *et al.*, 1992; Keyantash & Dracup, 2004). Much of the literature defining triggers builds on previous discussions of indices as useful metrics for defining drought categories, or levels, typically using nomenclature such as ‘mild, moderate, severe, extreme drought’ or ‘level 1, level 2, level 3 drought’ (AWWA, 1992; Steinemann & Cavalcanti, 2006). Because drought has many characteristics and degrees of intensity, multiple indicators and triggers are typically used to represent changing drought conditions (Steinemann, 2003). Regardless of how drought indicators and triggers are defined, together they should serve the municipal water agency by: (1) providing advanced drought warning while minimizing false alarms; (2) providing stable and smooth transitions between levels of drought; (3) provide assurance that conditions are improving as drought conditions become less severe.

Procedures for defining appropriate drought triggers are more developed than ideas on drought responses. Steinemann & Cavalcanti (2006) suggest both strategic longer term actions, usually implemented before a drought, such as water pricing policies and tactical shorter term actions, usually implemented during a drought, such as water use restrictions. Werick & Whipple (1994) provide a much longer list of strategic and tactical drought responses, without specifying specific characteristics of potential actions. Because the local context of both practical and political considerations is so important, it is not surprising that guidance on this step in drought planning is less detailed. Regardless, there seems to be an overarching drought management objective, which is to meet the customers’ expectations, even if those expectations are lowered during a drought (Bruvold, 1979; Narayanan *et al.*, 1985).

## The El Dorado Irrigation District and its drought plan

The EID lies on the western slope of the Sierra Nevada Mountains and receives water primarily from the American River. Some of the diversion infrastructure dates back to the California Gold Rush of the 19th century (Figure 1). The EID provides water to a population of more than 110,000 people within its service area for municipal, industrial and irrigation use; provides wastewater treatment and recycled water services; operates recreational facilities at its reservoirs; and owns and operates a small hydroelectric facility known as Project 184. While agricultural water customers still remain within the EID service area, single family residential (SFR) customers represent nearly 75% of the total revenue and 55% of the total volume from water sales by EID (Sharon Fraser, Water Conservation Coordinator, EID, personal communication).

Total operating revenue for EID in 2010 was US\$46.3 million, with water-related revenues of US\$37 million for 44 million cubic meters (MCM) or 36 thousand acre-feet (TAF) of delivered water. This equates to US\$0.85/m<sup>3</sup>. Water, reclaimed water and wastewater sales represented 92% of revenues from 2001 to 2005, dropping to 86% from 2006 to 2010, while hydropower grew from 6 to 12% of revenue for the same period. Recreational revenues have remained at 2% of total revenue.

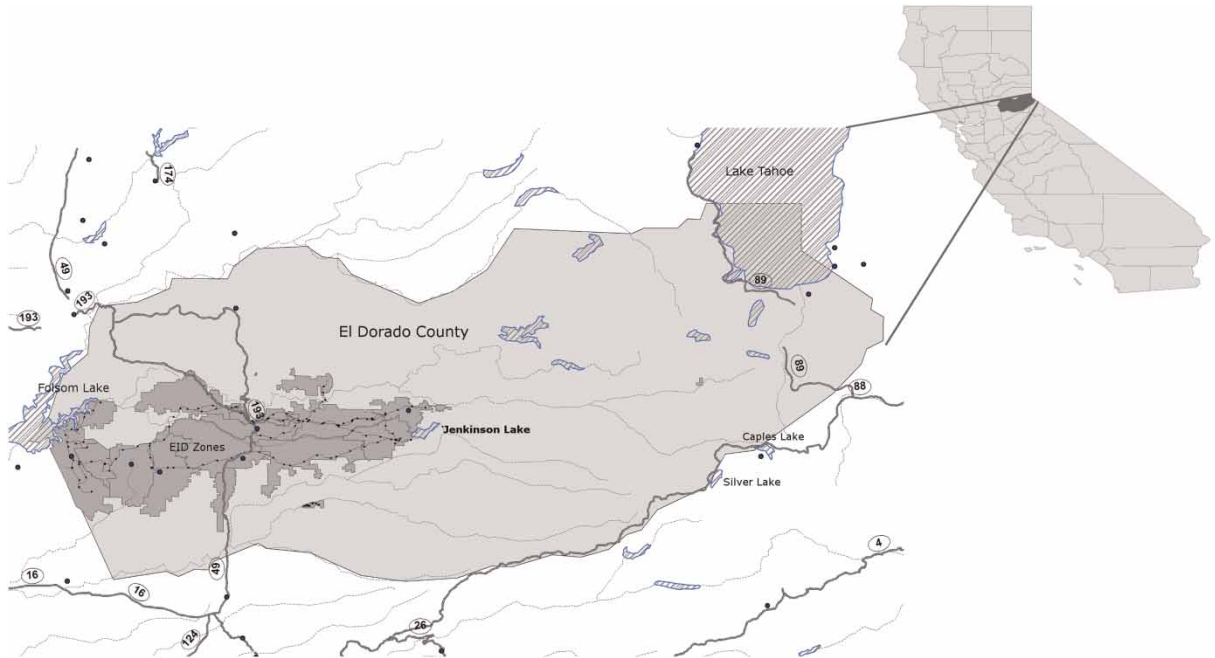


Fig. 1. Location of El Dorado County in California and the EID service area (dark polygon) and the location of various water resource features such as the Kyburz Diversion and Jenkinson Lake.

While hydropower revenue has grown as a percentage of the total, it has varied considerably from year-to-year based on both climate and electricity markets. EID has owned and operated the hydropower facility since 2005, generating a high of 111 GWH (gigawatt-hours) in the wet year of 2005 corresponding to US\$5.6 million in revenue and a low of 60 GWH in the dry year of 2008, yielding US\$4.8 million in revenue. The highest and lowest revenue years were 2010 and 2009, when 79 and 73 GWH were generated corresponding to US\$7.8 million and US\$2.9 million in revenue, respectively.

#### *EID's water supply and demand*

In terms of water supplies, the EID system comprises: (1) long-standing water rights in the South Fork of the American River watershed, including several small reservoirs (Project 184), (2) an interbasin connection to the larger Jenkinson Lake which is adjacent to the Cosumnes River Watershed and (3) a series of contracts and agreements with the US Bureau of Reclamation and others that allow EID to withdraw water from Folsom Lake, which is located downstream at the western end of the system. These contracts allow the larger western zones, notably Zones 1 and 2, access to more reliable supplies but also require substantial pumping.

Access to water varies across the EID system, with water levels in Jenkinson Lake dictating how certain demand zones are supplied with water, with some zones only able to receive water from a single source. A main point of take for EID's project 184 water is the diversion at Kyburz from the South Fork of the American River. In-stream flow requirements to satisfy fish flows below Kyburz restrict when and how much water EID can take. Table 1 summarizes the current and future annual average

Table 1. Summary of EID current and future water supplies and the zones they serve.

Water supply sources	2010 MCM (TAF)	2030 MCM (TAF)	Zones served
Jenkinson Lake	28 (23)	28 (23)	All
Project 184, El Dorado Forebay	19 (15.1)	19 (15.1)	All
Project 184, Permit 21112 <sup>a</sup>	–	21 (17)	Z1 and Z2
Folsom USBR <sup>b</sup>	9.3 (7.6)	9.3 (7.6)	Z1 and Z2
Folsom, Fazio <sup>b</sup>	–	9.2 (7.5)	Z1 and Z2
SMUD, El Dorado <sup>c</sup>	–	49 (40)	Z1–Z7, Z18, Z28
Recycled water	3.7 (3)	9.5 (7.7)	Z1–Z2
Total	60 (49)	145 (118)	

<sup>a</sup>The Permit 21112 water is part of Project 184, which is a senior water right acquired by EID from Pacific Gas and Electric.

<sup>b</sup>The Folsom supplies are negotiated with the US Bureau of Reclamation, with the point-of-take limited to the Folsom Reservoir.

<sup>c</sup>The Sacramento Municipal Utility District (SMUD) and EID entered into a cooperative agreement in 2005 to provide a future supply from the Middle Fork of the American River, via Folsom. We have assumed that in drought conditions, SMUD allocation will be reduced to 50, 30 and 15% of total under 1-, 2- and 3-year multi-year drought conditions.

available water supply by source and the zones they serve. In 2010, EID's previous 5-year, average raw water delivery was 33 million m<sup>3</sup> (MCM) or 41 TAF. Current EID projections of future demand in 2030 are about 50 MCM (62 TAF).

### Summary of the EID drought plan

Motivated by the evidence that hydrologic conditions in the EID source water region were highly uncertain, EID developed a drought preparedness plan that would: (1) effectively anticipate the occurrence of all drought conditions and reduce impacts by activating the conditions of the drought plan and (2) reliably satisfy the curtailed levels of customer demand during periods of drought plan activation (Brown & Caldwell, 2008).

For EID, selecting robust indicators and setting a trigger value for each drought stage to minimize supply shortages required trial and error experimentation. This process was informed by an understanding of how the EID water supply system works and a mathematical analysis of potential water shortfalls. Various indicator values were tested for each stage, to 'trigger' soon enough to warn and late enough to correspond to drought. Potential drought indicators and corresponding trigger levels were tested by comparing how accurately they predicted drought over the entire hydrological record (1922–2004). One trigger that performed well was the days-of-water-supply-remaining index or SRI, which ranges from a value of 1.0 for full supply to 0.0 for no supply. The SRI was defined as a function of system-wide reservoir storage; worst case expected reservoir inflows based on the historical record; and normal (unconstrained) demand in the following months. It was also determined that the presence of a positive El Niño-Southern Oscillation (ENSO<sup>4</sup>) signal could improve the ability of the proposed

<sup>4</sup> ENSO is the large scale warming of the tropical Pacific Ocean at irregular intervals of between about 2 and 7 years and lasting for 1-3 years. The positive or warm phase is El Niño, while the negative or cool phase is La Niña.

triggers to anticipate droughts in the historical record. The final triggers used to determine drought threshold and stage based on the SRI values are shown in Table 2.

The fact that SRI is based on storage within EID's own reservoirs is important. If EID were to terminate reservoir releases, the SRI would remain near 1.0 and strictly speaking, no drought stage would be called. This would, of course, mean no delivery of water either. At the other extreme, if EID did not constrain reservoir releases, the SRI would hover near 0.0 and stage 3 drought would persist artificially. Thus, we reiterate the goal of the drought preparedness plan, to find the ideal set of triggers and actions, which would:

*'... define water demand curtailments that can reasonably be accomplished in drought conditions, are financially sustainable, administratively appropriate, user-friendly and will perform well for all customers and stakeholders' (Brown & Caldwell, 2008).*

Using the triggers summarized in Table 2, EID concluded that to navigate a 3-year hypothetical drought successfully, demand curtailments of 15% in stage 1, 25% in stage 2 and 50% in stage 3 would be needed. The hypothetical drought was derived from the actual drought-of-record, 1976 and 1977, with a third year of drought artificially imposed by assuming a repeat of the 1977 hydrology. To evaluate the plan's performance under these hydrologic conditions, it was assumed to occur under a 2030 estimated level of demand. In formulating the plan, EID concluded that this drought sequence and level-of-demand would lead to no unanticipated reductions in the level of customer demand satisfaction.

### Analytical support of the EID drought plan via a water evaluation and planning model

The EID drought preparedness plan was developed from a 2004 shared vision planning (SVP) process that included broad public participation to capture public input, incorporate scientific information and develop 'what if's' for discussing preferences and expectations. One outcome of the SVP was a shared vision model (SVM) of El Dorado Counties water systems, which assumed stationary hydrology based on historical observations and bulk aggregated demand as a planning hypothesis (Brown & Caldwell, 2008).

This work built from the SVM by developing a water evaluation and planning (WEAP) model of the EID system on a weekly time-step that incorporates: (1) spatially disaggregated and climate driven

Table 2. Number of days supply remaining trigger plan summary.

Month	ENSO	SRI	Last month's stage	This month's stage
May	Any	<0.60	0	1
			1,2,3	Last month's stage
June–Sept	Any	<0.35	2	3
	<0.35 <sup>a</sup>	<0.4	0,1,2	2
	<0.35 <sup>a</sup>	<0.4	3	3
Any	Any	>0.75	0,1,2,3	0

<sup>a</sup>The ENSO average of three previous months must be less than 0.35.

demand that evolves over time, with SFR demand modeled as a discrete and continuous decision developed from billing record data; (2) climate-driven hydrology that generates stream-flow for input to reservoirs and diversions; and (3) the explicit consideration of the regulatory environment, including environmental flow standards (Yates et al., 2005, 2006). The model is referred to as WEAP–EID and Figure 2 demonstrates the graphical nature of the model, showing the western boundary of the service area new Folsom Reservoir and the time varying demand through the year for zone 2.

*EID demand and a single family residential discrete choice model*

EID’s water demand was explicitly represented in the WEAP model to characterize the diverse range of users and water supply services. Each of the 15 service zones was geographically located and disaggregated according to the unique account types managed by EID, including single family, multi-family, commercial/industrial, domestic irrigation, agriculture, recreational turf, small and farm, among others. The districts many account types suggests the broad diversity of its customer base, now dominated by the single family. These zonal demands were configured to receive water from their physical connection to the water distribution system. Within each zone, the number of accounts and water use per-account-type were estimated from data provided by EID. With the exception of SFR, the number of accounts was

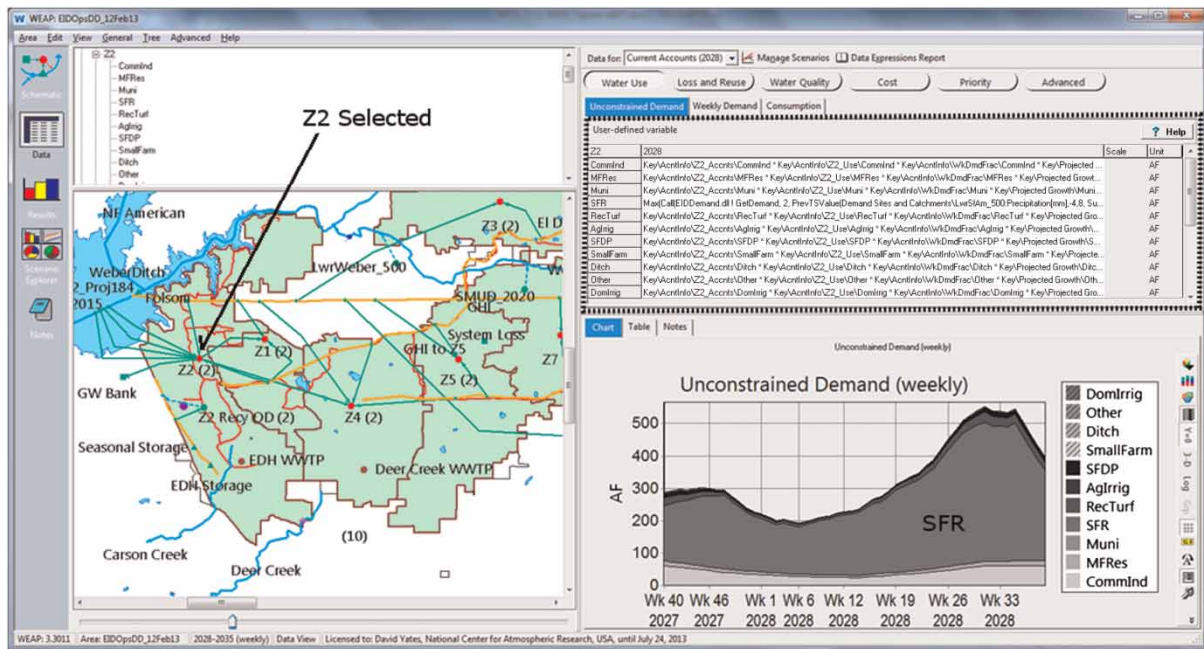


Fig. 2. Screen shot of the WEAP–EID model, depicting the western portion of the service area, where several zones are shown including Zone 2, which has been selected and shows the demand for each user class for a single year. Single family residential demand (SFR) is the largest user class in this region and indicted on the graph. demand. Other user classes with considerable demand in this zone are commercial-industrial (CommInd), multi-family residential (MFR), and single family, dual plumbing (potable and reclaimed) or SFDP. The area highlighted with the dashed line is the WEAP expression builder, where the demand models are entered (for illustration only).



taken from 2007 data, with water use per account estimated as the average of all account types within a zone over the 4-year period, from 2004 to 2007.

For the SFR account-type, an econometric demand model was developed from a set of observed parameters to estimate the observed demand for each customer from 2004 to 2007. This demand model was then be used to predict future water use under different parameters, most notably varying climate. The form of the SFR demand model was log–log after [Hewitt & Hanemann \(1995\)](#):

$$\ln w = Z\delta + \beta \ln \rho + \gamma \ln m + \omega + \varepsilon \quad (1)$$

where  $w$  is the observed level of consumption,  $Z$  is a vector of household and weather-related characteristics that include household size, number of rooms, median age and home ownership, among others. The climate data include bi-monthly total precipitation and average temperature. The marginal price of water is  $\rho$ ,  $m$  is the income of the individual and  $\delta$ ,  $\beta$  and  $\gamma$  are parameters to be estimated. This is a two error structure model, where  $\omega$  represents unobserved heterogeneity of preferences among consumers and  $\varepsilon$  represents unobservable error for the consumer as well as to the econometrician ([Olmstead et al., 2007](#)). We assume the two error terms are independent and normally distributed with mean zero and variance as  $\sigma_\omega^2$  and  $\sigma_\varepsilon^2$ .

The demand model is then formulated as a discrete continuous choice (DCC), as it considers the case where consumers face an increasing block rate price, or IBP (see [Olmstead et al. \(2007\)](#) for details). The first decision is the block price decision, where customers choose the block in which they want to consume. Since there are a discrete number of blocks, this is a discrete decision. Second, customers decide how much to consume within that block or segment, which is a continuous decision. The model takes into account the probability that an individual chooses any of the blocks and consumes a given quantity within that block. Additionally, it will consider the probability that an individual decides to consume at any of the thresholds that define the different blocks. [Olmstead et al. \(2007\)](#) show that the price elasticity of a DCC is a complex function of the parameters of the model, since the calculation has to consider a change in the whole price structure and includes a price effect and an income effect produced by a virtual subsidy implicit in the block rate structure.

[Table 3](#) summarizes the parameters estimated for the DCC model derived from the 8-year billing record of EID's SFR accounts. These were bi-monthly bills that included more than a million records, where a demand model is estimated from each customer's record (e.g. six bills per-year for 8 years, totaling 48 records). The mean and standard error of the parameters for each explanatory variable are presented in [Table 3](#). The strong correlation with temperature is suggestive of the strong Mediterranean climate of California, characterized by warm, dry summers, with housing density the largest, negatively correlated value.

Because of the non-linearity of the selected model, the mean parameter values cannot be used in a single aggregate model run using mean values of the explanatory variables. Using a model for each consumer, however, it is possible to estimate the mean of the expected consumption and the elasticity. The mean value of simulated consumption was  $129 \text{ m}^3$  [45.5 hundreds of cubic feet (ccf)] while the mean of the observed consumption was  $124 \text{ m}^3$  (43.9 ccf), resulting in an average bias of 3.6%. The mean price elasticity was estimated according to [Olmstead et al. \(2007\)](#) to be  $-0.309$ , which is higher than the price coefficient of  $-0.174$ . As [Olmstead et al. \(2007\)](#) show, overall price elasticity of demand is a complex combination of both the price and income elasticity of demand associated with demand at each segment of the IBP. This overall price elasticity will be different from the simple price elasticity (the PRICE coefficient of

Table 3. Demand coefficient estimates for the single family residential DCC model<sup>a</sup>.

Parameters	Estimates	Standard error	Estimate/s.e. <sup>b</sup>
CONSTANT	−6.5	0.216	300.3
ROOMS	0.143	0.003	42.1
AGEFAMIL	0.034	0.002	14.7
HHSIZES	0.118	0.003	34.7
YEARHOUS	0.067	0.024	4.06
DENSITY	−0.213	0.014	−15.37
OWNHOUSE	0.183	0.009	19.61
TEMP	0.712	0.002	298.
PRECIP	−0.126	0.002	−60.9
PRICE	−0.174	0.008	−22.4
INCOME	0.138	0.101	13.6
S_N	0.007	0.007	1.15
S_E	−0.786	0.001	1,004

<sup>a</sup>Parameters include number of rooms (ROOMS); average family age (AGEFAMIL); number of people in household (HHSIZE); the year the house was built (YEARHOUS); relative population density in the district (DENSITY); home ownership state (OWNHOUSE); air temperature (TEMP); precipitation (PRECIP); marginal price of water (PRICE); income of household (INCOME). S\_N and S\_E are the variances of the two error terms. Column 4 is the ‘*t*-test’ of statistical significance, showing that almost all coefficients are statistically significant CONSTANT is parameter associated with all factors that influence demand but are not modeled.

<sup>b</sup>This is the estimated divided by the standard deviation, which is the ‘*t*-test’ value. If it is greater than 2 it is significant at a 5% level.

the demand function given Table 3). In general, it is not possible to identify either the direction or the magnitude of the difference because several factors are involved in the formation of the overall elasticity.

Having developed a DCC for EID’s SFR customers, the model was implemented in WEAP to estimate water demand for the individual SFR accounts for which there were data. All input parameters were fixed in time, except for air temperature and precipitation. Individual demand estimates were aggregated to represent the total water demand within each of the 15 demand zones in the model. A scaling factor was used to estimate total SFR demand in each zone by relating the number of customers in that zone for which a demand model was successfully developed to its total number of customers. The WEAP allocation routine was then run in response to these simulated demands, with a full description of the drought plan imposed within the model. The models performance in simulating the EID’s water system for a historic period is described in the next section.

#### *WEAP calibration results for the historic period*

The WEAP model of the EID water system simulates stream-flow, water demands, diversions and deliveries, reservoir storage, in-stream-flow rights and hydropower generation in a weekly time-step for both historic periods and under future conditions. The historic period 1985–1995 was used for model calibration with corresponding demand estimates. These are water years, which begin in October and end in September of the following calendar year. This period was chosen because it encompasses an extended dry episode and a complete climate record for the region was available (Maurer & Hidalgo, 2008). The purpose of calibration is to ensure credibility and validity of the model in terms of its ability

to: (1) represent the actual EID water system; (2) depict the drought plans triggers and the corresponding stage and cut-back targets properly; and (3) simulate other important measures such as stream-flow, reservoir storage, in-stream flow requirements, hydropower production, and so on. Note that the current drought plan was not in place during this period.

In WEAP, water allocation among competing uses is achieved through a hierarchical ranking of priorities among those uses. The allocation priorities are integer values, with the lowest number corresponding to the highest priority. Although WEAP's demand priorities could be used to represent legal water rights, in WEAP–EID they are used to constrain water diversions and prioritize sources of supply and generation of hydropower, whose values were derived through discussions with district staff (Sharon Fraser, EID, personal communication).

The primary district water supply is from the south fork of the American river via a water diversion near Kyburz (Figure 1), with EID obligated to meet an environmental in-stream flow requirement. Thus, this in-stream flow requirement is assigned the highest priority value of 1 and if the flow requirement cannot be met, the diversions to the EID canal will be reduced accordingly. The second priority is the EID demands themselves, which were assigned a priority value 2, while hydropower generation and Jenkinson Lake fill priorities were assigned priority values of 3 and 4, respectively. These priorities reflect EID's historic policy of utilizing Jenkinson Lake to its full potential to meet water supplies (Table 4, column '1985–95') and its 2006 hydropower acquisition. To simulate future conditions, including the drought plan, priority 1 (in-stream flows) and priority 2 (demands) remain unchanged, while utilization of Jenkinson Lake and hydropower generation priorities switch based on the severity of the drought stage (Table 4, column '2028–34').

Figure 3 shows the simulated weekly stream-flow below EID's main diversion on the south fork of the American river. The simulated flows show good skill, with a Nash–Sutcliffe efficiency (NSE) of 0.79 (McCuen et al., 2006). The model tended to under-represent the highest flows, most notably in 1995.

The main storage reservoir for EID is Jenkinson Lake. Historically, EID has allowed the lake to be drawn down considerably during water-short conditions, but more recently they have realized the risks of using this policy and, in response, developed the drought plan and revised their operating objectives to store more water in the lake. During this same period, EID acquired a 21 MW (megawatt), 530 m fixed-head hydropower facility, with an annual generating capacity of about 110 GWH.

The WEAP–EID uses ranked priority among competing demands to allocate water under shortage conditions, where the demand(s) with the highest priority are assigned the lowest integer value of 1 (Yates et al., 2005). For the historic period, environmental flows were assigned the highest priority value of 1; EID demands were assigned the next highest priority of 2, while the fill priority for Jenkinson Lake was set at priority 3. This emphasizes the lake as EID's primary water supply. Hydropower generation was considered a secondary benefit and thus assigned a priority value of 4.

Table 4. Allocation priorities (bold) in WEAP for the calibration period and future analysis, where the smaller integer value represents the higher priority. In the future analysis, the priorities change based on the drought stage (i.e. transition from Stage 0 to Stage 1 drought, the Jenkinson Fill priority shifts from 4 to 3).

	1985–95	2028–34
In-stream flow requirements	<b>1</b>	<b>1</b>
EID water deliveries	<b>2</b>	<b>2</b>
Jenkinson Lake fill	<b>4</b>	Stage_0,1 <b>4</b> Stage_2,3 <b>3</b>
Project 184 hydropower	<b>3</b>	Stage_0,1 <b>3</b> Stage_2,3 <b>4</b>

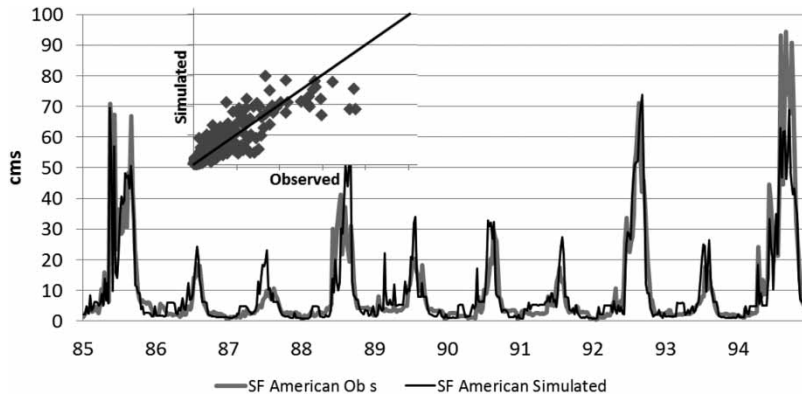


Fig. 3. Simulated (dark line) and observed (light line) South Fork of the American stream-flow below the Kyburz diversion. Calibration statistics include: a Nash–Sutcliffe = 0.79; root mean square error (RMSE) = 6.6 cm; total observed volume = 3.37 billion cubic meters (BCM) and total simulated volume = 3.40 BCM. The inset shows these same data on an  $x$ - $y$  plot.

Releases from Jenkinson Lake were constrained to a maximum of 5% of available storage in any single week. Figure 4 shows the simulated and observed Jenkinson Lake storage under these fill and release criteria, with an NSE of 0.76, suggesting the model is good at simulating storage. Figure 4 includes the simulated total EID raw water delivery (bars) and observed total deliveries (marks) for all zones. Total deliveries were underestimated in 1985 and 1986 and overestimated in 1988. Interestingly, although no formal drought plan was in place, EID delivered nearly 25% less water in the 1988 drought year than for the previous 5-year average, suggesting substantial welfare loss from unmet demands. Note the limited recovery of Jenkinson Lake storage, as it still served as EID’s primary water supply, despite its relatively low storage state (Sharon Fraser, EID, personal communication). Figure 4 also shows the drought stage, where there was persistent stage 1 drought from mid-1987 to 1989.

For the historic calibration period, hydropower generation ranged from a high of 120 GWh in the wettest year (1997) to a low of 63 GWh in the driest year (1992). The corresponding simulated drought stage is included in Figure 4, showing persistent stage 1 drought conditions from 1987 to 1989 and periodic stage 1 conditions in 1985, 1991 and 1992 and 1994.

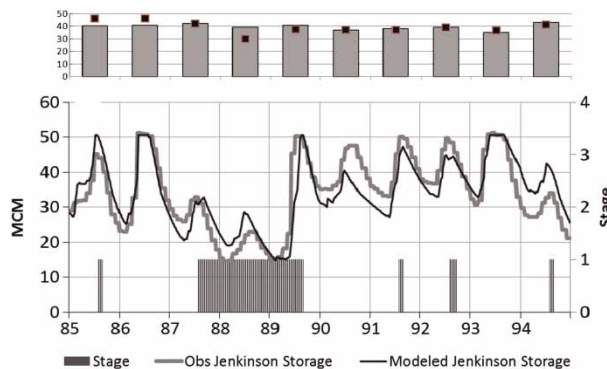


Fig. 4. Simulated (dark line) and observed (light line) Jenkinson Reservoir storage (Nash–Sutcliffe = 0.76; RMSE = 5.6 MCM; average observed volume = 36.5 MCM and average simulated volume = 33.8 MCM), and drought stage. Top graph shows the simulated total EID demand for the same period in MCM during a period with no formal drought action plan.

With a water systems model capable of simulating both past and future EID conditions, we turn to evaluating the performance of the EID drought plan. Both monetary and non-monetary measures were used for the evaluation. Welfare loss from cutbacks and/or shortage was estimated as compensating variation (CV) for SFR customers, with reservoir storage and hydropower generation as other valuation metrics. While the EID generates recreational revenue from Jenkinson Lake, recent historical data do not support deriving recreational revenue estimates from lake levels.

The WEAP model of the EID water system was configured to simulate the future period 2028–34, using EID's recent estimate of future demand and a concurrent worst-case drought scenario. Before the assumptions and results of the future analysis are presented, the CV model used to estimate SFR welfare loss is described.

### *Calculation of welfare loss due to rationing and/or shortage*

An advantage of developing an econometric model of SFR demand is that since price is included as one of the explanatory variables, it is possible to estimate the loss in consumer welfare in the case where a customer does not receive water to match a preferred level of demand, as reflected by their historic pattern of use. This reduction can take place for two reasons. First, a drought plan calls for consumers to reduce consumption when the system reaches defined levels of water scarcity. This is rationing and we will refer to this as *planned-shortage* in contrast to the second kind of reduction, where there may be insufficient water to meet demand, whether or not rationing has been imposed. We refer to this to as *unplanned shortage*.

Using the demand models developed from the observation of consumer demand over the historic period, we estimated welfare loss, as measured by CV, associated with a reduction in the amount of water actually provided to each customer for a given WEAP model run. CV measures a consumer's willingness to pay to make up for their loss associated with a reduction in the quantity of a good (i.e. water) consumed.

Calculating a welfare change caused by quantity restrictions has theoretical and practical challenges. First, from a theoretical perspective, a change in quantity involves solving a consumer maximization problem under an additional constraint (the quantity constraint) which means that the preference structure estimated with the original data, considering only a budget constraint, is not completely correct (Lankford, 1988). The challenge is to find the price (virtual price) that would lead a customer to consume exactly the restricted amount of water when this price is not observable. Furthermore, we need to find this price in what economists call the Hicksian demand function, whose arguments are price and the level of satisfaction that a person achieves at the initial budget constrained situation, not in the demand function given in Equation (1).

Using the ordinary Marshallian demand function (Equation (1)) as a point of departure and integrability theory (see Mas-Colell et al., 1995), it is possible to recover the Hicksian demand function which is given by:

$$w = \frac{e^{Z\delta} p^\beta}{1 - \lambda} \left( (1 - \lambda) \left[ e^{Z\delta} \left( \frac{p^{\beta+1}}{\beta + 1} \right) + u^0 \right] \right)^{\frac{\lambda}{1-\lambda}} \quad (2)$$

where  $u^0$  denotes the level of satisfaction or utility at the initial budget constrained situation,  $p$  is the price and the other parameters are the same parameters of the ordinary demand function given in Equation (1).  $\lambda$  is

the ‘income effect’ in the demand function. In this case it can be considered the income elasticity since we have a log–log functional form. Second, from a practical perspective, the Hicksian demand function needs to be inverted to find the virtual price  $\pi$  that satisfies:

$$\bar{w} = \frac{e^{Z\delta} \pi^\beta}{1 - \lambda} \left( (1 - \lambda) \left[ e^{Z\delta} \left( \frac{\pi^{\beta+1}}{\beta + 1} \right) + u^0 \right] \right)^{\frac{\lambda}{1-\lambda}} \tag{3}$$

in which  $\bar{w}$  is the new (restricted) water consumption. For this particular functional form of the demand function  $u^0$  is given by:

$$u^0 = \frac{m_0^{1-\lambda}}{1 - \lambda} - e^\alpha \left( \frac{p_0^{\beta+1}}{\beta + 1} \right) \tag{4}$$

In other words, the initial level of utility is calculated using the initial consumption, initial price and income. Unfortunately given the functional form chosen for the demand function, it is not possible to solve the Hicksian demand explicitly for  $\pi$ , therefore a *bisection routine* was used to find  $\pi$ . The numerical nature of this routine prevented it from being recompiled into WEAP, so under a given set of climate inputs and system configurations including the drought plan, weekly values of the unconstrained demand and actual water deliveries were taken from WEAP–EID run and used as input for an *ex ante* evaluation of CV.

After converging on the virtual price we calculate the CV as the area below the Hicksian demand function between the initial and final price. For example, in the case depicted in Figure 5 for a 10% reduction in water consumption, we have the following information: the original price is  $p_0 = 0.69$  and the virtual price is  $p_1 = 1.42$ , with the associated quantities given as  $w_0 = 40$  and  $w_1 = 36$ , then the estimated CV would be 4.22.

It is worth noting that the actual range of prices experienced by EID costumers over the 8-year period of observation is somewhat limited, although behavioral changes associated with one increase in the price levels when a three-tier price structure was in place, were observed. In addition, water supply

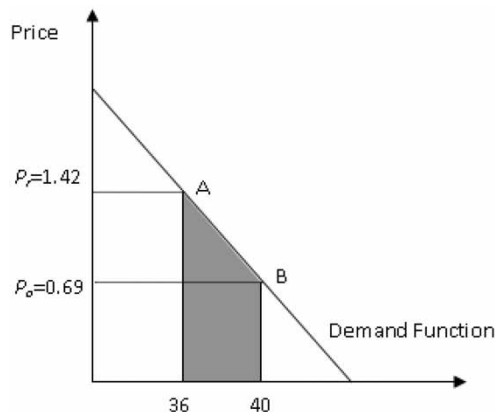


Fig. 5. Graphical representation of compensating variation estimation.

conditions during the period of observation were not extremely constrained, so the records do not capture actual customer behavior in times of extreme shortage (Figure 4). This limits the potential fidelity of the welfare calculations derived directly from the inverted demand functions and explains why the decision was made to extrapolate the estimation of CV under extremely supply limited conditions from values calculated under more moderate supply shortages. This was accomplished by running a Tobit regression of estimated CV against the level of reductions. From this regression, the CV was estimated for extreme cases where the water reductions were above 70%, while using the direct estimation of CV for less extreme levels of water supply reduction.

### Evaluating the EID drought plan under future conditions

California's Urban Water Management Act requires urban water suppliers to submit a water management plan every 5 years to the California DWR. EID's UWMP was submitted in 2010 and included projections of demand and supply to 2030 and the drought preparedness plan. These documents served as a basis for this analysis, where projections of future demand and supply were made for a period around 2030 (e.g. 2028–34). Water use reduction set forth in the EID drought plan calls for annual reductions goals of 15, 30 and 50% corresponding to stage 1, stage 2 and stage 3 drought, respectively. Since reductions target outdoor use, it was assumed that in late spring, summer and early fall reductions dominate and for each stage reductions are 20, 35 and 60%, while for the other seasons, the reduction targets are 10, 15 and 40%, which together are meant to achieve the overall annual reduction goals.

#### *Simulating future water supply and demand under severe drought conditions*

The UWMP reports 2010 water deliveries of about 48 MCM (39 TAF), with a planned demand projection of nearly 75 MCM (61 TAF) by 2030. The bulk of this increase occurs in the lower elevation, western zones (Z1 and Z2), where there is greater access to future supplies. Current non-drought annual average water supplies are 60 MCM (49 TAF), with plans to develop future water supplies through development and acquisition leading to about 145 MCM (118 TAF) of annual capacity (Table 1).

Since EID's UWMP is projected to 2030, we chose to explore the ramifications of a severe drought during this period, given EID's projected levels of future demand and supply. This future simulation was made for a 7-year period, 2028–34, where the historic climate of 1974–79 was assumed to repeat again in this future period. The historic period contains the 2-year drought-of-record, 1976 and 1977 and a third, consecutive drought year was assumed to follow the second drought year by repeating the 1977 climate-year. Thus, the climate-years of the past were mapped to the future years as:

1974 → 2028; 1975 → 2029, 1976 → 2030, 1977 → 2031, 1977 → 2032, 1978 → 2033, 1979 → 2034.

Note how the climate of 1977 repeats itself, as it was used for both 2030 and 2031, with the three concurrent drought years denoted by italics.

In addition to SFR demand, future water demands for the other water account types were estimated around 2030 based on projected population growth and estimated water use rates by account type for each zone. The sum of all demands under the assumption of no drought plan cutbacks is referred to

as unconstrained demand,  $u_z$  and is given for each zone and for each week as:

$$u_z = \sum_{a=1}^{A_z} \frac{P_f}{P_c} N_z^a \bar{R}_z^a \quad (5)$$

where  $A_z$  is the total number accounts types in each zone,  $z$ ;  $P_f$  and  $P_c$  are the current and future population projections,  $N_z^a$  is the number of accounts of type  $a$  in zone  $z$  in 2007; and  $\bar{R}_z^a$  is the average use rate for all accounts for the period 2003–07, in zone  $z$ .

SFR demand was estimated using the econometrics model for the representative customers within each zone ( $S_z$ ), where all input parameters except for temperature and precipitation were held constant (see Table 3).

We have assumed that the representativeness of SFR customers within each zone does not change and thus total SFR is scaled according to the population projection similar to the other accounts as shown in Equation (6). Finally, the total weekly unconstrained demand for each zone is simply,  $U_z = u_z + S_z$ , where total unconstrained demand,  $U_t$  is the sum of the zonal demand.

#### Defining scenarios to reflect future operating policies

To assess the performance of the drought plan, two scenarios were created. The first is referred to as the Full plan scenario, which assumes an active drought plan that fully meets the conservation objective. The second is referred to as the No-plan scenario, which assumes a *laissez-faire* level of demand by EID customers or no conservation cutbacks. The results from two scenarios were analyzed for the future 7-year period, 2028–34, with particular emphasis on the three drought years, 2031, 2032 and 2033.

For both the future scenarios, the operating objectives of Jenkinson Lake and hydropower generation were modified to reflect the evolving EID operating policies. The Jenkinson Lake fill priority was increased during stage 2 and stage 3 drought conditions, while the Project 184 hydropower generating priority was decreased (Table 4, column ‘2028–34’). Also, to meet the growing demands in the western zones served only by Jenkinson Lake and Project-184 Forebay water (see Table 1), the allowable maximum release from Jenkinson Lake in any given week was increased from 5 to 15% of available stored volume.

## Results

With year 1 (i.e. 2028) used as model spin-up, conclusions are drawn from 6 of the 7 years of simulation, which includes a wet year preceding (i.e. 2029) and two wet years following (i.e. 2033 and 2034) the 3-year drought (i.e. 2030, 2031 and 2032). A drought declaration is made in the mid-summer of the 2030 water-year, when a stage 1 drought is issued (Figure 6). ‘Official’ drought conditions end in the late summer of 2033, with the drought having occurred through some portion of four summer seasons. Figure 6 includes the storage in Jenkinson Lake and the drought stage for both the Full plan and No plan scenarios.

The triangles in the top of Figure 6 indicate the total unconstrained demand,  $U_t$  for the simulation period, which ranges from 72 MCM (59 TAF) in 2029 to 82 MCM (67 TAF) in 2034, consistent with EID UWMP 2030 projections. The bars in the top of Figure 6 are the water delivered for the



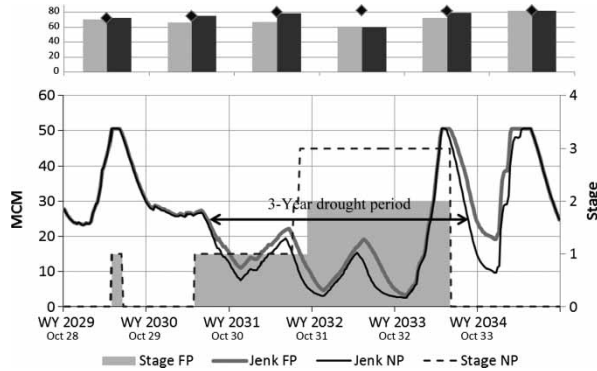


Fig. 6. Jenkinson Lake storage and drought stage for the Full plan (FP) scenario (Jenk FP and stage FP) and the No plan (NP) scenario (Jenk NP and stage NP). Top graph shows the total unconstrained demand (triangles) and the simulated EID water deliveries for the Full plan (light) and No plan (dark) scenarios in MCM.

Full plan and No plan scenarios. Overall, the No plan scenario delivers more water, as there are no mandated cutbacks caused by drought restrictions. However, in the third drought year, the Full plan deliveries 60.9 MCM (49.4 TAF), which is slightly greater than the No plan delivery of 60.0 MCM (48.7 TAF).

For the Full plan scenario, water conservation under stage 1 and stage 2 drought conditions yielded higher Jenkinson Lake storage when compared to the No plan scenario. Assuming conservation targets are met for the Full plan scenario, water conservation in the first and second years of drought help to avoid a stage 3 drought declaration in the third year of drought, although just barely. At the end of September and while in stage 2 drought conditions, the SRI nears but does not reach a value of 0.35 (Figure 7 which is the established SRI cutoff value when stage 3 drought would be declared (see Table 2, row 4).

For the Full plan scenario, the targeted reductions in water demand were assumed to be fully achieved in the first and second drought years, with no unplanned shortage and reductions in delivered water of 16 and 26% of  $U_t$ , respectively. Near the end of the third drought year, five of the western zones (zones

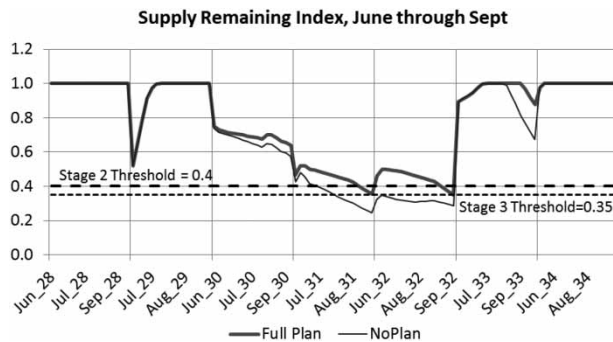


Fig. 7. Supply remaining index for late spring, summer and early fall period for both the Full plan and No plan scenarios. The horizontal lines at 0.4 and 0.35 indicate the thresholds at which stage 2 and stage 3 drought are declared.

9, 10, 11, 12 and 13) experience only a small amount of unplanned shortage of about 7% of each zone's total annual demand. These zones represent about 18% of EID's total delivery, so the total unplanned shortage is less than 1% of the total delivery over the 3-year drought. Recall that these zones are in EID's western service area and have fewer supply options and must rely primarily on Jenkinson Lake or Project 184 supplies.

For the No plan scenario, all shortages are considered unplanned and are relative to  $U_t$ . The No plan scenario implies stage 3 drought conditions near the end of the second drought year. While there is almost no unplanned shortage in years 1 and 2 of the drought, by year 3, nearly all zones experience some unplanned shortage. The total delivered water for all zones is 27% less than  $U_t$ , with unplanned shortages in the spring and summer months of the third drought year. However, for many of the zones, the water system has 'failed', delivering in some cases, only 10% of  $U_t$ . Only zone 2, with full access to Folsom Water has no unplanned shortage. Table 5 summarizes drought plan performance measures, including CV, average Jenkinson Lake storage for the summer months and total delivered water.

The CV estimate for the Full plan scenario and for all 3 years of drought is US\$0.90 million, with the majority of this welfare loss occurring in the third drought year (Table 5). Note that the objective and functional forms of water demand and CV as a welfare measure recognize water as both an essential and non-essential good, as the compensating value of having no water is infinite. Thus, our problem moves from being continuous in having less water, to a discrete problem, where in some cases and places, there is no water provided at all. This fact becomes more apparent for the No plan scenario, where the CV estimates balloon to roughly US\$14 million (Table 5). The high CV is the result of zones moving from having to not-having water, as the data and economics theory remind us of the essential nature of water. These results suggest that a successfully implemented drought plan would help EID avoid maneuvering into the decision space of zones not-having water.

The results also suggest that the majority of cost associated with the drought plan would be borne by EID and not its customers. We estimated that a successfully implemented drought plan would deliver 18 MCM (22 TAF) less water over 3-year drought (Table 5), which at US\$0.85/m<sup>3</sup> would mean roughly US\$15.3 million of lost revenue in 2010 US dollars. In addition, EID has possibly avoided a drought surcharge, with the current plan likely only to enact a surcharge during a stage 3 drought (Brown & Caldwell, 2008).

Storage in Jenkinson Lake in the No plan scenario is lower relative to the Full plan scenario, with substantial differences in the summer months in the third drought year (i.e. the 2032 water year). The Full plan scenario leaves the reservoir at 26% of total storage, while the No plan scenario results in a nearly empty reservoir at 9% of total storage. Water conservation from drought plan restrictions

Table 5. EID performance measures for the Full plan and No plan scenarios for the three drought years. Summer is defined as June 1 to August 31.

	Full plan			No plan		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Compensating variation ('1,000s) (US\$)	45	66	902	0	2,200	13,800
Average summer Jenkinson Lake storage (MCM)	22.2	18.1	13.0	20.4	12.9	5.5
Total delivered water, MCM (% of $U_t$ )	67 (88%)	67 (84%)	61 (74%)	75 (100%)	78 (98%)	60 (73%)

has led to increased storage in Jenkinson Lake, achieved through conservation and diversions of EID's Project 184 water.

This storage implies maintained recreational benefits for the public and associated revenues for EID. The amount of hydropower generated for both the Full plan and No plan scenarios is nearly identical. Under drought conditions, hydropower generation is restricted primarily to the winter months, when there are few generating constraints and very little summer generation owing to the limited water supply and the higher priority to fill Jenkinson Lake. Total generation in 2029, a wet year, was 110 GWh, while generation for the three consecutive drought years was 80, 45 and 30 GWh.

### **Summary, conclusions and recommendations**

The stated goal of the EID drought plan was to 'define demand curtailments that can be reasonably accomplished and that perform well for all customers'. We have suggested that for EID, a key measure of their drought plan performance would be to achieve no 'unplanned' shortages. This paper has explored measures that can be used to evaluate the performance of EID's drought plan, allowing for a more rigorous and analytical analysis than being purely conjectural and speculative.

The results suggest that EID has formulated a very efficient drought plan to navigate a drought more severe than their drought-of-record. If EID were to experience a more severe drought than their drought-of-record and if they were to implement their drought plan successfully and achieve their stated reduction targets, then the plan could avoid EID having to impose the most severe drought restrictions – stage 3, be likely to avoid unplanned shortages and not need to impose a possibly unpopular surcharge on its customers.

A shortcoming of this welfare estimation is the lack of low levels of consumption in the observed data, therefore the ability to estimate CV at low levels of consumption is limited. The EID drought plan does not try to define the minimum level of essential consumption, but if the plan achieves its goals, EID would successfully keep this as a continuous problem (less significant) rather than a discrete, very significant problem. This result also shows that at higher levels of consumption, 'demands' are preferences and not 'needs', as people consume water for many uses beyond the basic levels.

From a EID policy perspective, this analysis will help EID managers communicate to their board the level of financial and other losses associated with drought and how the drought plan could reduce these losses if it were to achieve its fully implemented goals. In advising similar analysis for other utilities, we acknowledge that considerable effort was undertaken to: (1) engage with EID staff and managers to formulate the analysis; (2) collect and process water use, price and household data; (3) build a credible and relevant model of the EID water system that could adequately explore the impacts of drought and drought response; and (4) develop the econometrics models of demand and CV. That said, we believe these kinds of analysis will become more common, as the value of water increases in general, and with the help of readily available electronic databases and analysis tools, should be easier to undertake.

### **Acknowledgements**

The research was supported by the Societal Applications Research Program of the National Oceanic and Atmospheric Administration's (NOAA) Climate Program Office (CPO) under grant

NA07OAR4310370; the Weather and Climate Assessment Program of the National Center for Atmospheric Research (NCAR); and the El Dorado Irrigation District. NCAR is supported by the National Science Foundation.

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Received 28 December 2011; accepted in revised form 8 December 2012. Available online 4 March 2013