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The Welfare Implications of Bankruptcy Allocation of the Colorado River Water: The Case of the Salton Sea Region

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Abstract
This paper focuses on assessing a policy for reallocation of Colorado River water for major stakeholders in the state of California, to set a standard for sustainable long-term public and environmental use. We address the policy of allocating scarce water resources to competing stakeholders of different sectors in the Salton Sea region under over-committed water rights agreement. We determine the value of water applied to the agricultural, urban and tourist sectors to estimate the regional welfare under different allocation frameworks. We use two models for allocation: one involving a social planner approach that maximizes regional welfare, the second focusing on the bankruptcy rules of proportional deficit (cutback), and constrained equal award. We find the proportional cutback framework to be less conducive to regional welfare, although it presents a more politically feasible and robust option.

Keywords Colorado River water · Salton Sea · Water scarcity · Bankruptcy allocation · Regional welfare · Sectoral equity · Social planner

JEL Classification Q25

1 Introduction

With the realization of global trends in water scarcity (Liu et al., 2017) it becomes harder to establish sustainable water allocation schemes among users, both domestically (e.g., Stern and Sheikh 2019) and internationally (Dinar and Dinar 2017; Dinar et al. 2015). This is evident in

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regions where population growth leads to conflicts with other water-intensive production sectors and environmental amenities.

Water allocation agreements among users sharing this common pool resource, under supply uncertainty introduce challenges to regional economic performance and stability (Griffin and Mjelde 2000). This is likely when such agreements are based on fixed quantities of the resource, assigned as property rights to each user. An example is the Colorado River basin water, which is shared by seven western U.S. states and Mexico. Sharing is done by an allocation mechanism (Compact) based on fixed quantities that was set at the 1922 level of river flow. But due to the long-term reduction in water flow within the Colorado River, the 1922 compact fails to fulfil the agreed upon allocations of 16.46MAF to users, resulting in possible welfare losses and disputes.

Much published work on allocation of scarce water exists, utilizing several approaches for water allocation, including market mechanisms, legal arbitration, social planner, inter-basin transfer, environmental flows allocation, and allocation by negotiation (Booker and Young 1994; Clyde 2008; Nigatu and Dinar 2015; Klein 2012, Quantification Settlement Agreement—QSA 2015; Kahil et al. 2016; Acquah and Ward 2017; Crespo et al. 2019, to name a few). Most of the published work on allocation of scarce water did not address the situation where water users were not able to realize their water right/quotas. A situation where water has to be allocated under bankruptcy situation (as was described earlier) necessitates bankruptcy allocation approaches.

The literature includes examples of several bankruptcy allocations of water globally and in the Colorado River Basin, which are relevant to our work. Mianabadi et al. (2014) discussed water allocation among separate governing entities by applying a bankruptcy model to the Tigris River. They had determined the allocation of water based upon the "weight" of a given stakeholder, which includes Turkey, Syria, and Iraq. These weights were predicated, based on multiple factors, including proportion of population that is dependent on the watershed, and stakeholder power. Most importantly the weight of a stakeholder was based upon the amount of water that is contributed to the watershed by the hydrology of each stakeholder's jurisdiction. In Iran, basin-wide water allocation frameworks were developed by Oftadeh et al. (2016) for Lake Urmia, based on the quantity of water required by the stakeholders and referred to as the Proportional Rule method. This disregards the "on-paper" claims of stakeholders, only utilizing what is being used currently and historically. This method is also weighted in favor and prioritizes the agricultural sector. It thus does not address urban and agricultural sectors as equally competing interests. Madani and Dinar (2013) indicate four major governance models for managing groundwater in situations of overuse of scarce water supplies. One of the governance models is bankruptcy management, in which the groundwater table is treated as a bankrupt entity whose assets must be distributed among the users. This is generally fulfilled either through asking each stakeholder to reduce their use by a given proportion, referred to as proportional bankruptcy; or by a CEA model, in which more vulnerable stakeholders are satisfied before more resilient stakeholders.

While this paper focuses on a particular situation and geographical characteristics, the problem analyzed, and the methodology developed are general and applicable to many locations and issues in the water sector globally. Although most of the works reviewed earlier that applied modeling of the region in question, or bankruptcy allocation rules addressed the acceptability and stability of these allocation agreements, using concepts from cooperative game theory (Read et al. 2014), our analysis focuses only on the welfare implications of the various allocation schemes and their relative efficiency compared with the social planner allocation. Regarding the empirical focus of the Colorado River region, the paper seeks to address two issues that present themselves to the region surrounding the Salton Sea. The first issue being the shrinkage and resulting environmental degradation of the sea itself. The second, is the lack of available water within the region to commit towards sustaining the sea and the economic activities of the communities.

More specifically, the contribution of the paper is several folds. First, we refer in this paper to actual water demand and benefit functions of water-claiming entities, such as specific irrigation districts, urban utilities, and the Salton Sea itself. We develop a methodology to estimate water demand functions by consuming and producing sectors and the recreational value of water in the Salton Sea region. We apply a social planner approach to optimize the deficit allocation such that the regional welfare is maximized and provides a benchmark for other allocation policies. We then apply two bankruptcy allocation methods to a set of scenarios that are similar to positions and principles used in past and on-going water allocation negotiations in the region, to calculate the resulting sectoral and regional welfare, and compare these measures of welfare between the social planner and the bankruptcy allocations we applied.

2 Data and Methodology

The paper addresses the over commitment of a water resource and suggests a comparative analysis of the policies' effects on individual and regional welfare. We develop a methodology to deal with water deficit allocation in the Colorado River Basin service area and apply it to the Salton Sea region. As can be seen in Fig. 1, between 1922 and 2015 river flow was lower than 16.46MAF in 55 of 92 years (nearly 60%). Clearly, the claims of the riparians were not met in the past. As is expected (McCabe et al. 2017), occurrence of drought in the Colorado basin will increase due to climate change, leading to further reduction in the flow and the ability to allocate the agreed-upon quantities to the riparian states/countries. Addressing the likely water shortages in the basin will require water users to continue reducing consumption in a way that minimizes economic and social welfare losses.

A situation in which a commitment of a common pool resource to users cannot be fulfilled is defined as a bankruptcy. Generally, a bankruptcy situation exists when agents submit claims that are larger than the available amount, and that deficit must be allocated among the

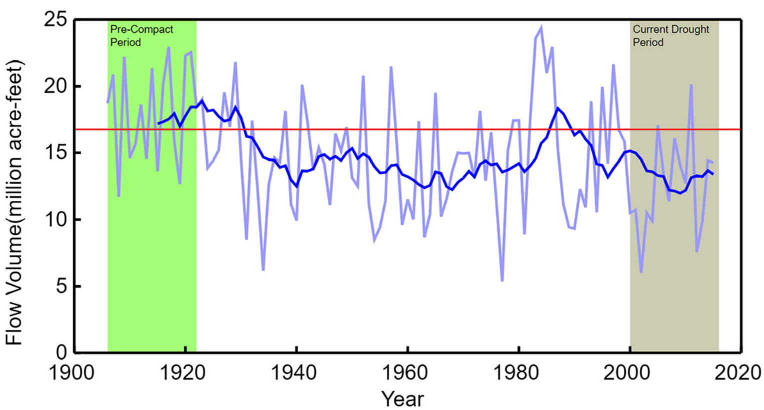

Fig. 1 Colorado River Natural water flow 1906–2015. Light blue line marks the annual water flow; dark blue line marks the 10-year average flow; red line marks the 16.46MAF in the 1922 compact. Source: U.S. Department of the Interior (n.d)

claimants such that each receives a non-negative amount that cannot exceed the claim. Bankruptcy allocations rules have been developed for financial/economic situations (O'Neill 1982; Aumann and Maschler 1985; Branzei et al. 2008, to name a few).

Bankruptcy allocation rules were applied also to the water sector by, for example, Madani and Dinar 2013; Mianabadi et al. 2014; Madani et al. 2014; Degefu and He 2016; Degefu et al. 2018; and Shenlin et al. 2020. The objective was to improve groundwater or reservoir management under overexploitation, or to sustain management of shared international waters with claims that exceed the flow. The legal principles of bankruptcy allocation have been demonstrated with examples for various applications (Klein 2012). This paper focuses on the Colorado water bankruptcy situation that affects Southern California, particularly, the Salton Sea region (Fig. 2 and Auxiliary Annex A1).

2.1 Analytical framework

We assume that a regional regulator (such as the 1922 Colorado compact) allocates a given amount of water Q among n users such that $\sum_{i=1}^{n} q_i \leq Q$, where q_i is the agreed quantity to be provided to user i. However, given the natural climate in the region leading to volatile water supply (see Fig. 1) the regulator cannot meet the overall quantity Q and it faces a significantly lower available amount to be shared, Q^*. The deficit, Q-Q^*, is now to be allocated among the different n users such that each gets $q_i^* \leq q_i$. We use several allocation schemes utilized in previous work. We apply the Social Planner allocation to water rights that are in deficit across rights holders, and two bankruptcy allocation rules: proportional rule and the CEA rule (as is explained below) because they allow us to mimic stakeholder conflicts and certain water allocation policy approaches.

2.1.1 Social Planner Allocation

A social planner considers reducing the water allocations to each user such that at the regional welfare will be maximized. The social planner allocates the available water $\sum_{i=1}^{n} q_i \leq Q^*$ such that the marginal welfare is equalized.

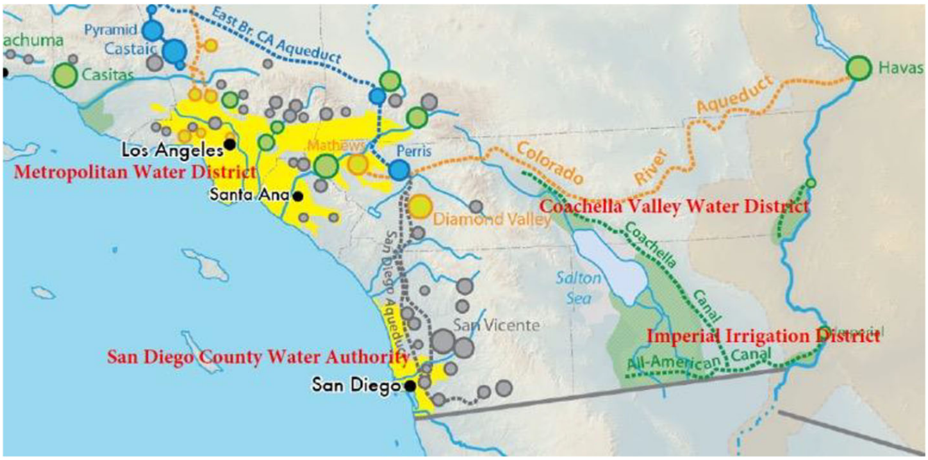

Fig. 2 The Colorado River Basin Water Service Region. Source: Wikipedia, Water in California https://en.wikipedia.org/wiki/Water_in_California. (No permission needed)

The optimization problem of the social planner is (in a static setting):

$$MaxW = \sum_{i=1}^{n/S} D_i^j \left| q_i^* + S \right| q_S^* \tag{1}$$

where W is the regional welfare, D_i^j is the area under the inverse demand function of user i, i = 1, ..., n/S, and S is the welfare function of recreation that is associated with the quantity of water in the Salton Sea.

Subject to:

$$\sum_{i=1}^{n} q_i^* \leq Q^* \tag{2}$$

$$Q^* \leq Q \tag{3}$$

We refer to the social planner as the first allocation model.

2.1.2 Bankruptcy Allocations

We use two bankruptcy allocation measures: the proportional rule and the CEA rule. We will refer later to these as our second and third allocation models.

The bankruptcy proportional allocation rule allocates a reduction of Q-Q* among the n users such that each user is faced with a reduction that is proportional to their compact allocation.

The percent reduction faced by user i under this rule is $R_i^P = \frac{Q-Q^*}{Q} q_i$. It has been argued that this rule benefits users with relatively larger original allocations, thus it is not valued as fair, although it is efficient in the sense it maximizes the regional welfare (Madani and Dinar 2013).

The constrained equal award (CEA) allocation rule allows the regulator to introduce social preferences, such as weights on the bankruptcy allocations to certain users. One example could be a preferred weight to the Salton Sea due to its regional welfare effects, or a preferred weight to areas sensitive to water availability. The percent reduction faced by user i under the CEA rule is $R_i^{CEA} = \frac{Q-Q^*}{Q} \varphi_i \cdot q_i$, where φ_i is the weight assigned by the regulator to user i, with $\sum_{i=1}^{n} \varphi_i = 1$. Madani and Dinar (2013). In our analysis, we applied the constraint that no user can be allocated water in excess of their historical allocations.

2.1.3 Welfare Loss Calculations

The calculations of the welfare losses of each user, and of the region, are based on the increase in willingness to pay for water after reducing the 1922 compact allocation.

We developed an algorithm to calculate regional welfare loss from the various deficit allocations. Below is a general model that presents the calculation principles.

$$\begin{aligned} LW = \sum_{i=1}^{6} & \left[\left(\int_{Q_i^1}^{Q_i^0} \mathrm{D}_i(Q) dQ - P_{Q_i^1} Q_i^1 \right) - \left(\int_{Q_i^2}^{Q_i^0} \mathrm{D}_i(Q) dQ - P_{Q_i^2} Q_i^2 \right) \right] \\ & + \left[\left(\int_{Q_7^1}^{Q_7^0} P_{Q_7^1} Q_7^1 - \mathrm{V}_7(Q) dQ \right) - \left(\int_{Q_7^2}^{Q_7^0} P_{Q_7^2} Q_7^2 - \mathrm{V}_7(Q) dQ \right) \right] \end{aligned} \tag{4}$$

where LW is the regional welfare loss, $D_i(Q)$ is the demand function of user i, Q_i^1 is the quantity allotted to user i under the original scenario, Q_i^2 is the quantity allotted to user i under the deficit allotment scenario; $P_{Q_i^l}$ is the price faced by user i when allotted quantity Q_i^l. The index 7 refers to the Salton Sea region. Given the variability of the water flow in the Colorado River and given that compact allocations were unmet, we use empirical results that pertain to welfare values calculated at the level of the allocation of water under deficit rather than the loss in consumer welfare between the compact and deficit allocations.

2.2 Empirical Methodology

Our methodology for optimal allocation of Colorado River water will be performed in two stages. We first estimate relationships that quantify the value of water for each stakeholder at each allocation level. We then apply allocation methods described above using the estimated water value relationships.

The value of water will be represented by demand curves of consuming sectors, indicating the willingness to pay for an additional unit of water in the case of the urban stakeholders, and the derived demand for an additional unit of water for the agricultural stakeholders. An additional 'user' is the Salton Sea, engaged in recreational uses of the water. We use data on water inflow to the Salton Sea, recreational visits to the Salton Sea region, and monetary spending by visitors in the region.[1] Once we have established the relationship between quantity and value of water for each stakeholder, we then determine the effects of allocations to ensure social welfare, social justice, and robustness (Madani and Dinar 2013).

For determining agricultural water demand we employ the residual approach (Young and Loomis 2014) for each of the three agricultural users in the region. The residual approach subtracts the costs of producing a crop net of cost of applied water from the revenues gained in the sale of that crop, leaving only the revenue that is attributed solely to the applied water. We determine the costs and revenues associated with growing crops by pulling data from the University of California Cooperative Extension crop budgets in the three counties of the Salton Sea region (Imperial, Riverside, San Diego). Recent available data is from 2017 although we have used earlier years for crops with no up-to-date data (these are listed in Sect. 3.1). By ordering the crops in a declining value per unit of water and by accounting for the area grown of each crop, hence, the total amount of water used to irrigate each crop, we can obtain the derived demand for water for each agricultural water user.

The value of water for urban uses is derived from a demand curve, presenting the willingness of end users to pay for an additional unit of water. Changes in available amount of water affect the consumer surplus (Bithas and Stoforos 2006). We utilize these curves to calculate a change to welfare form allocation for urban stakeholders. This method has been implemented and successfully replicated statewide across California, and we applied the findings in Dziegielewski and Optiz (1991) to the three urban centers in the Salton Sea Region.

To determine the value of water to the Salton Sea itself and compare it to agricultural or urban uses, we estimate the value of the recreational sector of the Salton Sea. We employ the approach used by Iamtrakul et al. (2005) and by Esteban and Dinar (2015), by estimating the relationship between inflow of water into the Salton Sea and the number of tourist visits and dollars spent by tourists in the region. This comparison is viable due to the relationship of the tourism industry being directly tied to Salton Sea visits, which can be affected by the sea's

[1] We recognize that by referring only to recreational benefits from the Salton Sea we ignore several important aspects associated with water level in the Sea, such as health impacts.

health or by other tourist activities that can be impacted by the Salton Sea's effects on air quality and ecosystem health (Schwabe et al. 2008).

Once the demand functions for the urban and agricultural sectors and the value function for recreational water are estimated, we evaluate the impact of various allocation methods on the sectoral and regional welfare by calculating the consumer surplus from the reduced allocation. We apply two allocation methods: the social planner approach, and the proportional deficit allocation. The social planner model maximizes the regional welfare by allocating water to the stakeholder that provides the highest marginal welfare for an additional unit of water. The proportional deficit allocation has three nuances: The first is based upon the proportion of available water each stakeholder has used during historic drought years. The second provides stakeholders with an allocation from the available water after the deficit is applied, which is proportional to their current legal claims. The final form considers that the senior water rights of IID are upheld in any deficit scenario (Sechi and Zucca 2015).

3 Empirical Application

We begin by estimating the derived water demand in agriculture, utilizing existing crop values, production costs, and water used. We then implement the demand curves developed for urban water use by Dziegielewski and Optiz (1991). Finally, we derive the value of water afforded to the Salton Sea by running a regression on the relationship between water inflow into the sea and tourist visits and spending.

Water demand estimations are as follows: The MWD necessitates urban water demand estimation. The IID requires only agricultural water demand estimation, whereas CVWD and the SDCWA necessitate both agricultural and urban demand estimations. Recreational water valuation will be applied only to the Salton Sea itself.

3.1 Estimating Irrigation-Agriculture Demand

The value of water as applied to crops, has been determined through existing crop cost/return studies (UCCE Riverside 2018; UCCE Imperial 2018; UCCE San Diego 2018). The most recent cost/return studies have been published for the year 2017, thus all crops are assessed at their 2017 value. In the case of crops with no published cost/return studies for 2017, we utilized studies from earlier years (1960, 1969, 1977, 1980, 1983, 1987, 1989, 1990, 1991, 1992, 1996, 1997, 1998, 1999, 2000, 2002, 2005, and 2011) and adjusted for inflation using the Bureau of Labor Statistics website for official conversion calculations (BLS 2019).[2]

Not included in the agricultural valuation for IID are what is listed as "miscellaneous crops and cattle" in official crop reports, and aquatic products. This is because we are unable to determine the composition or value of these individual products, thus rendering them unable to be factored into our valuation. We note that aquatic products and miscellaneous livestock produced a gross value of $60,889,000 (Imperial County 2018). The CVWD agricultural valuation is similarly limited to the available data on the cost of growing an acre of listed crops.

[2] Based on BLS (2019) inflation between 1960 and 2017 was 724 percent, and between 2011 and 2017 it was 10 percent.

The valuation of SDCWA agricultural crops is limited by a small body of official cost/return data on nursery plants, and to official crop reports aggregating all nursery plants into broad classes (i.e., succulents, perennials, fruit trees). This aggregation, the lack of official studies on ornamental crop watering in California and the difficulty of measuring water input due to pot growing and different measuring metrics makes it difficult to determine the production cost of individual crops (Garcia-Navarro et al. 2004; Burger et al. 1987). We estimated production cost and water needs by utilizing representative plants within that category whose production costs act as a stand-in for all crops in the category. For example, for perennial flowers, only cost-and-return studies for carnations are available through the UC Cooperative Extension, thus the cost of producing carnations is applied to all SDCWA perennial production. The agricultural derived demand functions for water can be found in Figures A.3, A.4, A.5 (Auxiliary Annex) for IID, CVWD, and SDCWA, respectively.[3] We use the quantity-economic value pairs to estimate for each irrigation district the derived demand function (Table 1).

3.2 Estimating Urban Demands

We selected demand functions as the means of estimating urban water value for MWD, SDCWA, and CVWD urban water districts.

For the demand function method to accurately represent the value of water for urban stakeholders, we must make three assumptions. First, that the statewide price elasticity is both representative of urban Southern California and is constant along the demand curve. Second, that we can consolidate monthly fluctuations in water usage into a single demand function for the year. Third, we have collective assumptions that underlie all demand functions, although most pertinent to our research is the assumption that usage needs, and consumer preferences will remain the same in the future and under scarcity scenarios.

We applied the demand function methodology to determine the value of water within the state of California, which was developed by Jenkins et al. (2003). It relies on factoring in the regional price elasticity (expressed as), and an integration constant (expressed as C), along with the price P and quantity of water, Q, to develop the demand curve. Important to this method is utilizing the correct price elasticity, which was used for MWD estimated by Dziegielewski and Optiz (1991). Their methodology considered the seasonal demand fluctuations from winter (-0.240) to summer (-0.390), which we have aggregated to produce a single annual price elasticity of (-0.315). We will be utilizing the price elasticity developed for MWD for all urban stakeholders in the region, due to similar characteristics between all MWD-served districts, and a lack of existing price elasticity data for CVWD and SDCWA. The latter being included as part of MWD in Dziegielewski and Optiz's (1991) study.

We first derive the integration constant represented by $C = \ln(P) - \{\ln(Q)/\varepsilon\}$, where P is the observed price of water for the given stakeholder, and Q is the observed quantity of water drawn by that stakeholder in the year 2018. ε represents the regional price elasticity. This will then be factored into our demand function represented by $P = e^{\frac{\ln(Q)}{\varepsilon}+C}$.

The graphs of the urban demand functions for MWD, SDCWA, and CVWD, respectively, can be found in Figures A.6, A.7, A.8 (Auxiliary Annex).[4] The pairs of water quantity-

[3] It should be noted that the value of unit of water in the agricultural sector is very low for consumption above nearly 125,000, 300,000, and 60,000AF for IID, CVWD, and SDCWA, respectively.

[4] Note that the value of unit of water in the urban sector is very low for consumption above nearly 447,000, 147,000, and 303,000AF for MWD, CVWD, and SDCWA, respectively.

Table 1 Estimated equations of water demand in urban/agricultural sectors and recreational water value in The Salton Sea Region

Sector Variables	IID	MWD[a]	CVWD AG	CVWD URB[a]	SDCWA AG	SDCWA URB[a]	$'s Spent in the Salton Sea region	Salton Sea Tourism
Intercept	17.05 (24.59)*	60.58	19.94 (23.18)*	55.5	32.84 (9.43)*	55.48	3,171,912,314 (3.30)*	7,926,128 (3.09)*
W	-0.774 (-6.43)*	-4	-1.25 (-17.73)*	-4	-2.36 (-6.98)*	-4	1,039 (1.03)*	2.6 (0.91)*
F-Test	41.35 (9.84E-07)*		314.45 (1.06E-13)*		48.82 (1.46E-05)		1.05 (0.36)	0.83 (0.43)
Adjusted R^2	0.608		0.937		0.786		0.011	0.241
Number of Observations	27	55	22	22	14	34	6	6
Equation Type	Log-Log	Log-Log	Log-Log	Log-Log	Log-Log	Log-Log	Linear	Linear

Note: t-test in parentheses. *=Significant in 1% or less

[a] Coefficient calculated based on Dziegielewski and Optiz (1991)

[b] Given comment a, statistical performance is not included due to extraction from existing reported equations

economic values are used to estimate demand functions for the various urban centers. Refer to Table 1 for the coefficients of the estimated urban demand functions.

3.3 Estimating Recreational Value of Water in the Salton Sea

The travel cost method benefits from being more directly comparable to the valuation methods utilized for urban and agricultural users. We estimated a relationship between the total water inflow to the Salton Sea and the number of visitors to the region (Figure A.9 Auxiliary Annex). The data concerning annual tourism visits and revenues is sourced from (Tourism Economics 2014). Annual inflows into the Salton Sea were established using data from the United States Geological Survey (USGS 2007). Using data for 2013–2018, we were able to estimate a linear relationship using OLS regression. These $ amounts, that vary with the inflow to the sea represent the value they attribute to the Salton Sea.

A similar regression was used to estimate the relationship between dollars spent in the Greater Palm Springs/Salton Sea region and the acre-feet of inflow to the Salton Sea. We assume that visitors to the region are motivated by the Salton Sea ecosystems health. Ecosystem health is assumed to be a direct impact on those who would visit the sea itself, and an indirect impact on tourism in the region due to the hazardous air quality that the seas environmental degradation is responsible for. This means that the sea is assumed to have major influence on visitation to the region regardless of whether those visits are to the sea itself. We used the same time frame (2013–2018) to plot the linear relations below (Figure A.10 Auxiliary Annex). See Table 1 for the equations' coefficients.

4 Policies for Allocation of the Water Supply Deficit

The policy of allocating a deficit is best viewed from the lens of a social planner approach, and the planner's goal is to minimize losses incurred through water restrictions. The regional welfare will be determined through the dollar value produced in the region by the application of water to different economic activities. A bankruptcy allocation treats scarce common pool resources as a bankrupt entity, which must have its deficit assets distributed among stakeholders to whom more was promised than can be allocated. The best regulatory framework is one that ensures social welfare, social justice, and robustness (Madani and Dinar 2013).

In pursuing a social planner allocation, we evaluate the social welfare (measured as consumer surplus) produced within each sector of the major stakeholders. The simulations for these water allocations have been derived by developing a model that utilized our existing sector-stakeholder demand curves to indicate the potential benefits of providing a proportion of the long-term sustainable withdrawal for the region. These proportions ranged from no allocation at all to the maximum volume of water that a given stakeholder-sector could utilize. We used this model to assess the highest proportion each stakeholder-sector could receive until an additional allocation of water would produce greater social welfare when placed elsewhere. Thus, the maximum welfare a single stakeholder-sector could produce relative to the other stakeholder-sectors is derived.

Our second model, following the relative proportional rule of bankruptcy allocation, does not break our stakeholders into sectors, because this model is dependent on both the agreed water entitlement and the total water use for each stakeholder. The first simulation for this model involves taking each stakeholders proportion of the annual withdrawal, and scaling it down to a portion of the sustainable withdrawal for the state of California. The second simulation is instead applied to the allocations that each stakeholder has been promised by the regulator or in a water-transfer agreement. The last simulation is derived from the proportion of existing use but with the addition of an allocation set aside for the Salton Sea, and is designed to close the gap between current inflow and a historically sustainable flow.

Our third model is a version of the CEA rule of bankruptcy allocation. This model is one in which the available resources are distributed equally among all stakeholders, with some form of constraint or weighted preference set by the regulator. In this case, the constraint is that no stakeholder receives more than their maximum historic entitlement. This should produce a model which favors stakeholders who have historically used less water.

We will also address the IIDs present perfected rights, which mandates that in scarcity situations the needs of IID must be satisfied prior to any other stakeholder. IID has agreed to water restrictions within the district in past agreements, such as the QSA. However, when developing a new reallocation model, we cannot assume that this trend will continue. Therefore, we have developed two scenarios for our models: the first is one in which IID agrees to limit its water usage according the same rules as all other stakeholders. The second scenario is one in which IID's seniority is upheld, while the burden of deficit is placed on all other stakeholders.

A summary of the different simulations is presented in Table 2 and the welfare results are presented in Figs. 3, 4, 5 and 6 (in Sect. 5.2) for 3 state of water deficits (0.250, 1.250, 2.250 MAF annually).

5 Results and Discussion

5.1 Water Delivery Simulations

To derive the extent of the water bankruptcy, we have utilized data of historic Colorado River flows and allocations (Table 3). The 1922 Colorado River Compact assumes that the Colorado River will have a flow equal to or greater than 16,450,000 acre-feet annually and divides this among the major stakeholders. The state of California is entitled to 4,400,000 acre-feet annually. For each year's annual flow sourced from the United States Geological Survey, we have subtracted the amount of water potentially used if all beneficiaries of the Colorado River Compact take their full allotment (16.46MAF). These overdrafts are larger than California alone could account for. To determine what proportion of the shortfall is to be taken

Table 2 Summary of simulation runs

Allocation Scheme Simulation	Model		
	1	2 Bankruptcy proportional	3 Bankruptcy constrained equal award
Social Planner	X		
Bankruptcy based on proportional use		X	
Bankruptcy based on proportional claims		X	
Bankruptcy based on priority to SS		X	
Bankruptcy based on priority to IID water rights		X	
Bankruptcy based on constrained equal awards			X

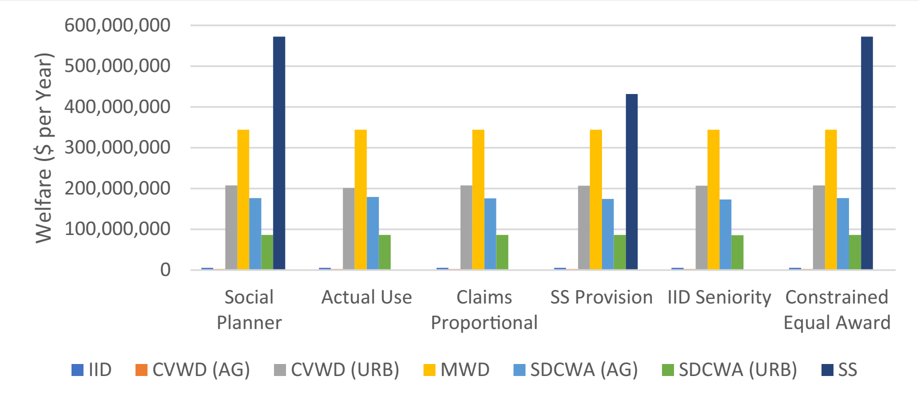

Fig. 3 Welfare produced by six models under annual deficit of 250,000 acre-feet

from California, we have derived from each year's shortfall a proportion that is equivalent to California's original allotment (4.4MAF/16.46MAF = 0.267). Therefore, we can assume that for a given year, Californian stakeholders are to be responsible for 26.7% of the shortfall.

From Table 3 we can observe that four out of 27 years exhibit a small deficit, 20 exhibit a medium deficit, and three exhibit a high deficit. Based on this distribution, we determined the three ranges for the welfare analysis as: small deficit 0-0.5MAF with mean of 0.250MAF; medium deficit 0.5-2MAF with mean of 1.25MAF; and high deficit 2-2.5MAF with a mean of 2.25MAF.

With the set of the estimated demand functions and the range of water available for allocation, we estimated sectoral and regional welfare (measured by consumer surplus) from allocation of the available water using social planner and bankruptcy allocations described previously.

5.2 Simulations Results

What follows is the comparison of welfare resulting from the six proposed allocation methods. Included is the social welfare produced by individual stakeholders under each regime, and the total regional welfare (Figs. 3, 4 and 5).

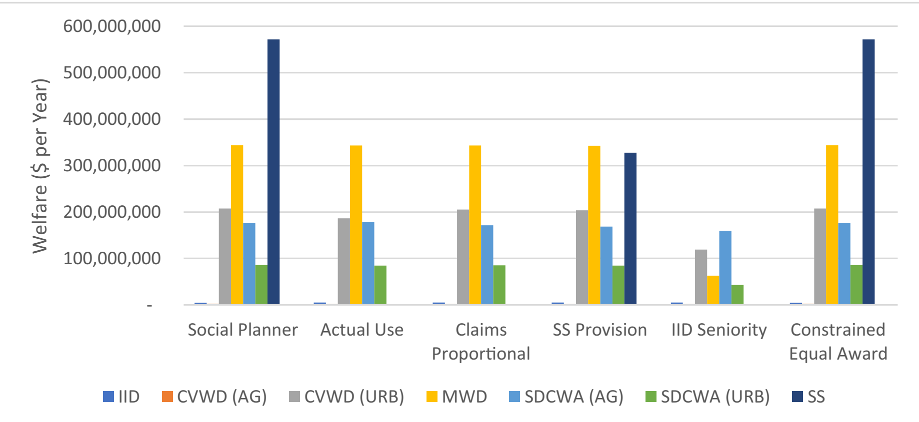

Fig. 4 Welfare produced by six models under 1,250,000 acre-feet of deficit

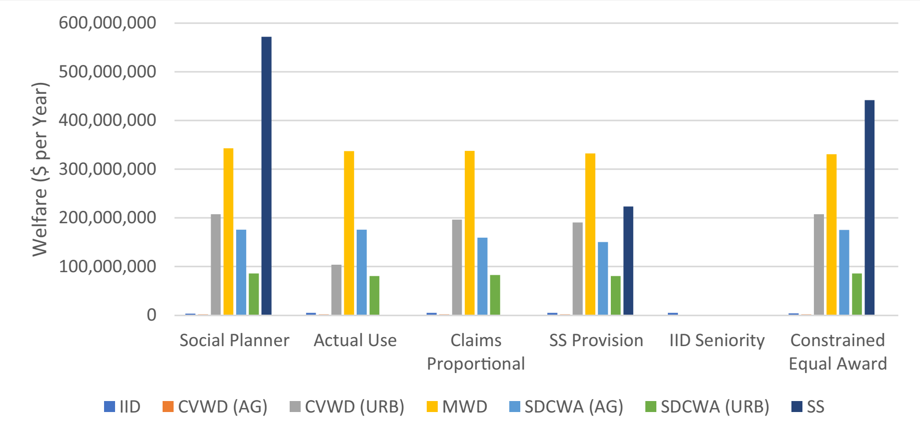

Fig. 5 Welfare produced by six models under 2,250,000 acre-feet of deficit

Results in Fig. 6 suggest that welfare produced with small and medium water deficits yield insignificant welfare losses in almost all simulated deficit allocations. The reason for this unexpected result is the relatively low value of water productivity in the high-amounts of water used (See Figures A.3-A.8, Auxiliary Annex). Therefore, reducing water available in the low and medium deficit ranges results in small losses, while a high deficit reduction will result in substantial loss.

5.3 Discussion: Impact and Policy Implications

The social planner allocation does not weigh the water needs of agricultural stakeholders as highly as that of urban stakeholders. All simulations produced under this framework result in major losses to the agricultural industry which has historically utilized an average of 2.5MAF a year (Table A.2 Auxiliary Annex), particularly the IID. The SDCWA agricultural sector fares

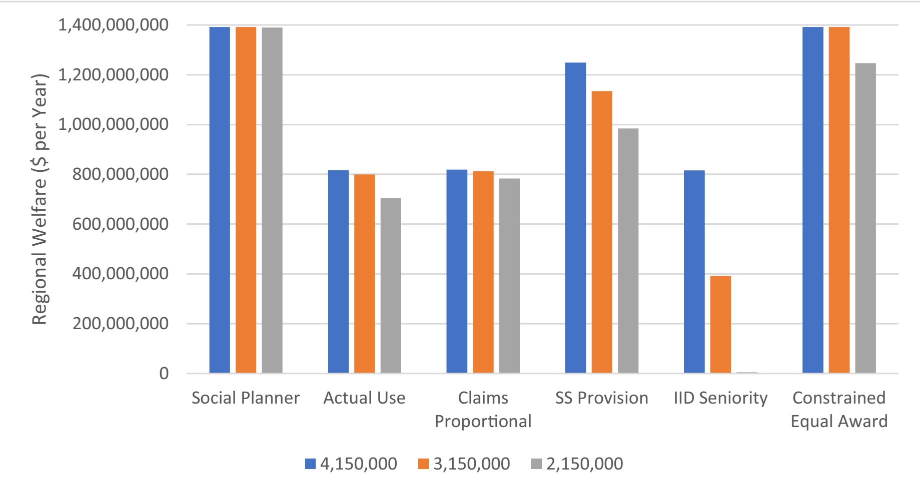

Fig. 6 Total regional welfare produced by all models under three levels of deficit

Table 3 Distribution of water deficit in the Colorado basin (1988–2015)

Deficit range (MAF)	Number of years
0-0.5	4
0.5-1	8
1-1.5	8
1.5-2	4
2-2.5	3

Source: Fig. 1, Table A.1–2

the best of all agricultural sectors, possibly due to the high value produced on a relatively small acreage. The urban sectors with higher willingness to pay are insulated from losses due to a reduction. The Salton Sea fares well in these models, due to the high marginal value produced by the tourist economy. Thus, the social planner model provides a sustainable allocation for the Salton Sea while shielding urban centers from major water cutbacks yet severely damaging the agricultural sector.

The simulations that provide stakeholders with water in proportion to their existing usage and claims produce a lower regional welfare versus the social planer model. Because agricultural water uses already account for most regional water use, these models protect agricultural interests by affording them the same proportion while supplies dwindle. Urban water sectors would not contribute to the regional welfare to the degree that they are able, considering their high consumer surplus. Furthermore, residential and industrial water values will increase greatly, and simulations involving deficits of 2,150,000AF may result in urban water shortages. The low water quantity dedicated towards the Salton Sea does not afford it a sustainable inflow. Yet by developing a model that sustains ecosystem, we can project the regional welfare with ecological provisions. This value is higher than that produced by a model considering only existing uses and entitlements, although lower than produced by social planner models. The proportional allocation model therefore is beneficial to the interests of the agricultural sector and may result in urban water price increases, while not sustainably providing water to the Salton Sea, unless water is legally committed to the environment.

The models in which the IID's senior rights are upheld are the most damaging to regional welfare. Simply reducing the regional water use to 4.15MAF results in the IID being allocated at minimum 65% of the region's water. Under scenarios in which the bankruptcy increases, we see massive reductions in the regional welfare. In years in which California is only able to receive 3.4MAF, IID will be entitled to over 76% of the region's water, drastically inhibiting other stakeholders' ability to utilize water, because they must divide 800,000AF between two major agricultural sectors and millions of residents. In major drought periods where the bankruptcy reaches 2.0MAF, IID would be entitled to all water California draws from the Colorado River. This leads to a devastating situation for other agricultural sectors, and water shortages in urban sectors.

At the lowest levels of scarcity, the CEA model produces a welfare level that is indistinguishable from the social planner model. As scarcity increases, the welfare resulting from this model is reduced to a greater degree than in the social planner model, although it remains greater than that of any other model. It provides a near-optimal welfare level while affording more water to agricultural districts, although agriculture is still impacted. Additionally, this method asks stakeholders with a lower historic use to make fewer reductions.

Regarding valuations favoring urban sectors, our assumption is that this tendency arises due to urban users paying full market rate for water, whereas agricultural water is subsidized, inflating urban willingness to pay for water. Additionally, the models that do not consider

IID's status as a senior water rights holder, indicate that these are not conducive to the general welfare, and produces systemic inefficiencies.

Regardless of the status of IID's present perfected rights, they would unlikely accept drastic deficits in their entitlement. This does not mean that they would never accept reductions in their entitlement, as they have agreed to previously. Additionally, IID is invested in maintaining the Salton Sea, due to the air pollution hazards it poses within its jurisdiction. IID declared Salton Sea restoration as its primary objective during the Lower Basin Drought Contingency Plan negotiations. Meaning it is politically feasible to persuade IID to follow a bankruptcy allocation model that sacrifices a portion of its allotment to sustain the Salton Sea, despite the welfare loss from the agricultural industry.

We should note that while urban districts produce a greater regional consumer surplus than agricultural users, they also can mitigate the loss of water through utilizing alternate sources. In particular, MWD and SDCWA have a robust portfolio of water sources (desalination, managed aquifer recharge) to replace deallocated Colorado River water (MWD 2018).

Meanwhile stakeholders CVWD and IID lack access to the ocean, receive less rainfall, and lack the capital to import water. IID, the region's largest user, relies on water drawn from the Colorado River and lacks alternatives. Therefore, IID has initiated programs and infrastructure at improving conservation and better utilize existing water supplies, such as the On-Farm Efficiency Program, which reimburses farmers for water conserved, and saved over 44,371AF annually. The CVWD similarly has no alternative water sources. While it cannot replace its water sources, it modified the economic use of that water. If a loss in allocation will affect the agricultural industry negatively, it is possible for them to mitigate this loss through strengthening its tourism sector.

Due to these factors, an allocation that favors the IID may be justified even without considering their senior rights. This does not mean that the regulator should allocate water to a stakeholder producing suboptimal welfare simply because of its inadaptability. It is merely a consideration when predicting regional welfare after implementation. The ability of most stakeholders to manage the loss of water in comparison to IID mitigates the suboptimal regional welfare that these models produce.

5.4 Sensitivity Analysis

We have conducted a sensitivity analysis aimed to indicate climactic fluctuations on estimated slope of demand and water value functions of representative agricultural district, urban district and the Salton Sea. Given findings in Brown et al. (2019) we selected a 2% changes in the slope of the demand functions (agriculture and Urban) and the water value function (Salton Sea). Results are summarized in Table 4 below.

Table 4 Sensitivity analysis of representative demand coefficient changes impact on stakeholder welfare under the social planner allocation

	Base	2% Increase	2% Decrease
AG (IID)*	$2,257,306	$1,596,868	$3,190,623
URB (MWD)*	$215,169,133	$78,364,131	$567,767,979
SS	$571,805,918	$583,242,036	$560,369,799

* Individual results are not reported but are available upon request

Note: Negative sign in the demand function for agriculture and urban sectors results in reduction in welfare as slope increases and vice versa

As can be seen the welfare of the agricultural sector is less sensitive to changes in the demand slope compared with the urban sector. These results suggest that the policy maker, in consideration of future climate change impacts, should consider variation across geographical regions and sectors in impact of the deficit allocation schemes Rightnar and Dinar (2019).

6 Conclusion

It is possible to minimize regional welfare loss as we move to establish a new norm in light of decreasing Colorado River flows. This can be fulfilled by treating the water system as a bankrupt entity. How to distribute these limited resources is answered by the benefits to the public derived from the new allocation. By calculating the consumer surplus, we can determine the welfare for the region by allocating water to a given stakeholder and establish the allocations that are most beneficial for the region as less water becomes available.

We must operate within the existing legal framework and stakeholder characteristics. Relating the value of water to a dollar amount helps provide initial estimates on regional welfare losses, but multiple factors affect the region once our allocation framework is implemented. Urban sectors/stakeholders experience a greater consumer surplus from water, yet these sectors/stakeholders are most equipped to deal with water scarcity. Conversely, agricultural users produce less regional welfare in terms of consumer surplus but are less able to adapt to a reduced allocation.

This study is limited in that it does not account for the social welfare costs associated with air quality and other health hazards stemming from the drying Salton Sea. Additionally, we cannot predict the long-term regional welfare effects (resulting from each deficit allocation evaluated in this paper). In addition, our estimate could be affected by changes to water consumption due to climate change that may affect the urban sector in particular. And finally, we faced difficulties finding costs and returns for individual ornamental crops in one irrigation district, needing to use representative crops and facing possible bias results. These approximations and uncertainties do not negate the benefits of assessing the value of water, and using these values to provide predictions on the future welfare of the region has allowed us to minimize the loss expected by reducing our usage of Colorado River water.

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Compliance with Ethical Standards

Conflicts of Interest No Conflict of Interest.

Code Availability Excel Macro can be made available upon request from the corresponding author.

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