



# Hydro-economic analysis of groundwater pumping for irrigated agriculture in California's Central Valley, USA

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**Abstract** As in many places, groundwater in California (USA) is the major alternative water source for agriculture during drought, so groundwater's availability will drive some inevitable changes in the state's water management. Currently, agricultural, environmental, and urban uses compete for groundwater, resulting in substantial overdraft in dry years with lowering of water tables, which in turn increases pumping costs and reduces groundwater pumping capacity. In this study, SWAP (an economic model of agricultural production and water use in California) and C2VISim (the California Department of Water Resources groundwater model for California's Central Valley) are connected. This paper examines the economic costs of pumping replacement groundwater during drought and the potential loss of pumping capacity as groundwater levels drop. A scenario of three additional drought years continuing from 2014 show lower water tables in California's Central Valley and loss of pumping

capacity. Places without access to groundwater and with uncertain surface-water deliveries during drought are the most economically vulnerable in terms of crop revenues, employment and household income. This is particularly true for Tulare Lake Basin, which relies heavily on water imported from the Sacramento-San Joaquin Delta. Remote-sensing estimates of idle agricultural land between 2012 and 2014 confirm this finding. Results also point to the potential of a portfolio approach for agriculture, in which crop mixing and conservation practices have substantial roles.

**Keywords** Agriculture · USA · Hydro-economics · Groundwater management · Remote sensing · Optimization

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## Introduction

Groundwater serves as the primary buffer against drought for irrigated agriculture worldwide, particularly in places like California (USA) that have both highly developed agriculture and water infrastructure. However, groundwater is often overexploited, threatening its availability during future droughts and for use in other human and environmental needs. California's recent Sustainable Groundwater Management Act, passed in 2014, requires and empowers local agencies to design and adopt basin-scale groundwater management plans. Given the complicated nature of integrated water management in California, it will likely take many years for overdrafted groundwater basins to re-equilibrate to long-term sustainable levels.

This paper explores the dynamic link between surface water and groundwater use in agriculture using a case study on the 2014 California drought. The analysis shows that replacing surface water with groundwater during drought can significantly mitigate the economic cost of drought. However, this additional groundwater pumping draws down the aquifer and imposes long-term costs including energy, pumping and well capital replacement costs, in addition to the standard long-term risks to water supply reliability.

The study of groundwater economics dates back to the early 1960s (Burt 1964) and is based on optimized temporal allocation of groundwater, with the goal of deriving decision rules for groundwater use. Later work (Bear and Levin 1966; Gisser and Mercado 1972) introduced demand curves for water into optimization for groundwater, a fundamental component in hydro-economic models (Harou et al. 2009). Knapp and Olson (1995) presented a case study of the economics of groundwater and surface-water interactions in Kern County, California, and derived decision rules for optimal groundwater extraction based on the energy costs of groundwater pumping. They showed that optimization does not necessarily provide substantial economic gains relative to unregulated conditions. Harou and Lund (2008) and Chou (2012) found that conjunctive management can help replace some overdrafted groundwater and reduce the economic costs of prohibiting overdraft.

Groundwater overdraft can also cause land subsidence and water-quality issues in some coastal areas, from seawater intrusion. In some cases, reducing water applications through so-called water efficiency programs can increase total consumptive use at a basin scale and reduce groundwater recharge (Pfeiffer and Lin 2014; Ward and Lynch 1996; Ward and Pulido-Velazquez 2008).

Although many studies have examined long-term groundwater use and the economic costs to agriculture under optimal allocation, few such comprehensive hydro-economic groundwater models exist for California's Central Valley, one of the world's largest and most economically important irrigated areas. Dale et al. (2013) examined this area using the CALAG model, which employs positive mathematical programming (PMP; Howitt 1995). Using the CALAG model, they ran Monte Carlo simulations of water availability and estimated the optimal cropping patterns. They fit logit functions to the model output, which were then embedded in the C2VSim groundwater-surface water model. This approach embeds the behavioral response by growers into the hydrologic simulation model. In contrast, the approach described in this paper embeds the hydrologic simulation model in the economic model; thus, enabling estimation of the economic responses to water availability.

In this study, a comprehensive approach to quantifying economic impacts of drought on the Central Valley is described. A linkage of the economic Statewide Agricultural Production (SWAP) model to the C2VSim Central Valley Groundwater model (Brush et al. 2013; Howitt et al. 2012) was employed. The C2VSim model is the application of the Integrated Water Flow model (IWFm; Department of Water Resources 2015) to California's Central Valley. C2VSim is a distributed-parameter, integrated hydrologic model that simulates the groundwater, stream, land surface and root zone flows as well as the flow exchange between surface and subsurface flow systems. The three-dimensional (3D) groundwater flows are simulated by solving the non-linear Boussinesq equation over multiple aquifer layers using the Galerkin

finite element method. Urban and agricultural water demands are calculated dynamically based on user-defined land use and crop distribution, precipitation, potential evapotranspiration, and soil and farm water management parameters (Dogrul et al. 2010). The calculated demands are then met with stream diversions and groundwater pumping. C2VSim accounts for hydrologic conditions from October 1921 through September 2009, but it also can be used in water planning studies by providing the appropriate time series input data.

The analysis examines economic costs of drought under expected surface-water deliveries to irrigated areas and groundwater availability. The approach is innovative in accounting for the changes in groundwater depths, pumping capacity and other economic factors as groundwater replaces drought-reduced surface-water deliveries. As a proof of concept, a 3-year drought and highlights from areas where water shortages have the greatest economic impact is analyzed. Region-wide economic effects of drought are also estimated using IMPLAN (IMPLAN Group LLC 2015; Day et al. 2012), an input-output model that calculates secondary effects in a region after an economic event such as drought has occurred.

## Central Valley, California

California's Central Valley extends from the north plains of the Sacramento Valley, located in Shasta County, to the southwest corner of Kern County (US Geological Survey, USGS 2000). This 58,000 km<sup>2</sup> valley hosts about 2.8 million ha (7 million acres) of agricultural land (about 76 % of California's irrigated land), and accounts for more than 60 % of the total crop value in the state (\$32 billion per year statewide). Figure 1 shows coverage of the SWAP and IMPLAN models for the Central Valley.

Agriculture in the Central Valley is irrigated with 27.2 billion m<sup>3</sup> (BCM) of water per year. The Central Valley Project operated by the US Bureau of Reclamation, the State Water Project operated by the California Department of Water Resources (DWR), and numerous smaller local and regional projects move water from Shasta to San Diego county. According to the California Water Plan Update (DWR 2013), contract water deliveries equal approximately 25 % of irrigation water supply in a normal water year. Groundwater accounts for 30–50 % of total water use depending on the water year type. Groundwater pumping by Central Valley users exceeds the natural recharge by 2 BCM/year (Faunt 2009). In dry years, this overdraft increases as natural recharge decreases and pumping increases to compensate for diminished surface water availability.

Table 1 summarizes the irrigated crop area, applied water and gross revenues for major regions of the Central Valley. The nearly \$26 billion in gross crop revenues are evenly distributed between the three regions. The Tulare Lake Basin has the largest irrigated area, equal to 1.2 million ha, about twice that of the Tulare Lake Basin.

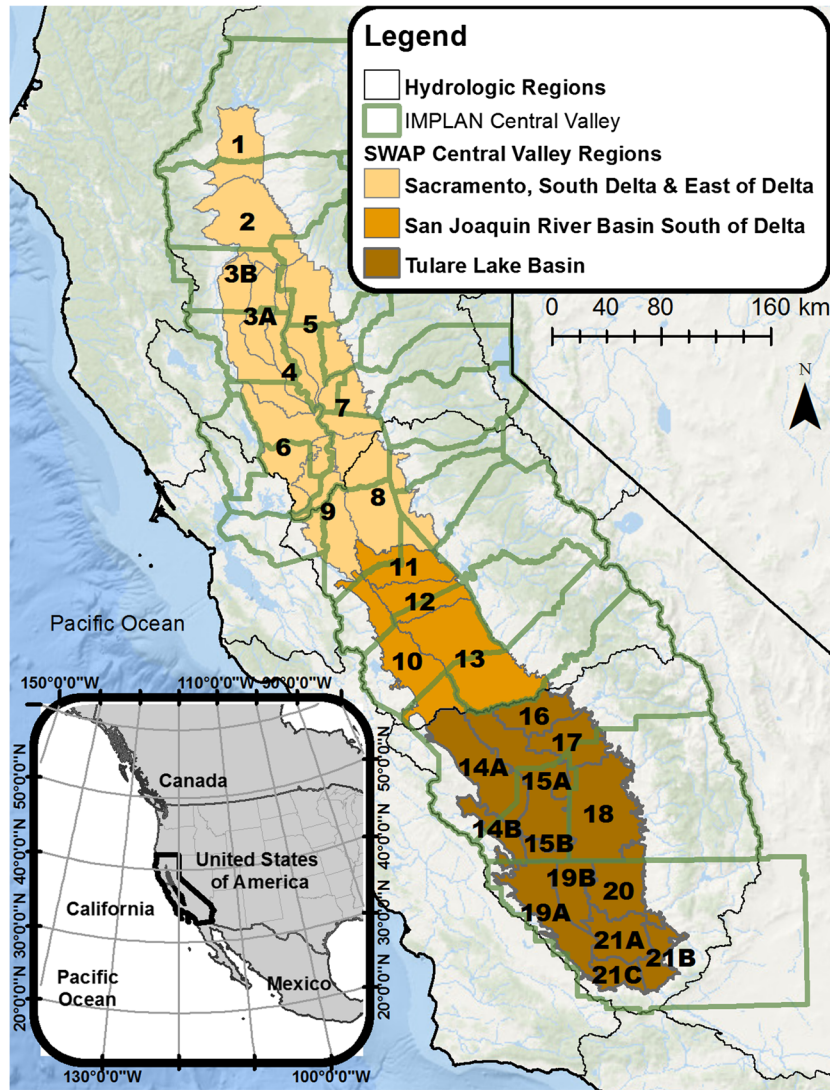


Fig. 1 Coverage of the SWAP model and the IMPLAN models for the Central Valley in California (after Howitt et al. 2014)

The 2014 California drought had the eighth lowest precipitation in a 106-year record according to the DWR flow database Dayflow (Department of Water Resources 2015). On January 17, the state government declared a water-supply emergency, triggering numerous response programs and research to estimate impacts and inform mitigation efforts. This paper examines the economic

impact of drought resulting from water shortages for agriculture, and its effects on groundwater.

**Methods**

The most current versions of the SWAP and C2VSim were integrated to analyze the effects of drought and groundwater overdraft. This section describes the mathematical structure of the SWAP and CSVSim models.

**Table 1** Irrigated crop area, applied water and gross crop revenues in California’s Central Valley

Region	Irrigated area (1,000 ha)	Applied water (1 BCM)	Crop revenue (\$ million)
Sacramento Valley, Delta and east of the Delta	908	8.9	6,847
San Joaquin Valley	655	6.1	5,384
Tulare Lake Basin	1,244	12.1	13,655
Central Valley	2,807	27.0	25,887
Total			

**SWAP model structure**

The SWAP model (SWAP, Howitt et al. 2012) is a hydro-economic model that maximizes net returns to land and management using positive mathematical programming (PMP), a self-calibrated algorithm that results in production inputs that exactly match a base dataset (Howitt 1995; Howitt et al. 2012). The PMP model formulation accounts for changes in groundwater elevations and consequent

Source SWAP model in Howitt et al. (2014)

changes in groundwater pumping capacity for a given year. SWAP uses a multi-stage approach, detailed in Howitt et al. (2012) and summarized in this paper, with some extensions and innovations from previous versions regarding groundwater and other water-supply cost changes.

The first stage of calibration is a linear program (LP) that derives the shadow values on the resource and calibration constraints. The LP maximizes net returns to crop production subject to resource constraints (water, land, and other input availability) and calibration constraints that force less profitable crops into the optimal solution. A representative farmer in region  $g$  maximizes net returns for all crops  $i$ , that is:

$$\max_{XL_{gi} \geq 0} \Pi = \sum_g \sum_i \left( v_{gi} YLD_{gi} - \sum_{j \neq \text{water}} c_{gij} a_{gij} \right) XL_{gi} - \sum_g \sum_w PWAT_{gw} WAT_g \quad (1)$$

where  $v_{gi}$  is the crop group  $i$  price in region  $g$  (in tons),  $YLD_{gi}$  is the yield (tons per hectare),  $c_{gij}$  is the linear cost of each production factor in dollars,  $a_{gij}$  is the Leontief coefficient for region  $g$ , crop  $i$ , and resource  $j$  estimated using Eq. (2).  $XL_{gi}$  is the decision variable for this first stage and represents land use in crop  $i$  in region  $g$ . The Leontief coefficient normalizes inputs such as water, labor, and supplies to land. Thus  $a_{gij}$  for land is unitary, for water is in units of  $hm^3/ha$ , and for labor and supplies is in dollars per hectare. For the case of water,  $WAT_{gw}$  equals the yearly applied water in region  $g$  in volume units ( $hm^3$ ) from source  $w$  where the source can be contract water, surface-water diversions, or groundwater, and the unit cost of water is given by monetary cost of water per unit of volume  $PWAT_{gw}$ . The Leontief coefficient equals:

$$a_{gij} = \frac{\tilde{X}_{gij}}{\tilde{X}_{gi,land}} \quad \text{and } j \in \{\text{land, water, labor, supplies}\} \quad (2)$$

where  $\tilde{X}_{gij}$  is the base (observed) use of production factor  $j$ , in region  $g$  for crop  $i$ , thus  $\tilde{X}_{gi,land}$  equals the base use of land in region  $g$  for crop  $i$ . In this formulation, land is in hectares, water is in  $hm^3$ , labor is in man-man hours, and supplies are in monetary units. The following resource constraint for one of the limiting production factors along with water is applied:

$$\sum_i XL_{gi,land} \leq b_{g,land} \quad \forall g \quad (3)$$

where  $b_{g,land} = \sum \tilde{X}_{gi,land}$  is in hectares. Two equations account for water<sup>1</sup> by source. First, Eq. (4) restricts water use by source to be less than the base water for all regions and sources. Second, Eq. (5) requires that the applied

water (WAT) from any source for all crops in a region not exceed the sum of applied water from all sources.

$$WAT_{gw} \leq W_{gw} \quad \forall g, w \quad (4)$$

and

$$\sum_i a_{gi,water} XL_{gi} \leq \sum_w WAT_{gw} \quad \forall g \quad (5)$$

The last constraint is the PMP calibration constraint (Howitt 1995), which constrains land uses to observed values plus a perturbation term  $\varepsilon$  that accounts for land use variations.

$$XL_{gi} \leq \tilde{X}_{gi,land} (1 + \varepsilon) \quad (6)$$

In the second step, a constant elasticity of substitution (CES) production function is parameterized (Arrow et al. 1961):

$$Y_{gi} = \tau_{gi} \left( \sum_j \beta_{gij} X_{gij}^\rho \right)^{v/\rho} \quad \forall g, i \quad (7)$$

where  $X_{gij}^\rho$  is the decision variable for all production inputs (land, water, labor and supplies),  $\beta_{gij}$  the cost share of the parameters,  $\rho = (\sigma - 1)/\sigma$ ,  $\sigma$  is the elasticity of substitution,  $\tau_{gi}$  denotes the scaling factor of the production function, and  $v$  equals the returns to scale factor. In the case of constant returns to scale,  $v=1$ .

Howitt et al. (2012) show that under optimality conditions for input allocation and imposing the restriction  $\sum_j \beta_{gij} = 1$ , the share parameters equal:

$$\beta_{gi,land} = \frac{1}{1 + \frac{X_{gi,land}^{-1/\sigma}}{\omega_{gi,land}} \left( \sum_{j \neq \text{land}} \frac{\omega_{gij}}{X_{gij}^{-1/\sigma}} \right)} \quad \forall g, i \quad (8)$$

and for the non-land inputs ( $j \neq \text{land}$ ):

$$\beta_{gij} = \beta_{gi,land} \frac{\omega_{gij} X_{gi,land}^{-1/\sigma}}{\omega_{gi,land} X_{gij}^{-1/\sigma}} \quad \forall g, i \text{ and } j \neq \text{land} \quad (9)$$

For all non-land and water production factors,  $\omega_{gij}$  the opportunity cost, equals the linear cost  $c_{gij}$  as defined in the previous. In the case of land, the  $\omega$  value equals the sum of land rental costs from the base dataset  $c_{gi,land}$ , the Lagrange multipliers from the optimal solution for land

from Eq. (3), and the calibration constraint of Eq. (6). That is:

$$\omega_{gi,land} = c_{gi,land} + \lambda_{gi,land} + \lambda_{gi,calibration} \quad (10)$$

Water opportunity cost,  $\omega_{gi,water}$ , equals the sum of the base cost of water  $c$  in each region and  $\hat{\lambda}_{g,water}$ , the largest Lagrange multiplier for water from Eq. (4):

$$\omega_{gi,water} = c_{gi,water} + \hat{\lambda}_{g,water} \quad (11)$$

The dimensionless scale parameter equals:

$$\tau_{gi} = \frac{YLD_{gi}/\tilde{X}_{gi,land}}{\left(\sum_j \beta_{gij} X_{gij}^\rho\right)^{1/\rho}} \quad (12)$$

In the third and last step, a PMP cost function (Howitt 1995) using an exponential function is parameterized. As in Howitt et al. (2012), the total land cost function in monetary units is defined as:

$$TC_{gi} = \delta_{gi} e^{\gamma_{gi} X_{gi,land}} \quad \forall g, i \quad (13)$$

The parameters  $\delta_{gi}$  and  $\gamma_{gi}$  are estimated using ordinary least squares regression in a system of two equations: (1) the economic first-order condition, and (2) the own-price acreage response elasticity condition, as detailed in Howitt et al. (2012). Price supply elasticities employed in the current SWAP version are obtained from Green et al. (2006).

In the final step of the PMP calibration, the sum of producer and consumer surplus is maximized. In this case a linear demand function allows the equilibrium crop price to be endogenously calculated. Thus, the objective function becomes:

$$\begin{aligned} \max_{X_{gij}, WAT_{g,ws}} \sum_i & \left[ \xi \alpha_{gi} \left( \sum_g Y_{gi} \right) + \frac{1}{2} \alpha_i^2 \left( \sum_g Y_{gi} \right)^2 \right] + \sum_g \sum_i \left[ RM_{gi} \left( \sum_j y_{gi} \right) \right] \\ & - \sum_g \sum_i \delta_{gi} e^{\gamma_{gi} X_{gi,land}} - \sum_g \sum_i \left( \omega_{gi,supplies} X_{gi,supplies} + \omega_{gi,labor} X_{gi,labor} \right) \\ & - \sum_g \sum_w \omega_{g,w} WAT_{gw} \end{aligned} \quad (14)$$

Following Howitt et al. (2012), the first two terms of Eq. (14) use the endogenous price to calculate total revenue production revenue. The other terms calculate the PMP cost function, the total costs of supplies and labor used in agricultural production, and water costs.

A limiting land constraint for water is:

$$\sum_i X_{gi,land} \leq \sum_w WAT_{gw} \quad \forall g \quad (15)$$

Other constraints restrict the short-term rate of change in perennial crops, and lower bound constraints on corn silage ensure dairy rations. Similar to Eq. (4), the total water volume available by region and source has an upper bound given by:

$$WAT_{gw} \leq \tilde{W}_{gw} \quad \forall g, w \neq GW \quad (16)$$

Two innovations are developed in linking SWAP to groundwater models in this paper. First, the upper bound in Eq. (16) now integrates with the C2VSIM model

(Brush et al. 2013). This groundwater model provides the percentage change in the baseline average depths to the water table and a change in the pumping capacity. Thus:

$$WAT_{g,GW} \leq W_{g,GW} \quad \forall g \quad (17)$$

and

$$W_{g,GW} = \tilde{W}_{g,GW} (100 - PCH_g) \quad (18)$$

where  $PCH_g$  is a percentage change in the pumping capacity for each region resulting from a change in depth to the water table with respect to baseline levels. For this study,  $PCH_g$  is the percentage pumping capacity to be lost (or gained if negative) obtained by using an estimate of the distribution of existing well depths based on well log data in each groundwater region. In addition, groundwater pumping costs also change in proportion to the change in the average depth  $v_g$  in a region.

$$\omega_{g,GW} = \phi_g + (\mu + \sigma)v_g \quad \forall g \quad (19)$$

where  $\varphi_g$  equals fixed pumping costs for region  $g$ .  $o$  equals the operating and maintenance marginal cost and is multiplied by the average depth to groundwater in the region  $v_g$ . Pumping costs are assumed  $\mu=1.02/0.7$ , in which 1.02 (in kilowatt hours, KWH) equals a conversion factor that translates the unit costs of energy (in dollars per KWH) into total energy for pumping costs when multiplied by the depth to the water table  $v_g$ . A pumping efficiency of 0.7 is assumed.

For the calibrated base case, Eqs. (14)–(19) are employed plus perennial and silage minimum land-use constraints. Modifications to Eqs. (16)–(18) provide alternative water-management scenarios with varying water availability and costs.

### Coupling of the SWAP and C2VSim models

SWAP requires the calculation of depth-to-groundwater values for each SWAP/C2VSim subregion to determine the cost of groundwater at the beginning of each water year. In turn, C2VSim requires the crop acreages for the same water year to calculate the agricultural water demands, the necessary stream diversions and groundwater pumping amounts to meet these demands, and the effect of pumping on depth-to-groundwater. In the coupled SWAP-C2VSim model, C2VSim calculates the average depth-to-groundwater for each subregion at the beginning of a water year and then passes this information to SWAP. Using these values, SWAP calculates the crop acreages. SWAP then passes these acreages back to C2VSim, and C2VSim calculates the corresponding water demands, diversions, and groundwater pumping to meet these demands. The groundwater heads, along with all other hydrologic flow processes, were also simulated for the same water year. At the end of that water year, C2VSim calculates new average depth-to-groundwater values, passes them to SWAP, and then the process repeats for each simulated year.

### Water management scenarios

A 3-year drought scenario for California's Central Valley is evaluated, with base 2012 condition to estimate the economic costs of drought. The base condition is an average year with close to the historical average surface-water availability. As already mentioned, the Central Valley is split into three large areas, namely: (1) the Sacramento Valley, Delta, and east of Delta; (2) the San Joaquin Valley; and (3) the Tulare Lake Basin from north to south (Fig. 1). Table 2 describes the estimated change in water availability with respect to an average year by region.

The 2014 drought is based on surface-water availability from a survey conducted in early April 2014 of water districts and agencies in the Central Valley about their expectations for deliveries, public announcements on reduced state and federal water projects deliveries, and water right curtailments. In summary, an estimated

**Table 2** Change in surface-water availability by region relative to an average year (in billion m<sup>3</sup>/year)

Region	Surface-water-use change		
	2014	2015	2016
Sacramento Valley, Delta and east of the Delta	-2.2	-2.8	-2.8
San Joaquin Valley	-2.2	-1.7	-1.7
Tulare Lake Basin	-3.7	-2.8	-2.8
Central Valley subtotal	-8.0	-7.4	-7.4

Adapted from Howitt et al. (2014)

reduction of 8.14 BCM (6.5 million acre feet or MAF) for 2014 was expected. Nearly half of this reduction was in the Tulare Lake Basin. In an average year such as 2012, the total applied water in agriculture is estimated at 32.1 BCM (26 MAF), with at least 10 BCM from groundwater. For 2014, 8.14 BCM represents an approximate 36 % reduction in total surface-water availability compared to an average year like 2011. Droughts for 2015 and 2016 assume water deliveries at the level of the 2009 drought, with a surface-water shortage of about 7.4 BCM/year; however, cutbacks are higher in the northern part of the state.

In the part of Central Valley with access to groundwater, it is assumed that growers will replace surface water with increased pumping. Estimates of installed pump capacity show that up to 6.2 BCM (5 MAF) could be pumped during every year of the drought. Historically, groundwater as a share of the total water supply for agriculture increases from 35 % in an average year to 53 % during drought in the Central Valley. Table 3 shows the breakdown of water replacement and its cost for the 3 years of drought modeled. Pumping costs per unit of groundwater increase as the water table drops. In 2016 for example, declining water tables cause a 5 % increase in pumping costs relative to 2014. The map in Fig. 2 illustrates the distribution of pumping costs in 2014 by groundwater basin.

### Results

The Economic impacts of drought are aggregated into three large areas: (1) the Sacramento Valley, Delta and east of the Delta, (2) the San Joaquin Valley south of the Delta, and (3) the Tulare Lake Basin. For the impact analysis, crop types were further aggregated from the standard 20-crop groups in the SWAP model into the following four-crop groups compatible with the IMPLAN input-output model, namely: (1) cotton, grain and oilseed, (2) vegetables and non-tree fruit, (3) tree fruit and nut and (4) feed and other crops. Table 4 and Fig. 3 summarize the changes in irrigated area by region for 2014–2016. The SWAP model was used to estimate response of growers to drought, including the decision to fallow land due to drought.

In the Central Valley, higher-value crops (including vegetables, non-tree fruits and permanent crops), which

**Table 3** Additional groundwater use and cost by region relative to an average year

Region	Additional use (BCM/year)			Additional cost (\$million/year)		
	2014	2015	2016	2014	2015	2016
Sacramento Valley, Delta and east of the Delta	1.1	2.0	2.0	35.4	63.2	65.5
San Joaquin Valley	1.9	1.5	1.5	71.9	63.2	68.7
Tulare Lake Basin	3.2	2.7	2.7	340.3	312.5	324.8
Central Valley subtotal	6.2	6.2	6.2	447.6	438.9	459.1

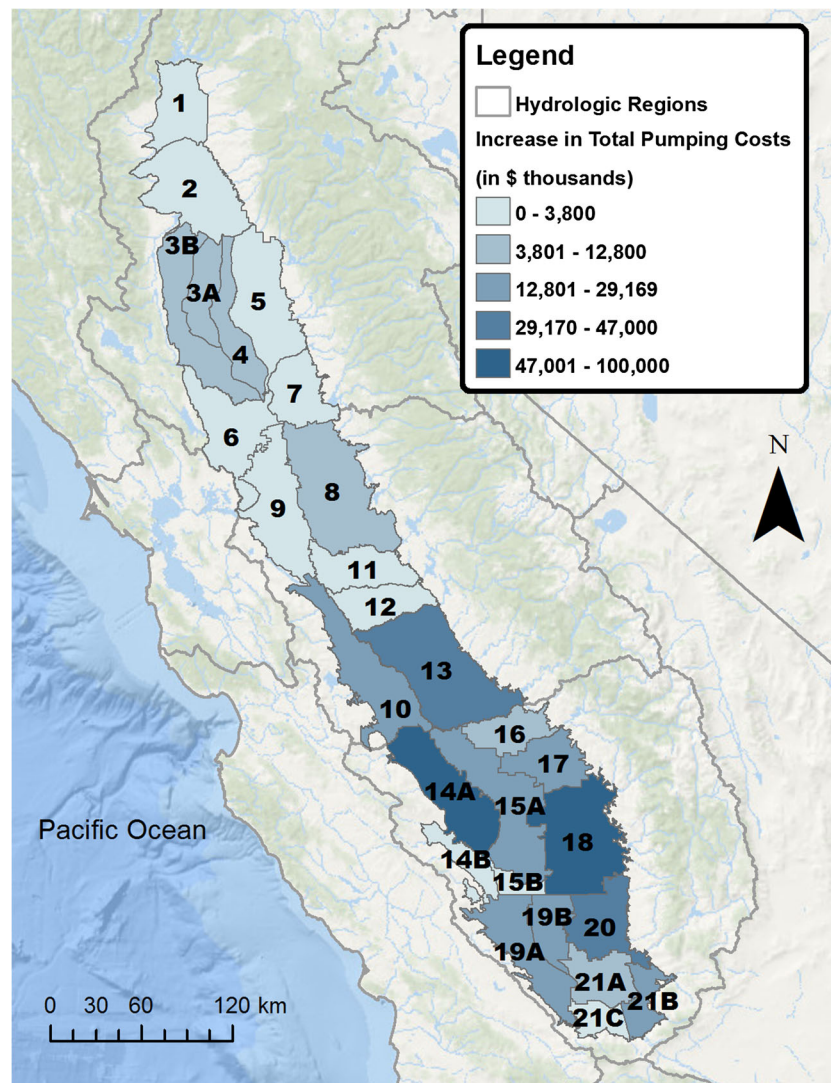
Adapted from Howitt et al. (2014)

account for 45 % of the total irrigated crop area, show less than 13 % of the total fallowing response, since growers allocate the scarce water to these more profitable crops. Most crop fallowing is estimated to be from areas growing feed and other lower-value annual crops. This pattern is repeated across years. Fallowing in the Central Valley due to drought declines from 165,500 ha in 2014 to 98,300 ha by 2016 under the assumed 2009 surface-water availability conditions for 2015 and 2016. Nevertheless, idle land can also be the result of various conditions other than

drought such as crop rotation or price expectations in a given year.

### Drought effects on gross crop revenues

Table 5 and Fig. 4 summarize the estimated change in gross crop revenues attributable to drought. The 2014 drought cost the Central Valley approximately \$800 million in gross crop revenues. Approximately 70 % of these losses occur south of



**Fig. 2** Increase in groundwater costs (\$1,000/year) per groundwater basin in the Central Valley

**Table 4** Losses in irrigated crop areas by region and crop group (in thousands of hectares)

Region	Cotton, grain and oilseed	Feed and other crops	Fruit and nut trees	Vegetables and non-tree fruit	Total
Year 2014					
Sacramento Valley, Delta and east of the Delta	21.9	33.6	3.6	1.6	61.1
San Joaquin Valley	30.8	15.8	3.2	1.2	50.6
Tulare Lake Basin	32.8	9.7	9.7	1.6	53.8
Total for 2014	85.4	59.5	16.6	4.0	165.5
Year 2015					
Sacramento Valley, Delta and east of the Delta	21.0	39.3	2.8	1.2	64.3
San Joaquin Valley	6.9	12.9	1.6	0.2	21.9
Tulare Lake Basin	2.8	2.0	6.1	0.2	10.9
Total for 2015	31.2	53.8	10.5	1.6	97.1
Year 2016					
Sacramento Valley, Delta and east of the Delta	21.0	39.3	2.0	1.2	63.5
San Joaquin Valley	6.9	12.9	1.6	0.2	21.9
Tulare Lake Basin	5.3	3.2	4.0	0.4	12.9
Total for 2016	33.2	55.4	8.1	1.6	98.3

Adapted from Howitt et al. (2014)

the Delta, largely because of the severe cutbacks in Delta exports, which provide much of the regional water supply. A similar pattern emerges if the drought persists through 2015 and 2016, with somewhat increased surface-water deliveries. However the gross revenue losses in 2015 and 2016 are somehow smaller than for the 2014 drought since the largest proportion of the cutbacks occur in the Sacramento River Basin, which has a relatively lower crop value than the San Joaquin and Tulare Lake basins

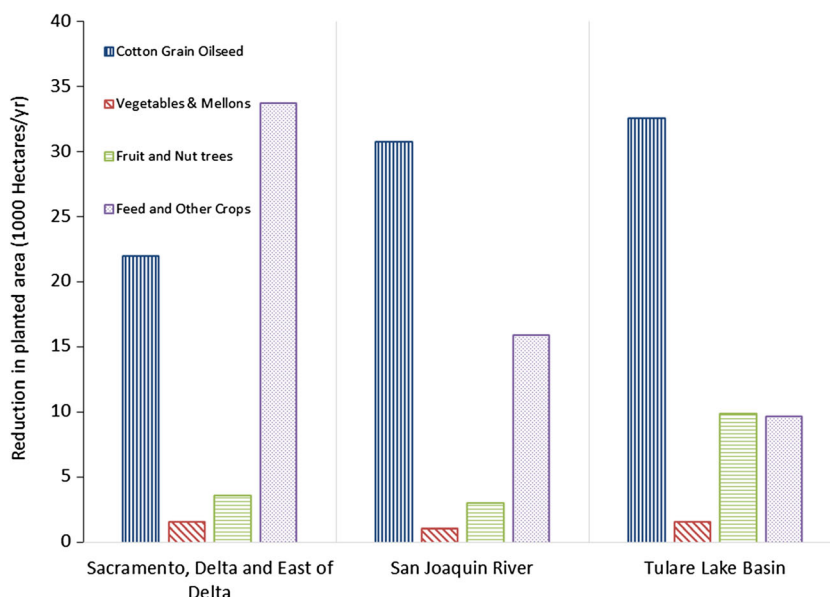
### Region-wide economic effects

Reductions in direct value of agricultural production due to the 2014 drought have secondary effects on other

sectors of the region's economy. Changes in crop revenues calculated by SWAP are used to calculate additional effects by IMPLAN, an input–output model.

The employment parameters in IMPLAN are adjusted to account for both part-time and full-time employment. Labor income represents both wages from employees and proprietor (self-employed individuals and unincorporated business owners) income. Value added is the difference between total sector output (gross revenues) and the non-labor business expenses. Changes in value added can be used as measures of the agricultural sector's gross domestic product and a region's economic activity (Medellín-Azuara et al. 2012).

Direct effects show the first-round effects of an economic change. Indirect effects are the estimated changes from all other sectors associated with crop



**Fig. 3** Predicted change in irrigated crop areas for the 2014 California drought in the Central Valley regions. Adapter from Howitt et al. (2014)



**Table 5** Crop-revenue losses by region and crop group (in millions of dollars, 2014 values)

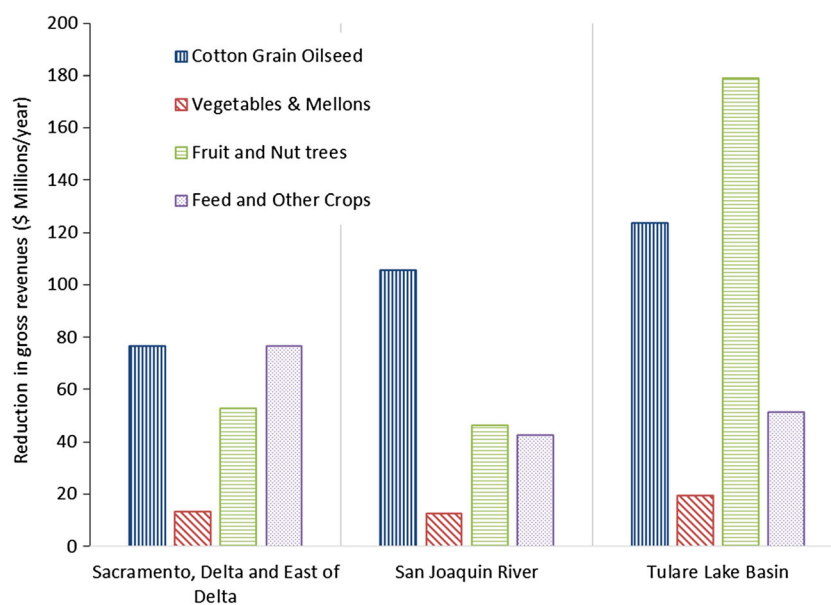
Region	Cotton, grain and oilseed	Feed and other crops	Fruit and nut trees	Vegetables and non-tree fruit	Total
2014 drought					
Sacramento Valley, Delta and east of the Delta	76.8	76.8	52.7	13.2	219.4
San Joaquin Valley	105.7	42.6	46.3	12.7	207.3
Tulare Lake Basin	123.8	51.2	179.0	19.5	373.4
Central Valley total, 2014	306.3	170.5	277.9	45.4	800.1
2015 drought					
Sacramento Valley, Delta and east of the Delta	76	80	43	10	209
San Joaquin Valley	25	25	27	2	79
Tulare Lake Basin	11	9	100	3	123
Central Valley total, 2015	112	114	170	15	411
2016 drought					
Sacramento Valley, Delta and east of the Delta	76	80	31	10	197
San Joaquin Valley	24	25	27	2	78
Tulare Lake Basin	19	13	70	5	108
Central Valley total, 2016	120	118	128	17	383

production. The induced effects trace expenses from households employed in crop farming and households receiving income from related sectors of the economy. The sum of the direct, indirect and induced effects is called the total effect of the economic impact.

### Economic impacts by year and region

Tables 6 summarizes the economic impacts of drought on crop farming for the Central Valley and also includes the effect of a prolonged drought lasting through 2016. Direct losses to dairies and livestock (about \$200 million) and other areas in the state are discussed in Howitt et al. (2014). Four measures of impact are included in Table 6 namely, employment, labor income, value added and

sector output. Employment includes seasonal and full time jobs and is the number of jobs linked to the revenue losses from drought. Base employment numbers were cross-checked with the California Employment and Development Department estimates. Labor income change includes losses to household and proprietor income, it is predominately comprised of salaries and sole proprietor profits and compensations. The change in value added is the difference between farm gross revenues and non-labor business expenses. Value added is a measure akin to gross domestic product in a region. Sector output compares to gross revenues on farm production (output) and, as such, these correspond to the gross revenue losses in Table 5 (\$800 million). For simplicity, only direct and total (direct, indirect and induced effects) are reported for the Central Valley.

**Fig. 4** Crop revenue reductions for 2014 drought, Central Valley regions (after Howitt et al. 2014)

**Table 6** Economic impacts (as losses) of a 3-year drought, 2014–2016, in California’s Central Valley

	Impact type			
	Employment (No. of jobs)	Labor income (dollars in millions)	Value added (dollars in millions)	Output (dollars in millions)
2014 drought				
Direct effect	6,722	274.5	310.5	800.1
Total effect	15,183	581.2	894.6	1,728.9
2015 drought				
Direct effect	3,158	146.9	167.3	408.7
Total effect	8,495	349.0	551.1	1,016.8
2016 drought				
Direct effect	2,965	129.2	147.1	378.4
Total effect	8,047	323.8	519.8	969.6

Total effects include direct, indirect and induced effects. Indirect effects range from 25 to 30 % of the total impacts and induced effects from 21 to 28 % of the total impacts for the sectors and impact measurements reported in this study

## Total economic impacts

Table 7 summarizes the total economic impact of the drought on agriculture and compares the estimated losses against an average water year for California’s Central Valley. Overall, a net shortage of 1.85 billion cubic meters of water results in 166,000 ha in idle land, \$800 million in revenue losses, \$454 million in increased pumping costs and about 15,500 lost jobs for the Central Valley. Although this is a relatively small proportion of overall farm employment (4 %) and the Central Valley’s crop value (3.2 %), there will be areas (especially those without access to groundwater) that will bear higher socioeconomic impacts of the drought. Some of these areas in the Tulare Lake Basin also have the poorest population in the state. Howitt et al. (2014) accounts for other crop areas in the state as well as livestock and dairies, resulting in about \$1.5 billion in direct economic losses and \$2.2 billion once the direct and induced effects are taken into account.

## Estimates of agricultural idle land

The idle land attributable to the 2014 drought was estimated using the SWAP model. The model results can be compared with estimates from the US Department of Agriculture (USDA) crop area surveys and idle land estimates calculated from time series of satellite data. The

USDA surveys and remote-sensing methods can identify the total change in irrigated area. However, these cannot estimate the proportion of that change attributable to the 2014 drought without more detailed statistical analysis to control for other factors that affect following in a normal water year. As such, survey and remote-sensing data should be viewed as estimates of the total idle agricultural land, as opposed to following directly attributable to the drought such as the estimates from the SWAP model. For this comparison, 2011 and 2012 were considered base years and are close to the base irrigated areas in SWAP.

The USDA’s National Agricultural Statistics Service (NASS) publishes estimates of crop areas for selected crops in California. However, this information is not directly comparable to SWAP estimates of idle land for two reasons. First, the USDA collects information only for some crops (called principal crops) based on the total national area. This selection accounts for only half of California’s irrigated area. Second, the USDA measurement of the winter wheat crop in California includes rainfed wheat and partially irrigated winter wheat. Aside from these caveats, USDA estimates are largely consistent with SWAP estimates for the three Central Valley regions.

In an ongoing research effort, a research team at NASA Ames Research Center and California State University Monterey Bay, in collaboration with USDA and the USGS, estimated and compared farmed and idle agricultural land in California in 2011, 2013 and 2014. The team

**Table 7** 2014 Summary of the Economic Impact of the 2014 California Drought on the Central Valley

Crop production features	Estimated impact		
	Loss quantity	Total in average year	Percent loss
Water Use	7.4 BCM	32.1 BCM	25
Net shortage after increased groundwater pumping	1.85 BCM	32.1 BCM	6
Fallowed irrigated land	166,000 ha	2.82 million ha	5.6
Crop revenue loss	\$800 million	\$25 billion	3.2
Crop revenue loss plus \$454 million in pumping costs	\$1.26 billion	NA	NA
Region-wide economic impacts (direct, indirect and induced effects on sector output)	\$1.75 billion	NA	NA
Direct crop production job losses	6,722	170,000	4.0
Direct, indirect and induced job losses	15,480	NA	NA

NA not applicable

used time series of Normalized Difference Vegetative Index (NDVI) data—collected by instruments onboard the Terra, Aqua, Landsat 5, Landsat 7, and Landsat 8 satellites, and composited every 8 days—to generate separate estimates of idle cropland for the winter and summer growing seasons. For all Central Valley fields, the NASA estimates of cropped and idle land for the irrigation season ending 30 September 2014 have an overall classification accuracy of 95 % correct classifications based on a comparison against monthly field observations collected during the year at 670 field validation sites. For the idle class, the producer’s accuracy for September is 92 % and the user’s accuracy is 89 %. For the Central Valley region, NASA estimates that there was an increase of 212,700 ha of idle land from 2014 to 2011, with the highest proportion in the Tulare Lake Basin. The NASA team selected 2011 as the baseline year, since 2011 was the last year following a winter with average or above-average precipitation across the state.

The UC Davis Center for Watershed Sciences used a similar approach to estimate idle acreage, using data from three Landsat 7 and 8 scenes for late July and early August in the Central Valley (excluding some portion of Shasta County, the Delta and southern Kern County). All SWAP, NASA and UC Davis (UCD) idle land estimates between 2014 and base year are closer in range for the Sacramento Valley and the San Joaquin Valley than for the Tulare Lake Basin, in part due to the smaller area covered by UCD and the total irrigated area in that region. Table 8 shows the range of idle cropland estimates from SWAP and NASA.

## Discussion and limitations

Methods and results from the case study presented in this paper highlight the usefulness of economic optimization models like SWAP, coupled with hydrologic groundwater models like C2VSIM, in improving understanding of water supply and user response during drought. Virtues of this hydro-economic modeling approach include organization of information on the following: water supply and use in a region, quantification of water supply and use, calculation of the economic costs of water shortages, and increased use of groundwater to cope with drought. Hydro-economic models help identify promising water-management alternatives considering a range of institutional, hydrologic and economic conditions. Management alternatives include conjunctive water use, water trades and managing proportion of

permanent versus annual crops. Exploring these in detail is beyond the scope of this paper. Landsat or other remotely sensed data are helpful for refining model calibration to base conditions and better representation of farming and other responses during the periods of drought.

For California’s Central Valley, a 25 % reduction in the total water supply during a critically dry year will not necessarily result in proportionate economic losses for agriculture, which raises more than \$40 billion in gross revenues, including dairies and livestock. This response is due to the ability of many areas in the Central Valley to replace surface water with groundwater during drought. This ability to cope with drought will be reduced in the future without local groundwater management strategies to mitigate declining groundwater levels. A larger proportion of permanent crops, groundwater overdraft, the lack of a statewide groundwater monitoring network, and the lack of long-term groundwater management plans in much of the Central Valley may accelerate depletion of aquifers (increasing pumping costs and decreasing basin pumping capacity) and consequently increase water supply costs. This study shows that continuing the current drought for 1 or 2 more years may have more severe economic impacts, especially in terms of pumping costs and reduced capacity to replace surface water with groundwater.

Some limitations of the approach employed in this study merit discussion. SWAP model results are driven by water availability estimates based on early April surveys of irrigation districts, announced CVP and SWP contract deliveries, and DWR estimates of groundwater pumping. It is possible to update these estimates once the irrigation season is completed and then re-estimate the economic impacts of drought and reduce inherent errors from these first estimates.

Region-wide effects within the Central Valley of reduced water supply and increased pumping costs do not account for the statewide benefits from increased electric power sales. Accounting for these effects would require a general equilibrium approach that is beyond the scope of the present study. The aggregate regional impacts mask significant sub-region variability of economic impacts in some areas. This is the case of the eastern part of the Central Valley, where less access to groundwater could increase loss or agricultural production and farm employment. Further work is needed in the areas of integration between groundwater and agricultural production and water optimization models like SWAP, and use of remote sensing information to recalibrate the optimization estimates and projections.

**Table 8** Estimates of idle irrigated cropland for 2014 relative to 2011 and 2012 in the Central Valley (1,000 ha)

Region	SWAP 2014–2012	NASA 2014–2011	UC Davis (NDVI) 2014–2012	Range
Sacramento Valley	61	57	71	57–71
San Joaquin Valley	51	28	41	28–51
Tulare Lake	54	128	67	54–128
Central Valley total	166	213	179	166–213

## Conclusions and policy recommendations

The following conclusions arise from this analysis:

- Under the 2014 California drought, surface water availability for agriculture is expected to be reduced by about one-third.
- Groundwater is the main backup resource for the 2014 drought and future droughts. In the Central Valley of California, about 6.2 BCM (5 MAF) of the roughly 8-BCM (6.5 MAF) reduction in available surface water will be replaced through pumping of groundwater. This increases the overall groundwater contribution to agriculture from 31 % in an average year to 53 % in a drought year, and reduces water shortage to Central Valley agriculture by about 77 %.
- If the drought continues for two additional years (assuming surface-water availability at the 2009 drought levels), groundwater substitution will remain the primary response to surface-water shortages. Decreases in groundwater pumping capabilities and increasing costs due to declining water levels will occur.
- Net water shortages for agriculture during the 2014 drought most severely affect the Central Valley. At least 166,000 ha were lost to fallowing, resulting in \$800 million in lost farm revenues and \$447 million in additional pumping costs. These effects are more severe in the Tulare Lake Basin.
- State and regional policymakers concerned with drought should pay special attention to (1) groundwater reliability, (2) the ability of state and county governments to provide technical and organization assistance to rural communities, and (3) facilitating voluntary water trades between willing parties, including defining a standard environmental impact report for water transfers that can be assessed and approved prior to droughts. These policies would increase the ability of local governments to mitigate the impacts of droughts on rural and agricultural areas and economies susceptible to water scarcity.

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