by sensitivity analysis in output prices and input price and quantities.

At this point in the program, the six-step calibration routine is complete and, assuming all conditions are met, the modeler can be confident the model has successfully calibrated. The final stage involves specification of a policy scenario for a second non-linear program. We call this the policy analysis phase. In this phase the modeler specifies the non-linear program (calibrated from the previous six-step procedure) with relevant policy constraints. Policy constraints include adjustments ranging from simple shocks to relative prices to complicated adjustments to production technology and interactions with biophysical models.

3. Policy application of SWAP

3.1. Water markets application background

In theory, fully-flexible agricultural water markets allow water to flow from low to high-value uses such that marginal value product is equalized across regions. Historical water rights holders, such as farmers in the Central Valley, are able to evaluate tradeoffs between production and selling water in the market which leads to more efficient allocation of the resource across the state. In practice, California has a limited history with water markets. The 1991 water bank, managed by the California Department of Water Resources (DWR), was a recent example which was only brought on by catastrophic drought. The water bank was a fairly rigid market institution but managed to buy and sell over 975 million cubic meters of water per year (Mm^3/yr). However, California has yet to adopt more flexible markets. As of 2003, 22 of 58 counties in the state had restrictions to prevent sales of groundwater and less than 3 percent of the water used is sold through markets (Hanak, 2003).

Transfers remain important for managing water in years of shortage. In 2009, the last year of a three-year drought in California, the Water Transfer Database compiled by the UCSB from the Water Strategist reports over 600 Mm^3/yr of water were transferred for agricultural use. Even with limited markets there are strong incentives to transfer water during years with shortage.

An important function for water markets in California is to help agriculture smooth drought losses. This is critically important when planning for a future with climate change and increasing demands for environmental water uses. During drought, water markets reduce land fallowing and stress irrigation. The former increases cultivated area and, in turn, generates additional agricultural jobs for the economy, and the latter increases crop yields. Both effects increase agricultural revenues which create jobs and helps rural communities. Additionally, in response to drought farmers may invest in new wells and increase groundwater pumping which has a cost to both farmers and the environment. Flexible water markets may mitigate this effect by encouraging the sale and transfer of surface water.

The potential for water markets in California is limited by physical and political constraints. Physical constraints include regional connections, conveyance capacity, and existing reservoir operation regulations. Political constraints include legal restrictions on the sale of groundwater and an aversion to water transfers out of the county. Out-of-county water transfers may shift agricultural jobs from the region. For example, farmers may idle land and sell water out of the region which would shift production and jobs out of the county. While this is acceptable from an economic efficiency standpoint it may harm local communities and, as such, may not be politically acceptable.

We evaluate the effect of water markets in the San Joaquin Valley, south of the Sacramento-San Joaquin Delta (the Delta), on groundwater pumping, stress irrigation, and the economy. Policy-makers are often interested in estimating the extent of these effects and, in particular, if benefits outweigh the cost of facilitating a water transfer market.

3.2. SWAP Model with water transfers

To simulate a moderate-to-severe drought we reduce water exports from the Delta by 30% which translates into 1350 Mm^3/yr of surface water shortage to regions south of the Delta. Water exports from the Delta include Central Valley Project (CVP1) and State Water Project (SWP) deliveries, which vary by SWAP region as detailed in the data description. We base this scenario on the 2009 drought and environmental pumping restrictions (the Wanger decision) experienced in California. The shortage in 2009 followed dry years in 2007 and 2008 and was estimated to cause the loss of over $350 million in farm revenues, 115,000 ha of land fallowing, and 7500 agricultural jobs (Howitt et al., 2011). It generated significant interest from policymakers and agricultural water markets were frequently discussed.

We link the SWAP model to a hydro-economic network model of California's water infrastructure, incorporate political transfer constraints, and introduce the drought scenario to evaluate the effects of water shortage with and without water markets. We include restrictions to account for political difficulties of water transfers. First, we do not allow the sale of groundwater. This is consistent with regulations adopted by many counties in the Central Valley. Second, we do not allow water transfers out of the county to account for political difficulties from jobs flowing with the water out of the region. The second point is a restrictive assumption and, as such, our estimates represent a lower-bound on the effects of water transfers. We link water supply infrastructure to SWAP by using the hydro-economic network representation of California's water system provided by the CALVIN model (Draper et al., 2003). Fig. 5 illustrates a schematic of the water delivery system in the San Joaquin Valley which includes SWAP regions 10–21C. Fig. 5 includes agricultural demand regions, rivers, dams, other points in the distribution system, and flow volume and direction. We only report flow volumes and label select components of the system to keep the illustration clear.[4] Agricultural demand regions are shown as ovals. Circles and lines indicate various points in the distribution system, including canals, waste-ways, dams, and rivers. The lines are both color and style coded to represent ownership by one of four entities including, (i) SWP shown as a red dotted-line, (ii) CVP shown as a purple dashed-line, (iii) intakes shown as a green dashed-dotted-line, and (iv) natural flows shown in solid blue. Arrows denote the direction of flow and relevant maximum flow volumes are reported below labels. For example, the California Aqueduct, managed by the SWP, has a flow capacity of 12,000 Mm^3/yr.

The SWAP water markets model represents transfers that are physically feasible given the existing water network in California. To test the value of an additional infrastructure development, we allow two "wasteways" (Westly and Newman) to be operated in reverse to facilitate transfers from the east side of the Central Valley to the west. The distribution system is also geo-coded so we can estimate distances between regions for potential water transfers. We introduce a transfer cost which is a function of the distance between regions and assumed constant. We assume that import

[4] For further information and schematics, we refer the interested reader to the CALVIN website: http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/.

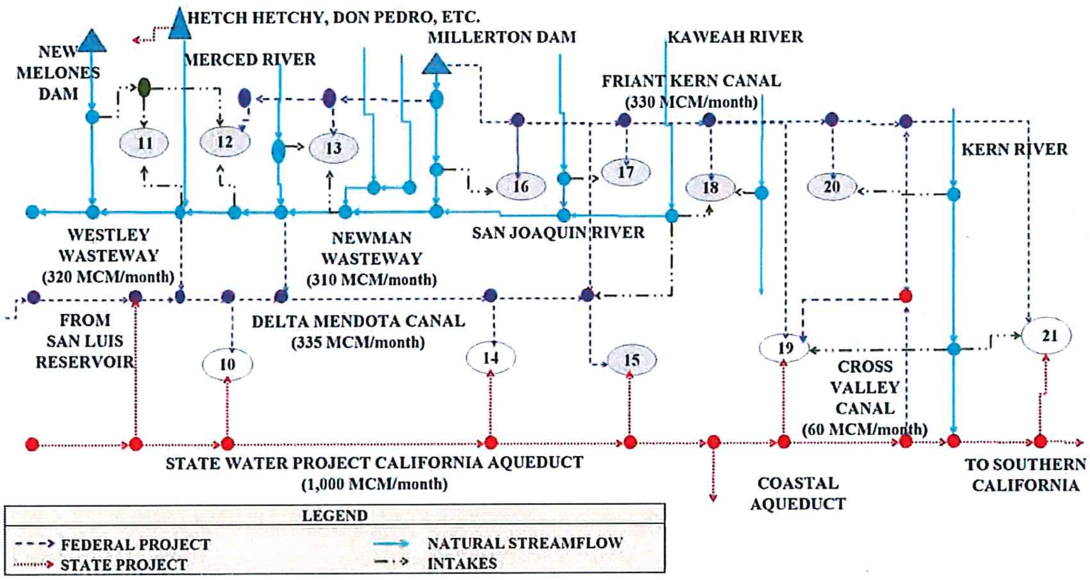

Fig. 5. Water supply and demand network in the San Joaquin Valley of California, flow conveyance capacities in million m^3 per month (MCM/month). Darker ovals represent exporting agricultural regions.

regions pay the transaction cost plus the cost per unit of water transferred. Incorporating these additions to the model, we rewrite the objective function, Equation (26), as

$$\begin{aligned}\max_{x_{gij}, wat_{gw}} PS+CS = & \sum_i \left(\xi\alpha_i^1\left(\sum_g y_{gi}\right) + \frac{1}{2}\alpha_i^2\left(\sum_g y_{gi}\right)^2\right) \\ & + \sum_g\sum_i \left(rm_{gi}\left(y_{gi}\right)\right) \\ & - \sum_g\sum_i\left(\delta_{gi}\exp\left(\gamma_{gi}x_{gi,land}\right)\right) \\ & - \sum_g\sum_i\left(\omega_{gi,supply}x_{gi,supply}+\omega_{gi,labor}x_{gi,labor}\right) \\ & - \sum_g\sum_w\left(\varpi_{gw}wat_{gw}\right) - \sum_g\sum_w\left(trc\cdot d_{gh}\cdot xwt_{ghw}\right),\end{aligned} \quad (33)$$

where xwt and trc are the amount of water transferred between region g and h and the (constant) transaction cost per million cubic meters per km, respectively. The matrix d_{gh} is the transfer distance between region g and h, as estimated from the geo-coded hydrologic model. Under this specification, the importer pays the cost of the water plus the transaction cost which varies by volume and distance. Additionally, we incorporate water transfer constraints into the model. With the water trade variable xwt_{ghw} the regional water constraint, Equation (5), becomes

$$wat_{gw} \le \text{watcons}_{gw} + \sum_h xwt_{ghw} - \sum_g xwt_{ghw}. \quad (34)$$

We additionally impose the constraint that a region cannot simultaneously import and export a water source to avoid unrealistic arbitrage opportunities,

$$\left(\sum_h xwt_{ghw}\right)\left(\sum_g xwt_{ghw}\right) = 0. \quad (35)$$

Finally, we include physical and political transfer constraints such that only regions that are physically connected and within the same county are able to transfer water. These constraints take the form of a series of equality constraints based on the transfer feasibility matrix shown in Table 1.

In addition to physical and political constraints, the transfer matrix includes identity restrictions such that a region cannot trade with itself. The shaded cells indicate potential for transfers between regions. We define physical conveyance capacity constraints as

$$\sum_w xwt_{ghw} \le cap_{gh}, \quad (36)$$

where cap_{gh} is the maximum water transfers between regions g and h as estimated from the hydro-economic network model. This implicitly assumes water transfers from all sources are through the same facilities. This assumption could be relaxed by imposing additional infrastructure which differentiates between individual water sources.

This analysis holds groundwater pumping constraints fixed at the observed base level. In other words, groundwater pumping may change within regions but it cannot be sold and regions cannot pump in excess of observed capacity (i.e. drill new wells).

We combine the basic policy model constraints, Equations (27) and (29)–(32), and water transfer model constraints, Equations (34)–(36), plus the water transfer restriction matrix and maximize the modified objective function, the sum of consumer and producer surplus, Equation (33). We estimate the benefits of flexible water markets to agriculture in the San Joaquin Valley by comparing model runs with and without water markets under reductions that results in Delta export deliveries being 30% of normal (mean) quantities.

4. Modeling results and discussion

In response to water markets we anticipate changes in production at both intensive and extensive margins. At the extensive margin water markets allow water to flow from lower to higher value uses, thus inducing changes in total irrigated land area and in the crop mix. Regional water use will change as regions buy and sell water. At the intensive margin we expect applied water per unit

Table 1
Water transfer feasibility matrix. Darker boxes indicate institutionally and physically feasible inter-regional water transfers.

	Exports																
Imports	10	11	12	13	14a	14b	15a	15b	16	17	18	19a	19b	20	21a	21b	21c
10	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14a	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
14b	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
15a	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
15b	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
16	1	0	0	0	1	0	0	0	0		0	0	0	0	0	0	0
17	1	0	0	0	1	0	0	0		0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19a	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
19b	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
20	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1
21a	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1
21b	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1
21c	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0

area will change in response to water markets, such as by increased irrigation efficiency. We summarize results in terms of total water transfers, land use change, farm revenue effects, and regional impacts on total employment. We discuss all results by comparison of with and without water markets.

4.1. Water transfers

We model a drought of 30 percent of surface water deliveries through the Delta (1350 Mm^3/yr). Net export regions include 10, 12, 15A, 16, 17, and 21A. These represent regions on the east-side of the Central Valley (see Fig. 2) and regions, such as 10, with priority water rights. Net import regions include 13, 14A, 14B, 15B, 19A, 19B, 20, 21B, and 21C. This is consistent with prior expectations as these regions generally have lower-priority water rights, higher reliance on SWP and CVP deliveries, and limited access to groundwater. West-side regions typically realize higher losses during water shortage. Import regions are concentrated along the west-side of the San Joaquin Valley whereas export regions are on the east-side, where snow runoff and local stream inflows increase available water. Regions 11 and 18 don't trade water due to political (within county) transfer constraints.

Table 2 summarizes total imports and exports by region in response to a 30% reduction in Delta exports. The water supply network in Fig. 5 includes two new conveyance options, not currently used. Since the point of the model was to show the value of expanding the conveyance system, we cannot compare the model results with actual transfers, due to the difference in conveyance options. The results show that a total of 582 Mm^3/yr of water could be transferred between regions during drought, corresponding to just over 40 percent of the total amount of shortage. The largest importer, 303 Mm^3/yr, is region 14A which is located on the west-side of the San Joaquin Valley. This region is Westlands Water District which relies heavily on CVP exports and is consequently one of the most affected regions during drought. The largest exporter is region 10, 271 Mm^3/yr, which is in the northern portion of the west-side of the San Joaquin Valley. This region is largely Settlement and Exchange Contract water users (CVPS) which have higher priority and are rarely shorted during droughts. As such, region 10 typically fares well during drought and this is reflected in SWAP model results.

The level of detail in the SWAP water supply data allows us to estimate individual transfers by water source between regions. For example, region 10 exports 35 Mm^3/yr of CVP1 and 236 Mm^3/yr of CVPS to region 14A during the drought. Thus all of the 271 Mm^3/yr region 10 exports flows into region 14A and the majority of this transfer is from settlement and exchange water. Table 3 shows another example of water transfers between regions in Kern County (19Aa–21C) from local surface water supplies (LOC). We estimate water transfers of 160 Mm^3/yr between regions in Kern County, of which nearly 60 percent (90 Mm^3/yr) comes from local surface water supplies. The largest transfer is from 21A (Central Kern) to 19A (West Kern), 53 Mm^3/yr. From Fig. 5 we can see that this transfer is through the Cross-Valley Canal which has capacity of 60 million cubic meters per month, which exceeds the capacity needed for this trade. In general, Kern County transfers are through the Cross-Valley Canal, Friant Kern Canal, or the Kern River.

The SWAP model linked to the hydrologic network allows us to estimate transfers between regions and surface water sources in the San Joaquin Valley. Next, we evaluate the effect of drought with and without water markets for production, revenue, and employment across regions in the San Joaquin Valley.

Table 2
Estimated water transfers between regions during drought (in Mm^3/yr).

Region	Total imports	Total exports	Net trade
10	72.1	271.8	−199.8
11	0.0	0.0	0.0
12	0.0	0.7	−0.7
13	0.7	0.0	0.7
14A	303.1	0.0	303.1
14B	34.3	0.0	34.3
15A	0.0	46.8	−46.8
15B	12.5	0.0	12.5
16	0.0	86.3	−86.3
17	0.0	17.0	−17.0
18	0.0	0.0	0.0
19a	57.0	0.0	57.0
19B	7.2	0.0	7.2
20	16.4	7.6	8.9
21A	0.0	117.8	−117.8
21B	45.5	16.4	29.1
21C	33.6	17.9	15.8

Table 3
Local surface water transfers in Kern County (in Mm^3/yr).

	Exports		
Imports	Region	20	21A
	19A	3.78	53.19
	21C	3.78	29.87

4.2. Change in land use

In response to drought farmers may shift crop mix and increase land fallowing. The former action results from directing water to lower water use and/or higher value crops and the latter from the decision to devote scarce water to existing crops. For example, farmers may decide allocate scarce water to perennial crops, which would be permanently damaged by shortage, by fallowing fields in annual crops (Marques et al., 2005). We also anticipate more intensive water management on existing fields which our model captures through maximum 15 percent deficit irrigation. The CES production functions capture the corresponding yield effects.

Table 4 summarizes the change in total irrigated hectares by region under the base (no drought) case, drought without water markets, and drought with water markets. In the third column we show the average revenue per unit area by region highlighted to show exporting and importing regions. Interestingly, the average revenues range in the both importing and exporting regions are similar, emphasizing that it is the crop specific marginal revenues that determine exporting and importing regions. In the fourth and fifth columns we summarize the change in total irrigated hectares due to the existence of water markets. Without water markets 87,000 ha are fallowed during the drought, representing just over 4.5 percent of all irrigated land. Allowing for politically feasible (limited) markets prevents 14,000 ha of land fallowing or, in other words, decreases fallowing due to drought by over 16 percent. Finally, some regions increase land fallowing during drought due to the ability to export water. As discussed below, these regions choose to fallow lower-value land and export water out of the region. Table 5 summarizes the total change in irrigated hectares by crop. Fallowing increases for pasture, corn, and rice (region 10) as farmers sell the water to other regions where it is applied to higher value crops.

4.3. Change in farm revenue

The change in farm revenues shows the aggregate effect of a drought water market. Table 6 summarizes the change in farm revenues under base conditions, drought without water markets, and drought with water markets. As with total irrigated land, revenues fall significantly under drought. Without water markets, total farm revenues decrease by over $355 million across the region, or 2.8% of total farm revenues. This includes the effect of increased land fallowing and a shift in crop mix to reflect the increased water scarcity due to drought. If water markets are allowed, farmers can reduce total losses by $104 million in farm revenues across the region. Thus, water markets decrease aggregate farm revenue losses by approximately 30 percent.

Water markets smooth aggregate and regional losses due to drought. We can see these effects in the region-specific revenue changes in Table 6. Farm revenues increase by 18, 15, and 5 percent in regions 14A, 19A, and 15B, respectively. However, revenues fall by 16 percent in region 21A due to water transfers out of the region.

Changes in agricultural revenues will affect other sectors of the economy. These effects are typically modeled with Input-Output ("multiplier") models, which take SWAP model results and estimate changes in related sectors of the economy. Multiplier models capture a snapshot of a region's economy and the interrelations that exist among sectors and institutions. These models estimate direct, indirect, and induced effects for relevant sectors of the

Table 5
Irrigated crop area (in hectares) with and without drought and water markets.

Crop	Base land use	Drought without markets	Drought with markets	Additional land due to markets	Percent change (%)
Alfalfa (Lucerne)	210,413	195,961	201,095	5134	2.62
Almonds/pistachios	265,144	263,917	264,252	334	0.13
Corn	205,381	186,221	176,984	−9237	−4.96
Cotton	267,843	245,496	260,690	15,195	6.19
Cucurbits	23,222	22,471	22,834	364	1.62
Dry beans	11,958	9464	11,101	1637	17.30
Fresh tomatoes	10,712	10,666	10,669	3	0.03
Grain	86,228	81,329	83,901	2572	3.16
Onions/garlic	17,407	17,288	17,352	64	0.37
Other deciduous	119,891	119,398	119,455	57	0.05
Other field	150,131	142,744	144,522	1778	1.25
Other truck	72,270	70,957	71,495	538	0.76
Pasture	59,402	53,810	49,196	−4614	−8.57
Potato	9475	9425	9441	16	0.17
Processing tomatoes	70,010	66,625	68,632	2007	3.01
Rice	5153	4752	2555	−2197	−46.24
Safflower	2901	1910	2295	385	20.16
Sugar beet	8482	7913	8337	424	5.36
Subtropical	89,160	88,474	88,486	12	0.01
Vines	184,264	183,406	183,495	90	0.05
Total	1,869,446	1,782,225	1,796,787	14,562	0.82

Table 4
Irrigated crop area with and without drought and water markets (in hectares).

Region	Base land use	Revenue per ha ($/ha)	Drought no markets	Drought with markets	Additional land with markets	Percent change (%)
10	173,557	4367	170,918	162,225	−8692	−5.09
11	97,705	2992	97,691	97,666	−26	−0.03
12	103,714	2853	103,698	103,608	−90	−0.09
13	229,417	4140	226,056	225,957	−98	−0.04
14A	196,046	4321	161,618	190,980	29,362	18.17
14B	15,405	2647	15,390	15,420	30	0.19
15A	254,698	3574	249,822	248,026	−1796	−0.72
15B	7717	3312	7239	7630	392	5.41
16	62,035	5776	62,073	61,630	−444	−0.71
17	106,113	6110	106,283	105,997	−286	−0.27
18	291,202	4776	282,799	282,754	−45	−0.02
19A	34,113	3621	28,419	32,701	4282	15.07
19B	66,417	4353	56,189	56,793	604	1.08
20	84,236	5524	79,262	79,658	397	0.5
21A	78,141	4288	72,151	60,300	−11,851	−16.43
21B	41,478	6534	37,184	39,130	1946	5.23
21C	27,453	6112	25,434	26,312	877	3.45
Total	1,869,446	4370	1,782,225	1,796,787	14,562	0.82

Table 6
Farm revenues with and without drought and water markets (in $1000 2008).

Region	Base revenues	Drought with markets	Drought without markets	Revenue change due to markets	Percent change
10	757,990	657,180	642,610	14,560	2.27
11	292,360	356,050	357,320	−1260	−0.35
12	295,850	394,640	400,380	−5730	−1.43
13	949,900	1,048,370	1,052,320	−3940	−0.37
14A	847,030	781,010	721,260	59,750	8.28
14B	40,770	46,040	48,530	−2490	−5.13
15A	910,340	693,140	707,820	−14,680	−2.07
15B	25,560	55,920	40,200	15,720	39.10
16	358,320	385,120	385,120	0	0.00
17	648,320	547,070	547,070	0	0.00
18	1,390,780	1,223,140	1,223,140	0	0.00
19A	123,540	223,650	168,160	55,490	33.00
19B	289,140	189,540	189,540	0	0.00
20	465,320	565,290	565,290	0	0.00
21A	335,080	168,160	186,660	−18,500	−9.91
21B	271,000	285,370	277,100	8270	2.98
21C	167,800	146,650	144,280	2370	1.64
Total	8,169,190	7,766,420	7,656,870	109,550	1.43

Table 7
Total agricultural jobs change due to water markets.

Region	Additional jobs
10	332
11	−29
12	−131
13	−90
14A	1362
14B	−57
15A	−335
15B	358
16	0
17	0
18	0
19A	1265
19B	0
20	0
21A	−422
21B	189
21C	54
Total	2498

economy. Typical results include changes in sector output, employment, value added, and tax revenues due to changes in crop revenues. We follow the methodology of Howitt et al. (2011) and estimate that water markets would save 2500 total jobs. Table 7 summarizes the change in total jobs by region due to water markets.

4.4. Summary of water market effects

Water markets reduce the localized effects of drought in the San Joaquin Valley, and in particular significantly reduce effects in regions heavily reliant on Delta exports. Of course, the water comes from other regions which must reduce hectares, revenues, and employment. However, regional shifts in employment are within the counties due to political policy constraints added to the model. Water markets allow transfers which preserve county economies and reduce the local and regional effects of water shortage in the San Joaquin Valley. If we allow out-of-county water transfers, revenue losses decrease by an additional $39 million (15 percent), which translates into 890 additional total jobs.

Our analysis with SWAP shows that one way to dampen the effects of drought on California agriculture is the use of water markets for regions south of the Delta. Under unrestricted trading, SWAP results indicate that water markets could reduce total fallowing by 16 percent, total farm revenue losses by 30 percent, and total job losses by 28 percent. In general, if water could be transferred among regions, most regions on the west side of the Central Valley are willing buyers of water while some eastern regions are willing to sell. Even moderate transfers of water between regions within the same county significantly reduce economic drought impacts.

This example highlights the wide range of policy simulations available from calibrated models like SWAP. We linked SWAP with a hydrologic model of the San Joaquin Valley, added a water transfer variable and corresponding constraints, and were able to estimate the effects of drought and water markets.

4.5. Further model development and limitations

Usually, we want to perform sensitivity analysis after checking the results from the policy model. Sensitivity analysis normally focuses on key parameters in the model defined by the analyst. For example, if exogenous yield growth due to technological innovations is incorporated in the model, it may be important to assess the size of the effect. Other important variables for sensitivity analysis include crop prices, groundwater availability, and water costs. Fully-calibrated optimization models like SWAP are well-suited for sensitivity analysis which will be determined by the specific research project.

Extensions and other improvements to SWAP include enriching the dataset of coastal regions and the Colorado River. Future versions of the model will include disaggregate estimation of changes in yields and shifts in future demands that incorporate results from research in-progress. Production cost information is also continuously updated in the SWAP database. Inputs, in addition to fertilizer and other supplies, are being added. Disaggregate inputs to the production function allow for a more accurate representation of the response of farmers to external shocks in policy simulations.

Limitations of the SWAP model and its applications have been discussed elsewhere (Medellin-Azuara et al., 2012). The most important limitations are due to data availability, for example disaggregate input data. One area not explicitly addressed in SWAP is uncertainty in the calibrated model from hydrological conditions. This uncertainty in water supply availability is inherent to the hydrological simulation or hydro-economic optimization models that are used in the calibration stage of SWAP. However, applications of SWAP often quantify the economic effects of water availability as a policy outcome. Uncertainty in SWAP parameters, including crop prices and production costs, is addressed by running sensitivity analyses based on the model application at hand.

Groundwater is an alternative source to augment local surface water supplies and SWP and CVP delivery in many regions. The cost and availability of groundwater therefore has an important effect on how SWAP responds to water shortage. Changes in hydrologic head over time and in response to short run drought are important inputs to the model. However, SWAP is not a groundwater model and does not include any direct way to adjust pumping lifts and unit pumping cost in response to long-run changes in pumping quantities. Economic analysis using SWAP must rely on an accompanying groundwater analysis (such as CVHM) or at least on careful specification of groundwater assumptions.

5. Conclusions

Several conclusions arise from the SWAP calibration and modeling framework and the application presented in this paper. Calibrated programming models such as SWAP provide useful policy insights and a framework to easily accommodate changing market conditions, improved datasets, and increased regional coverage. Such models provide a versatile tool for regional water management and policy as well as a framework for integrating many aspects of regional water and agricultural management. Models like SWAP can be easily linked to agronomic, hydrologic, and other biophysical models which provides the researcher with a rich and flexible modeling framework. We also demonstrated that model output can be linked to multiplier models in order to estimate effects in related sectors of the economy.

From a policy perspective, we used the SWAP model framework to show revenues losses during drought may be significantly reduced through more flexible water allocations and better markets. However in practice, infrastructure and institutional limitations often prevent some economically worthwhile water exchanges. Results from this work can help policymakers by highlighting worthwhile opportunities for water transfers across the state and the associated opportunity costs of these transfers.

The stepwise systematic calibration procedure outlined in the paper has diagnostic check criteria calculated at each stage. This approach enables a sequential and focused approach to diagnosis of problems in model calibration or policy response. The empirical example of the drought water markets shows that the disaggregation scale of SWAP is sufficient to meaningfully interact with detailed water distribution networks. In this sense detailed calibrated economic models such as SWAP can be useful in the management of natural resources, and the economic and environmental tradeoffs that this entails.

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