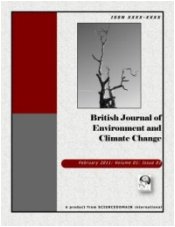

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Simulating the Impact of Drought on California's Central Valley Hydrology, Groundwater and Cropping

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Authors' contributions

This work was carried out in collaboration between all authors. Authors LLD and NLM designed the study. Author SDV assembled the drought scenarios and carried out the CalSim-II runs. Author LLD developed the crop adaptation equations. Author ECD implemented the linkage between C2VSim and CVPM models through the crop adaptation equations. Author CFB carried out the linked C2VSim-CVPM runs with drought scenarios and compiled the results for analysis. Authors LLD and ECD wrote the manuscript. Authors TNK and FIC supplied oversight of the study. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

This paper describes an efficient methodology to link a comprehensive, distributed hydrologic model for California's Central Valley to a crop production model. The resulting hydro-economic model allows for the dynamic calculation of crop acreages in response to water availability without simplifying groundwater or stream flow dynamics by the assumption of linearity or by resorting to a lumped-parameter approach.
The linked hydro-economic model is used to simulate the effects of several drought scenarios on Central Valley's agriculture and the groundwater resources. The drought scenarios are constructed as surface flow reductions that range from 30% to 70% for periods spanning from 10 to 60 years, with a 10-year spin-up and a 30-year recovery. The main finding is that Central Valley agriculture as a whole is resilient to severe

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drought. Despite an almost 40% cut in surface water deliveries for irrigation, the region suffers only a 10% cut in irrigated crop acres. However, after 60 critically dry years in a row, the linked model suggests that there will be regional impacts, including moderate impacts in the north Central Valley (Sacramento River Basin), locally severe in the middle of the Valley (San Joaquin River Basin), and severe in the south (Tulare Basin). The model runs indicate that extensive pumping during such a drought can cause permanent subsidence and may lead to new equilibrium groundwater levels.

Keywords: Drought; hydro-economic model; groundwater; hydrology; crop acreage; subsidence; California Central Valley.

1. INTRODUCTION

Since 1850, California's Central Valley agriculture has expanded over most of the Central Valley. To meet its water needs, the industry depends on a system of surface and subsurface water storage, managed irrigation, and water conveyance. The California climate is extremely variable, with yearly rainfall totals often varying from 25% to 200% of the average annual recorded rainfall total. Thus, the agricultural system relies heavily upon water storage in dry years, particularly water stored in a series of large aquifers that underlie most of the Central Valley. On average, farmers draw upon these aquifers for about 30% of applied water. However, in dry years, groundwater withdrawals can account for more than 60% of applied water.

Recently, the State water agencies have begun to evaluate how to manage water resources in response to a changing climate and more severe droughts [1]. To provide decision makers with a better understanding of the consequences of persistent droughts, we have developed a series of model investigations to determine system behavior and economic impacts under a range of prescribed hypothetical drought conditions. The goals of this study are to quantify the impacts of long-term droughts on aquifer levels and to illustrate how changes in cropping and natural recharge may limit the overall drop in groundwater levels. The study addresses three principal questions:

1. How will climate change and prolonged drought affect groundwater levels and cropping in the Central Valley?
2. How effectively do crop shifting and natural recharges limit the drop in groundwater levels during drought?
3. How much storage does the aquifer lose due to subsidence after the drought?

Like many efforts to determine the impacts of climate change, our effort has involved linking existing models of the natural system, including surface and groundwater models, with models of the managed system, including crop production models. In Section 2, we review the hydrology of California's Central Valley and previous work to estimate drought impacts on Central Valley groundwater and cropping. In Section 3, we describe our methodology for estimating the impact of drought on aquifer levels and cropping. This section includes descriptions of the hypothetical droughts used to perturb the groundwater system and the models used to estimate drought impacts on groundwater and cropping. Section 4 presents the results of our analysis, including estimates of drought impacts on crop acreage, pumping, and groundwater depth. The key findings of this section are summarized in charts illustrating key hydrologic and economic relationships. Section 5 lists the limitations of the

study. The paper concludes (Section 6) with a short discussion of the implications of these findings for future water management and suggestions for future research.

2. LITERATURE REVIEW

California's Central Valley supports a thriving agricultural economy, including 2.8 million hectares (6.8 million acres) of farmland producing crops that are worth 10% of the U.S. total cash farm receipts. Virtually all Central Valley cropland have access to surface water delivered by a system of reservoirs, canals, and rivers. However, the climate is variable, and in dry years groundwater is required to supply up to 60% of the water needed for crops. Without groundwater, the agricultural economy of the region would be vastly different, and much smaller.

The central role of groundwater is illustrated with a water balance chart of Central Valley water use (Fig. 1). In an average year, the groundwater supplies roughly 11 km^3 (9 million acre-feet (maf)) of irrigation water to agriculture—the largest single source of water used by agriculture. Surface diversions, imports, and rainfall supply most of the remaining crop water requirements. At the same time, in an average year the groundwater receives about 11 km^3 (9 maf) back, in the form of recharge from irrigated lands and stream seepage. Thus, the groundwater is in a rough balance in normal times, supplying about as much water for agriculture and other uses as it receives back.

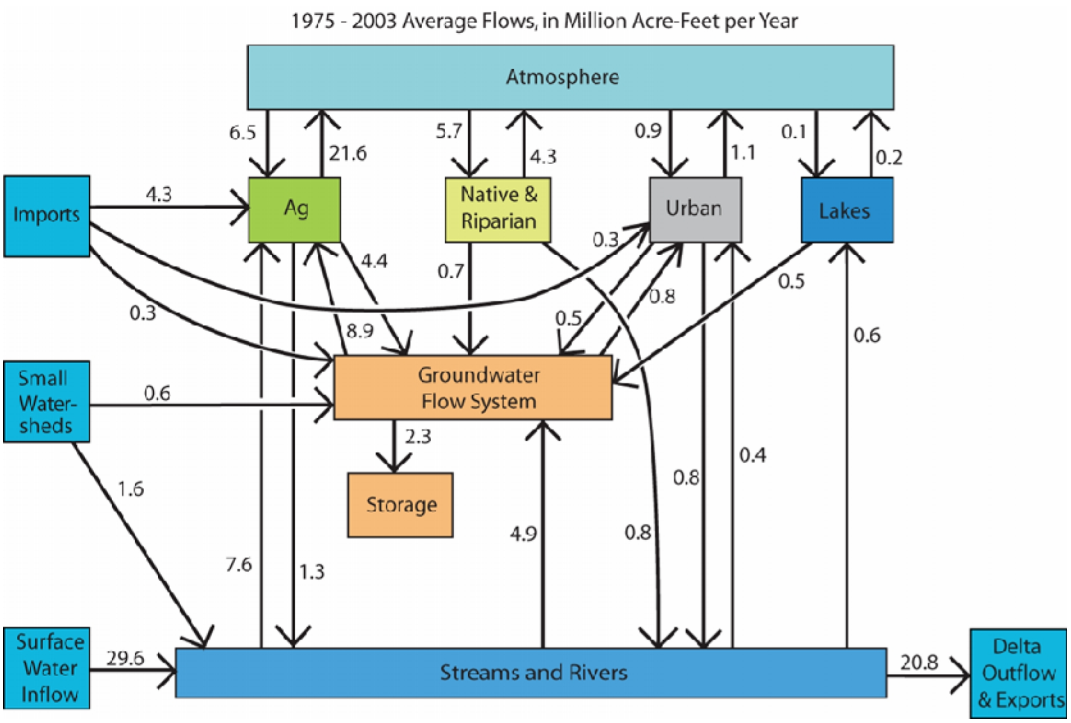

Fig. 1. Central role of groundwater in the Central Valley water balance

Periodically, the region experiences droughts when streams dry up and groundwater becomes not just the largest single source, but the main source of water supporting Valley crops. A variety of models have been built, and studies conducted, to better understand the dynamics of groundwater in the Central Valley and the impact of drought on that groundwater system. Miller et al. [2] studied the effects on the groundwater system of droughts with different levels of severity and durations of up to 60 years. In their model the land use and water demands were held fixed at 2003 levels. Purkey et al. [3] considered several climate change scenarios for the Sacramento River basin—the northern half of the Central Valley—and analyzed the impacts on the aquifer with and without adaptations in water management using the Water Evaluation and Planning (WEAP) model [4]. They considered improvements in irrigation efficiency and shifts in cropping patterns as possible water management adaptation scenarios. The shifts in cropping patterns in their model were based on an econometric analysis of observed shifts in cropping pattern associated with periods of surface and subsurface water scarcity. Later, Joyce et al. [5] applied this same approach to the entire Central Valley. Medellin-Azuara et al. [6] and Connell-Buck et al. [7] analyzed the possible water management adaptation scenarios as a response to warm and warm-dry climates in the Central Valley and the impact on reservoir and groundwater storages using the California Value Integrated Network (CALVIN) model [8]. Both studies assumed fixed agricultural and urban water demands projected for year 2050. One of the most significant drawbacks of CALVIN was its limited ability to represent important physical phenomena, such as stream-aquifer interactions and groundwater flow dynamics under different climate and water management scenarios [8].

During long periods of drought, farmers generally adjust their cropping mix in response to the availability of surface and subsurface water resources, the cost of energy as it relates to the cost of operating pumps to meet irrigation water demand using groundwater, and the market value of crops. Therefore, to study the possible impacts of droughts on the groundwater resources of California's Central Valley in a realistic way, it is necessary to link a hydrologic simulation model to an agro-economic model.

Harou et al. [9], Brouwer and Hofkes [10], and McKinney et al. [11] list different approaches to linking hydrologic and economic models, and discuss their advantages and disadvantages. The two main approaches to linking hydrologic and economic models are-

- *Modular:* a connection between the hydrologic and economic models is maintained to exchange input and output data, but the two models are run separately; and
- *Holistic:* the hydrologic and economic models are fully linked and the resulting combined system of equations are solved simultaneously.

Economic models generally use optimization methods to find a feasible solution to the problem at hand by maximizing or minimizing an objective function subject to a set of constraints. On the other hand, hydrologic models use simulation techniques where mass and momentum conservation equations are solved in a time-marching fashion to represent the movement of water through the physical system.

The modular approach to linking hydrologic and economic models allows realistic representations of economics and hydrology, but information transfer between the two models is difficult to achieve [9,11,12]. When hydrologic and economic models are linked together in a holistic way, the conservation equations representing the hydrologic model are generally used as a new set of constraints in the economic model. To avoid excessive computer run-times, the conservation equations are simplified [11] by either using a lumped-

parameter approach to represent the hydrologic system, assuming linearity in the stream and groundwater flow dynamics, conceptually simplifying the physical system (e.g. assuming a single-layer aquifer regardless of the existence of vertical hydraulic gradients), or by employing a combination of these approaches [13,14,15,16].

Although such simplifications may be justified for some river basins, they lack the ability to properly simulate the complex and non-linear behavior of the hydrologic system in California's Central Valley. First, the Central Valley aquifer is composed of multiple hydro-geologic layers, and irrigation wells are screened according to the water-yielding capacity of these layers. Pumping from a multi-layer aquifer generally creates vertical head gradients and non-linear flow patterns that cannot be represented by simplified equations. Second, although the linearity assumption for the groundwater flow and stream-aquifer interaction may be adequate in some parts of the Central Valley, there is no guarantee that this assumption will hold under different water management and climate scenarios, which an integrated hydro-economic model is built to simulate. Finally, a lumped-parameter approach, where the Central Valley groundwater system is represented with a handful of large cells, falls short of representing the effects of near-stream pumps on stream flows, restricting the ability of a hydro-economic model to properly study the conjunctive use scenarios.

This paper describes an efficient methodology to link a comprehensive, distributed hydrologic model for the Central Valley to a crop production model in order to properly represent farmers' responses to droughts, and the combined effects of drought and variable crop mixes on the groundwater resources of California's Central Valley. The approach and the resulting hydro-economic model are unique, as compared to the previous studies, in that the crop acreages as a response to water availability are calculated dynamically without having to simplify groundwater or stream flow dynamics by the assumption of linearity or by resorting to a lumped-parameter approach. The resulting model can also be used to analyze the effects of droughts on important physical phenomena such as stream-aquifer interactions and land subsidence, as well as the effects of such farm management adaptation strategies as improving irrigation efficiencies.

3. METHODOLOGY AND MODEL INTEGRATION

To estimate impacts of drought on groundwater levels, three different models were used: the water allocation and flow model (CalSim-II) from the California Department of Water Resources (CDWR) [17], the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) [18,29], and Crop Adaptation Equations derived from the Central Valley Production Model (CVPM) [19]. These models are described below.

3.1 California Central Valley Groundwater-Surface Water Simulation Model (C2VSim)

The C2VSim model [18,29] was developed as an application of the CDWR's Integrated Water Flow Model (IWFM) [20] to the Central Valley of California. IWFM is an integrated hydrologic model that uses the Galerkin finite element approach to solve groundwater flow equations. C2VSim simulates the land surface, root zone, stream and groundwater flow processes, and their interactions in the Central Valley using a monthly time step. The model covers an area of 51,394 km^2 (19,834 mi^2) using 1,392 grid cells with an average cell area of 37 km^2 (9184 acres) (Fig. 2). The model area is divided into 21 subregions, which are mainly used as computational units to resolve the water demand and supply relations as well as for

water-budget reporting purposes. The Central Valley aquifer is represented using three vertical layers with thicknesses varying throughout the model domain. The stream network is represented by 431 stream nodes with 97 diversion locations. Using climatic, soil, land-use distribution, and crop and farm water management parameters (e.g., irrigation efficiency, minimum soil moisture as an irrigation trigger, fraction of agricultural tail water that is re-used) , the land surface and root zone module of C2VSim dynamically calculates crop water demands and the allocation of precipitation, irrigation, and available soil moisture to meet these demands. Where diversions are known, it can automatically compute groundwater pumping as the difference between the total irrigation requirement and the prescribed diversions. C2VSim also simulates rainfall runoff, irrigation return flows, infiltration due to precipitation and irrigation, and recharge to the groundwater as a consequence of precipitation and irrigation events. Additionally, it simulates stream flows as a function of diversions, irrigation return flows, rainfall runoff, and the stream-aquifer interaction. Other processes such as tile drainage, subsidence, and land surface and root zone flow processes at urban and native vegetation lands are also simulated. Hence, C2VSim is a comprehensive, distributed-parameter representation of the Central Valley hydro-geologic system.

3.2 California Simulation Model version II (CalSim-II)

The CalSim model [17] is a general-purpose, network-flow reservoir and river basin water resources allocation model developed jointly by CDWR and the U.S. Bureau of Reclamation. It is used for evaluating operational alternatives of large, complex river basins. CalSim integrates a simulation language for flexible operational criteria specification, a mixed integer linear programming solver for efficient water allocation decisions, and graphics capabilities for ease of use. A linear objective function describes the priority in which water is routed through the system, and the constraints set the physical and operational limitations toward meeting the objective. CalSim maximizes the objective function in each time period to obtain an optimal solution that satisfies all constraints.

CalSim was originally designed, and has been successfully implemented, as a planning model of the State Water Project (SWP) and Central Valley Project (CVP) system to examine the range of options to improve supply reliability. The second generation version used here (CalSim II) calculates reservoir operations and time dependent rim inflow into the Central Valley under drought scenarios on monthly timesteps, providing the needed boundary conditions to C2VSim.

3.3 Central Valley Production Model (CVPM)

The CVPM is a multi-regional model of irrigated agricultural production that can forecast changes in crop acres as a function of changes in the availability of water supplies. The model is based on an optimization technique known as Positive Mathematical Programming and is used to address many agricultural policy issues in California [21,22,23,24,25]. The model includes 22 crop production regions and 26 categories of crops. All CVPM crop production regions correspond to the 21 subregions of C2VSim (Fig. 2) with the exception that subregion 3 of C2VSim is represented as a combination of two regions in CVPM. The model's objective function maximizes the sum of producer and consumer surplus across these regions and crops, subject to a variety of constraints involving land and water availability, and other legal, physical, and economic limitations including the cost of water.

CVPM's ability to replicate the historical cropping patterns under drought conditions has been shown by Dale and Dixon [28].

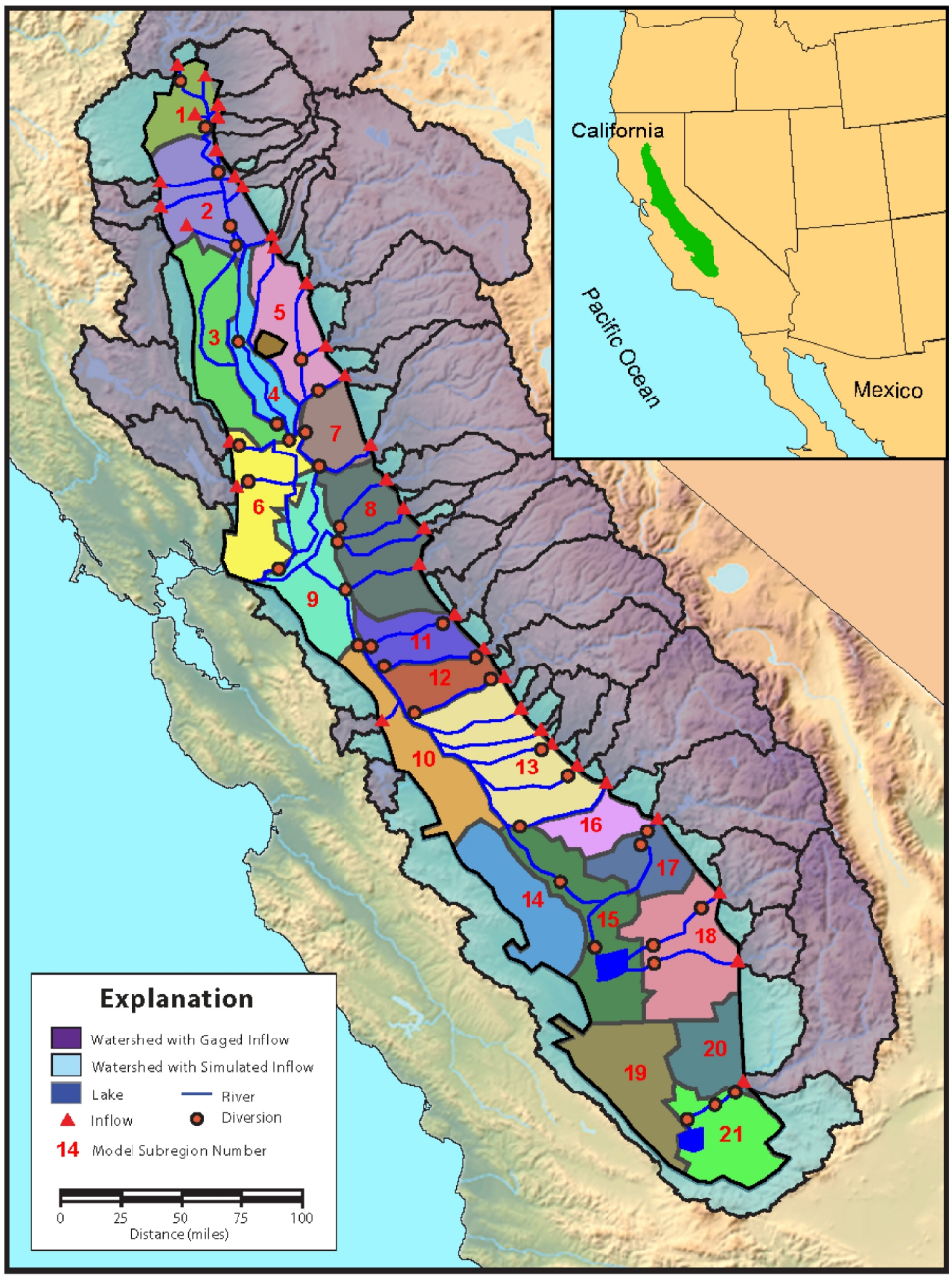

Fig. 2. C2VSim model and subregions

Our estimates of the impact of drought on groundwater levels and cropping are conducted in three analytical steps:

1. Link groundwater and crop production models to estimate drought impacts;
2. Define drought scenarios and associated surface hydrology; and
3. Use the models to estimate drought impacts on groundwater and cropping.

These steps are described below.

3.4 Linking Hydrology and Crop Production Models

Adjusting cropping patterns in response to the availability of water supplies is an important potential adaptation to drought and climate change. Over the course of a drought, farmers increase groundwater pumping until declining groundwater levels and rising pump costs force changes to the crop mix. At that point, farmers may introduce water-saving crops and irrigation methods or fallow land as needed to maintain profitability. In the long run, such water-saving efforts may lead to a new hydrologic equilibrium, with roughly stable groundwater levels and crops. To model this process of drought, falling groundwater, and changing crops, it is necessary to link a hydrologic simulation model and a crop production model that takes agro-economics into account.

In this study a unique approach has been used in which the crop production model, CVPM, was embedded in the distributed integrated hydrologic model, C2VSim, using crop adaptation equations. The linkage between the two models was established using the following steps:

1. Derive crop adaptation equations by running CVPM under many hydrologic and water availability conditions.
2. Implement the crop adaptation equations in C2VSim to represent the response of the CVPM model to hydrologic conditions and water availability.
3. At the beginning of each water year (October 1st), solve the crop adaptation equations to define the crop areas by using hydrologic and water-availability parameters simulated by C2VSim.
4. Using the computed crop areas and the evapotranspiration rates defined for each crop; simulate total irrigation water demands in C2VSim.
5. Simulate the conjunctive use of surface and subsurface water resources in C2VSim to meet these demands (surface water deliveries are obtained from the CalSim-II model for a specified year in the drought period––the construction of which is explained later in the paper––and groundwater pumping is calculated as the difference between the total irrigation demand and the surface water delivery).

This approach effectively emulates the CVPM within the C2VSim, which is then used to estimate the joint impact of drought and changing crop areas on irrigation water demand and, consequently, groundwater levels. A similar approach was also used by Joyce et al. [5] where the CVPM was emulated in the WEAP model [4]. However, WEAP uses a single-layer, lumped, “bathtub” style representation of the groundwater system. Such an approach has limitations when the underlying aquifer has multiple hydro-geologic layers, pumping can occur at one or more of these layers, and there is a significant vertical gradient of the groundwater heads. Additionally, a simplified bathtub approach can misrepresent the stream-aquifer interaction [14,26], which is an important flow term in modeling the conjunctive use of surface and subsurface water resources. As C2VSim is a multi-layer, distributed integrated hydrologic model, it can more accurately represent the pumping from

multiple aquifer layers and its effects on groundwater flow dynamics, as well as on the stream-aquifer interaction.

It should be noted that CVPM simulates changes in irrigation efficiency as a response to prolonged drought so these changes are implicitly represented in the crop adaptation equations. However, other possible changes in irrigation methods such as stressing the crops through deficit irrigation are not simulated in the linked modeling approach.

3.5 Derivation of the Crop Adaptation Equations

The crop adaptation equations used in this study are derived from a multinomial logit regression analysis of synthetic crop share data generated by the CVPM for 22 regions in the Central Valley. The crop share data were obtained from the output of 1,000 CVPM model runs, assuming a base water supply and groundwater depth, with random perturbations from these base levels generated using Monte Carlo simulations. Using these synthetic crop share estimates, a multinomial logit regression analysis was used to estimate crop adaptation equations. These equations were programmed into C2VSim and used in this study to show crop acreage and water use trends over time as a function of changing climate represented as a function of changes in the availability of surface and groundwater.

As mentioned above, the crop adaptation equations were derived from a multinomial regression analysis of synthetic crop share data generated by the CVPM. The CVPM has two modes: long run and short run. The long-run model was used to estimate annual and permanent crop shares in each region based on changes in surface water supply and groundwater depth over the next century. This approach tends to overestimate the ability of farmers to adapt to changes in water supply—for example, allowing farmers to shift permanent crops and irrigation technology more rapidly than ought to be the case. The net result is that the CVPM model runs in the long-run mode may tend to underestimate the amount of crop shifting that would likely take place during prolonged drought periods, at least for the annual crops. This result may be compared to CVPM model runs in the short-run mode, which would tend to overestimate shifts of annual crops during drought. Nevertheless, we feel this approach is justified, because the object of this study is to evaluate the impact of long-run changes in water supply and groundwater on long-run cropping patterns.

The multinomial logit analysis of these synthetic crop share data was used to derive crop adaptation equations to predict the share of a given crop in a given region:

$$X_{c,r} = \frac{e^{\alpha_c S + \beta_c G + \gamma_{c,r}}}{1 + \sum_{c \neq cotton} e^{\alpha_c S + \beta_c G + \gamma_{c,r}}} \tag{1}$$

where X is the share of crop c in region r; c is a crop type index; r is a region index; S is a percentage reduction in surface water supply; G is an increase in groundwater depth; β is the logit coefficient; and γ is a region-specific dummy variable.

The share for the reference crop (cotton) is given by:

$$X_{cotton,r} = \frac{1}{1 + \sum_{c \neq cotton} e^{\alpha_c S + \beta_c G + \gamma_{c,r}}} \tag{2}$$

In this study, cotton was chosen as the reference crop because it is widely grown in much of the Central Valley. Several calculations were performed to assess the accuracy of the crop adaptation equations to match the CVPM modeled crop shares. First, crop adaptation equations and CVPM estimates were compared across 500 assumed groundwater depth and surface water application "scenarios". Denoting the crop share for each region estimated from the crop adaption equations and CVPM, respectively, as $\hat{y}_{i,r,c}$ and $y_{i,r,c}$ where *i* indexes scenarios, *r* indexes regions, and *c* indexes crops, the percentage variation in CVPM crop share explained by the adaptation equations was calculated as:

$$E = \frac{\sum_{i,r,c}\left(y_{i,r,c}-\bar{y}\right)^2 - \sum_{i,r,c}\left(y_{i,r,c}-\hat{y}_{i,r,c}\right)^2}{\sum_{i,r,c}\left(y_{i,r,c}-\bar{y}\right)^2} \quad (3)$$

where E = the percent variation of crop share explained by the crop adaptation equations and $\bar{y} = \frac{1}{N}\sum_{i,r,c} y_{i,r,c}$.

For the scenarios used in this analysis, the resulting statistic is 0.99, implying that the crop adaptation equations explain over 99% of the variation that exists in CVPM crop shares, across all regions and crops.

The accuracy of the crop adaptation equations is illustrated by indicating how closely they match CVPM estimates (Fig. 3). In this test, the CVPM and the crop adaptation equations are used to estimate crop shares in the Sacramento Valley. A comparison of the crop share equation and CVPM estimates indicates that crop adaptation estimates of crop shares are generally quite close (within 1%–3%) to the CVPM crop shares, showing significant divergence only at the extremes (Fig. 3). Compared to the CVPM model, the crop adaptation equations tend to slightly underestimate the impact of moderate shortages and slightly overestimate the impact of very large shortages of surface water on crop acreage. The droughts considered in this study, as large as they were, generally resulted in moderate to small changes in crop acreage.

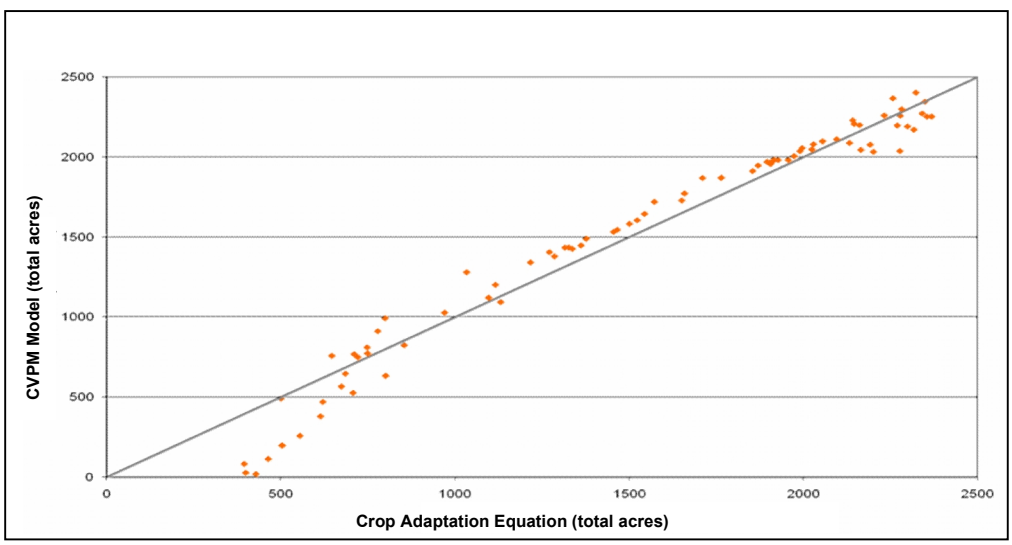

Fig. 3. CVPM model and crop adaptation equation estimates of crop shares in the Sacramento Valley

3.6 Implementation of the Crop Adaptation Equations in C2VSim

The crop adaptation equations were incorporated into C2VSim in a generic sense where the number of equations and parameters used in these equations are specified by the user. This allowed testing different forms of the crop adaptation equations without having to change their generic implementation in C2VSim. For instance, at the initial stages of this study the crop adaptation equations were derived with the assumption that the cropping pattern in each CVPM subregion was independent from the agro-economic and hydrologic parameters in other subregions, ignoring the effect of water transfers between subregions on cropping patterns, among other things. Later in the study, this dependency was recognized, and the crop adaptation equations were re-derived accordingly. These two approaches effectively generated different sets of crop adaptation equations with a different number of parameters. The generic implementation in C2VSim allowed efficient integration of these two equation sets without having to modify the underlying programming source code or the input data file structure. Such a generic implementation also means that crop adaptation equations derived from models other than CVPM can easily be integrated into C2VSim in the future.

An important consideration in linking economic and distributed hydrologic models is to address the different spatial resolutions that the two types of models use [9,10]. In this study, CVPM uses 22 subregions corresponding to the 21 subregions of C2VSim (with subregion 3 divided into 2 subregions in CVPM) as the spatial unit of computation. In addition, C2VSim divides these subregions further into a total of 1,392 finite element cells using 1,393 finite element nodes.

One of the decision variables that the crop adaptation equations use to determine the crop mix was the depth-to-groundwater at each subregion, which was computed at each finite element node of each simulated aquifer layer in C2VSim. Therefore, it was necessary to develop methods to compute subregion-level depth-to-groundwater values from their nodal counterparts in C2VSim. However, unlike most hydro-economic models, where the groundwater system is simulated as a single aquifer layer [5,14,15,16,27], the depth-to-groundwater value in a multi-layer model like C2VSim, where pumping can occur from several different layers, must be computed carefully. At this point, it is important to recognize that the concept of depth-to-groundwater is a surrogate for the cost of pumping in an agro-economic model; the greater the depth-to-groundwater, the costlier it is to pump. Therefore, in a multi-layer model it is important to consider the groundwater heads only in the aquifer layers being pumped when computing the depth-to-groundwater. For instance, the San Joaquin and Tulare basins of California's Central Valley include a clay layer (Corcoran clay) that vertically divides the aquifer into two distinct layers (an unconfined layer above the Corcoran clay and a confined layer below) with substantially different groundwater heads. Most pumping occurs below the Corcoran clay, necessitating the use of the groundwater heads at the confined layer in computing the depth-to-groundwater term to be used by the crop adaptation equations. As a further complication, CVPM and C2VSim model boundaries include areas with native vegetation with no pumping or irrigation. The groundwater heads at these areas should have no impact on farmers' decisions on choosing what crops to plant. To overcome these complications, pumping-weighted subregional depth-to-groundwater values were computed from simulated groundwater heads at finite element nodes. In other words, groundwater elevation at a finite element node with no pumping had no influence on the average depth-to-groundwater computed for a subregion whereas a node with pumping had an influence in proportion to the pumping amount occurring at that node. C2VSim is designed so that pumping at a single finite element node

at a given aquifer layer is computed based on the land-use type (agricultural, urban or native vegetation) and the well screening depths in the surrounding finite element cells. Using these nodal pumping amounts from C2VSim it was possible to compute meaningful, subregional weighted-average depth-to-groundwater values that were used in the crop adaptation equations.

3.7 Defining Drought Scenarios

Drought scenarios were constructed by randomly selecting hydrologic years from the 1972-2003 historical records of reservoir releases with reductions ranging from 30% to 70% (with respect to an average year) and appending them together. The constructed drought periods ranged from 10 years to 60 years, with 10-year spin-up and 30-year recovery periods. The C2VSim stream boundary inflows were then generated using the CalSim II model and historical flow observations of Central Valley rim flows based on the specified reductions corresponding to each drought scenario.

The intention was to create drought scenarios with corresponding agricultural surface water delivery reductions also ranging from 30% to 70%. However, historical reservoir releases reduced by a certain amount did not assure that the corresponding downstream surface water deliveries would also be reduced by the same amount. One reason for this is there is not a perfect correlation between reservoir releases and deliveries. Another reason is that the reductions were assumed to be homogeneous throughout the different regions included in the model.

An analysis of the input data to the model shows that the derived scenarios were underestimations of the expected reductions in the surface water deliveries, and the distribution of reductions was not homogeneous. Nevertheless, the remainder of this paper refers to the three drought intensity levels considered in this study as light (30%), moderate (50%), and severe (70%), noting that the reductions in deliveries are lower than the reductions in reservoir releases. The specific drought scenarios, reservoir releases, and deliveries are presented in Table 1.

Table 1. Percent cut in deliveries and releases in the drought scenarios

Scenerio*	Percent reduction in		
	Precipitation	Reservoir releases	Deliveries
30_10	18%	40%	4%
30_60	18%	41%	4%
50_10	27%	50%	18%
50_60	27%	54%	19%
70_10	33%	61%	36%
70_60	33%	59%	36%

** Each scenario is represented by [drought intensity]_[drought duration]*

4. RESULTS AND DISCUSSION

In this section the principal findings of the study, including impacts on crop acreage, groundwater pumping and level, crop water use, aquifer recharge, and land subsidence are discussed.

4.1 Crop Acreage Maintained During Drought in Most of the Valley

The main finding of this study is that Central Valley agriculture is resilient to prolonged, severe drought. Prior to the drought, the region supports almost 2.4 million irrigated crop hectares (6 million acres). After 60 years of severe drought the region still supports 2.1 million irrigated crop hectares (5.3 million acres). In other words, despite an almost 40% cut in surface water deliveries, the region suffers only about 10% cut in irrigated crop acres (Fig. 4). Based on observed data, Dale and Dixon [28] also report a similar finding for Fresno and Kern counties located in the San Joaquin Basin during the 1986-1992 drought: only 14% decrease in irrigated acreage under a 53% decrease in surface water deliveries.

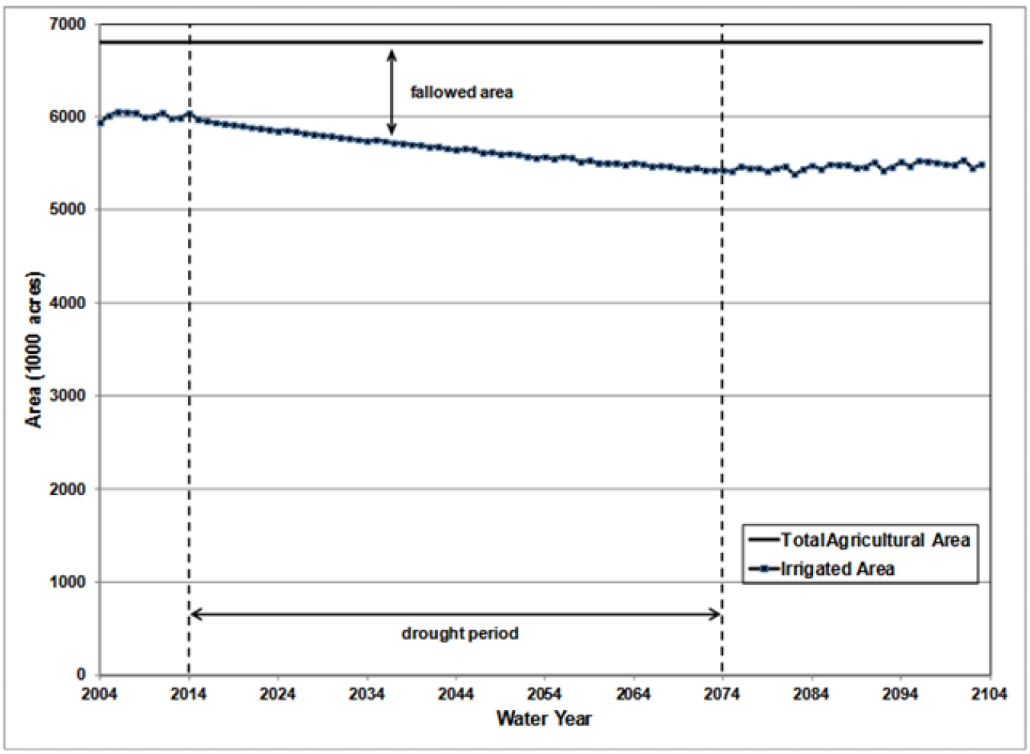

Fig. 4. Crop fallowing before, during, and after a 60-year severe drought

The principal explanation for agricultural resilience is the abundance of groundwater in the Valley. Reduced stream inflows at the model boundary for the 60-year severe drought are shown in Fig. 5. Over the 60-year period, farmers successfully tap groundwater to irrigate cropland that would otherwise be fallowed. The changes in water source are revealing: on average annual groundwater pumping is increased by 6.2 km^3/year (5 million acre-feet per year (maf/year)) during the drought, from 7.4 km^3/year (6 maf/year) to 13.6 km^3/year (11 maf/year), to maintain total water use close to its pre-drought levels of 26 km^3/year (21 maf/year) (Fig. 6).

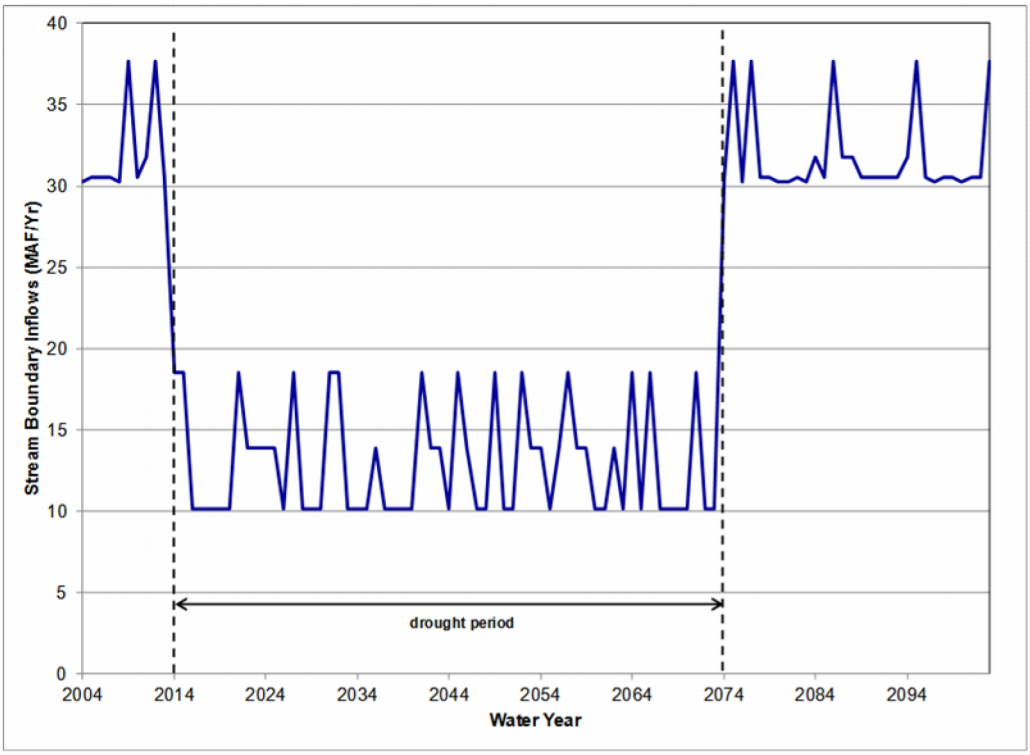

Fig. 5. Stream boundary inflows for 60-year severe drought

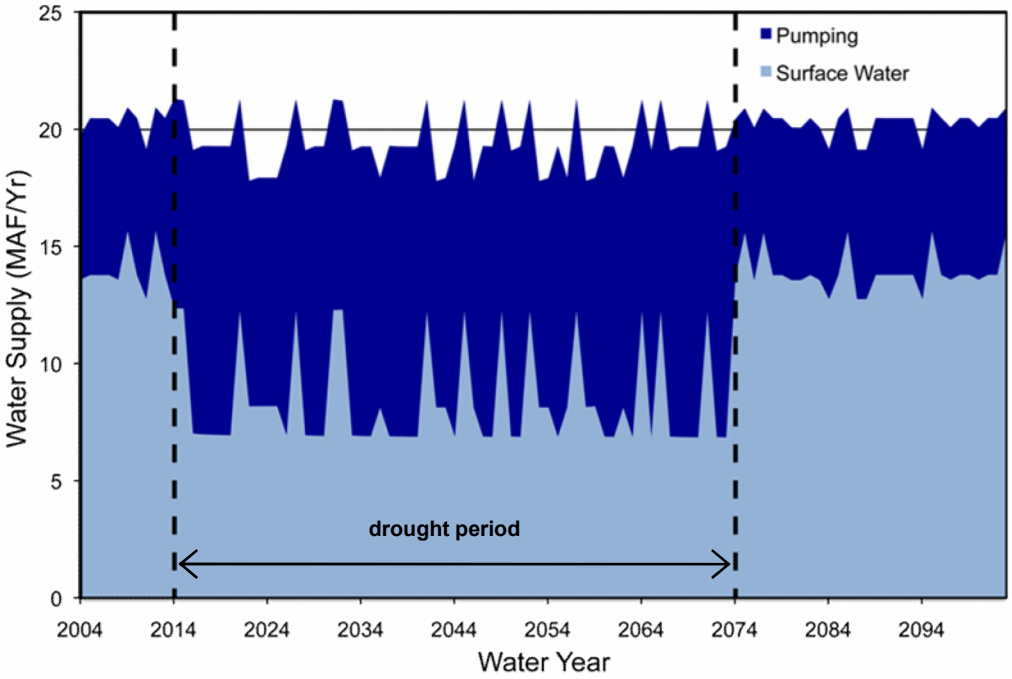

Fig. 6. Pumping and surface water deliveries during the 60-year severe drought

A second explanation for resilience is the relatively inelastic demand for groundwater estimated for crops in the Valley. The crop model and adaptation equations suggest that crop acreage is largely maintained despite falling groundwater levels. Over the entire valley, about a 27.5-meter (90 feet) drop in average groundwater levels is associated with a 10% increase in fallowed acreage (Fig. 7). The sensitivity of crop acreage to changes in groundwater level varies across the Valley. San Joaquin Basin crops are less sensitive and Tulare Basin crops more sensitive to the changes in average groundwater levels. This is likely due to Tulare Basin agriculture being more dependent on groundwater than other parts of the Central Valley.

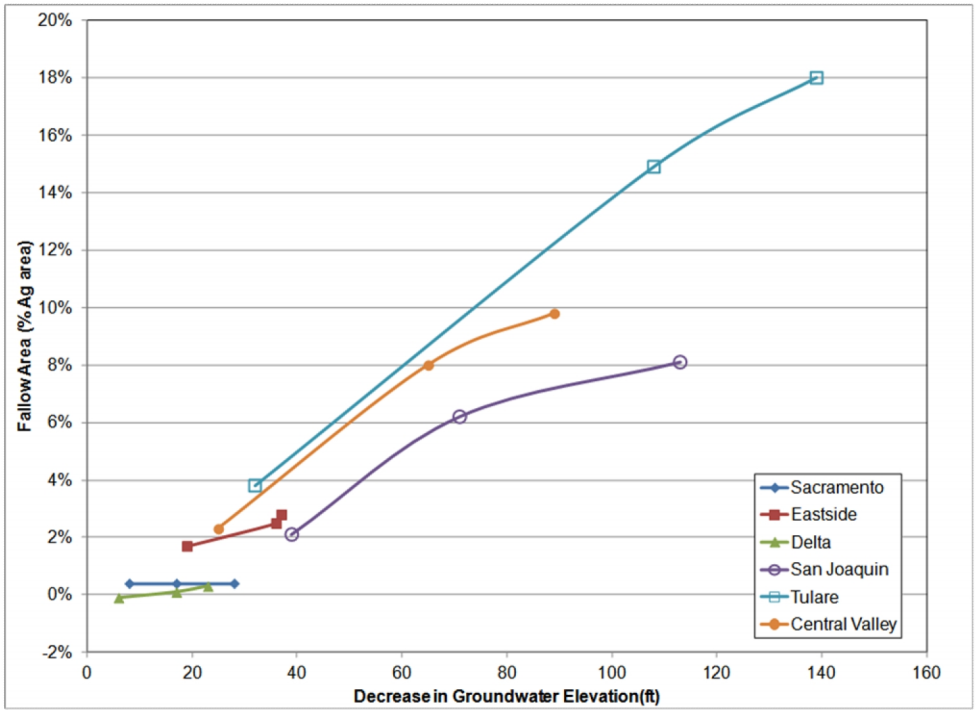

Fig. 7. Crop fallowing and changes in groundwater depth

A third explanation for resilience is natural aquifer recharge, which prevents large drops in groundwater during the drought. In much of the Valley, groundwater levels remain within 20 meters (66 feet) of the pre-drought levels during the light and moderate droughts. In the Sacramento and much of the San Joaquin Basin, groundwater levels rarely decline more than 20 meters (Table 2). Only in the Tulare do groundwater levels decline as much as 43 meters (140 feet).

One reason groundwater levels remain as steady as they do has to do with changes in the amount of natural recharge from streams to aquifers during the drought, particularly in the Sacramento and San Joaquin Basins. On average, during normal years streams in the Central Valley gain between 2.5 and 3.7 km^3/year (2 and 3 maf/year) from groundwater.

Table 2. Average decrease of groundwater elevations in meters *(feet in parentheses)* for 60-year drought with different intensity

Hydrologic Region	Severe Drought	Moderate Drought	Light Drought
Sacramento	8.5 *(28)*	5.2 *(17)*	2.4 *(8)*
Eastside	11.3 *(37)*	11.0 *(36)*	5.8 *(19)*
Delta	7.0 *(23)*	5.2 *(17)*	1.8 *(6)*
San Joaquin	34.4 *(113)*	21.6 *(71)*	11.2 *(39)*
Tulare	42.4 *(139)*	33.0 *(108)*	9.8 *(32)*
Central Valley	27.1 *(89)*	19.8 *(65)*	7.6 (25)

During the 60-year severe drought, aquifers retain much of this water, with inflows from groundwater to streams dropping about 2 km^3/year (1.5 maf/year) (Fig. 8).

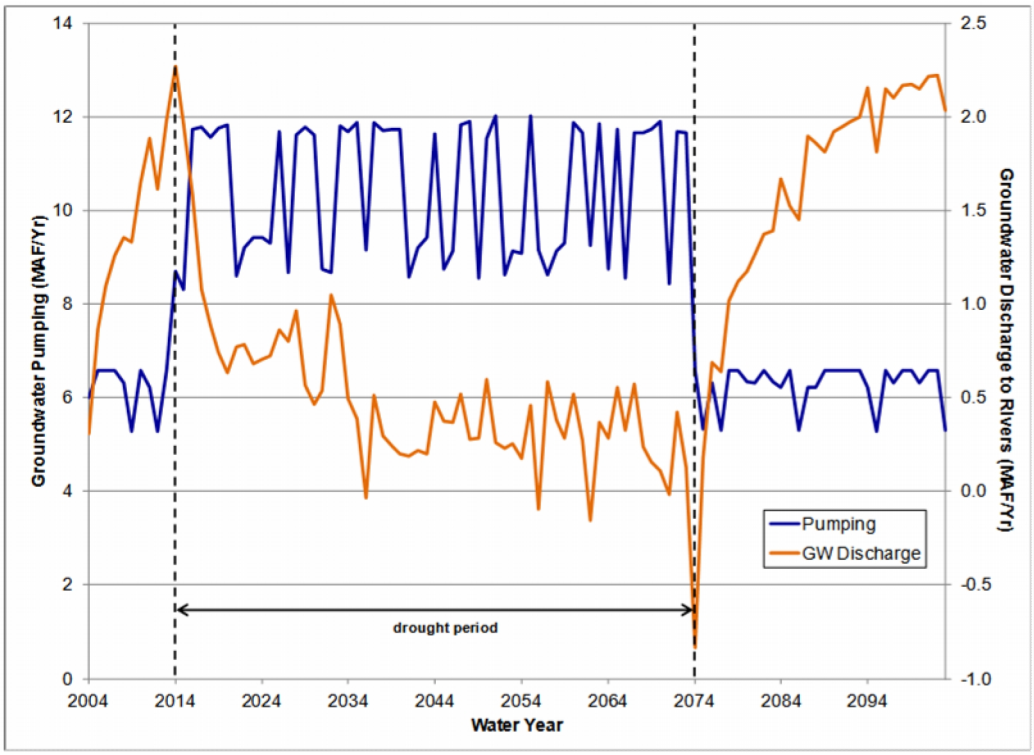

Fig. 8. Decrease in aquifer releases to streams during drought

4.2 Aquifer Compaction and Land Subsidence

The increase in pumping that occurs during the drought results in land subsidence and compaction of the aquifer (Fig. 9). During the severe drought, pumping increases from 7.4 to 12.3 km3/year (6 to 10 maf/year) on average and, as a result, the aquifer is compacted about 0.04 km3/year (31,000 acre feet per year)—or around 2.5 km3 (2 maf) over the course of the 60-year drought. Fig. 9 shows that the aquifer bounces back very little during the 30-year recovery period, gaining back only about 0.25 km3 (200,000 acre-feet) of storage, suggesting that the subsidence caused by the drought may partially be inelastic and the

amount of aquifer storage lost may be permanent. This "cost" to the aquifer is difficult to value, but it is clearly substantial, and compaction remains a large concern with regards to using the aquifer to maintain irrigation during long drought periods.

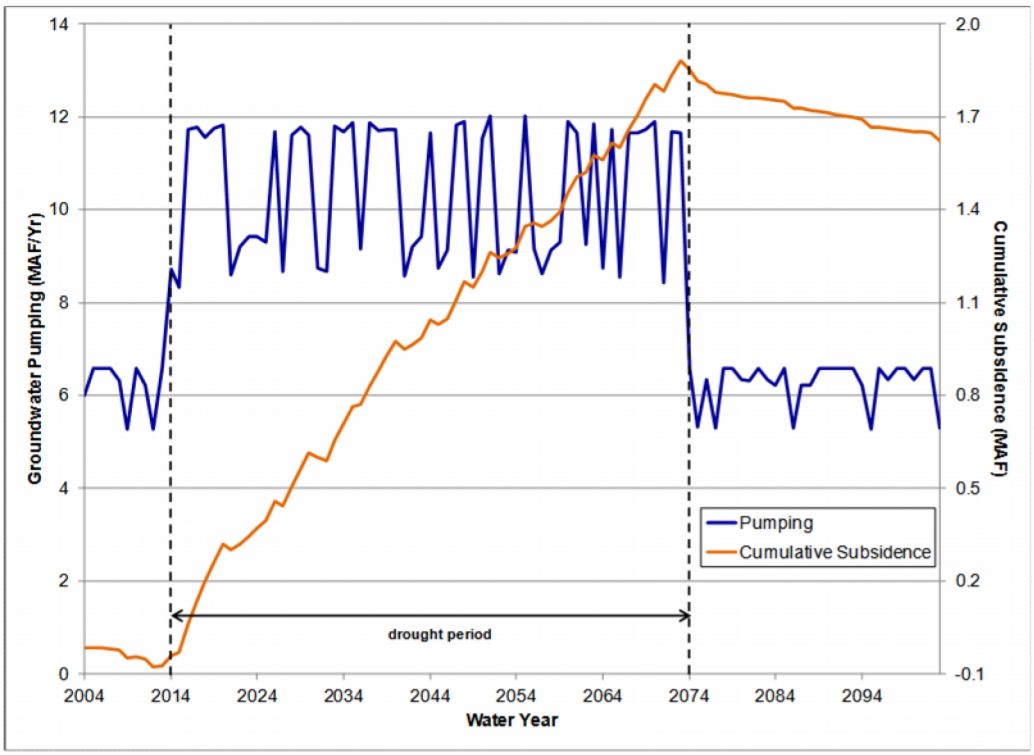

Fig. 9. Subsidence increases as a result of pumping

5. LIMITATIONS OF THE STUDY

We highlight two limitations to the study regarding the impacts of climate change on drought and the impact of drought on crop water use. Our study describes the impact of drought—something that climate models suggest will become more prevalent in future—on cropping and groundwater levels in California's Central Valley. Climate change will affect many other things about agriculture, including crop yield and crop water requirements, but this study is limited to impacts on crop choice, fallowing and groundwater levels. Other factors ignored in this study include the effect of climate change on crop prices, urbanization and the change in the timing of the stream flows caused by earlier snowmelt.

Farmers will likely adapt to climate-induced drought in many ways, including increased groundwater pumping, changes to crop mix, land fallowing, crop stress, and changes to irrigation techniques. The crop adaptation equations incorporate most of these adaptations to climate-induced drought, including changes to pumping, crop mix, fallowing and irrigation technique. The C2VSim model incorporates most adaptations as well, but it assumes irrigation efficiency to be constant. This simplification means that the C2VSim model will tend to overstate irrigation water demand in regions with falling groundwater levels and rising irrigation efficiency.

Nevertheless, this simplification only tends to reinforce the principle finding of this study, which is the surprising resilience of Central Valley agriculture and the Central Valley aquifer, to prolonged drought. This resilience is due primarily to the abundant groundwater resource, but it is assisted by the ability of farmers to shift crops, fallow land and changing irrigation techniques. This last effect—changes to irrigation efficiency—is missing in C2VSim. Including this effect in our model will strengthen the finding in this study that Central Valley agriculture is resilient to climate-induced drought.

6. CONCLUSION AND FUTURE WORK

Climate change will impact natural and economic systems at the same time, so estimating climate impacts requires linking several types of models. This paper describes one example of this approach—linking hydrologic and agro-economic models to obtain a consistent estimate of climate change impacts on groundwater and cropping in California's Central Valley.

In this case a unique approach was used to link crop and groundwater models by emulating CVPM, an agricultural production model for California's Central Valley, within an integrated hydrologic model of the Valley (C2VSim) through the use of crop adaptation equations. Drought scenarios with varying duration and intensity were constructed, and the linked model was used to evaluate the impact of these drought scenarios on cropped acreage, groundwater levels, subsidence and stream-aquifer interactions. The new approach maintained the complexity of the groundwater and surface water flow dynamics as well as the complexity of the flow exchange between the aquifer and streams while effectively simulating the crop acreages as a response to the drought.

Despite the severe climate change defined for this study—60 critically dry years in a row—the linked model suggests that the impacts will be region specific, including moderate impacts in the north Central Valley (Sacramento River Basin), locally severe in the middle of the Valley (San Joaquin River Basin), and severe in the south (Tulare Basin). However, overall, the results suggest that Central Valley agriculture and aquifers are both resilient in the face of drought.

On the other hand, the model runs indicate that extensive pumping during such a drought can cause permanent subsidence and may lead to new equilibrium groundwater levels. One lesson that can be drawn from this study is the value of the Central Valley aquifers for maintaining agricultural production in the region. An equally important lesson is the necessity of protecting the aquifer and preventing land subsidence and compaction that may damage the aquifer.

The new approach used in linking CVPM and C2VSim allows studying the impacts of climate change on California's Central Valley from multiple viewpoints. Although the results of this study suggest that falling groundwater levels under prolonged severe droughts may not adversely affect the agriculture in California's Central Valley, it may have adverse effects on stream flows by altering the stream-aquifer interactions or may cause permanent subsidence and loss of aquifer storage. Proper representation of complex groundwater dynamics and surface-subsurface flow interactions without any simplifications in the linked C2VSim-CVPM hydro-economic model allows better representation of stream-aquifer interaction or subsidence under drought conditions. Thus, this study demonstrates the use and flexibility of the linked C2VSim-CVPM hydro-economic model for evaluating and providing insights regarding climate change impacts on Central Valley aquifers.

There are a number of ways to expand this study to provide results to further understand the response of Central Valley agriculture and the underlying aquifer to climate change. These include defining additional climate change scenarios and evaluating more flexible cropping and economic responses to climate change.

In this study we imposed a synthetic long-term drought to analyze climate change impacts. In the future, evaluating actual downscaled GCM precipitation and runoff scenarios may provide a more realistic picture of future climate change impacts. At the same time, we recommend a more long-term-impact evaluation of the climate system on groundwater levels and cropping. Such an evaluation would help to determine when and where groundwater levels might stabilize, once crop demands fall and aquifer recharge equals aquifer withdrawals. Ultimately, such information could help water managers determine how to actively manage surface and groundwater through crop subsidy, water transfer, and groundwater recharge programs.

We also recommend an expanded crop production model to show the impact of changes in crop yields, crop water use, and energy prices likely to result from climate change since these factors also affect the crop acreage which in turn influences groundwater elevations.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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