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Irrigation demand and supply, given projections of climate and land-use change, in Yolo County, California

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ABSTRACT

We assess the potential effects of climate change and adaptive management on irrigation water supply in the Cache Creek watershed in California. Our model, built using the Water Evaluation And Planning (WEAP) system, is calibrated using historical data (1971–2000) on streamflow, irrigation deliveries, and reservoir operations. We examine three adaptation scenarios to 2099: (1) changes in cropping patterns based on econometric forecasts, (2) a shift toward a more diversified and water-efficient cropping patterns, and (3) a combination of irrigation technology improvements and changes in cropping patterns. Results show irrigation demand increasing by 26% and 32% under B1 and A2 baseline climate scenarios respectively in the latter part of the century under baseline climate scenarios. Irrigation water supply from upstream reservoir releases is less vulnerable, because of increased spring precipitation upstream. However, legal limits on reservoir releases mean that increased demand can only be met by increasing groundwater extraction. Increases in demand from climate change alone exceed applied water reductions from changing cropping patterns by an order of magnitude. Maximum applied water savings occur by combining a diversified water-efficient cropping pattern with irrigation technology improvements, which decreases demand to levels 12% below the historical mean, thereby also reducing groundwater pumping.

1. Introduction

In California, competing water demands for agriculture, industry, urban areas and the environment have meant that most watersheds in the state are consistently over-allocated (California Department of Water Resources, 1998). In the near term, projections suggest that by 2020 demand for water will exceed the available supply by more than 2.96 billion m^3 in average rainfall years and up to 7.65 billion m^3 in dry years (California Department of Water Resources, 1998). In the long term, climate change and population growth are expected to place additional demands on the state's water resources, with the impacts on California's water resources likely to be outside the range of past experience (Kiparsky and Gleick, 2003; Milly et al., 2008). Climate change is already having a measurable effect on California's water supply (Hidalgo et al., 2009). Statewide, mean annual temperatures have increased by 0.6–1.0 °C during the past century, with the largest increases seen in higher elevations (Anderson et al., 2008; California Department of Water Resources, 2008). This warming trend has contributed to a 10% decline in average spring snowpack in the Sierra Nevada mountains over the same period, which equates to a loss of approximately 1.85 billion m^3 of snow water storage (Barnett et al., 2008; California Department of Water Resources, 2008). Global climate models suggest that this warming trend will accelerate, with temperatures expected to increase by 2–6 °C by the end of this century (Brekke et al., 2008; Cayan et al., 2008). Model projections of precipitation are less consistent about direction of change, but inter-annual variability is already on the rise and projected to increase further during the latter half of this century (Anderson et al., 2008; Cayan et al., 2008, 2010). Consequently, state agencies such as the California Department of Water Resources (DWR) and the California Energy Commission (CEC) have urged water managers at the regional, district, and local levels to examine the potential impacts of, and responses to climate change as a part of their planning efforts (California Department of Water Resources, 2008; Kiparsky and Gleick, 2003). Agriculture, a 30-plus billion dollar industry in California (USDA, 2011), is heavily dependent on irrigation water supply with irrigation withdrawals from surface and groundwater accounting for 80% of total freshwater withdrawals in the state (Hutson et al., 2005). In the Mediterranean

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climate prevalent over much of California – cool, wet winters and warm, dry summers – water is stored in the winter in the Sierra Nevada snow-pack and numerous reservoirs in the Sierra Nevada and Coast Range mountains, and is released in the summer for irrigation. In dry years, farmers face cuts in surface water allocation and use more groundwater instead (Famiglietti et al., 2011). California's Central Valley, one of the world's most productive agricultural regions, has been home to irrigated agriculture for over 200 years. Early surface water irrigation schemes gave way to extensive groundwater extraction in the 1930s, especially in the southern, San Joaquin valley portions of the Central Valley. This led to decades of declining water tables, and land subsidence. Massive deployment of surface water storage and conveyance systems from wetter northern California for agriculture and urban areas in drier southern California have led to partial recovery of water tables since the 1960s, although Central Valley aquifers remain in a state of overdraft (Faunt et al., 2009; Famiglietti et al., 2011).

Changing climate will impact agriculture to varying degrees and directions that are crop-specific, via several pathways. Lobell et al. (2006) and Lobell et al. (2007) use regression approaches to assess crop yield response to climate signals state-wide, using county level data. Lee et al. (2011) use biogeochemical models under 18 climate projections to conclude that changing climate will negatively impact yields of major crops in the Central Valley especially toward the end of this century. These studies did not include impacts on water supply that could affect agricultural production. Given agriculture's heavy dependence on irrigation water and the tight coupling of climate variability to both surface and groundwater resources (Faunt et al., 2009), water availability strongly mediates agricultural vulnerability to climate change (Schlenker et al., 2007). Lee et al. (2001) estimate crop-revenue losses of $11 million in the Sacramento Valley in response to a hypothetical 25% reduction in irrigation deliveries from surface water, underscoring the importance of reliable irrigation supplies to agriculture in the region. Both locally and state-wide, irrigated agriculture's linkages to climate change and hence to adaptation strategies are very likely to be substantially influenced by the water resources infrastructure, operating rules and water rights.

Adaptation strategies can include supply and/or demand side management responses. Examples on the supply side include expanding water storage, updating levees and aqueducts, interstate transfers, modifying existing operating rules, expanding conjunctive use or groundwater banking (Tanaka et al., 2006; Medellín-Azuara et al., 2008). Demand management options may include water pricing and markets, allocation limits, improved water use efficiency, public and private incentives for irrigation technology adoption, reuse of drainage water, and shifting to less water intensive crops and fallowing (Tanaka et al., 2006). As higher temperatures increase crop ET demand, as well as the losses associated with water storage, delivery and irrigation, improved management of irrigation delivery requirements is an important climate adaptation strategy (Lévite et al., 2003; Joyce et al., 2009, 2010, 2011). Jackson et al. (2011) and Lee et al. (2001) have shown that three of the important adaptive responses to climate change by growers include shifts in cropping patterns toward greater crop diversity, shifts in cropping patterns toward less water intensive crops, and adoption of low volume irrigation technologies that reduce applied water. Increased adoption of low volume irrigation technologies across the state has been documented over recent decades by Orang et al. (2008) and have been attributed in contributing to increased overall irrigation efficiencies and reduced delivery requirements, through reduced non-beneficial losses from the field, such as surface runoff and percolation from over-irrigation (Faunt et al., 2009).

Various approaches have been used to include technology considerations for future agricultural water management. In an economic optimization approach for assessing climate adaptation in the water sector in California, Medellín-Azuara et al. (2008) model technological change simply as a yield increase per year, assigning a value informed by yield increases in the past 50 years. In a global study on irrigation water requirements and water withdrawals with changing climate, Fischer et al. (2007) use a linear increase in irrigation efficiency (defined therein as irrigation water requirements/water withdrawals) over time to incorporate the impact of changing irrigation technologies. In studying climate impacts on irrigation water requirements and potential adaptation paths, Purkey et al. (2008) and Joyce et al. (2011) conceptualized irrigation management technology scenarios that could meet crop water demands with less applied water. Conceptually, this is realized through reductions in non-beneficial soil evaporation and/or reduced percolation and runoff from over-irrigation, and is consistent with published literature on improved irrigation efficiencies made possible by low volume irrigation technologies (Faunt et al., 2009; Orang et al., 2008). In this paper, as described in the Methods section, we use the same approach as in Purkey et al. (2008) and Joyce et al. (2011).

1.1. Objective

We build an integrated water resources model of the Cache Creek watershed to assess the potential effects of climate change and adaptive management on agricultural water demand and supply. Surface water supply for irrigation of approximately 40% of Yolo County originates in the Cache Creek watershed and is managed by the Yolo County Flood Control and Water Conservation District (YCFCWCD, henceforth, "the District"). We chose this district for several reasons. First, most studies examining climate impacts on the state's water resources have focused on watersheds fed by the Sierra Nevada, while those originating in the Coast Range have received little attention. Examining the Cache Creek watershed therefore provides an opportunity to investigate how watersheds that are not reliant on Sierra Nevada snowmelt may be impacted by climate change. A second reason is that Yolo County is the site of an ongoing interdisciplinary case study on agricultural adaptation to climate change (Jackson et al., 2012). As such, the hydro-climatic analysis is further informed by locally relevant agronomic and socio-economic data and concerns. Several integrated water management plans have been formulated for the district over the past decade (Borcalli and Associates, 2000; Water Resources Association, 2005, 2007; WRIME, 2006), but this study simulates the hydrology of the catchments in Lake County which form the headwaters of Cache Creek. In addition, it captures the explicit operating rules and legal decrees (e.g. Solano Decree) which govern local water management decisions. Then, downscaled climate projections (GFDL-BCCA) from two IPCC emissions scenarios (A2 and B1) are used to simulate the district's future water supply and projected demand under one baseline and three adaptation scenarios.

1.2. Study area

Agriculture is the dominant land use in Yolo County, covering approximately 57% of the land area (California Department of Water Resources, 1997). Between 1970 and 2008, total irrigated agricultural area in the county averaged 1345 km^2, varying between a maximum of 1600 km^2 in 1980 and a low of 1134 km^2 in 1982 (Yolo County Agricultural Commissioner, 1970–2008). Overall, there has been a downward trend in total agricultural area. The county covers a portion of two geomorphic provinces: the Coast Range and Central Valley. Surface water supply comes from a number of drainages: the eastern and northern parts of the county depend on the Sacramento River, Colusa Basin Drain, and Yolo

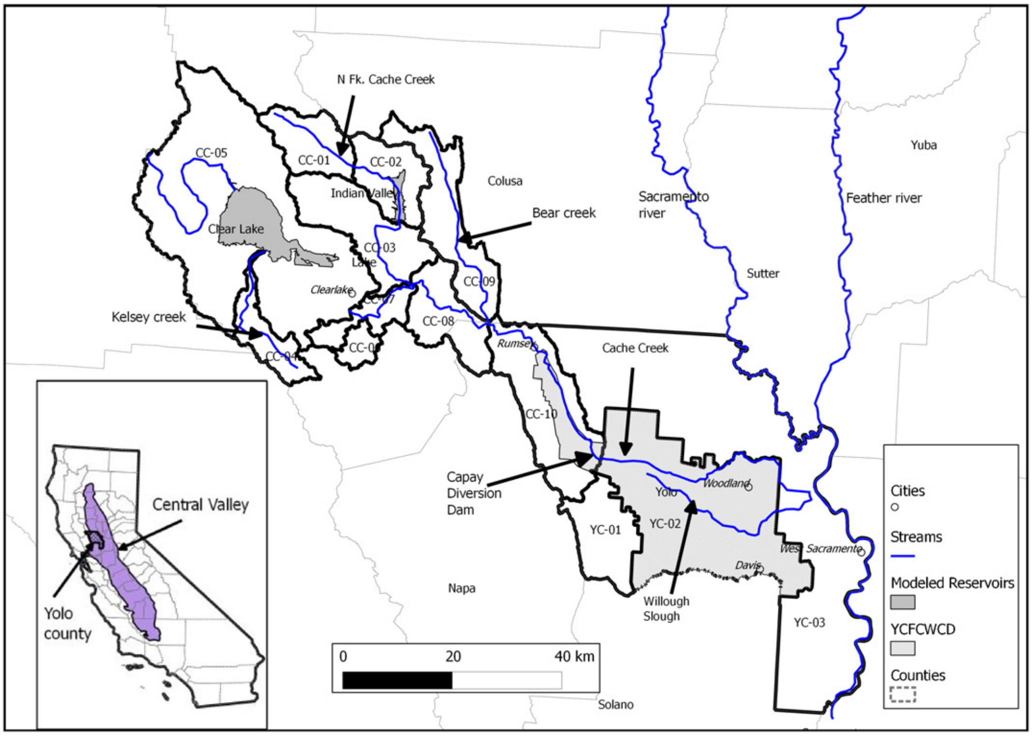

Fig. 1. Study area with modeled catchments, showing local rivers and the irrigation district. Inset: California counties, showing the location of Yolo county and the Central Valley.

Bypass, while the western part depends on Cache Creek (with minor contributions from Willow Slough). Agriculture accounts for almost 95% of the approximately 1.23 billion m^3 of the county's total water withdrawal. About 70% of that water is estimated to be supplied by surface water; the remaining is pumped from groundwater (but pumping is not monitored) (Water Resources Association, 2005). Alfalfa, tomatoes, wheat, almonds, walnuts, wine grapes, and rice (in the eastern portion of the county) are the dominant crops.

The district service area covers 41% of the county's irrigated area and is located in the western and central portion of the county (Fig. 1). The district was established in 1951 and supplies surface water for irrigation from Cache Creek. The climate is Mediterranean, with a cool wet season from November to March and a dry, hot season from May to September. Upstream reaches of the Cache Creek watershed are wetter and cooler than the valley floor. Average (1971–2000) annual rainfall and temperature in areas upstream of Clear Lake are 988 ($\pm$386) mm and 13.3 ($\pm$0.56) °C respectively, compared to 560 ($\pm$223) mm of precipitation and 16.5 ($\pm$0.65) °C respectively in the valley. Snow does not occur in the watershed, except occasionally in high elevations. Upland soils to the west are well drained but shallow to bedrock composed of marine shales, siltstones and sandstones. Lowland soils are part of alluvial fans, underlain by the Tehama formation (California Department of Water Resources, 2006).

Two reservoirs located upstream in neighboring Lake County in the Coast Range are critical for district water deliveries: Clear Lake and Indian Valley. The District purchased water rights from Lake County in 1967, amounting to a maximum of 185 million m^3 annually. The actual amount available for District release in any given year is strictly controlled by the stipulations of the Solano Decree (Superior Court of the State of California, 1978), described below. In 1976, the Indian Valley reservoir was completed. Since it is owned and operated by the District, it allows greater flexibility in supplying water to its downstream customers. Water is delivered to customers via a network of canals and ditches downstream of Capay diversion dam. The District does not own or operate any groundwater wells for the purpose of meeting customer demands. However, many privately owned wells exist throughout the District and landowners rely on these wells for domestic purposes and to add flexibility to their farming operations. The groundwater basin experienced some depletion in the 1960s and early 1970s. The increased storage and provision of surface water by Indian Valley Reservoir has been a key factor in the recovery of groundwater levels in Yolo County in recent decades (Borcalli and Associates, 2000).

The Clear Lake release schedule (Superior Court of the State of California, 1978 (modified 1995)) specifies how much water is available annually and monthly to the District during the peak agricultural season from April to September. The decree's 'quantity criteria' sets allowable seasonal withdrawal (ASW) limits based on April 1 (with a revision on May1) water levels recorded at Rumsey, known as the Rumsey gauge. If the Rumsey gauge is at or above 2.29 m, then 185 million m^3 of water is available for the growing season from April 1 to October 31. Monthly percentages of the ASW are available for release each month. If Rumsey levels are below 0.98 m, no water can be released that year apart from flood flows. For in-between levels, ASW are set in the release schedule that increases to a maximum of 185 million m^3. Accordingly, the District did not make any releases in the severe drought of 1976–1977, as well as in 1990 at the end of several dry years. The Solano Decree also stipulates 'stage criteria' that set limits to drawdown, posing an additional constraint to the District's withdrawal of water in any given month. Clear Lake releases in the winter are also controlled by the 1920 Gopcevic Decree for flood control operation (Superior Court of Mendocino County, 1920). The highly-controlled nature of this lake can be attested by the historical monthly average lake levels which have varied only 1.74 m on average (1970–2000) within a water year, with a maximum range of 3.32 m and a minimum of only 0.7 m.

Table 1
Catchment characteristics of the Cache Creek watershed model.

ID	Area (km^2)	Catchment	Description	Dominant land use
CC-01	150	Upper Indian Valley	Twin Valley and Bartlett Creeks	Forest
CC-02	162	Middle Indian Valley	Spanish Creek and Indian Valley Reservoir	Forest
CC-03	268	Lower Indian Valley	Wolf, Long Valley, Hog Hollow and Grizzly Creeks to confluence with Cache Creek	Forest
CC-04	115	Kelsey Creek	Kelsey Creek	Forest
CC-05	1149	Clear Lake	Clear Lake except Kelsey Creek, Copsey Creek and Siegler Canyon	Forest, grassland, some urban
CC-06	45	Copsey Creek	Copsey Creek	Forest, grassland
CC-07	93	Seigler Canyon	Seigler Canyon which ends below gauge at confluence with North Fork	Forest
CC-08	183	Upper Cache Creek	From North Fork confluence to Bear Creek confluence, including Rocky and Davis Creek	Forest
CC-09	266	Bear Creek	Bear Creek to confluence with Cache Creek	Forest, grassland
CC-10	349	Capay Valley	Capay Valley to Capay Diversion Dam	Forest, grassland, agriculture
YC-01	186	Willough Slough	Willow Slough headwaters outside District service area	Grassland, forests, agriculture
YC-02	753	YCFCWCD Lower	District service area below Capay Dam	Agriculture
YC-03	1308	Yolo East	Yolo County portion outside District service area	Agriculture

2. Methods

2.1. Model description

The integrated water resources model was built using the WEAP software. WEAP is a modeling platform that enables integrated assessment of a watershed's climate, hydrology, land-use, infrastructure, and water management priorities (Yates et al., 2005a, b). In California, WEAP has been used to model the impact of various climate change, land-use and adaptation scenarios on the Sacramento and San Joaquin River Basins in the Central Valley (Joyce et al., 2006; Purkey et al., 2008; Joyce et al., 2009, 2011). Likewise, Mehta et al. (2011) used WEAP to evaluate potential climate warming impacts on hydropower generation in the Sierra Nevada. Recently, Joyce et al. (2010) have combined these regional models into a statewide WEAP application that is being used for integrated scenario analysis by the California Department of Water Resources.

WEAP's rainfall-runoff hydrology routine consists of a lumped, one-dimensional, two-storage soil water accounting that uses empirical functions to describe evapotranspiration, surface runoff, interflow, and deep percolation. Additionally, WEAP provides three routines for handling groundwater: a connection to MODFLOW models if available, a groundwater–surface water interaction routine, and a simple linear reservoir representation of groundwater in which percolation from the top soil layer recharges the groundwater reservoir. The surface hydrological balance is typically performed by discretizing the model area into hydrologic response units which in WEAP is referred to as a 'catchment' object. Multiple catchment objects can recharge a single or multiple groundwater objects. A catchment can have multiple land uses, including irrigated crops. Crop water demand at each time step is determined using reference crop evapotranspiration and crop coefficients. Irrigation water requirements are simulated in WEAP by setting crop-specific irrigation thresholds. The irrigation threshold corresponds to volumetric soil moisture percentage (relative to available water capacity) below which irrigation water is demanded by the crop. Applied water is the volume of water applied to a specific crop, and in the WEAP framework, when water supplies are sufficient to meet irrigation requirements, the model will apply water equal to the required irrigation. Conveyance and transmission losses can also be input, thus enabling irrigation delivery requirements and water withdrawals from each source to also be evaluated. Complete details on the specific routines for the hydrologic balance, infrastructure operations, crop water requirements and irrigation demand, and allocation are provided in Yates (1996) and Yates et al. (2005a).

The Cache Creek model, run at a monthly time step, uses climate and land-cover information to simulate the water balance. It uses the results to simulate the management of Clear Lake and Indian Valley reservoirs and water supply for irrigation downstream. On the demand side, the model simulates irrigation requirements for 17 crop types within Yolo County, which is met through surface and groundwater sources. Surface water is allocated as a higher priority source over groundwater. The model was calibrated to a historical run from 1971 to 2000. The calibrated model was then run under various combinations of climate and agricultural land-use (i.e. crop proportions) projections as described below. Fig. 1 shows the study area along with the spatial discretization of the model. The spatial domain of the model covers 5027 km^2 and includes the Cache Creek watershed up to Capay, and all of Yolo County. The focus of the irrigation water requirements and supply analysis is on the District service area although the model can also simulate irrigation requirements for the rest of the county. Table 1 summarizes each catchment's characteristics. A water balance is simulated for each of the catchments in Fig. 1. GIS data on elevations, watersheds, and land use were acquired and used in defining and characterizing each catchment. Elevation data were extracted from the Digital Elevation Model (DEM) provided by the U.S. Geological Survey (USGS). Land cover information was assembled from two sources. For the non-agricultural landscape, the National Landcover Data Set (NLCD) was used (Homer et al., 2007). For the agricultural areas, the Agricultural Commissioner's reports and DWR Land Use surveys were used (Yolo County Agricultural Commissioner, various years; California Department of Water Resources, 1997). In Fig. 1, catchments upstream were aggregated from the detailed DWR watersheds layer. This aggregation was based on climate considerations, the locations of major infrastructure (reservoirs), in-stream flow requirements, and flow gauges. Historical monthly climate data were extracted for each catchment from a gridded dataset (Maurer et al., 2002).

2.1.1. Hydrologic parameterization

Parameters of the rainfall-runoff module were calibrated against the longest available continuous data from USGS gauges in unregulated watersheds – these were at Kelsey Creek (WY 1975–WY 2000) and Hough Springs on the north fork of Cache Creek (WY 1975–WY 1994), in the headwaters of Clear Lake and Indian Valley respectively. Goodness of fit metrics (bias and Nash–Sutcliffe index (Nash and Sutcliffe, 1970)) were computed for each set of simulated and observed hydrographs. Two groundwater objects were defined and conceptually aligned to the groundwater sub-basins delineated by DWR: one below Capay Valley (CC-10 in Fig. 1) receiving recharge as infiltration from the Capay Valley catchment, the other below the Yolo Valley floor (YC-01, YC-02, and YC-03 in Fig. 1), receiving recharge from the catchments downstream of Capay. Our model's treatment of groundwater is similar to the Central Valley application (Joyce et al., 2011). It is capable of relative comparison among scenarios of groundwater recharge

Table 2
Cropping patterns and applied water for Yolo County's irrigated agricultural area.

Crop type	Historical crop proportions				Average annual applied water 1998–2001	
	1980	1990	2000	2008	DWR	WEAP Model
	% irrigated area				cm	
Grain	37.3	25.3	18.3	19.2	36.6	33.5
Alfalfa	4.7	10.5	11.6	17.5	161.5	158.5
Other field	6.6	12	12	16.4	76.2	70.1
Tomatoes	14.2	17.3	14.5	11.6	945.0	945.0
Rice	9.9	7.3	10.8	9.3	164.6	161.5
Vine	0.2	0.8	3.4	4.2	57.9	57.9
Safflower	1.9	8	7.3	4.2	21.3	21.3
Pasture	4.6	3.8	3.9	4	173.7	164.6
Other deciduous orchards	2.6	3	4	3.9	128.0	128.0
Almond	2.7	2.2	1.7	3.5	131.1	131.1
Other truck	0.3	1	1.2	3.4	128.0	125.0
Corn	10.1	4.4	8.4	2.5	88.4	85.3
Cucurbits	0	1.5	1.3	0.4	51.8	51.8
Sugarbeets	3.9	2	0.3	0	94.5	94.5
Dry beans	1.2	1	0	0	91.4	91.4
cotton	0	0	1.2	0	70.1	73.2
Subtropical orchards	0	0	0	0	125.0	125.0

(from infiltration and conveyance leakage) and extraction volumes, but not of simulating absolute groundwater depths.

2.1.2. Infrastructure and operations: reservoirs and conveyances

The model simulates the operations of Clear Lake, Indian Valley, and the water delivery through canals. WEAP's reservoir object stratifies total storage capacity into flood control, conservation, buffer and inactive zones. Typically, reservoir flood control curves are programmed as the top of conservation zone, while the buffer zone allows for increased flexibility in simulating reservoir operation at lower storage levels. Detailed description of how WEAP simulates reservoir releases through conservation storage and flood rules is available in Yates et al. (2005a). Reservoir physical characteristics (e.g. storage capacities, volume-elevation curves) were obtained from California Data Exchange Center (CDEC) and the District. Indian Valley operating rules (flood rules and priorities) were obtained from the District. Clear Lake operating rules were obtained from the District, and from documentation of the Solano and Gopcevic Decrees. Details, including the stepwise procedure on implementing the Solano Decree are available in public documents and through the District (Superior Court of the State of California, 1978). Clear Lake releases during the wet season are controlled by flood control rules set by the Gopcevic Decree, and come into play from January to March (Superior Court of Mendocino County, 1920). These maximum allowed storage levels were set as WEAP's "Top of Conservation" in the model's Clear Lake reservoir object. The second operating constraint, also from the Solano Decree, is its stage limitation criteria which sets minimum allowable stages in the dry season. These criteria were programmed and set as "Top of Buffer" in the reservoir object. The third constraint is the hydraulic capacity of Clear Lake's outlet channel. Hydraulic capacity varies by the stage; data obtained from the District was used to develop a hydraulic capacity constraint as a function of stage. This expression was set as a hydraulic constraint on the releases from Clear Lake in the model. Outlet flows were then constrained to be a minimum of the hydraulic capacity constraint, and the allowable monthly withdrawal as determined by the Solano decree's quantitative criteria – the latter are also entirely encoded within WEAP.

Clear Lake does not provide carryover storage for irrigation demand. Although Indian Valley does provide carryover storage, typically it is operated with no carryover storage (Borcalli and Associates, 2000). In general, the District attempts to utilize all its Clear Lake allocation each year; this means that Clear Lake usage is prioritized over Indian Valley as much as possible. In the model's setting of supply priorities, this translates to a lower filling priority for Clear Lake over Indian Valley. Simulation of reservoir operations was verified by comparing simulated versus observed reservoir levels.

The District's main conveyance is in the form of 280 km of mostly unlined canals and arterial ditches that run off the West Adams and Winters Canals from Capay Diversion Dam on Cache Creek. In the model, these conveyances are aggregated into a single transmission link object, with capacity set to the total distribution's capacity of 21.2 m^3/s, and with an estimated leakage of 40% of conveyance flows obtained from calibration attempts and informed by District estimates of mass balances (Borcalli and Associates, 2000).

2.1.3. Historical crop area and irrigation water requirements

Seventeen crop categories were modeled for the catchments dominated by agriculture. Table 2 lists the different crop categories considered along with county-wide crop areas from four selected years. The crop categories are informed by DWR's irrigated crop area and water use portfolio, taking into consideration both the crop categories and corresponding areas available through the County Agricultural Commissioner's reports as well as estimates of the District scale cropping pattern. An annual time series of total irrigated area and irrigated crop areas was assembled at county level through the County Agricultural Commissioner's reports (Yolo County Agricultural Commissioner, various years). Individual crop areas were spatially distributed among the four agricultural catchments using GIS datasets available for 1989 and 1997 through the DWR land use surveys (California Department of Water Resources, 1989, 1997). This allowed a dynamic cropping pattern to be represented in the model for the historical period for each agricultural catchment.

Crop-specific parameters for simulating crop water demand and irrigation requirement were adapted from the Central Valley application by Joyce et al. (2011), who calibrated the parameters at the spatial scale of the DWR Planning Area level against four annual estimates of applied water published by DWR for 1998,1999, 2000 and 2001 (i.e. the DWR portfolio data). In our model, we also used DWR portfolio data available for the same years, but at a finer spatial level – the Detailed Analysis Unit (DAU). The irrigation threshold parameter in WEAP was calibrated for each crop to match DWR's applied water estimates for 1998, 1999, 2000, and 2001 for the Lower Cache Creek DAU. DWR's 'Lower Cache Creek' DAU (ID 162)

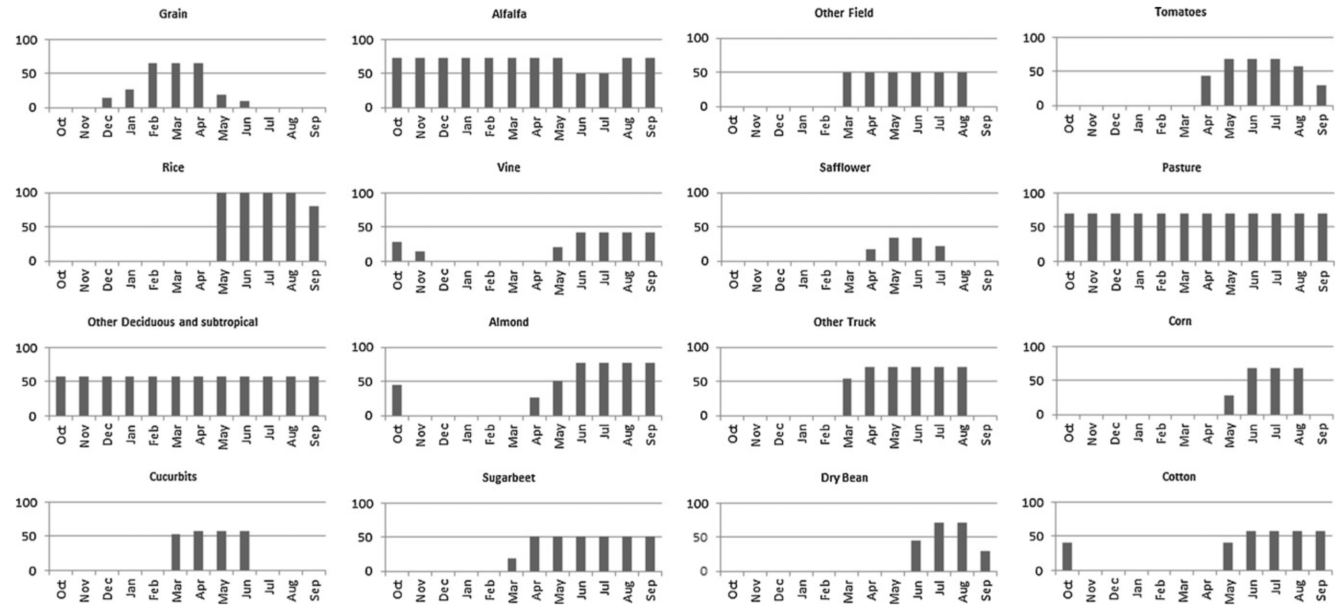

Fig. 2. Crop-specific irrigation thresholds, as percentage of available water capacity. Soil moisture below these thresholds triggers irrigation application in the model.

closely follows the county boundaries. Fig. 2 presents the calibrated irrigation thresholds for each crop.

It should be noted here that the model's estimation of water demand represents a departure from the operations of the District. The District solicits water demands from its customers every year in March, and then decides by April how much total quantity will be available. This decision is based on water levels in the two reservoirs and a projection of the season ahead. Since our goal was to look to the future, we used a simulation approach instead of hard-coding the historical demand based on the District's historical roster. The latter would not have provided us the means of projecting demand into the future.

2.2. Adaptation scenarios based on climate, land-use, and irrigation technology projections

Adaptation scenarios for Yolo County agriculture are informed by the work of Jackson et al. (2011) and Jackson et al. (2012), in which future climate and land use projections were developed using a "narrative storyline" approach patterned on the IPCC's Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart, 2000). Three types of future projections were investigated: climate, land-use, and irrigation technology. To characterize the future climate of the study area (present-2099) we used projections from a global climate model produced by the National Oceanic and Atmospheric Administration (NOAA) Geophysical Dynamics Laboratory; referred to here as the GFDL CM2.1 (Delworth et al., 2006; Knutson et al., 2006; Stouffer et al., 2007). Climate sequences from the GFDL model were generated for two greenhouse gas emissions scenarios: A2 (medium-high emissions) and B1 (low emissions), which have been outlined previously by the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic and Swart, 2000). Monthly climate data (temperature, precipitation, wind speed, humidity), downscaled using the Bias Corrected Constructed Analog (BCCA) method, are available for all of California on a 1/8th degree grid (Maurer et al., 2010). These were extracted for each of the catchments in the model. The GFDL model is one of several that were used in the IPCC Fourth Assessment, and has been found to produce a realistic representation of California's recent historical climate, as well as the spatial distribution of temperature and precipitation within the region (Cayan et al., 2008). Relative to other global climate models, the GFDL model is generally more sensitive to greenhouse gas forcing processes and thus tends to project a warmer and drier climate for California in particular (Cayan et al., 2008). The GFDL model is therefore useful for long term planning to address plausible extremes in the future climate of California.

Two projections of agricultural land-use were developed to evaluate the adaptive potential of local cropping patterns to climate-driven changes in water demand. The first projection is based on a dynamic econometric analysis of cropping area trends in Yolo County conducted by Jackson et al. (2012). To summarize, Jackson et al. (2012) developed time series models up to 2050 for individual crops in Yolo County based on the relationship between historical crop area, a set of economic variables (e.g. commodity prices) and climate variables (e.g. temperature, precipitation, growing degree days, chilling hours). Forecast crop types and areas based on this model use the same GFDL climate projections as used in the WEAP model. Economic variables were held constant in the forecast, since they are difficult to project due to uncertain changes in market conditions and other factors. This uncertainty was not accounted for in the econometric analysis, so Jackson et al. (2012) limited their forecast horizon to 2050. Since most of the differences in climate between B1 and A2 projections manifest themselves beyond 2050 (Cayan et al., 2008) and climate change impacts on crop yields are also projected to be particularly severe toward the end of the century (Lee et al., 2011), we developed another land use projection up to 2099. The second land use projection is based on envisioning an agricultural landscape which adapts to climate change in two ways: (1) by allocating a smaller fraction of land to water-intensive crops, and (2) by increasing crop diversity. For example, the area of rice, alfalfa, and other water intensive field crops are gradually reduced to the lows observed during a period of severe drought in the mid-1970s (USDA, 2011). Likewise, an increase in crop diversity over time is simulated by progressively allocating a larger fraction of land to vineyards, winter grains, almonds, deciduous orchards, subtropical orchards, tomatoes, cucurbits, and other truck crops (Table 3). In the case of almonds, subtropical orchards, and some truck crops, which tend to be high value and well-adapted to warmer temperatures, we assumed that their land area would increase despite their

Table 3
Land use projections in Yolo County's irrigated agricultural area. Econometric projections (used in Adaptation 1) are based on downscaled climate data from the GFDL general circulation model for the B1 and A2 emissions scenarios. The hypothetical land use projections (used in Adaptation 2 and 3) assume a more diverse cropping pattern and gradual shift toward crops that require less water.

Crop type	Historic	Econometric projections				Hypothetical land use projections			
		GFDL B1		GFDL A2					
	2008	2025	2050	2025	2050	2025	2050	2075	2099
	% of irrigated area								
Grain	19.2	18.8	17.5	18.8	18.2	20.3	21.9	23.5	25
Alfalfa	17.5	17.4	19.9	17.3	18.8	15.0	11.3	7.6	4.0
Other field	16.4	16.2	14.9	16.0	15.5	13.5	9.3	5.1	1.0
Tomatoes	11.6	12.6	13.7	12.4	13.5	12.1	12.7	13.4	14.0
Rice	9.3	10.8	10.7	10.2	10.9	8.3	6.9	5.4	4.0
Vine	4.2	3.8	3.6	3.7	3.7	5.3	6.9	8.5	10.0
Safflower	4.2	4.4	2.9	5.4	3.1	3.8	3.2	2.6	2.0
Pasture	4.0	3.7	3.6	3.9	3.7	4.0	4.0	4.0	4.0
Other deciduous	3.9	3.4	3.1	3.6	3.3	4.1	4.4	4.7	5.0
Almond	3.5	3.7	3.5	3.5	3.6	4.2	5.1	6.1	7.0
Other truck	3.4	3.4	3.1	3.4	3.3	4.1	5.1	6.1	7.0
Corn	2.5	1.5	3.0	1.3	1.8	3.9	6.0	8.0	10.0
Cucurbits	0.4	0.4	0.4	0.4	0.4	0.7	1.1	1.6	2.0
Sugarbeets	0	0	0	0	0	0	0	0	0
Dry beans	0	0	0	0	0	0	0	0	0
Cotton	0	0	0	0	0	0	0	0	0
Subtropical orchards	0	0	0	0	0	0.9	2.3	3.7	5.0

GFDL B1and GFDL A2 refer, respectively, to the B1 (low) and A2 (medium-high) emissions scenarios of the Geophysical Dynamics Laboratory (GFDL) global climate model.

relatively high water requirements. It should be noted that it was not possible to consider how crop area might change in response to global commodity demand.

Statewide there has been a notable shift in irrigation methods from surface water applied using flood or furrow irrigation toward low volume sprinkler and drip irrigation, particularly for vegetable crops, orchards, and vineyards (Orang et al., 2008). As mentioned earlier, these methods can potentially reduce applied water (Kallenbach et al., 2010), without compromising consumptive water use (crop ET) and crop yield. Furthermore, a recent survey of grower perspectives on water scarcity and climate change in Yolo County indicates a strong inclination to expand their use of low volume irrigation among local farmers (Jackson et al., 2012). Likewise, incentive programs to promote adoption of improved irrigation technology are seen as a politically feasible water demand management strategy. We include a scenario which assumes that gradual adoption of improved irrigation technology in the coming decades will reduce the amount of water applied to certain crops. We assume no change in irrigated area. We reflect these trends in the scenario, by decreasing the irrigation threshold parameter, in a manner similar to the work of Joyce et al. (2011) and Purkey et al. (2008). Conceptually, this approach leads to reduced applied water while satisfying crop ET needs, through a combination of reductions in non-beneficial soil evaporation, and/or percolation and runoff losses from excess irrigation. Irrigation thresholds were set to reach 70% of the historically calibrated values (which are illustrated in Fig. 2) by 2099 for each crop, except for wine grapes, winter grains, and safflower. For the latter crops, no change in irrigation technologies was assumed because vineyards are already on drip irrigation, winter grains are mostly supplied by rain and stored soil water, and safflower is already a low water consuming crop.

These projections were combined into four scenarios to investigate the potential effects of climate change and adaptation as follows:

(1) *Climate only*. The potential impacts of climate change alone, under the two IPCC emission scenarios (GFDL B1 and A2). Land-use is held constant at the 2008 pattern.
(2) *Adaptation 1 (climate and dynamic cropping)*. These correspond to the dynamic econometric model which simulates future cropping patterns based on the B1 and A2 climate sequences. The analysis evaluates the combined impact of climate change and a cropping pattern adaptation driven by similar climate and economic drivers as in the past.
(3) *Adaptation 2 (climate and crop diversification)*. These correspond to a run of the hypothetical diversified cropping pattern, under the two climate-only scenario runs. The corresponding analysis evaluates the adaptive potential of a diversified cropping pattern dominated by low-water consuming crops.
(4) *Adaptation 3 (climate, crop diversification and technology)*. This corresponds to a run of the diversified land use projection from Adaptation 2 and the irrigation technology projections described in the paragraphs above. The analysis evaluates the combined adaptive potential of a diversified cropping pattern (as in 3) plus irrigation technology improvements that reduce applied water.

3. Results and discussion

3.1. Model performance over the historical period

3.1.1. Unregulated hydrology

Unregulated hydrology was simulated reasonably well in Kelsey Creek and Hough Springs, located upstream of Clear Lake and Indian Valley respectively (Fig. 3a). At Kelsey Creek, monthly flows from WY 1975–2000 were simulated with a bias of 2%, Nash–Sutcliffe of 0.65 and $R^2 = 0.78$ ($n = 300$ months). At Hough Springs, monthly flows from WY 1975–1994 were simulated with a bias of 2.2%, Nash–Sutcliffe of 0.55 and $R^2 = 0.67$ ($n = 228$ months).

3.1.2. Reservoir levels

Fig. 3b shows simulated and observed reservoir storage volumes for Clear Lake and Indian Valley. Clear Lake storage was simulated with a bias of −1.9% and R^2 of 0.87 ($n = 840$ months from WY 1970 through WY2005). The model was adept at simulating the severe 1976–1977 droughts as well as the successive dry years of the late 1980s. Indian Valley storage was also simulated well with a bias of 4.3% and a R^2 of 0.70 ($n = 720$ months from WY 1976 through WY 2005).

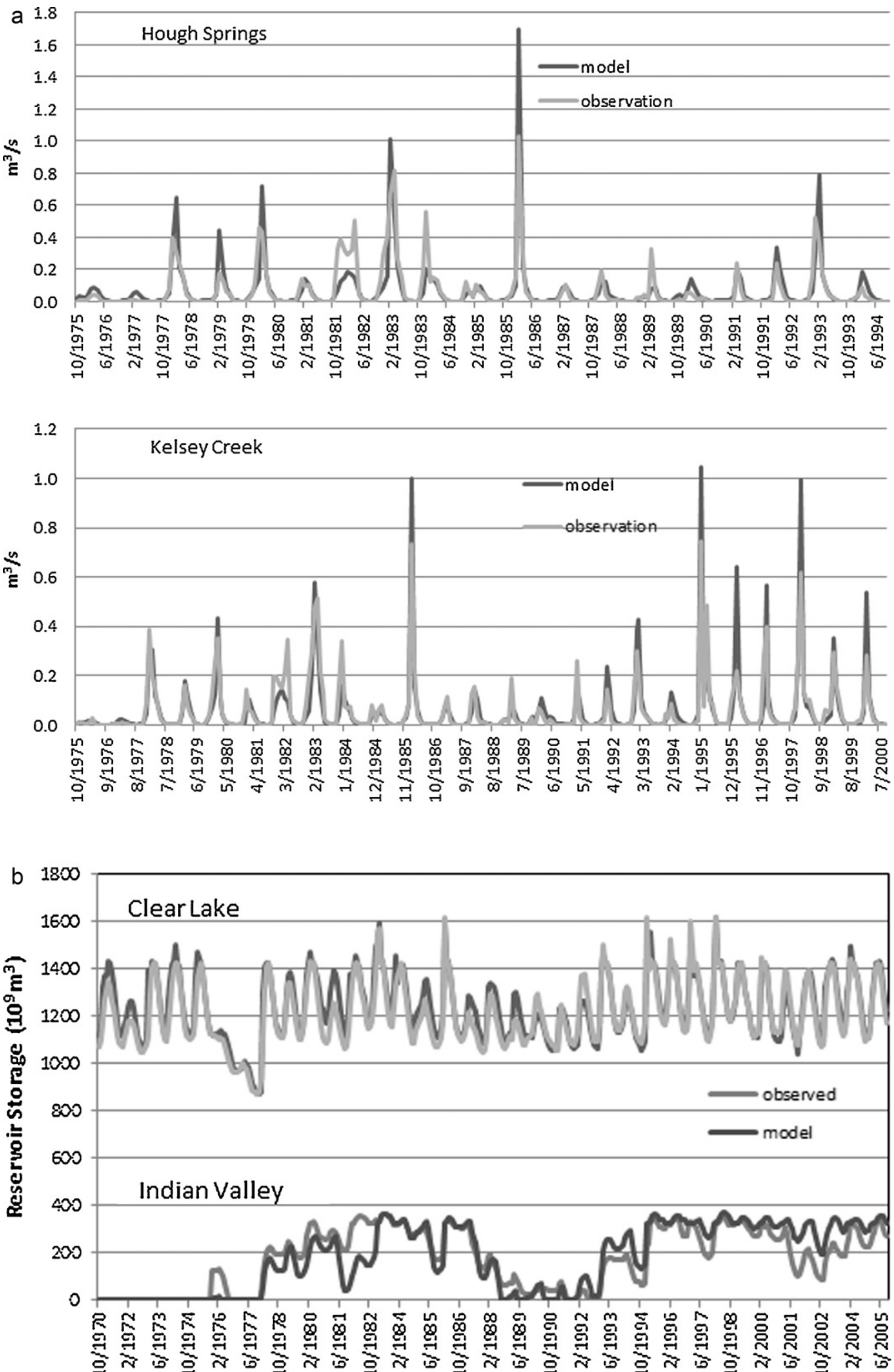

Fig. 3. Historical hydrology and reservoir operations: (a) hydrographs for Hough Springs and Kelsey Creek, in m^3/s, (b) reservoir storage for Clear Lake and Indian Valley, in million m^3.

3.1.3. Irrigation water requirements

Table 2 provides a comparison of each crop's simulated average annual applied water from 1998 to 2001 in the District's service area below Capay Dam, against DWR's portfolio data for DAU 162 (Lower Cache Creek). The mean deviation of the model across all crops was only 0.2%: the mean absolute deviation was 2.7%. This calibration leads to a District-wide estimate of total annual average irrigation requirement of $469.8 \times 10^6\,m^3$ over the historical period (1971–2000). The model estimated that on average, groundwater supplied 49% of applied water over the same period. This

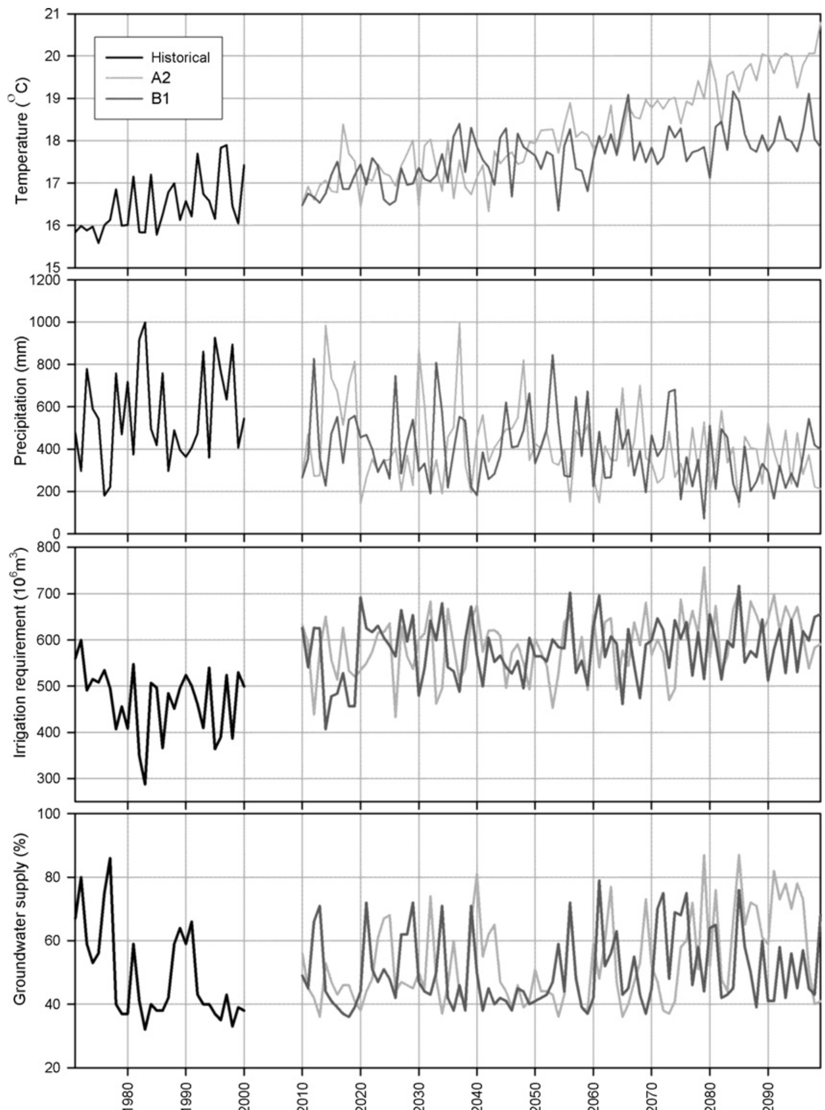

Fig. 4. Historical and projected climate, irrigation demand and groundwater supply for the District. The B1 and A2 climate scenarios are derived from downscaled projections of the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation climate model. These climate only scenarios assume no changes in land-use.

corresponds well with the District's water management plan and local water resource managers who estimate a value of 50% for the same (M. Stephenson, pers. comm.). However, two important points should be noted. First, supply from groundwater varies substantially year to year (e.g. coefficient of variation is 50%, with contributions from groundwater to irrigation of greater than 80% during the severe drought of 1976–1977). Second, post-Indian Valley construction, the dependence on groundwater has eased (Borcalli and Associates, 2000). On average, groundwater supplied 43% of irrigation demand from 1978 to 2000. For the county as a whole, simulated irrigation demand for 1971–2000 averaged 1.28 billion m^3 (not shown).

3.2. Climate and adaptation scenarios

The District's annual average temperature and annual precipitation during the historical and future periods are summarized in Fig. 4 and Table 4. The B1 and A2 climate projections are warmer and drier than the historical period. The A2 emissions scenario (medium to high emissions) diverged from B1 after mid-century, and projected somewhat warmer temperatures (Fig. 4 and Table 4). Both projections also show a change in precipitation after mid-century.

While the climate projections for the valley floor (as presented above) are warmer and drier, in the upstream reaches of Clear Lake the same projections are warmer but not appreciably drier in all periods except the far-term. Consequently, as described in Sections 3.2.1 and 3.2.2 below, the climate impacts on upstream (Clear Lake) operations are *different* than that on downstream irrigation demand and supply.

3.2.1. Surface water supply

The Solano Decree presents a hard limit of 185 million m^3 annually from Clear Lake releases for the District's use. Since April 1st lake levels recorded at the Rumsey gauge are the initial determinant of AWS from Clear Lake releases, they can be used as an indicator of surface water availability for the District. Table 5 shows that during the historical period, April 1 Rumsey gauge levels were less than 2.29 m during 18 of 30 years. Relative to the historical period, the model predicted a lower frequency of shortfalls in response to the climate-only scenarios (B1 and A2) in the near and mid-term. The climate-only scenarios did, however, result in more frequent shortfalls in the far-term (Table 5). Since irrigation water requirement is low in April, when allocations are set, lake levels are largely a hydrologic response to intra-annual variability in the climate sequence.

Table 4
Climate, irrigation water requirements and groundwater supply for the Cache Creek watershed.

			Annual precipitation (mm year^{-1})		Average annual temperature (°C)		Annual irrigation required (10^6 m^3 year^{-1})		Annual groundwater supply (%)[a]	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Historical	1971–2000		561	123	16.5	0.6	470	73	49	15
Near term	2010–2039	B1	446	80	17.8	0.6	575	76	50	12
		A2	428	73	17.4	0.8	571	65	49	10
Midterm	2040–2069	B1	430	73	18.2	0.5	567	56	47	10
		A2	417	67	18.5	0.8	581	60	51	13
Far term	2070–2099	B1	349	49	18.7	0.5	596	53	55	12
		A2	342	45	20.7	0.7	618	65	61	15

B1 and A2 refer, respectively, to the GFDL low and medium-high emissions projections used in the scenarios. 'SD' refers to 1 standard deviation.
[a] Annual groundwater supply is the proportion of required irrigation that is met by groundwater pumping. It assumes that irrigation requirements are first met with available surface water and the remainder is subsequently met with groundwater.

Notable exceptions are the Adaptation 2 and 3 scenarios during the far term of B1, which had smaller increases in frequency relative to the climate-only scenario (a difference of two and three years respectively).

Another measure of water shortage is the frequency of years receiving no water allocation from Clear Lake. If the Rumsey gauge is below 0.98 m, the initial AWS assessment is for no allocation of water that year. Model response for no-allocation under climate and adaptation scenarios showed the same behavior as that for shortfalls, i.e. reduced frequency in near and mid-term for all scenarios compared to historical, and a slight increase in the far-term. This behavior (for shortages and no-allocation) can be explained by the fact that in the upstream reaches of Cache Creek, (i) the climate projections are not significantly drier than the historical period, until the far-term, and (ii) A2 and B1 spring precipitation amounts are substantially higher than that in the historical period. In particular, as shown in Fig. 5, March precipitation is substantially higher in almost all periods of both A2 and B1 scenarios. Hence, wetter springs in the climate projections buffer against negative impacts on Clear Lake storage and operations.

3.2.2. *Irrigation water requirement*

Downstream, however, climate projections are progressively warmer and drier. Under the climate-only scenarios, where land-use is held constant at 2008 crop proportions, future irrigation requirement is projected to increase in the District (Table 4 and Fig. 4). In the near and medium term, average annual requirement is expected to increase by 98.7–111 million m^3 with no notable differences between the B1 and A2 projections (Table 5). The increase in annual requirement is expected to continue in the latter part of the century, where the warmer and drier A2 climate sequence ultimately prompts higher irrigation requirement than B1 (e.g. B1 and A2 project that requirement will increase by 126 and 148 million m^3). Relative to the historical period, this is an increase in annual irrigation requirement of approximately 26–32% due to changing climate alone. The increased demand and the greater impact of the GFDL A2 scenario observed in this study, are consistent with previous projections for the Sacramento Valley as a whole (Joyce et al., 2006).

Table 5 and Fig. 6 compare the difference in irrigation requirement among the three adaptation scenarios relative to historical period and climate-only scenarios, respectively. Under Adaptation 1, irrigation requirement varies to a small extent above and below the zero lines (Fig. 6). This indicates that the cropping patterns predicted by the econometric model have less impact on irrigation requirements than climate change alone. For example, increases in irrigation requirement from climate alone are on the order of tens of millions m^3 (Table 5), while the relative impact of Adaptation 1 is only a few million m^3 (Fig. 6). The econometric model predicts a cropping pattern that is likely to be the most economical or profitable rather than what might be the most water efficient, which is why there are small increases in irrigation requirement in several

Table 5
Comparison of water supply and irrigation water demand for historical and future periods under various climate and adaptation scenarios. The B1 and A2 climate scenarios are derived from downscaled projections of the GFDL general circulation model. Each time period is 30 years. The values in the shaded area represent the difference in each indicator relative to the historical period for a given time period.

Indicator	Period	Historical	B1	B1 climate + adaptation			A2	A2 climate + adaptation		
				1	2	3		1	2	3
			Difference relative to historical period							
Frequency of water years below full allocation[a]	1971–2000	18								
	Near term		−3		−3	−3	−3		−3	−3
	Midterm		−1	1	−2	−3	−3	1	−3	−4
	Far term		3		1	0	7		7	6
Annual irrigation demand (10^6 m^3)	1971–2000	470								
	Near term		105		97	63	101		94	57
	Midterm		97	100	77	−18	111	100	89	−16
	Far term		126		89	−58	148		109	−56
Annual groundwater extraction (10^6 m^3)	1971–2000	187								
	Near term		57		47	20	48		39	11
	Midterm		36	42	15	−59	65	54	43	−49
	Far term		96		59	−70	145		105	−41

[a] Frequency of water years below full allocation refers to the number of years in a 30 year time period when April 1 Rumsey gauge levels measured less than 2.29 m, which results in less than the full allocation of irrigation water for the District from Clear Lake.

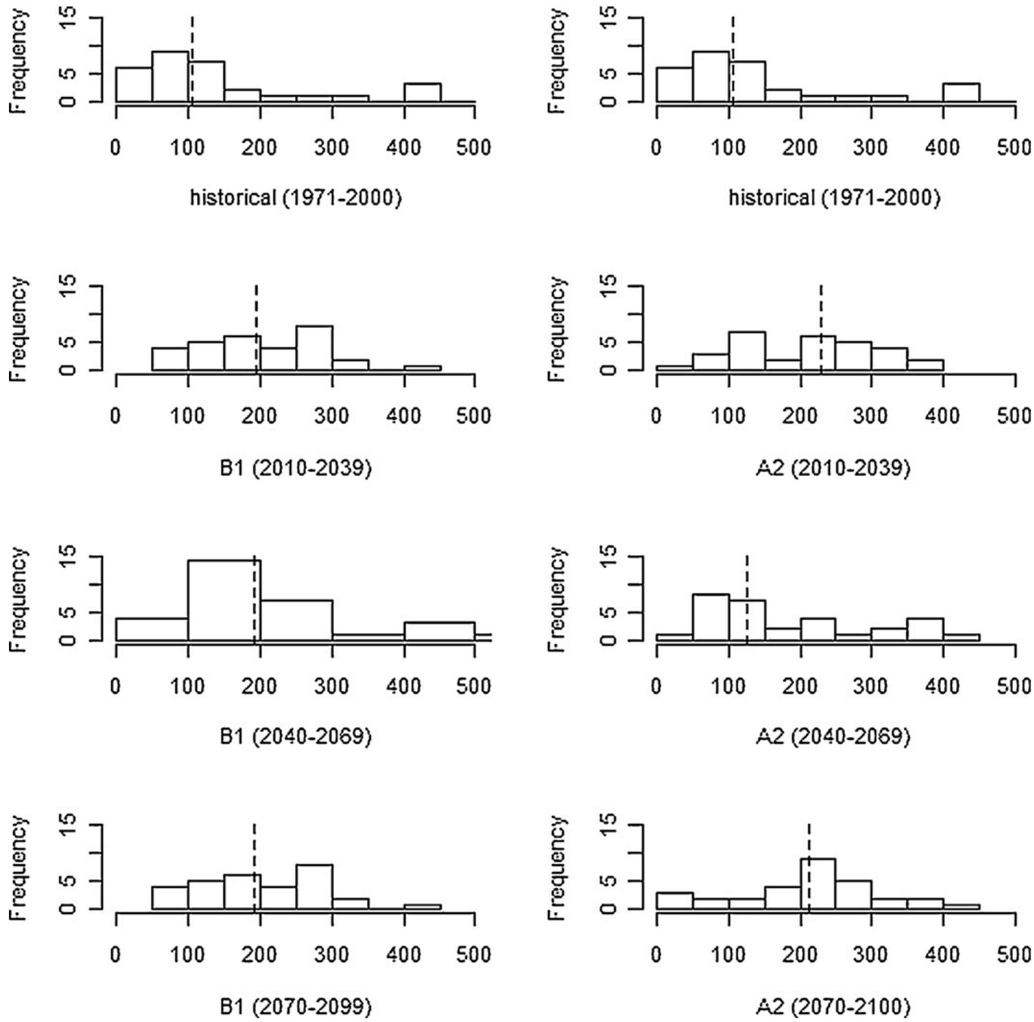

Fig. 5. Distribution of historical and projected March precipitation in mm. Vertical dotted line is the 30 year mean corresponding to each time period. B1 and A2 refer to the GFDL B1 and A2 climate scenarios respectively.

years (Fig. 6). The econometric model predicted similar cropping patterns for B1 and A2 prior to 2036, and irrigation requirements were also similar. However, beginning in 2036, the area of alfalfa (and to a lesser degree, tomatoes) expands significantly under the B1 climate. Since alfalfa has notably high water requirements, its expanded area leads to a corresponding increase in total irrigation requirement for B1 relative to A2 and the historical period (Fig. 6).

The Adaptation 2 scenarios – a gradual shift toward a more diverse and water-efficient cropping pattern – also show increased irrigation requirement compared to the historical period (Table 5).

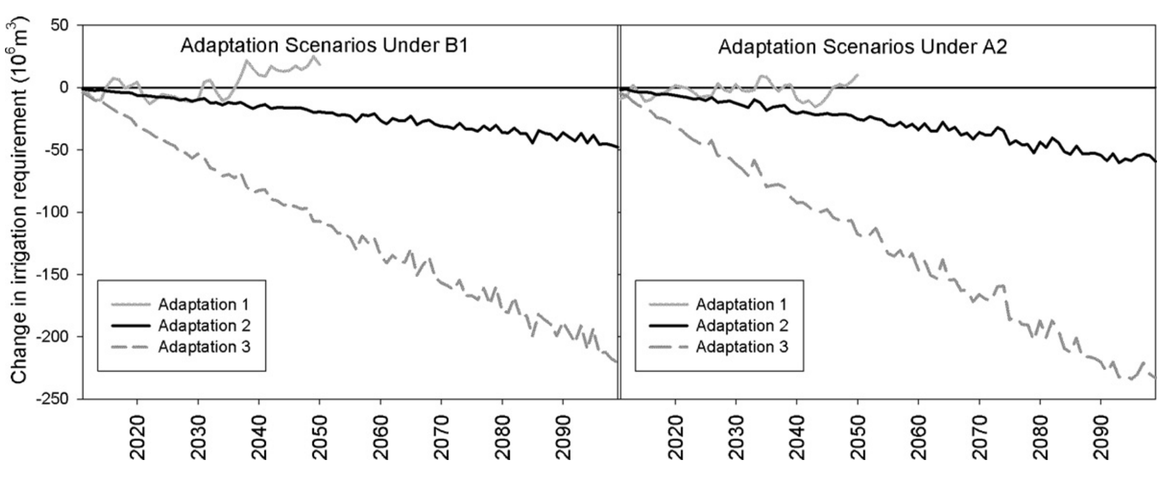

Fig. 6. Difference in projected irrigation required for adaptation scenarios relative to the impact of climate alone. Horizontal dashed lines represent no difference from climate-only scenarios. The B1 and A2 climate scenarios are derived from downscaled projections of the GFDL general circulation model. Adaptation 1 stops at 2050 because land use projections were only available until 2050 for this scenario.

However, the model also indicates that the increase in requirements can be minimized to some extent by such a shift in cropping patterns (Fig. 6). That said, the marginal savings toward the end of the century are still less than half of the increase in requirement due to climate-change alone.

The Adaptation 3 scenarios – assuming improvements in irrigation technology along with the cropping shifts in Adaptation 2 scenarios – show near-term requirements slightly greater than the historical period. However, as the diversified cropping pattern and improvements in irrigation technology are gradually implemented, far-term requirement declines to approximately 12% less than the historical mean for both the B1 and A2 climate sequences (Table 5 and Fig. 6). This illustrates that 'game-changing' savings in applied water – savings of the same order of magnitude of climate-induced increases – can occur through a combination of progressive irrigation technology improvement, and cropping patterns which are more water efficient and diversified.

3.2.3. Groundwater pumping

In response to an overall increase in irrigation requirement, groundwater pumping also tends to increase in the far term under both the B1 and A2 climate scenarios (Tables 4 and 5). Under A2, the groundwater proportion of the total applied water in the District service area (i.e. the fraction pumped by private landowners) rises from a value close to the historical mean of 49% in the near-term to as high as 61% in the far-term (Table 4). Overall, this corresponds to a volume of 145.5 million m^3 above the historical mean (Table 5). It should be mentioned that the historical estimate includes years prior to the operation of Indian Valley reservoir, thus the present fraction is somewhat lower than 49%. Relative to the climate only scenarios, the marginal benefits of Adaptation 1 and Adaptation 2 are somewhat limited in the near and mid-term (24.7 million m^3/year). Only in Adaptation 3 are substantial marginal benefits observed in total pumping over time. In short, by integrating cropping pattern changes and improvements in irrigation technology groundwater pumping was maintained at levels close to the baseline in the near-term and yielded reductions of 37–62 million m^3/year in the far-term.

4. Conclusions

Climate-only impacts on irrigation requirements were found to be substantial in the near, far and mid-term for both A2 and B1 climate projections, spanning an average of 97.5–148 million m^3 higher than during the historical period. These increases are due to progressively warmer and drier climate, especially in the far-term, and hence, projected climate-only impacts are greatest under the A2 conditions in the far-term. Surface water available to the District, largely dependent on Clear Lake, is less vulnerable, because of larger spring precipitation amounts in the projected climate in upstream reaches of the Coast Range. Still, because of the hard annual limit of 185 million m^3 released from Clear Lake, combined with increasing irrigation water requirements downstream, private groundwater extraction is expected to increase by an average of 35.7–145.5 million m^3/year (depending on the climate projection and time period), with the highest expected groundwater extraction in the far-term of the A2 climate projection.

Combining a water-efficient diversified cropping pattern with improved irrigation technology is required to keep future irrigation demand and groundwater pumping at or below mean levels of the historical period. Without any adaptation, groundwater extraction under A2 climate projections in the far-term would be close to levels during the severe drought of 1976–1977. The recovery of the water table since Indian Valley surface water became available to the District, could suffer a reversal. A return to falling water tables is likely under this scenario, along with associated impacts such as land subsidence, especially taking into account increasing water demands in other sectors. Of these, urban demands will increasingly depend on groundwater. At the same time, regulations to protect environmental goals or to prevent land subsidence may limit increased extraction of groundwater into the future. Conjunctive use of surface and groundwater, artificial recharge, increased recycling and re-use of treated wastewater are likely to be increasingly considered as adaptation options in the future, and integrated water management approaches, such as presented here, should prove increasingly useful (Faunt et al., 2009).

A limitation specific to our Adaptation 3 scenario, is that a large scale shift to drip and micro-sprinkler irrigation may have other tradeoffs such as an expansion of irrigated area and/or reduced groundwater recharge (Pfeiffer and Lin, 2009; Ward and Pulido-Velazquez, 2008), and increased costs (Wichelns et al., 1996). It may also affect preferences for surface water versus groundwater use, as groundwater is often preferred for drip irrigation because it contains less sediment and can be more reliable (Negri and Brooks, 1990; Burt and Styles, 2000; Schuck and Green, 2001; Burt et al., 2003). To date, growers in our study area have commented that this concern is overridden by the fact that large-scale changes to drip irrigation have lowered overall irrigation water applied and have contributed to higher yields (Tony Turkovich, pers. comm.).

Accordingly, we have focused on irrigation water supply and applied water.

Our findings suggest that strategic planning for improving irrigation technologies along with crop diversification will be essential for agricultural adaptation to climate change in California. Without attention to these issues, shortfalls may impose serious water deficits that impact agricultural production and livelihoods and thereby hasten the conversion of agricultural land to urban uses (Jackson et al., 2012). The combined use of new technologies and crop diversification would constitute transformative changes in the District, and would require substantial investment in agricultural research and extension, in order to minimize vulnerability and risk to farmers.

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