Integrated simulation of consumptive use and land subsidence in the Central Valley, California, for the past and for a future subject to urbanization and climate change

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Abstract Competition for water resources is growing throughout California, particularly in the Central Valley where about 20% of all groundwater used in the United States is consumed for agriculture and urban water supply. Continued agricultural use coupled with urban growth and potential climate change would result in continued depletion of groundwater storage and associated land subsidence throughout the Central Valley. For 1962-2003, an estimated 1,230 hectare meters (hm^3) of water was withdrawn from fine-grained beds, resulting in more than three meters (m) of additional land subsidence locally. Linked physically-based, supply-constrained and demand-driven hydrologic models were used to simulate future hydrologic conditions under the A2 climate projection scenario that assumes continued "business as usual" greenhouse gas emissions. Results indicate an increased subsidence in the second half of the twenty-first century. Potential simulated land subsidence extends into urban areas and the eastern side of the valley where future surface-water deliveries may be depleted.
Key words Groundwater; Climate change; Hydrologic model; Land subsidence

INTRODUCTION

Competition for water resources is growing throughout California, particularly in the Central Valley, where about 20% of all groundwater used in the United States is consumed for agriculture and urban water supply (Faunt *et al.*, 2009). Groundwater pumpage from 1926-1970 resulted in as much as 8.5 m of land subsidence in the Los Banos-Kettleman City area of the San Joaquin Valley (Poland *et al.*, 1975). Between 1980 and 2003, the Central Valley's population nearly doubled to 3.8 million people; projections suggest continued urban growth of 1.2% (Johnson, 2009) to 4% (Faunt *et al.*, 2009 a-d) per year. Continued agricultural use coupled with urban growth can be expected to result in further depletion of groundwater storage throughout the Central Valley and associated land subsidence in susceptible areas. Climate change is expected to reduce the quantity of water available for surface-water deliveries and groundwater recharge, which will exacerbate the problem. Linked physically-based, supply-constrained and demand-driven hydrologic models were used to simulate future hydrologic conditions, including land subsidence. Of the historical water withdrawn, depletion of interbed storage was a significant source of water locally in the Tulare Basin. Simulation of conjunctive use, it's related effects, and potential alternative scenarios of water use can be quantified through a series of linked physically-based hydrologic models; it can assess secondary effects such as land subsidence that are driven by the disparity between supply and demand. Linkage of these models to Global Climate Models (GCMs) allows for analysis of potential future conjunctive use.

SIMULATION OF SUBSIDENCE WITHIN A CONJUNCTIVE USE FRAMEWORK

The Central Valley Hydrologic Model (CVHM) (Faunt *et al.*, 2009a-d) simulates subsidence within a conjunctive use framework using MODFLOW (Harbaugh, 2005) with the Farm Process (FMP) (Schmid & Hanson, 2009) that includes the subsidence package (SUB) (Hoffman *et al.*, 2003). The SUB package was additionally modified to explicitly track elastic and inelastic compaction (Hanson *et al.*, 2009). Properties used for elastic and inelastic storage were based upon the estimates derived by Ireland *et al.* (1984) combined with critical head values that were derived from the calibration of the original Central Valley hydrologic model (Williamson *et al.*, 1989). The hydraulic properties, including subsidence

properties, were distributed on the basis of a new and detailed textural model of the alluvial deposits within the Central Valley (Faunt *et al*., 2009e). This included explicitly simulating the major confining unit known as the Corcoran Clay using two separate model layers.

The subsidence is driven by the climate and supply-and-demand forcings of conjunctive use through the simulation of monthly agricultural demand that is estimated implicitly with FMP and is linked to the additional forcings from seasonal to interannual climate variability. These demands are combined with urban demands that collectively drive the groundwater withdrawals within the Central Valley. Unlike previous models of the Central Valley the CVHM explicitly simulates multi-aquifer wellbore flow across the Corcoran Clay from municipal pumpage and from agricultural pumpage that is implicitly linked to irrigation demands estimated by FMP.

The supply and demand components are a combination of inflows and outflows simulated as the use and movement of water across the landscape, as well as from streamflow and groundwater flow. Flows on the landscape are based on historical crop and land-use attributes combined with monthly climate data (precipitation and potential evapotranspiration) for the period water years 1962-2003 for each 259 hectare model cell (Faunt *et al*., 2009b,c). Streamflow from 41 rivers and 66 agricultural diversions were simulated from reported inflows and diversions. Groundwater inflows as recharge and outflows owing to evapotranspiration, stream leakage, and pumpage are largely driven by the simulation of landscape processes by FMP and simulated streamflow.

Future hydrologic conditions were simulated by linking the results of the GCM GFDL-A2 (Delworth *et al.*, 2006) to a regional water-balance model and CVHM. The GCM GFDL-A2 climate projection scenario represents continued "business as usual" greenhouse gas emissions. The GCM climate data was downscaled to simulate recharge and runoff from the surrounding Coast Ranges and Sierra Nevada mountains using the Basin Characteristics Model (BCM) (Flint & Flint., 2007), a regional water-balance model (Fig. 1). The BCM simulated from 25% to more than 60%

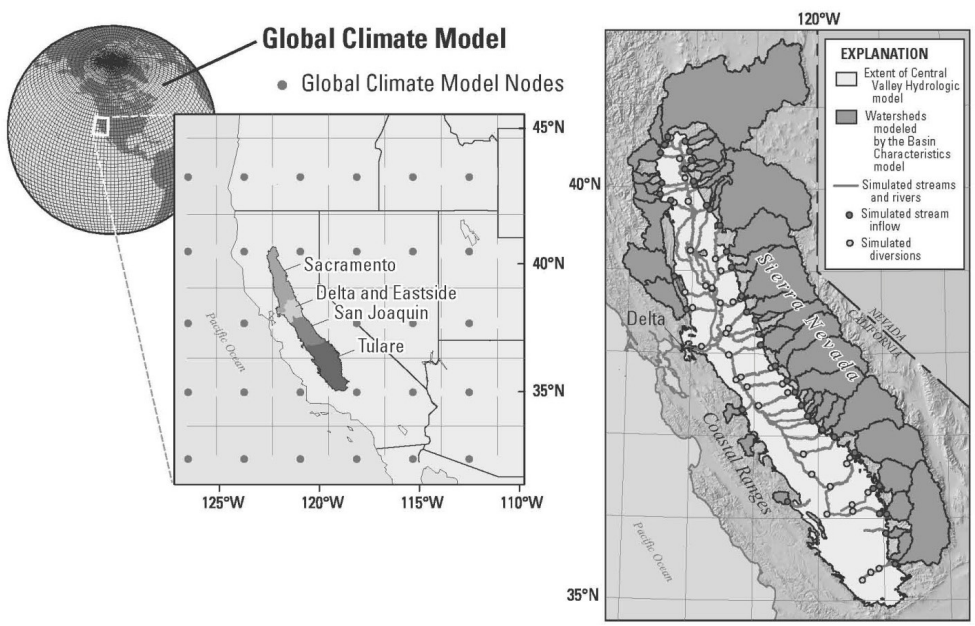

Fig. 1 Map showing linkage and downscaling from GCM to regional hydrologic models of the Central Valley, California, USA.

reductions in runoff using the GCM future climate, which reduces the surface water available for diversions and results in increased groundwater pumpage. The CVHM uses the downscaled climate data (Fig. 1), runoff and recharge of the surrounding mountains as stream inflows simulated from the BCM, climate-driven diversions, and groundwater outflow at the Sacramento Delta controlled, in part, by GCM driven sea-level changes of about 0.9 m. (Cayan *et al*., 2009). CVHM simulates a 30% increase in total farm delivery requirements as a result of increased ET from elevated minimum temperatures and reduced precipitation from climate change, which, in turn increases groundwater pumpage. This projection assumes no changes in land use and a 1.2% increase in urbanization through at least 2029 (Johnson, 2009) for urban groundwater demand.

SIMULATION OF SUBSIDENCE AND REGIONAL FLOW

From water years 1962-2003, agricultural water use in the Central Valley was supplied by surface-water deliveries and groundwater pumpage, with surface-water deliveries dominating during wet periods and groundwater pumpage dominating during dry periods (Fig. 2). Model simulations for 1962-2003 indicate that an additional 1,230 hm^3 of water was withdrawn from fine-grained beds during this period, resulting in more than 3 m of additional land subsidence locally (Fig.3). The projection of water use in the twenty-first century indicates a declining contribution of surface water and a potential increase in groundwater use in the second half of the century (Fig. 2). Model simulations indicate that as much as 70,800 hm^3 of water could be withdrawn from fine-grained beds from 2000-2099 that is predominantly occurring during the second half of the twenty-first century, resulting in 5 m to more than 30 m of additional subsidence throughout the valley (Fig. 3). The severity and distribution of the simulated land subsidence also is affected by the assumed sustained increases in urban demand for water. Simulated groundwater storage depletion largely occurs in the Tulare Basin in the southern portion of the Central Valley, but also is present in the eastern parts of the San Joaquin Basin and the northern regions that include the Delta, east-side streams, and the Sacramento Valley. These areas were more reliant on surface-water deliveries and show the largest impact in transition to more groundwater pumpage. While the historical areas sustain additional subsidence, the majority of the simulated future subsidence occurs along the Sierra Nevada on the eastern side of the valley (Fig. 3). The projected storage depletion is accompanied by differential land subsidence that may affect local and regional canals, agricultural drainage, flood hazard zones, urban infrastructure, and conveyance through these canals (Fig. 3).

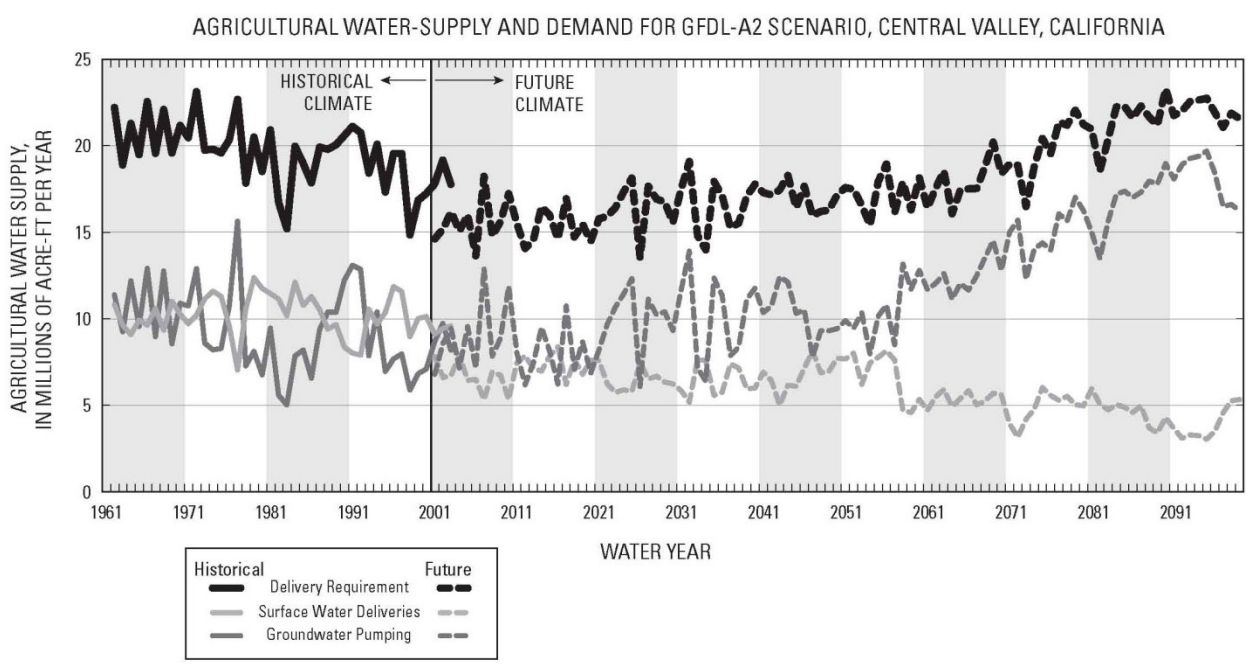

Fig. 2 Graphs showing the historical (1962 - 2003) and projected (2000 - 2099) water use for agriculture for the Central Valley (modified from Faunt *et al.*, 2009c).

With projections of increased urban demand, the potential storage depletion and land subsidence may extend into urban areas. Greater urban demand for water also may contribute to reduced groundwater outflow and increased streamflow infiltration in the Delta outflow region to San Francisco Bay, which may further restrict water transfers and deliveries through the Delta.

CONCLUSIONS

Overall, model results indicate that additional groundwater storage depletion may occur in the Central Valley under the A2 scenario assuming 2003 agricultural demand and a 1.2% increase in urban water demand per year. The greatest amount of groundwater storage depletion is simulated to occur during intermittent droughts in first half of twenty-first century followed by sustained drought in second-half of twenty-first century. During the droughts the models simulate a transition from surface-water to groundwater dominated irrigation supplies. Model simulations indicate that continued agricultural demand, increased urban-water demand, and climate change all impact conjunctive use and contribute to adverse effects on water sustainability in the Central Valley, including land subsidence and reduced outflow at the Delta. Increased land subsidence and differential subsidence are

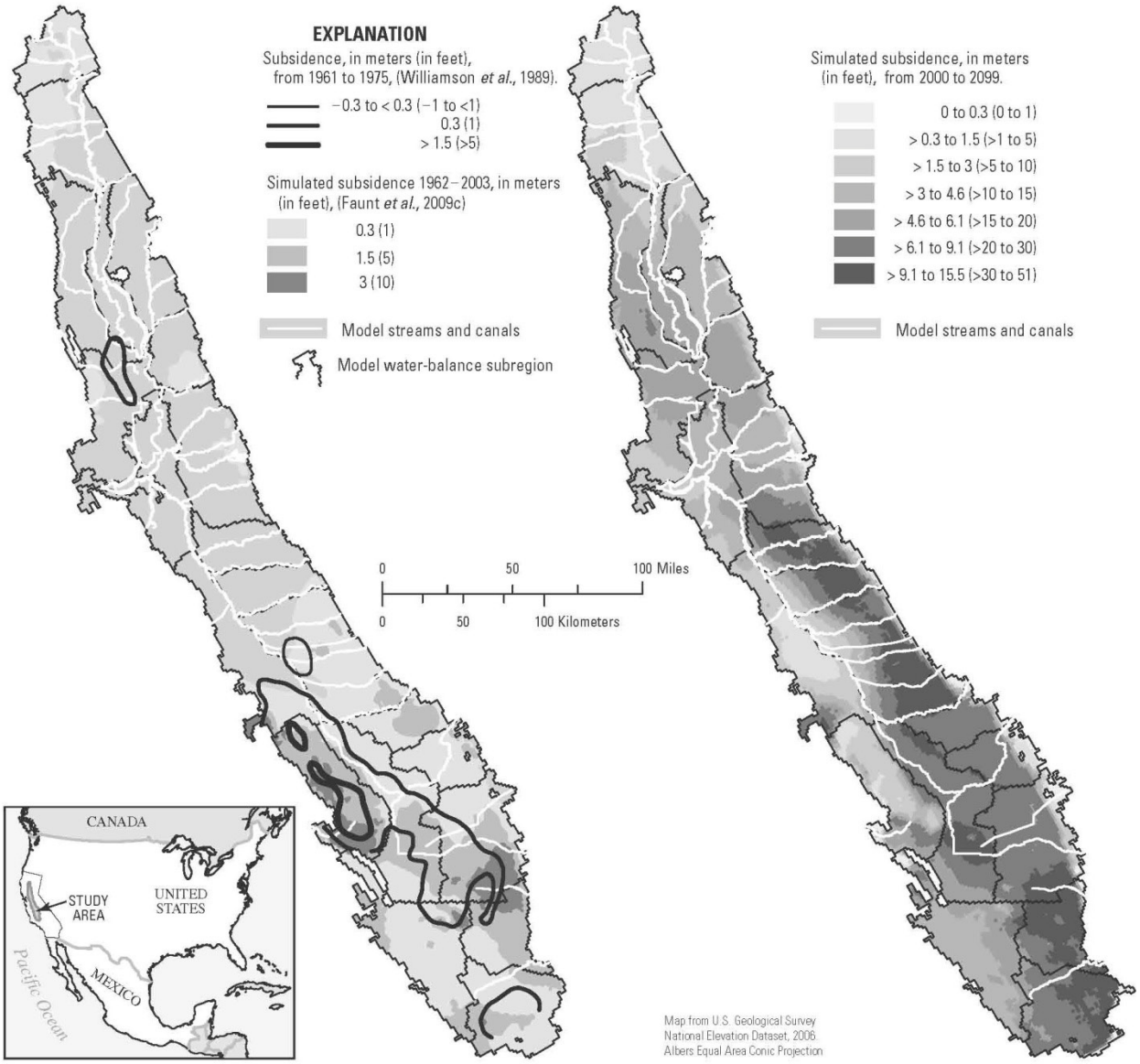

Fig. 3 Map showing the historical and projected future land subsidence for the Central Valley, California, USA.

simulated to occur throughout the Central Valley and especially in the Tulare Basin (southern Central Valley) and along the southeastern San Joaquin Valley where surface-water deliveries are depleted with decreased runoff from the southern Sierra Nevada. Because there are so many uncertainties in climate projections and the related hydrologic assumptions of future conditions made in this projection, only the general trends may be considered reliable relative to the assumptions made.

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