Research Paper/

February 29, 2020

Title: Integrated hydrologic modeling to untangle the impacts of water management during drought

Lauren M. Thatch
Corresponding author: Hydrologic Science and Engineering Program, Integrated Groundwater Modeling Center, Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401, United States; lmthatch@mines.edu

James M. Gilbert
National Oceanic and Atmospheric Administration; University of California, Santa Cruz; james.gilbert@noaa.gov

Reed M. Maxwell
Hydrologic Science and Engineering Program, Integrated Groundwater Modeling Center, Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401, United States; rmaxwell@mines.edu

Conflict of Interest: None

Key words: integrated hydrologic modeling, water management, drought, surface water-groundwater interactions, hydrology, groundwater pumping

Article Impact Statement: Integrated hydrologic modeling to assess the impacts of water management on water availability and terrestrial water fluxes during drought.

Abstract

Over the past century, groundwater levels in California's San Joaquin Valley have dropped more than 30 meters in some areas mostly due to excessive groundwater extraction used to irrigate agricultural lands and sustain a growing population. Between 2012 and 2015 California experienced the worst drought in its recorded history, depleting surface water supplies and further exacerbating groundwater depletion in the region. Due to a lack of groundwater regulation, exact quantities of extracted groundwater in California are unknown and hard to quantify. Recent adoption of the Sustainable Groundwater Management Act has intensified efforts to identify sustainable groundwater use. However, understanding sustainable use in a highly productive agricultural system with an extremely complex surface water allocation system, variable groundwater use, and spatially extensive and diverse irrigation practices is no easy task. Using an integrated hydrologic model coupled with a land surface model we evaluated how water management activities, specifically a suite of irrigation and groundwater pumping scenarios, impact surface water-groundwater fluxes and storage components, and how those activities and the relationships between them change during drought. Results showed that groundwater pumping volume had the most significant impact on long-term water storage changes. Comparison with total water storage anomaly (TWSA) estimates from NASA's Gravity Recover and Climate Experiment (GRACE) provided some insight as to which combinations of pumping and irrigation matched the GRACE TWSA estimates, lending credibility to these scenarios. Additionally, the majority of long-term water storage changes during the recent drought occurred in groundwater storage in the deeper subsurface.

Introduction

Increasing agricultural demands driven by growing populations across the world place additional stress on already over-allocated water management systems. Growth of these demands frequently coincide with droughts, leading to rapid depletion of available surface water supplies and increased reliance on groundwater resources to buffer insufficient water availability (Jenkins et al. 2004; Castle et al. 2014). This water management strategy often leads to excessive and unsustainable groundwater extraction practices, especially in heavily irrigated and arid regions such as the California Central Valley, resulting in widespread, and often permanent, depletions of the world's largest freshwater resource, groundwater (Kalf and Woolley 2005; Aeschbach-Hertig and Gleeson 2012). The last few decades have seen an increased focus on sustainable water management strategies all over the world; however, water management programs have historically focused on surface water resources while groundwater resources and extraction are often poorly or entirely unmonitored (Castle et al. 2014; Cooley et al. 2009). This lack of data on groundwater extraction rates and volumes makes sustainable management challenging. Accurate and reliable data are required to develop water management tools capable of addressing existing and projected increases in domestic and agricultural water demands (Cooley et al. 2009).

Understanding sustainable groundwater use, however, is more complex than simply expanding groundwater use data, especially in heavily managed conjunctive use systems. Despite historical and legal misconceptions in water management strategies, groundwater and surface water systems are intricately intertwined: changes to one can have significant implications for the other. Depletion of groundwater resources can have debilitating impacts on river flows especially when occurring in conjunction more efficient irrigation practices (Kendy and Bredehoeft 2006; Condon and Maxwell 2019). Alternatively, changes in surface water storage, streamflow, or irrigation efficiency can significantly decrease groundwater recharge (Scanlon et al. 2005), resulting in a repetitive feedback loop where groundwater depletions lead to decreases in surface water supplies and subsequent increases in groundwater pumping. Recent studies have explored these complicated dynamics, confirming the importance of climate change and drought on groundwater-surface water interactions and land-energy feedbacks (Maxwell and Kollet 2008; Tweed et al. 2009). However, there is more to learn about how water management practices impact the relationship between these two not-so-separate systems.

Integrated hydrologic models provide valuable tools to explore these complex interactions and their responses to water management activities. This study uses the integrated hydrologic model ParFlow-CLM, which fully integrates groundwater, surface water, and land atmosphere interactions. ParFlow-CLM has been used extensively at both the continental scale and the watershed scale (Bhaskar et al. 2015; Condon et al. 2013; Fang, et al. 2016; Keune et al. 2016; Maxwell et al. 2016) and has been benchmarked in multiple studies (Maxwell et al. 2014; Sulis et al. 2017). Additionally, this model has been used to evaluate the impact of water management practices, including groundwater extraction and irrigation, on basin water and energy cycles (Condon and Maxwell 2014; Ferguson and Maxwell 2011; Ferguson and Maxwell 2012).

This study uses the integrated hydrologic model ParFlow-CLM to evaluate the individual and combined effects of groundwater pumping and irrigation activities on water storage, including groundwater and soil moisture, and on major water balance fluxes, including surface water flows and evapotranspiration (ET). Furthermore, we evaluate how the impacts of these water use activities change during a period of extreme drought in San Joaquin River Basin, a highly productive agricultural region.

Background

The California Central Valley provides an excellent case study for assessing challenges facing water management systems all over the U.S. and the world. As its name would suggest, the California Central Valley is located in the geographic center of the State of California. The entirety of Central Valley watershed encompasses over a third of the total area of the state and lies in a trough between two mountain ranges: the Coast Range to the west and the substantially larger and higher elevation Sierra Nevada Range to the east. This highly productive agricultural region makes up only one percent of agricultural land in the United States but produces a quarter of its food supply (Faunt 2009), and yields over 20 billion dollars in agricultural production annually (Messer et al. 2016). Due to the Central Valley's arid climate, agriculture in the valley is heavily dependent on irrigation water sourced from a complex combination of surface water supplies and groundwater extraction.

Surface water management in the region is an intricate combination of allocations, diversions, and deliveries. This complex distribution system supplies surface water throughout the San Joaquin Valley as dictated by water rights. Historically, groundwater was unregulated and used freely by irrigators without surface water rights or to supplement surface water supplies, especially during drought periods when many water rights holders receive significant cuts in their allocations (Howitt et al. 2014). Recently, California adopted the Sustainable Groundwater

Management Act (SGMA) which requires the implementation of "groundwater sustainability plans" (GSPs) intended to set and meet groundwater sustainability targets within the next 20 years.

Between 2012 and 2015 California experienced the worst drought in its recorded history (Griffin and Anchukaitis 2014). Decreases in precipitation in conjunction with higher temperatures lead to significant declines in peak snow water equivalent (SWE), resulting in diminished spring runoff, reduced spring-summer soil moisture, and ultimately increased irrigation demands (Shukla et al. 2015). The Central Valley, not unfamiliar with drought, relies on groundwater to stabilize decreases in surface water supplies to meet agricultural and population demands (Scanlon et al. 2012). Growing populations and agricultural demands over the past century have led to an increased reliance on groundwater resources which often exceed recharge rates. This is especially problematic in the Tulare Lake Basin Region, immediately south of the San Joaquin River Basin, where groundwater levels in some areas of confined aquifers have decreased over 121 meters (Scanlon et al. 2012; Messer et al. 2016). These groundwater declines have been observed in groundwater wells and with remote sensing products, including terrestrial water storage anomaly (TWSA) estimates from the Gravity Recovery and Climate Experiment (GRACE) (Gilbert and Maxwell 2017; Scanlon et al. 2012).

The California Central Valley has been studied extensively. The Central Valley Hydrologic Model (CVHM), developed by the US Geological Survey (USGS), has been used to evaluate irrigation and water supply in the Central Valley using the Farm Process Model (FPM) (Faunt 2009; Hanson et al. 2010). Additionally, the California Simulation Model (CalSim) is an extensively detailed planning and operations model developed jointly by the US Bureau of Reclamation and the California Department of Water Resources (CA DWR 2017). For this study, we build upon data sets generated by these projects, refining the temporal resolution and including fully integrated surface and subsurface dynamics to better represent recharge, snowmelt, and mountain block processes.

Methods

Study Area

The study area (Figure 1A) encompasses the San Joaquin River Basin south of the Sacramento Delta. The San Joaquin River watershed includes the Tuolumne and Merced River Basins and receives its water supply from a combination of surface and groundwater flows from the Sierra Nevada Range. Conceptually, the domain is subdivided into two main regions: the Sierra Nevada Range and the Central Valley floor. Although the two regions share similar hydrologic and land-surface processes, the dominant processes vary significantly between the two. The Sierra Nevada Range receives the vast majority of precipitation, a large portion of which is stored as SWE in the Sierra Nevada at higher elevations during the winter. Most of the water supply into the Central Valley is provided by groundwater and surface water flows from the Sierras, with minimal input from local precipitation. Agricultural irrigation, the primary water use in the Central Valley, is sourced from variable combinations of groundwater and surface water supplies and leaves the domain via ET, recharge, or runoff. Though this study focuses on groundwater extraction to supply irrigation, it should be noted that water management in the region is complex and includes diversion, retention, and conveyance of surface water flows which can be imported from or exported to other areas of California.

The San Joaquin Basin Model

For this study we use an existing ParFlow-CLM model of the San Joaquin Basin region developed by James Gilbert and Reed Maxwell (Gilbert and Maxwell 2017, 2018; Gilbert et al. 2017). The San Joaquin Basin Model (SJBM) domain (Figure 1A) encompasses 59,400 km^2 from the mountain headwaters in the Sierra Nevada Range to the valley floor. The model was developed with a one-kilometer lateral resolution grid with a more refined vertical resolution in the upper four shallow layers with a total depth of two meters and a simplified 498-meter bottom layer. Shallower soil layers near the surface more accurately simulate land surface-atmospheric interactions, while the simplified bottom layer reduces computational time (Gilbert and Maxwell 2017).

The SJBM uses the integrated hydrologic model ParFlow (Kollet and Maxwell 2006; Kollet and Maxwell 2008; Maxwell 2013; Maxwell and Miller 2005) fully coupled with the Common Land Model (CLM), to evaluate groundwater, surface water, and land surface processes and interactions (Maxwell and Miller 2005). ParFlow is an open-source, integrated hydrologic model which solves Richards' Equation in three dimensions and overland flow at the ground surface using either the diffusive or kinematic wave equation. Coupling ParFlow with CLM (ParFlow-CLM) incorporates additional land-surface processes, including energy balance, ET, and snow dynamics.

Results from previous simulations using the SJBM were evaluated against satellite remote sensing products (such as GRACE) as well as streamflow and snow observational datasets (Gilbert and Maxwell 2017). Model results have been used to evaluate groundwater recharge from the Sierra Nevada mountain block (Gilbert and Maxwell 2017); explore connections between groundwater table drawdown, soil moisture, and the atmosphere through a coupling with Weather Research and Forecasting Model (WRF) (Gilbert et al. 2017); and evaluate the region's response to warming temperatures (Gilbert and Maxwell 2018).

Model Simulations

To fully understand the implications of water management in these complex systems, it is important to first understand how groundwater pumping and irrigation individually and conjunctively impact groundwater and surface water supplies. As a first step to integrate these water management practices into the SJBM, we ran a suite of simulations using simplified pumping and irrigation scenarios (Table 1). In its current configuration, the SJBM does not include reservoirs, surface water diversions, or other water management activities and infrastructure.

Table 1: *Model Simulation Details Table. Grayed out simulations indicate scenarios that were completed but not presented here for simplification.*

Simulation (Abbreviation)	Initial Condition	Groundwater Extraction Scenario	Irrigation Scenario
Baseline (BL)	Natural	None	None
Constant Pumping (BL.Pu)	Natural	Constant Rate	None
25% Constant Pumping (BL.Pu25)	Natural	25% Constant Rate	None
50% Constant Pumping BL.Pu50)	Natural	50% Constant Rate	None
Variable Pumping (BL.VP)	Natural	Monthly Variable Rate	None
Drip Irrigation (BL.Irr)	Natural	None	Drip
Spray Irrigation (BL.IrrS)	Natural	None	Spray
Pumping and Irrigation (BL.VP.Irr)	Natural	Monthly Variable Rate	Drip
Depleted Water Table (WTD)	Depleted Water Table	None	None
WTD, Constant Pumping (WTD.Pu)	Depleted Water Table	Constant Rate	None

WTD, Variable Pumping (WTD.VP)	Depleted Water Table	Monthly Variable Rate	None

Groundwater Pumping Simulations

Data on groundwater extraction rates in the Central Valley is sparse, however, a simplified groundwater extraction scenario was previously derived for the SJBM based on water table drawdowns from the USGS Central Valley Hydrologic Model (CVHM) (Gilbert et al. 2017). These extraction rates have some spatial variability based on groundwater basins but previously did not vary temporarily. To evaluate system response, including changes in water storage partitioning, runoff and ET, to groundwater extraction volume, three constant pumping run simulations were conducted using 100%, 50% and 25% of the initial extraction rates. To evaluate the impact of temporal fluctuations in groundwater pumping, a fourth pumping simulation was run using monthly variable extraction rates estimated using the same total annual volume of groundwater extraction from the constant pumping scenario scaled by estimated monthly extraction rates from the C2VSim model (CA DWR 2017). Total annual extraction volumes for each hydrologic sub-region are shown in Figure 1B. For the constant and variable pumping simulations, the total extracted volume over the entire model domain was 9.18 cubic kilometers (km^3) per year.

It is important to note that the SJBM, at a 1-km grid resolution, does not include individual wells and therefor does not capture the localized impacts of well drawdown and localized groundwater level and gradient changes. While these phenomena may have significant local impacts on water storage and fluxes, for this study we focus on the large-scale impacts of groundwater extraction, specifically extraction volumes, which we expect to have a more significant role in regional and basin scale water storage changes. However, more research is needed to assess the importance of model resolution in modeling water use impacts at larger scales.

Irrigation Simulations

A simplified irrigation scheme was implemented by estimating total applied annual irrigation volumes using the CA DWR, 2010 annual applied water (AW) values for each crop type weighted by the relative area of that crop type in the San Joaquin River Basin (Johnson and Cody 2015). Annual irrigation volumes were translated into a constant hourly irrigation rate applied from April through September from 7 AM to 5 PM. The same rate was applied to all areas in the SJBM denoted as cropland, with the exception of cropland at elevations greater than 2,000 meters (Figure 1C). The total modeled annual irrigation volume over the entire domain was 34.0 km^3. Drip and spray irrigation application methods, which apply irrigation water to the canopy through fall (i.e. below the canopy) and above the canopy (Ferguson and Maxwell 2011), respectively, were initially evaluated. Water storage changes for the two methods varied by less than one percent; therefore, for simplification, only the results of the drip irrigation simulation are presented.

A final water use simulation combined drip irrigation and monthly variable groundwater extraction to evaluate their combined impact. Total annual modeled groundwater pumping volume accounts for approximately 27% of total irrigation volume; this is consistent with previous pre-drought estimates around 30% (Howitt et al. 2014). Modeled irrigation water is assumed to be sourced from surface water supplies outside of the model domain. Though the combined water management simulation is intended to represent a simplified conjunctive use scenario, groundwater and irrigation water use activities are not specifically linked within the model and irrigation water is sourced from outside the domain and extracted groundwater is removed from the domain.

Model Initial Condition

Previous studies have shown that model initial conditions, including soil moisture and groundwater levels, can significantly influence model results, specifically surface water storage and runoff (Seck et al. 2015). To minimize biases in model output, the SJBM was initialized using a multi-year spin-up process to achieve a dynamic equilibrium groundwater storage condition in the SJBM. Model spin-up of the SJBM was conducted starting with initial conditions from Gilbert and Maxwell (2017) using the new forcing resolution data for water year 2009. The model was run repeatedly until an approximate dynamic equilibrium was achieved, when groundwater storage change in the model domain was below one percent of the total atmospheric forcing precipitation in one 2009 water year run. The model was spun up without groundwater extraction or irrigation and represents the model domain in its natural conditions prior to water management activities. To mimic present day conditions, a second model initial condition, created for a previous study using the SJBM, was developed using simulated water levels from the CVHM. These water levels were evaluated as the initial hydrostatic pressure field for the SJBM and "spun-up" for several years to allow the system to equilibrate (Gilbert et al. 2017) (Figure 1D).

Meteorological Forcing

All model simulations were driven using the same temporally and spatially distributed meteorological forcing data over the recent historic drought from water year 2010 through

2017. Meteorological forcing data for these simulations was provided by a 3-km resolution data set developed from the North American Data Assimilation Survey phase II (NLDAS-II) data product (Cosgrove et al. 2003; Mitchell et al. 2004). The 3-km resolution product was previously developed by downscaling the NLDAS-II 12-km resolution data which was adjusted for elevation and consistency (Pan et al. 2016). This 3-km data set was bi-linearly interpolated to the SJBM domain 1-km grid.

Results and discussion

The following sections evaluate how water use activities and drought impact water storage partitioning and water fluxes. First, we evaluate simulated water storage, including groundwater, soil moisture, SWE, and surface water storage, changed over the course of the drought and with the addition of groundwater pumping and irrigation. Remote sensing products were used to evaluate modeled storage changes: Soil moisture storage was compared with a combined soil moisture remote sensing product from European Space Agency (ESA) climate change initiative (CCI) (Dorigo et al. 2017; Gruber et al. 2017, 2019); Modeled SWE storage is compared with data from the Snow Data Assimilation System (SNODAS) data product (National Operational Hydrologic Remote Sensing Center 2004); and modeled total water storage (TWS) changes were compared with GRACE TWSA estimates.

Additionally, we evaluate how major components of the water balance, surface water flows and ET, changed over the course of the drought and their sensitivity to groundwater pumping and irrigation. Remote sensing data is also used to evaluate these fluxes: ET is compared with remotely sensed ET estimates from the MODIS Global Evapotranspiration Project MOD16 (Mu et al. 2007, 2011); surface water flows are compared with USGS streamflow data for the San Joaquin River near Vernalis (USGS 2001).

Water Storage Changes

Water storage results from the model were partitioned into surface water, SWE, and subsurface storage components. For the purpose of this study and based on the SJBM domain configuration, our analysis separates subsurface storage into two components: soil moisture in the top 4 layers of the model (top 2m of the domain at the surface); and deeper groundwater storage in the bottom layer (more than 2m below the ground surface). Daily average storage values for each of the four components are presented as equivalent depths over the SJBM domain (Figure 2). Additionally, average annual trends in groundwater, soil moisture, SWE, and surface water averaged over the modeling domain are presented for the drought period (2012 through 2015) in Figure 3.

Groundwater Storage Changes

Groundwater, neglecting soil moisture, accounts for more than 99 percent of total water storage in the system. Groundwater has a clear annual cycle for all water years of the simulation, with the lowest storage values in late fall or winter and highest storage in late spring or early summer. Compared with the surface water, SWE, and soil moisture, trends in daily average groundwater storage for all simulations show minimal daily fluctuations and clear annual trends. Possibly because of this slowness to change, groundwater storage changes account for most of the longer-term multi-year total storage changes in the system. For the baseline run, intended to mimic a pre-development system, the average annual decrease in total water storage was -5.65 cm per year over the drought period. Changes in groundwater storage during that period accounted for 74.6% of this change. Despite its slower rate of change, groundwater also has a large impact on interannual variations in total water storage in the system. Over the drought, the total annual amplitude, based on daily average groundwater storage values, over the domain slowly decreased from 14.34 cm in 2012 to 10.17 cm in 2014.

Soil Moisture Storage Changes

Though the total volume of water stored as soil moisture is relatively small, less than 0.5 percent of total water storage, it has a significant impact on both intra-annual and multi-year scale total water storage changes. Peak soil moisture in the baseline run occurs in late winter or early spring and decreases over summer reaching a minimum during late September, early October. Soil moisture plays one of the largest roles in intra-annual total water storage changes, and, similar to storage changes in the deeper subsurface, the total annual amplitude, based on daily average soil moisture storage values, decreases over the drought, from 16.9 cm in water year 2011 to 8.0 cm in 2014. Soil moisture also plays an important role in total water storage trends over multi-year periods, though it's less than groundwater likely due to its overall smaller portion of total water storage in the system and its relatively faster rate of change. Annual trends in soil moisture storage account for approximately 25% of the decreasing total water storage trend over the drought from 2012 to 2015 in the baseline run. Modeled soil moisture results shows good trend comparison with the ESA CCI remote sensing product with some differences in the total magnitude of annual variations; however, direct comparison with remote sensing data is challenging due to differences in measurement depth (2m in the ParFlow simulations and 0.1 m in the remote sensing product) as well as significant data gaps and limited spatial data availability, especially in the winter and spring.

SWE Storage Changes

Since SWE occurs at higher elevations and modeled water management activities for this study occur at lower elevations, modeled SWE volumes for all simulations were approximately equal (less than 0.01% difference in average daily volume) and dependent on meteorological forcing. Subsequently only the baseline results are presented (Figure 2). Like groundwater, SWE storage shows a clear annual cycle, starting at approximately zero at the start of the water year. During the winter, precipitation and low temperatures result in snow accumulation at high elevations, and peak SWE occurs approximately halfway through the water year, around April 1. SWE has a significant impact on intra-annual storage changes which varies significantly from year to year, especially when the snowpack is drastically reduced during a drought. SWE plays the largest role in intra-annual storage changes during cold years with high precipitation, such as water year 2011 where the total annual amplitude, based on daily average SWE storage values, was 17.8 cm. Drought, however, significantly decreases SWEs impact on interannual storage changes, such as water year 2015 where peak SWE was less than 1.4 cm. Drought also had a significant impact on timing of peak SWE storage in the system, which occurred in January and February in water years 2013 and 2015 respectively. Because SWE storage is essentially zero at the start of every water year, it has little direct impact on multi-year storage changes. Simulation results are slightly below SNODAS remote sensing data; however, the timing of snowmelt and accumulation is very consistent, with slightly more deviation over the drought when total SWE volumes were low.

Surface Water Storage Changes

Surface water storage is the smallest component of total water storage in the system. Surface water storage is heavily dependent on spring snow melt, with peak monthly flows occurring during snowmelt and decreasing over the summer. Surface storage can change rapidly and fluctuates significantly day to day, due to impacts from storm events or more rapid periods of snowmelt. However, the magnitude of these fluctuations in surface water storage are relatively small in comparison with other storage components and have a small impact on interannual total water storage. The amplitude of interannual changes also decreases over the drought period from 2.3 cm in 2012 to 0.5 cm at the peak of the drought in 2014. Because annual average surface water storage accounts for less than 0.02% of total storage, it has little impact on longer period trends.

Groundwater Pumping Impacts

Groundwater pumping decreases groundwater, soil moisture, and surface water storage, with the most significant reductions occurring in groundwater storage. As a comparison, over the drought period the baseline simulation saw an average decrease in groundwater storage of 4.21 cm per year. The 25% volume pumping run which extracted 2.29 cm per year, showed a 1.42 cm per year additional increase in groundwater depletion from baseline. That additional groundwater storage decrease only accounted for 61% of groundwater pumping in the deeper subsurface over the drought period. Doubling that extracted volume in the 50% pumping run showed a 3.97 cm increase in groundwater depletion compared to the baseline run, indicating that the second 25% pumping volume addition decreased groundwater storage 2.54 cm, 38.7% more than the first, but only accounting for 86.3% of the additional pumped volume. This trend continued for the 100% constant pumping run, which showed that the third and fourth 25%

pumping volume increases resulted in an additional 6.35 cm per year of groundwater depletion, or 123% more than the first 25%. Increases in groundwater extraction become increasingly “efficient” at removing water from longer term groundwater storage, slowly becoming more linear and approaching a 1:1 ratio of pumping to storage change. Initial groundwater extraction is offset by decreases in soil moisture availability at the subsurface and subsequent decreases in ET, as well as decreases in surface water flow and increases in recharge. Little difference in annual groundwater trends were observed between the constant pumping and monthly variable pumping rate schemes.

The impact of the groundwater pumping volume varied between wet and dry years. During 2011, a relatively wet year with ample surface water available for recharge into the subsurface, 25 percent pumping decreased the annual groundwater storage trend by only 0.8 cm/year. During the drought in 2012 and 2014, 25 percent pumping further decreased the already decreasing groundwater storage trend by 1.42 and 1.44 cm/year respectively. Larger volumes of groundwater pumping showed similar trends. However, the impacts of larger pumping increased over the drought with decreases in the annual groundwater storage trend of 9.33 cm/year in 2012 at the start of the drought to 10.69 cm/year at the peak of the drought in 2014. Conversely, groundwater extraction only slightly increased soil moisture depletion trends from the baseline annual soil moisture trend of 1.41 cm per year during the drought to 1.63, 1.67, and 1.64 cm per year, for the 25 percent, 50 percent, and 100 percent constant pumping simulations, respectively.

As noted previously, the SJBM does not capture smaller scale groundwater level drawdowns near pumping wells which would impact smaller scale hydraulic gradients. This could be especially important for wells located near streams, where hydraulic gradient has significant impacts on groundwater recharge and stream baseflow. Future research on the impacts of model resolution when assessing the impacts of water use activities is critical to understand the uncertainty induced by these resolution choices.

Irrigation Impacts

Application of irrigation water to the surface had important impacts on groundwater, surface water, and soil moisture storage. Irrigation had a more significant impact on soil moisture compared to groundwater pumping. The irrigation simulation resulted in a decrease in soil moisture of 1.0 cm per year over the drought period, 30% less than the baseline trend, in contrast to the constant groundwater pumping simulation which had a soil moisture decrease 15% greater than the baseline run**.** Despite the addition of groundwater pumping, the combined use simulation only saw a decline of 1.22 cm/year in soil moisture, approximately 13.3 percent less than baseline trend, indicating that soil moisture is more sensitive to irrigation during the drought period.

In the groundwater system, adding irrigation alone had a relatively small impact on groundwater storage – reducing the depletion trend over the drought by approximately 0.30 cm per year compared to the baseline run. However, when coupled with the groundwater pumping, irrigation played a more significant role in reducing groundwater losses, reducing the groundwater loss trend by 3.19 cm per year compared to the variable pumping run, more than 10 times the impact when irrigation was applied alone. This indicates that groundwater pumping significantly increases surface recharge from applied irrigation.

Total Storage and Comparison with GRACE

Data from the NASA GRACE are used to estimate total terrestrial water storage (TWS) changes or anomalies (TWSA) and evaluate changes in groundwater storage (Döll et al. 2012, 2014; Scanlon et al. 2005, 2012; Voss et al. 2013). Previous studies conducted specifically over the Central Valley using GRACE-estimated TWSA have shown an annual decrease in water storage of approximately 20 mm per year from October 2003 to March 2010 (Famiglietti et al. 2011). The SJBM has also been compared to GRACE in previous studies without water use activities over water years 2009 through 2013 (Gilbert and Maxwell 2017). This previous analysis showed a good comparison with GRACE TWS estimates, with some inconsistencies likely due to heavy water management activities in the region. In this study, ParFlow modeled results are compared to annual and seasonal trends in the GRACE signal to evaluate the relative impacts of groundwater pumping and irrigation.

GRACE estimates have a relatively coarse spatial resolution in comparison to ParFlow and only estimate TWS changes at the larger regional scale. Additionally, GRACE provides a single lumped measurement of changes in TWS which does not differentiate between groundwater, surface water, soil moisture, and SWE storage. For this study, TWS estimates are provided by three GRACE monthly surface mass grid data products based on the RL05 spherical harmonics from the University of Texas Center for Space Research (CSR), the NASA Jet Propulsion Lab (JPL), and German Research Centre for Geosciences (GFZ) (downloaded from http://grace.jpl.nasa.gov) (Landerer and Swenson 2012; Swenson 2012; Swenson and Wahr 2006). The GRACE solutions were adjusted using gridded-gain factors (Landerer and Swenson, 2012) and interpolated to the SJBM ParFlow domain for the simulation period. We compare to a simple arithmetic average of the GRACE solutions, referred to as the GRACE average, which has been proven to reduce noise in the individual solutions (Sakumura et al. 2014).

Annual Total Storage Changes

TWSA estimates from GRACE and the SJBM simulation results (Figure 4) show similar annual storage trends over the simulation period with TWS increases in the pre-drought and post-drought periods (water years 2010 and 2011, and 2016) and TWS decreases during the drought water years (2012 through 2015). However, TWS changes are overestimated by the full volume pumping runs and underestimated by the irrigation only simulations, indicating that GRACE observations are a representation of combination of these water use activities.

During the drought the GRACE average and ParFlow simulations show net decreases in TWS, however, the magnitudes of these decreases vary significantly. All ParFlow simulations show a greater decrease in TWS in comparison to the GRACE average during the first year of drought, water year 2012, however, the largest GRACE average TWS decreases occur in water years 2013 and 2014. There are several possible causes of this discrepancy, primarily the lack of variability in the modeled annual groundwater extraction volume, which was modeled as constant but would have increased during the drought due to decreases in available surface water supplies and increased temperatures. This highlights the importance of annual variations in total groundwater extraction volumes over the drought to more accurately estimate TWS changes. Additionally, since the baseline and irrigation simulations, which do not include groundwater extraction, also show larger changes in TWS compared to the GRACE average, other water management activities including surface water storage and diversion may have supplied more water from outside of the domain earlier in the drought. Excess surface water storage likely would have been more available during the first year of the drought and would have decreased as reservoir supplies dwindled. For example, water storage in the Don Pedro Reservoir, along the Tuolumne River, decreased by 0.49 km^3 over water year 2012 but only decreased by 0.20 km^3 in water year 2013 (CA DWR, 2016). Inclusion of additional surface water management, including reservoirs and diversion activities, are planned for future SJBM development. Lastly, the coarser resolution of the GRACE observations may have dampened fluctuations over the San Joaquin Basin due to inclusion of areas less impacted by the drought. Evaluation of water storage changes during water year 2012 outside of the SJBM would be required to evaluate this hypothesis.

Following the drought, all ParFlow simulations showed a greater increase in TWS during water year 2016 in comparison with the GRACE average. Similar to the differences between GRACE and the ParFlow simulations at the beginning of the drought, this discrepancy is likely due to a lack of annual variability in groundwater pumping rates, which may have remained higher than the modeled extraction rate in water year 2016 as California began to recover from the drought and reservoirs began to fill; other water management activities not simulated which may have impacted surface water supplies into the system; or the coarser resolution of the GRACE observations which may dampen TWS changes over the San Joaquin Basin.

Seasonal Changes

Seasonal variations in the ParFlow simulation results and the GRACE average were evaluated by comparing monthly TWSA over each water year (Figure 5). Monthly TWSAs are calculated as the variation or 'anomaly' of the monthly TWS from the annual average TWS for each of the

ParFlow simulation and for the GRACE average individually and calculated for each water year separately.

Seasonal comparisons between ParFlow results and the GRACE average vary greatly from year to year largely due the dampening of the total annual amplitude of monthly TWS fluctuations from a range of over 30 cm during the pre-drought water year 2011, to a just 12.5 cm in peak-drought 2014. This dampening is due to large decreases in annual precipitation and SWE storage during the drought in comparison to the pre-drought period. Pre-drought water year 2011 shows relatively good comparison between GRACE and the ParFlow simulations in comparison to the drought years, and model results generally capture seasonal variations in the GRACE signal over the domain. Constant pumping decreases the amplitude of monthly TWSA in all water years and is less consistent with the GRACE average, highlighting the importance of modeling intra annual variations in groundwater extraction to evaluate seasonal storage changes. In contrast, the monthly variable extraction simulation estimates the annual amplitude of monthly TWSA well, but the timing varies from the GRACE average, indicating that monthly variable pumping rates may need to be adjusted and vary between water years in timing and total volume. For example, the ParFlow groundwater extraction simulations in multiple water years underestimate larger storage depletions in November and December indicating that higher groundwater extraction rates may occur during these months than were modeled in this study.

The GRACE average and ParFlow simulation results show similar timing for peak monthly TWS throughout the course of the simulation period, however, the ParFlow baseline and pumping simulations show more rapid storage depletion following peak water storage in the spring/early summer in comparison to the GRACE average. The irrigation runs, however, show a less rapid decrease in spring storage as water is applied to the surface through irrigation. Similar to the constant groundwater extraction simulations, irrigation also dampens seasonal variations, this is partially corrected by adding variable pumping to the irrigation runs which has better correlation with the GRACE average TWSA range in comparison to the irrigation only and baseline runs. These results indicate, that similar to variable groundwater extraction, variations in irrigation rates within the irrigation season may also play an important role in seasonal storage variations.

Land Surface fluxes

Though this study focuses on changes in water storage, to evaluate the mechanisms through which these storage changes occur we have to evaluate how drought and water use activities impact how water moves through this system. To do this we assess the impacts of water management activities and drought on the two largest fluxes at the land surface: surface water flow and ET.

Surface Water Flows

Though surface water storage makes up only a small percentage of TWS in the SJBM, it provides an important method for the movement of water between different spatial regions and storage components, as well as conveyance of water out of the system. To discern the impacts of groundwater extraction and irrigation on surface water flows in the SJBM we evaluate the total annual flow out of the domain for each of the simulations in comparison with the baseline run (Figure 6). Modeled total annual surface water flow volumes decrease over the drought, even without water use activities and are further reduced by groundwater pumping. Though irrigation increases surface flows, drought still dominates resulting in a drastic decrease in surface water flows at the start of the drought between 2011 to 2012 in all simulations. Increases in groundwater extraction volumes result in further reductions in simulated surface water flows. However, unlike changes in groundwater storage where pumping volume has relatively larger impacts per volume pumped at increasing volumes, increases in groundwater pumping have declining incremental impacts on surface water flow reduction from baseline of 21.2, 35,2, 52.8 percent, for the 25, 50, and 100% groundwater pumping simulations, respectively. This decreasing impact on the reduction in surface water flows partially explains the increasing impact on groundwater storage; where initial groundwater pumping has a muted response on groundwater storage by increasing recharge resulting in decreased surface water flows. Subsequent increases in pumping volume have less impact on surface flows and recharge, resulting in a higher reduction in groundwater storage. The impact of groundwater pumping on surface water flow reductions increases throughout the drought and surface water flows in the 100 percent volume pumping run are reduced by 37.5 percent in 2012 to 74.5 percent in 2015.

Variations in monthly groundwater extraction rates had a less significant impact on total annual flow volume in comparison to variations in total volume, though constant pumping reduces annual accumulated surface water flows slightly more than variable pumping rates. This is likely due to higher pumping rates in the constant pumping simulation during snow melt in April and May resulting in a lower water table and subsequently less groundwater flow discharging into streams and more recharge.

Groundwater pumping also has large impacts on surface water groundwater interactions along streams and rivers. Near its headwaters at high elevations, the San Joaquin River is a predominantly gaining stream, as large changes in elevation lead to large hydraulic gradients toward the river and groundwater is discharged to the surface. As the river approaches lower elevations, the steepness of the river lessens, and the groundwater flux into the stream decreases until surface water begins to move into the subsurface (Figure 7). Comparison of the baseline and pumping simulations along the San Joaquin River show that groundwater pumping increases the flow of water from the river into the ground along the valley floor.

Irrigation increases surface water flow as excess water runs off to streams or percolates into groundwater, some of which will eventually discharge to downstream surface water bodies. The amount of return flow, however, varies significantly between water years, and is well correlated with changes in ET (Figure 6). During the drought years, with relatively little natural flow, irrigation return flow makes up a much larger proportion of total flow. This total annual total surface flow volume increase from irrigation is fairly consistent; in 2012 and 2013 irrigation increased surface water volume by 2,331 and 2,366 million cubic meters, respectively, approximately 16.5% of total applied irrigation water. Previous studies have indicated return flows around 28% for irrigated agriculture in the San Joaquin (Hanak et al. 2017), however, the relationship is impacted by temperature, and 2014, the hottest water year, saw a slightly smaller increase of 2,016 million cubic meters. The impacts of irrigation on surface water flow carry over into the following year, with higher surface water flows at the beginning of subsequent water years prior to the commencement of irrigation in April due to increased soil moisture and higher water table elevation at the beginning of the water year. The impact of irrigation on surface water-groundwater interactions is more complicated and evident along the San Joaquin River (Figure 7). Flux into and out of the San Joaquin River in the irrigation simulation generally follows the baseline run. However, as the river flows farther into the valley, recharge from the San Joaquin River into the subsurface lessens, likely due to a higher groundwater table from infiltration of irrigation water into the region surrounding the stream. Though irrigation has some impact, groundwater pumping has a larger impact on fluxes between surface water and groundwater.

Increases in annual accumulated surface water flow from the 'irrigation only' simulations exceeded the decreases in surface water flows modeled in the groundwater extraction simulations for all water years. Prior to the drought, the combined water use simulation results showed higher surface flows compared to baseline, however, as the drought progresses, annual accumulated flows for the combined water management simulation decline and ultimate fall below baseline run surface water flows. Like soil moisture and groundwater storage, we see that irrigation can increase surface water flows to a point, however, groundwater pumping impacts compound and increase in severity from year to year and eventually dominate as the drought progresses. Water use impacts on surface water flows is not a simple linear combination of groundwater extraction and irrigation impacts but a complicated non-linear process.

Evapotranspiration

ET is the largest flux at the land surface, with annual volumes exceeding surface water flows for all water years (Figure 6). As with surface water flow, initial groundwater pumping has the largest impact on ET per volume pumped and increasing volumes of groundwater pumping have declining impacts on total ET. The initial application of 25% pumping volume reduced ET over domain by 3.5 percent on average throughout the peak drought from 2012 to 2015, subsequent increases to 50% and 100% constant pumping reduced total annual ET by 5.3 and 7 percent from baseline, respectively. Variations in monthly extraction rates had little impact on total annual ET, with the largest difference of less than 0.3% in 2014, when variable pumping rates had the largest impact due to low moisture availability from a lack of precipitation and an increase in temperature.

Simulated ET increases with irrigation application to the land surface. Evaluating accumulated ET over water years 2011 and 2014 (Figure 6G and 6H), there is little difference between the water years during winter months and large divergences in the spring and summer when irrigation occurs. As the drought progresses the percent difference between annual accumulated ET in the baseline and the irrigation simulations increases significantly, because baseline ET is reduced, however, the absolute difference between the total annual ET values is fairly constant at 11,711 and 12,488 million cubic meters in 2012 and 2014, respectively. The higher value in 2014 is likely due to higher potential ET caused by higher temperatures. The impacts of irrigation dominate in the combined simulation and the difference between the total annual accumulated ET compared to the baseline run are fairly consistent between water years from 9,869 million cubic meters in 2012 to 10,546 million cubic meters in 2014. Similar to surface water flows, the impacts of irrigation carry over from one year to the next, and the irrigation simulation shows higher ET rates compared to the baseline run during winter months, when irrigation water is not being applied, caused by residual increases in water table elevation and soil moisture availability.

The combined impacts of groundwater extraction and irrigation on ET show a less complex relationship in comparison to impacts on surface water flows. ET increases from irrigation are less impacted by groundwater table elevations compared to surface water flows, which are more affected by increased infiltration into the subsurface and reduced flows from the subsurface to the surface.

MODIS remote sensing data compare well with the baseline run in water years 2010 and 2011, indicating that groundwater pumping, and irrigation activities had less impact in the relatively wet pre-drought period. Though the magnitude of changes in not consistent between the ParFlow and MODIS ET values, they show similar behavior over the drought, initially decreasing from water year 2011 to 2012 and diverging more from the baseline run as the drought progresses.

Conclusions

Water use activities have significant effects on water storage changes in the San Joaquin Basin. Without water use activities, ParFlow baseline simulation results painted a picture of a resilient water storage system, that, while impacted by drought, quickly rebounded. Overall groundwater pumping had a more significant impact on water storage compared to irrigation. Conversely, irrigation plays a larger role on increasing fluxes out of the system, such as ET and surface flows, while groundwater pumping impacts storage by increasing recharge into the subsurface and reducing surface water flows. These findings match other similar studies in smaller systems (e.g. Ferguson and Maxwell 2011).

Groundwater extraction volume had the greatest influence on multi-year water storage changes over the drought. Though there was a clear long-term trend in soil moisture storage over the drought, the majority (approximately 75 percent) of the multi-year total water storage changes occurred in the deeper subsurface. Interannual variability in groundwater extraction rates had little impact on annual trends, however, comparison with GRACE showed that the inclusion of simpler constant pumping rate dampened the interannual amplitude of storage changes and highlighted the importance of including intra-annual variability of groundwater extraction rates to evaluate seasonal fluctuations in water storage availability. GRACE storage changes are well bounded by the irrigation and pumping simulations, indicating that simulations used for this study represent a reasonable range of agriculture water use over the drought. Additionally, results indicate that comparison with GRACE TWSA estimates provides a valuable tool for evaluating how groundwater pumping volumes and interannual pumping rates may have changed over the drought.

This study illustrates how fully integrated hydrologic models can be used to provide valuable insight on the impacts of water management activities on water fluxes, storage and availability in complex agricultural systems. Though the simulations in this study only begin to capture the complexity of agricultural water use this highly productive region, they offer a means to explore the impacts of groundwater pumping and irrigation individually and to understand how the impacts of these activities combine in highly non-linear systems. Results of the study highlight what components of the system are important for assessing long-term trends in water storage and confirm that better estimates of total annual groundwater pumping volumes, which had the largest impact on long-term trends, are critical for identifying sustainable groundwater use in the Central Valley. Lastly, GRACE provided an effective means to evaluate groundwater extraction rates and volumes and demonstrated the significance of including both seasonally and annually variable groundwater extraction rates. Though challenges remain, and specific quantities are difficult to determine, this method provides a path forward for refining these estimates and pinpoints the largest contribution factors.

References

Aeschbach-Hertig, W., and T. Gleeson. 2012. Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience* 5, no.12: 853-861.

Bhaskar, A. S., Welty, C., Maxwell, R. M., and A. J. Miller. 2015. Untangling the effects of urban development on subsurface storage in Baltimore. *Water Resources Research* 51, no. 2: 1158-1181.

California Department of Water Resources (CA DWR). 2017. A Water Resources System Planning Model for State Water Project (SWP) & Central Valley Project (CVP): CalSim 3.0 Draft Report. Sacramento, California

Castle, S. L., Thomas, B. F., Reager, J. T., Rodell, M., Swenson, S. C., and J. S. Famiglietti. 2014. Groundwater depletion during drought threatens future water security of the Colorado River Basin. *Geophysical Research Letters* 41, no. 16:5904-5911.

Condon, L. E., Maxwell, R. M., and S. Gangopadhyay. 2013. The impact of subsurface conceptualization on land energy fluxes. *Advances in Water Resources* 60: 188-203.

Condon, L. E., and R. M. Maxwell. 2014. Feedbacks between managed irrigation and water availability: Diagnosing temporal and spatial patterns using an integrated hydrologic model. *Water Resources Research* 50, no. 3: 2600-2616.

Condon, L. E., and R. M. Maxwell. 2019. Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion. *Science Advances* 5, no. 6: eaav4574.

Cooley, H., Christian-Smith, J., and P. Gleick. 2009. Sustaining California Agriculture in an Uncertain Future. Pacific Institute.

Cosgrove, B. A., Lohmann, D., Mitchell, K. E., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A., Marshall, C., Sheffield, J., Duan, Q. and L. Luo. 2003. Real-time and retrospective forcing in the North American Land Data Assimilation System (NLDAS) project. *Journal of Geophysical Research: Atmospheres* 108, no. D22.

Döll, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G. and B. R. Scanlon. 2012. Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics* 59: 143-156.

Döll, P., Schmied, H., Schuh, C., Portmann, F. T., and A. Eicker. 2014. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resources Research* 50, no. 7: 5698-5720.

Dorigo, W., W. Wagner, C. Albergel, F. Albrecht, G. Balsamo, L. Brocca, D. Chung, M. Ertl, M. Forkel, A. Gruber, E. Haas, P. D. Hamer, M. Hirschi, J. Ikonen,,R. de Jeu., R. Kidd, W. Lahoz,, Y. Y. Liu, D. Miralles, … P. Lecomte. 2017. ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. *Remote Sensing of Environment 203*: 185-215.

Famiglietti, J.S., Lo, M., Ho, S.L., Bethune, J., Anderson, K.J., Syed, T.H., Swenson, S.C., de Linage, C.R. and M. Rodell. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters* 38, no. 3.

Fang, Z., Bogena, H., Kollet, S., and H. Vereecken. 2016. Scale dependent parameterization of soil hydraulic conductivity in 3D simulation of hydrological processes in a forested headwater catchment. *Journal of hydrology* 536: 365-375.

Faunt, C. C. (Ed.). 2009. Groundwater Availability of the Central Valley Aquifer, California. USGS Professional Paper 1766: 225.

Ferguson, I. M., and R. M. Maxwell. 2011. Hydrologic and land–energy feedbacks of agricultural water management practices. *Environmental Research Letters* 6, no. 1: 014006.

Ferguson, I. M., and R. M. Maxwell. 2012. Human impacts on terrestrial hydrology: climate change versus pumping and irrigation. *Environmental Research Letters* 7, no. 4: 044022.

Gilbert, J. M., and R. M. Maxwell. 2017. Examining regional groundwater–surface water dynamics using an integrated hydrologic model of the San Joaquin River basin. *Hydrology and Earth System Sciences* 21, no. 2: 923–947.

Gilbert, J. M., Maxwell, R. M., and D. J. Gochis. 2017. Effects of Water-Table Configuration on the Planetary Boundary Layer over the San Joaquin River Watershed, California. Journal of *Hydrometeorology* 18, no. 5: 1471-1488.

Gilbert, J. M., and R. M. Maxwell. 2018. Contrasting warming and drought in snowmelt-dominated agricultural basins: revealing the role of elevation gradients in regional response to temperature change. *Environmental Research Letters* 13, no. 7: 074023.

Griffin, D., and K. J. Anchukaitis. 2014. How unusual is the 2012–2014 California drought? *Geophysical Research Letters* 41, no. 24: 9017-9023.

Gruber, A., W. Dorigo, W. Crow, and W. Wagner. 2017. Triple Collocation-Based Merging of Satellite Soil Moisture Retrievals. *IEEE Transactions on Geoscience and Remote Sensing* 55, no. 12: 6780-6792.

Gruber, A., T. Scanlon, R. van der Schalie, W. Wagner, and W. Dorigo. 2019. Evolution of the ESA CCI Soil Moisture climate data records and their underlying merging methodology. *Earth System Science Data* 11, no. 2: 717-739.

Hanak, E., Lund, J., Arnold, B., Escriva-Bou, A., Gray, B., Green, S., Harter, T., Howitt, R., MacEwan, D., Medellín-Azuara, J., Moyle, P., and N. Seavy. 2017. Water stress and a changing San Joaquin Valley. Public Policy Institute of California.

Hanson, R., Schmid, W., Faunt, C., and B. Lockwood. 2010. Simulation and Analysis of Conjunctive Use with MODFLOW's Farm Process. *Groundwater* 48, no. 5: 674-689.

Howitt, R., Medellín-Azuara, J., MacEwan, D., Lund, J. R., and D. Sumner. 2014. Economic analysis of the 2014 drought for California agriculture. University of California Center for Watershed Sciences. Davis, California.

Jenkins, M.W., Lund, J.R., Howitt, R.E., Draper, A.J., Msangi, S.M., Tanaka, S.K., Ritzema, R.S. and G.F. Marques. (2004). Optimization of California's Water Supply System: Results and Insights. *Journal of Water Resources Planning and Management* 130, no. 4: 271-280.

Johnson, R., B.A. Cody. 2015. California agricultural production and irrigated water use. Congressional Research Service Report R44093: 20.

Kalf, F. R., and D. R. Woolley. 2005. Applicability and methodology of determining sustainable yield in groundwater systems. *Hydrogeology Journal* 13, no. 1: 295–312.

Kendy, E., and J. D. Bredehoeft. 2006. Transient effects of groundwater pumping and surface-water-irrigation returns on streamflow. *Water Resources Research* 42, no. 8

Keune, J., Gasper, F., Goergen, K., Hense, A., Shrestha, P., Sulis, M., and S. Kollet. 2016. Studying the influence of groundwater representations on land surface-atmosphere feedbacks during the European heat wave in 2003. *Journal of Geophysical Research: Atmospheres* 121, no.22: 13-301.

Kollet, S. J., and R. M. Maxwell. 2006. Integrated surface–groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. *Advances in Water Resources* 29, no. 7: 945-958.

Kollet, S. J., and R. M. Maxwell. 2008. Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model. *Water Resources Research* 44, no. 2: W02402.

Landerer F.W. and S. C. Swenson. 2012. Accuracy of scaled GRACE terrestrial water storage estimates. *Water Resources Research* 48, no. 4.

Maxwell, R. M. (2013). A terrain-following grid transform and preconditioner for parallel, large-scale, integrated hydrologic modeling. *Advances in Water Resources* 53: 109-117.

Maxwell, R. M., and N. L. Miller. 2005. Development of a Coupled Land Surface and Groundwater Model. *Journal of Hydrometeorology* 6, no. 3: 233-247.

Maxwell, R. M., and S. J. Kollet. 2008. Interdependence of groundwater dynamics and land-energy feedbacks under climate change. *Nature Geoscience* 1, no. 10: 665-669.

Maxwell, R. M. 2013. A terrain-following grid transform and preconditioner for parallel, large-scale, integrated hydrologic modeling. *Advances in Water Resources* 53: 109-117.

Maxwell, R.M., Putti, M., Meyerhoff, S., Delfs, J.O., Ferguson, I.M., Ivanov, V., Kim, J., Kolditz, O., Kollet, S.J., Kumar, M. and S. Lopez. 2014. Surface-subsurface model intercomparison: A first set of benchmark results to diagnose integrated hydrology and feedbacks. *Water Resources Research* 50, no. 2: 1531-1549.

Maxwell, R. M., Condon, L. E., Kollet, S. J., Maher, K., Haggerty, R., M. M. Forrester. 2016. The imprint of climate and geology on the residence times of groundwater. *Geophysical Research Letters* 43, no. 2: 701-708.

Messer, C., Stock, C., and T. Averill. 2016. California Agricultural Statistics Review 2015–2016. California Department of Food and Agriculture. Sacramento, California.

Mitchell, K. E., Lohmann, D., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A., Cosgrove, B. A., Sheffield, J., Duan, Q., Luo, L. and R. W. Higgins. (2004). The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. J*ournal of Geophysical Research: Atmospheres* 109, no. D7.

Mu, Q., Heinsch, F., Zhao, M., and S. W. Running. 2007. Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote Sensing of Environment* 111, no. 4: 519-536.

Mu, Q., Heinsch, F., Zhao, M., and S. W. Running. 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sensing of Environment* 115, no. 8: 1781-1800.

National Operational Hydrologic Remote Sensing Center. 2004. Snow Data Assimilation System (SNODAS) Data Products at NSIDC, Version 1. Boulder, Colorado. NSIDC: National Snow and Ice Data Center.

Pan, M., Cai, X., Chaney, N. W., Entekhabi, D., and E. F. Wood. 2016. An initial assessment of SMAP soil moisture retrievals using high-resolution model simulations and in situ observations. *Geophysical Research Letters* 43, no. 18: 9662-9668.

Sakumura, C., Bettadpur, S., and S. Bruinsma. 2014. Ensemble prediction and intercomparison analysis of GRACE time-variable gravity field models. *Geophysical Research Letters* 41, no. 5: 1389-1397.

Scanlon, B.R., Reedy, R.C., Stonestrom, D.A., Prudic, D.E. and K. F. Dennehy. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology* 11, no. 10: 1577-1593.

Scanlon, B., Longuevergne, L., and D. Long. 2012. Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA. *Water Resources Research* 48, no. 4.

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., and P. B. McMahon. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences* 109, no. 24: 9320-9325.

Seck, A., Welty, C., and R. M. Maxwell. 2015. Spin-up behavior and effects of initial conditions for an integrated hydrologic model. *Water Resources Research* 51, no. 4: 2188–2210.

Shukla, S., Safeeq, M., AghaKouchak, A., Guan, K., and C. Funk. 2015. Temperature impacts on the water year 2014 drought in California. *Geophysical Research Letters* 42, no. 11: 4384-4393.

Sulis, M., Williams, J. L., Shrestha, P., Diederich, M., Simmer, C., Kollet, S. J., and R. M. Maxwell. 2017. Coupling groundwater, vegetation, and atmospheric processes: a comparison of two integrated models. *Journal of Hydrometeorology* 18, no. 5: 1489-1511.

S.C. Swenson. 2012. GRACE monthly land water mass grids NETCDF RELEASE 5.0. Ver. 5.0. PO.DAAC, CA, USA. Dataset accessed January 30, 3018 at http://dx.doi.org/10.5067/TELND-NC005.

Swenson, S. C. and J. Wahr. 2006. Post-processing removal of correlated errors in GRACE data. Geophysical Research Letters 33: L08402.

Tweed, S., Leblanc, M., and I. Cartwright. 2009. Groundwater–surface water interaction and the impact of a multi-year drought on lakes conditions in South-East Australia. *Journal of Hydrology* 379 no. 1–2: 41–53.

U.S. Geological Survey (USGS). 2016. National Water Information System data available on the World Wide Web (USGS Water Data for the Nation), accessed March 28, 2019, at URL http://waterdata.usgs.gov/nwis/.

Voss, K. A., Famiglietti, J. S., Lo, M., Linage, C., Rodell, M., and S. C. Swenson. 2013. Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. *Water Resources Research* 49 no. 2: 904–914.

Watkins, M. M., Wiese, D. N., Yuan, D. N., Boening, C., and F. W. Landerer. 2015. Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. *Journal of Geophysical Research: Solid Earth* 120 no. 4: 2648-2671.

Wiese, D. N. 2015. GRACE Monthly Global Water Mass Grids NetCDF Release 5.0. Ver. 5.0. PO. DAAC, CA, USA.

Wiese, D. N., Landerer, F. W., and M. M. Watkins. 2016. Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution. *Water Resources Research* 52 no. 9: 7490-7502.

Acknowledgments

This work was supported by the National Science Foundation under Grant No. 1805160. We would like to acknowledge high-performance computing support from Cheyenne (doi:10.5065/D6RX99HX) provided by NCAR's Computational and Information Systems

Laboratory, sponsored by the National Science Foundation. GRACE land are available at http://grace.jpl.nasa.gov, supported by the NASA MEaSUREs Program.

Figure Text

Figure 1: San Joaquin River Basin Model Domain. (a) overview of the SJBM domain within California (b) CVHM groundwater basin locations used to estimate groundwater extraction rates (c) land cover type highlighting irrigated crop land; and (d) difference between the initial model state for the natural condition and depleted water table simulations.

Figure 2: Daily average water storage in equivalent depth averaged over the San Joaquin River Basin Model Domain. (a) groundwater storage changes more than 2 m below the ground surface (b) surface water flows (c) soil moisture within 2m of the surface compared to remote sensing data product from ESA CCI; and (d) SWE storage compared to SNODAS. The recent drought period, from 2012 through 2015 is delineated by grey shading.

Figure 3: Average annual trends in major water storage components: groundwater and soil moisture, and average annual values in major water fluxes: groundwater pumping, surface water flow, transpiration, ET, applied irrigation, and precipitation, over the drought period (2012-2015) presented as domain averaged equivalent water depths.

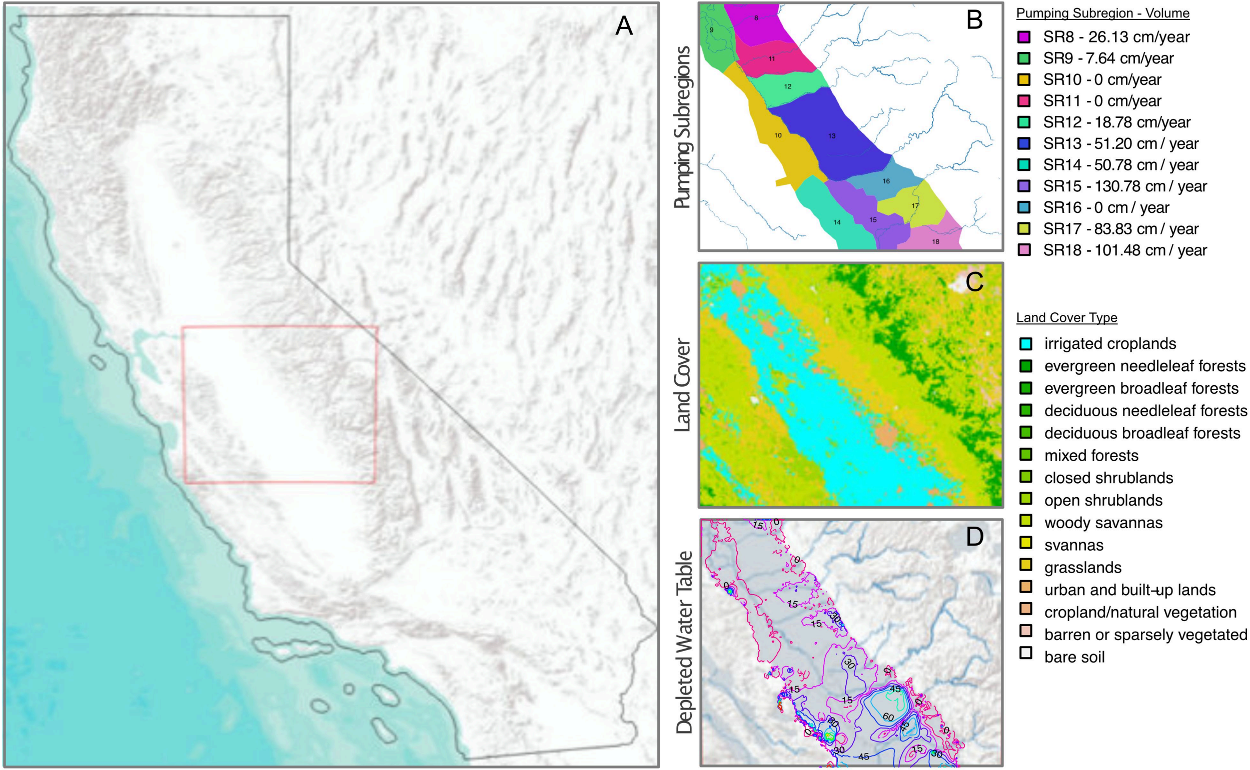
Figure 4: Total Water Storage Change over water years 2010 through 2016. ParFlow simulation Results are shown as daily domain averages compared to GRACE solution average monthly values.

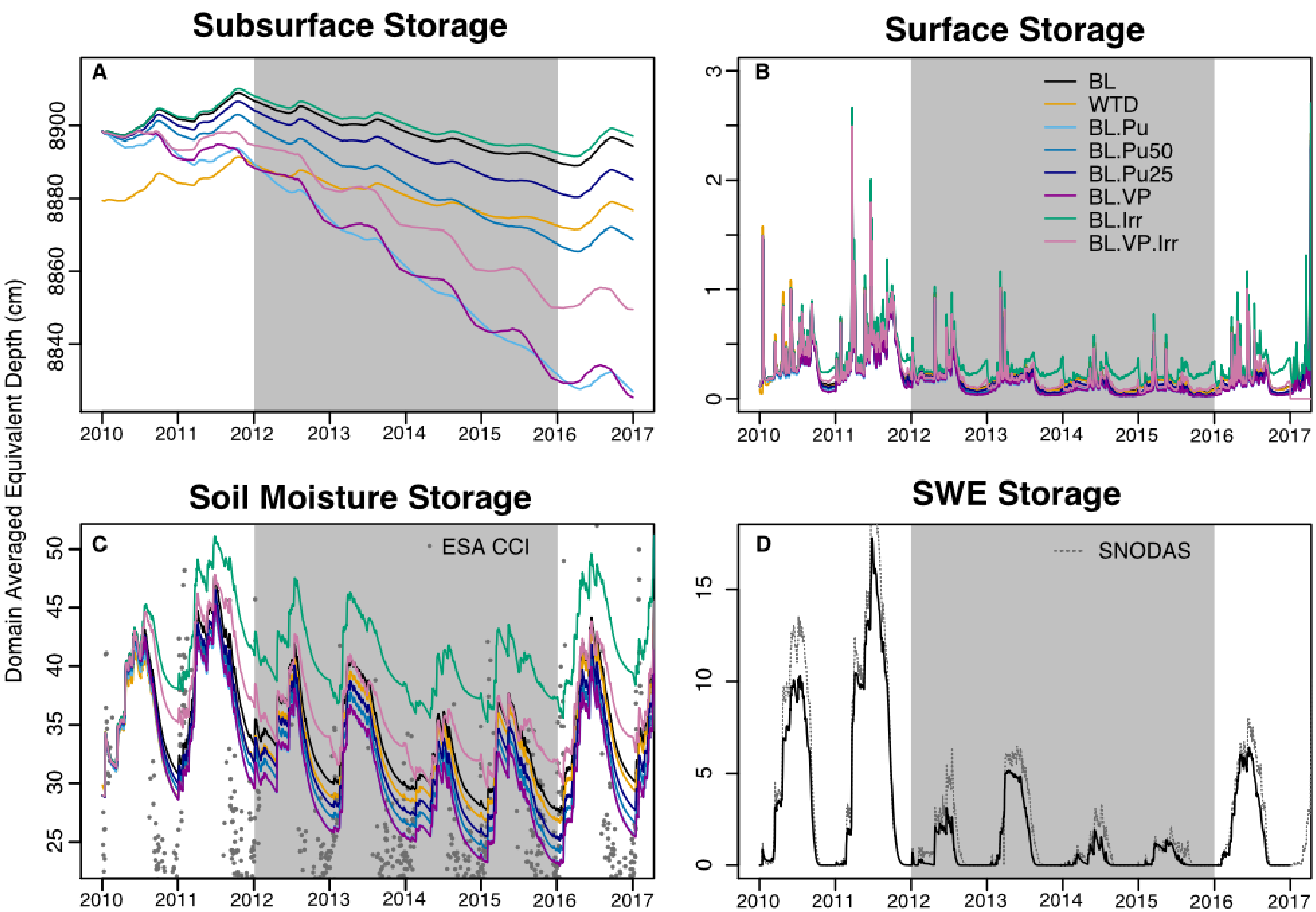
Figure 5: Monthly comparison of GRACE TWSA and ParFlow-CLM modeled total water (PF-TS), groundwater (PF-GW), soil moisture (PF-SM), surface water (PF-SW) and SWE (PF SWE) storage

anomalies. Monthly storage anomalies are normalized to their respective annual average storage.

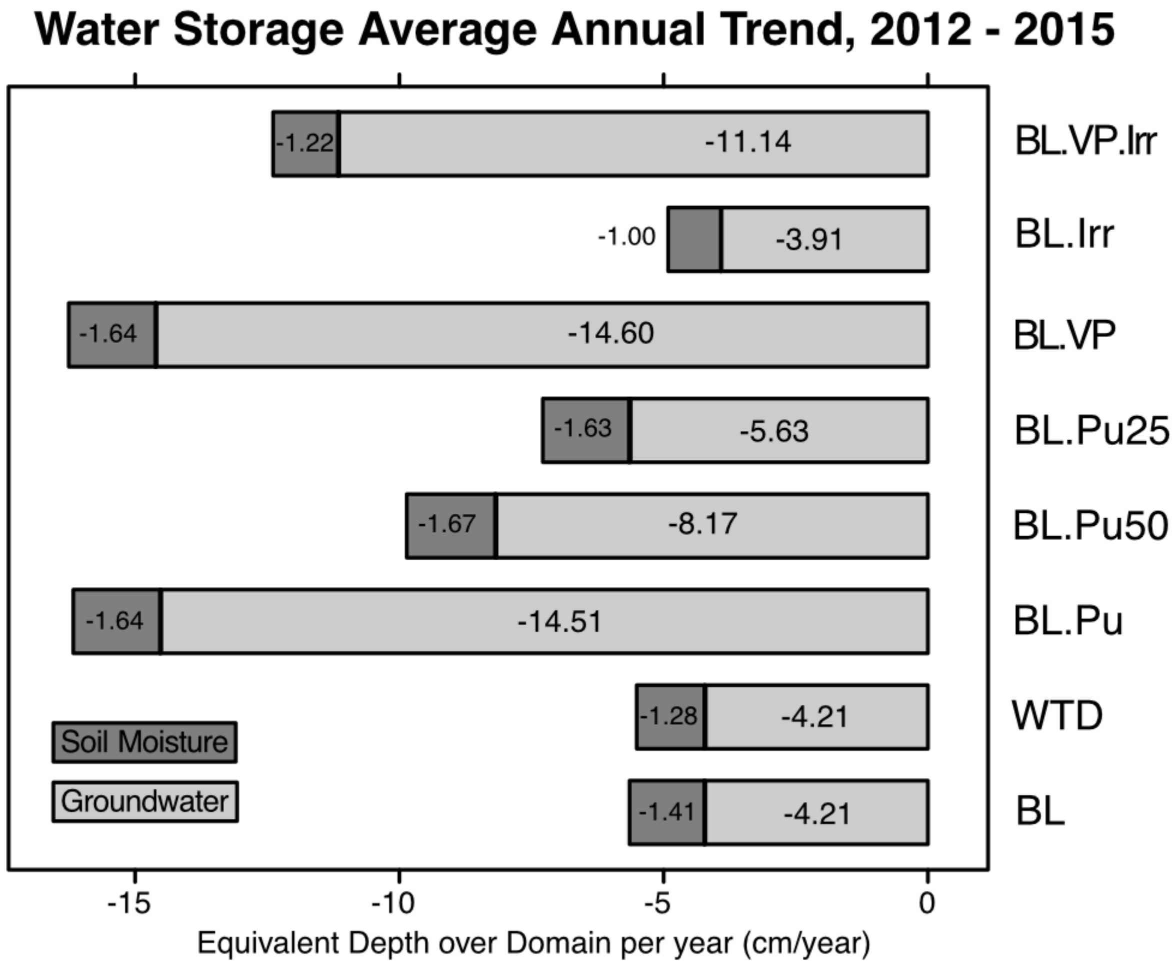
Figure 6: Impacts of water use activities on annual accumulated surface water flows and evapotranspiration over the model domain. Evapotranspiration results are presented as total annual accumulated ET over the drought (a), difference from baseline (b), and daily accumulated ET for water years 2011 (c) and 2014 (d). ET results are compared to MODIS monthly ET estimates. Surface water flows are presented as annually accumulated flow for the drought period (e), annual accumulated flow difference from baseline (f) and for water years 2011(g) and 2014 (h). Surface flows are compared to the USGS gage at the San Joaquin River at Vernalis, near the modeled San Joaquin River Basin domain outlet.

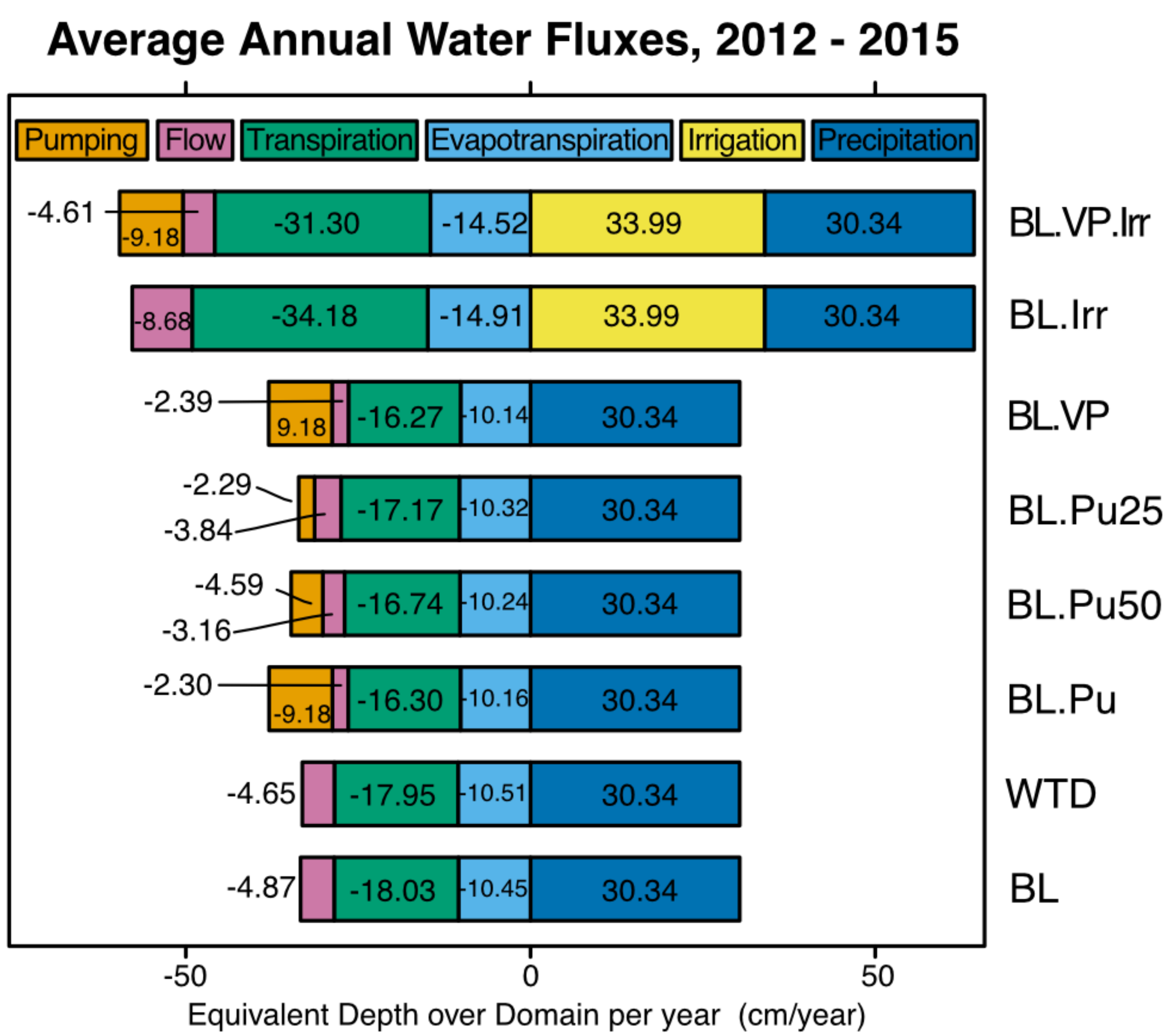
Figure 7: Average water flux between surface and subsurface along 5-km stretches of the San Joaquin River in the SJBM domain. Negative values indicate flow of water into the subsurface (losing stream), positive values indicate flow from the subsurface to the surface (gaining stream).

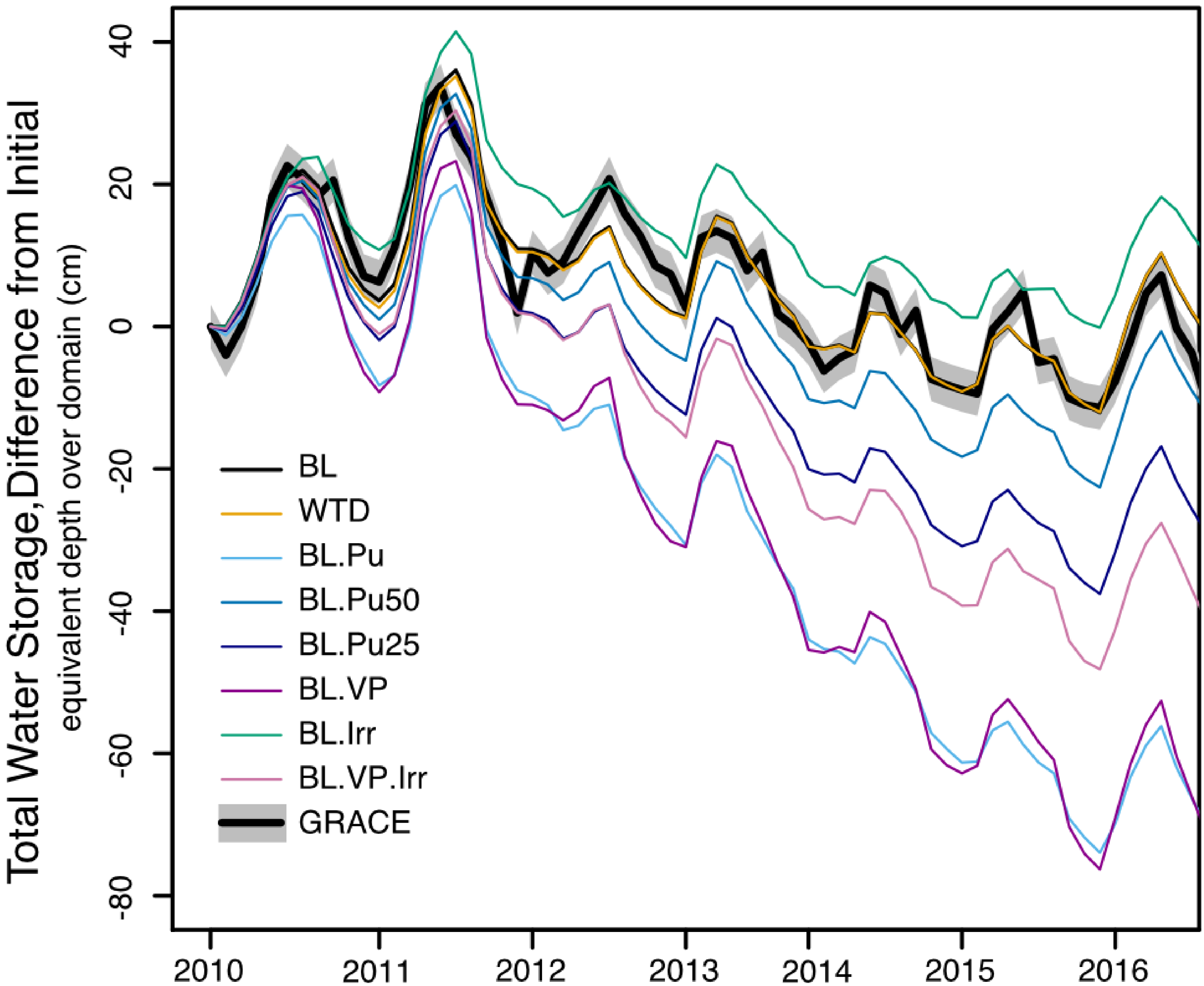

A
B
Pumping Subregions
Pumping Subregion - Volume
SR8 - 26.13 cm/year
SR9 - 7.64 cm/year
SR10 - 0 cm/year
SR11 - 0 cm/year
SR12 - 18.78 cm/year
SR13 - 51.20 cm / year
SR14 - 50.78 cm / year
SR15 - 130.78 cm / year
SR16 - 0 cm / year
SR17 - 83.83 cm / year
SR18 - 101.48 cm / year
C
Land Cover
Land Cover Type
irrigated croplands
evergreen needleleaf forests
evergreen broadleaf forests
deciduous needleleaf forests
deciduous broadleaf forests
mixed forests
closed shrublands
open shrublands
woody savannas
svannas
grasslands
urban and built-up lands
cropland/natural vegetation
barren or sparsely vegetated
bare soil
D
Depleted Water Table



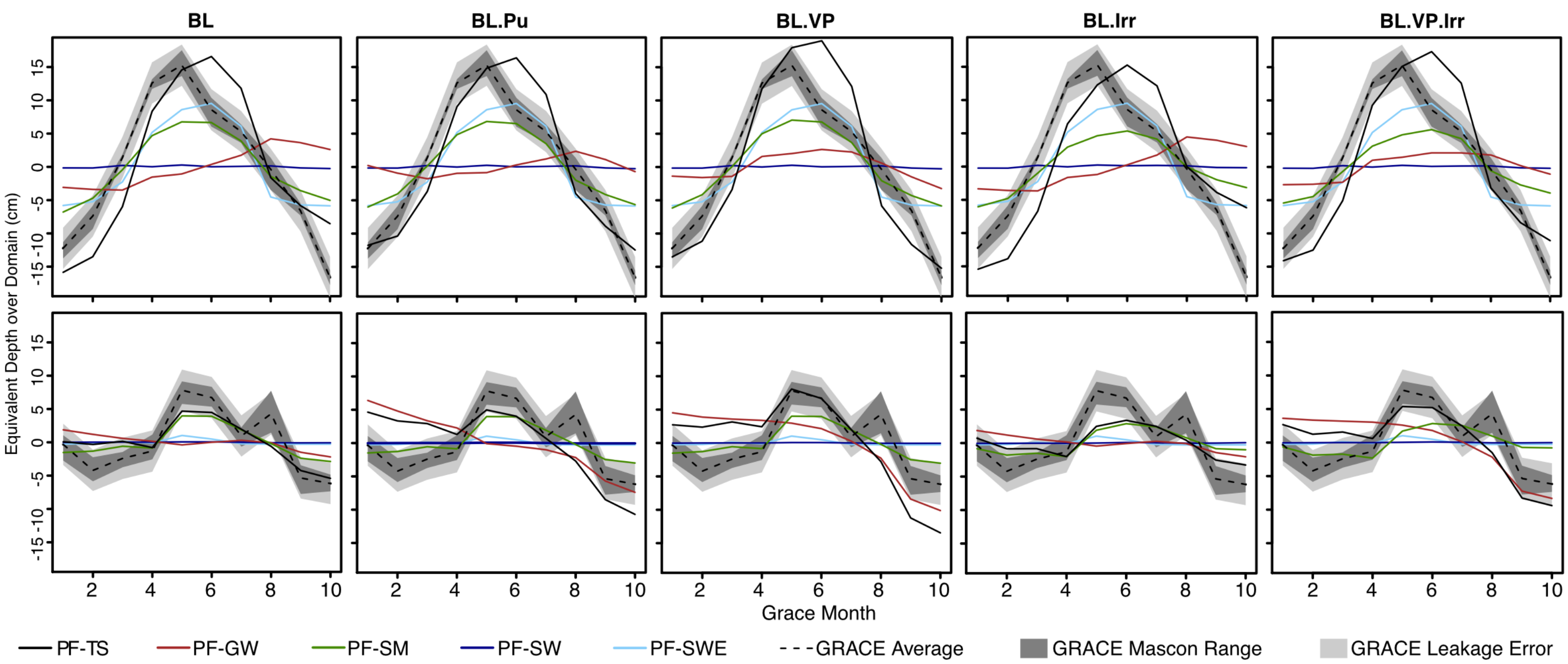
Subsurface Storage
A
Surface Storage
B
BL
WTD
BL.Pu
BL.Pu50
BL.Pu25
BL.VP
BL.Irr
BL.VP.Irr
Soil Moisture Storage
C
ESA CCI
SWE Storage
D
SNODAS
Domain Averaged Equivalent Depth (cm)


Water Storage Average Annual Trend, 2012 - 2015
-1.22
-11.14
BL.VP.Irr
-1.00
-3.91
BL.Irr
-1.64
-14.60
BL.VP
-1.63
-5.63
BL.Pu25
-1.67
-8.17
BL.Pu50
-1.64
-14.51
BL.Pu
-1.28
-4.21
WTD
Soil Moisture
Groundwater
-1.41
-4.21
BL
-15
-10
-5
0
Equivalent Depth over Domain per year (cm/year)

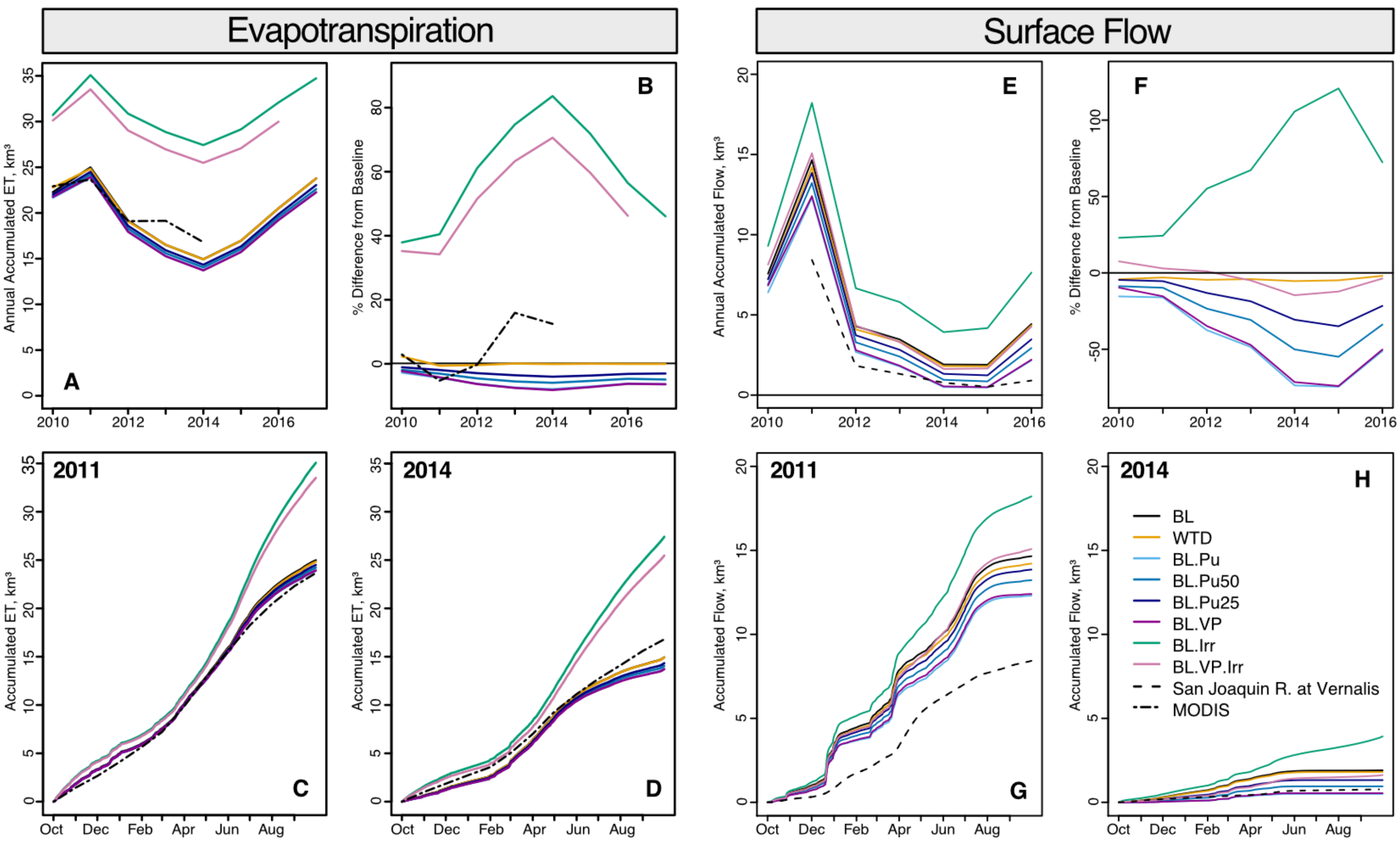

Average Annual Water Fluxes, 2012 - 2015
Pumping
Flow
Transpiration
Evapotranspiration
Irrigation
Precipitation
-4.61
-9.18
-31.30
-14.52
33.99
30.34
BL.VP.Irr
-8.68
-34.18
-14.91
33.99
30.34
BL.Irr
-2.39
9.18
-16.27
-10.14
30.34
BL.VP
-2.29
-3.84
-17.17
-10.32
30.34
BL.Pu25
-4.59
-3.16
-16.74
-10.24
30.34
BL.Pu50
-2.30
-9.18
-16.30
-10.16
30.34
BL.Pu
-4.65
-17.95
-10.51
30.34
WTD
-4.87
-18.03
-10.45
30.34
BL
-50
0
50
Equivalent Depth over Domain per year (cm/year)

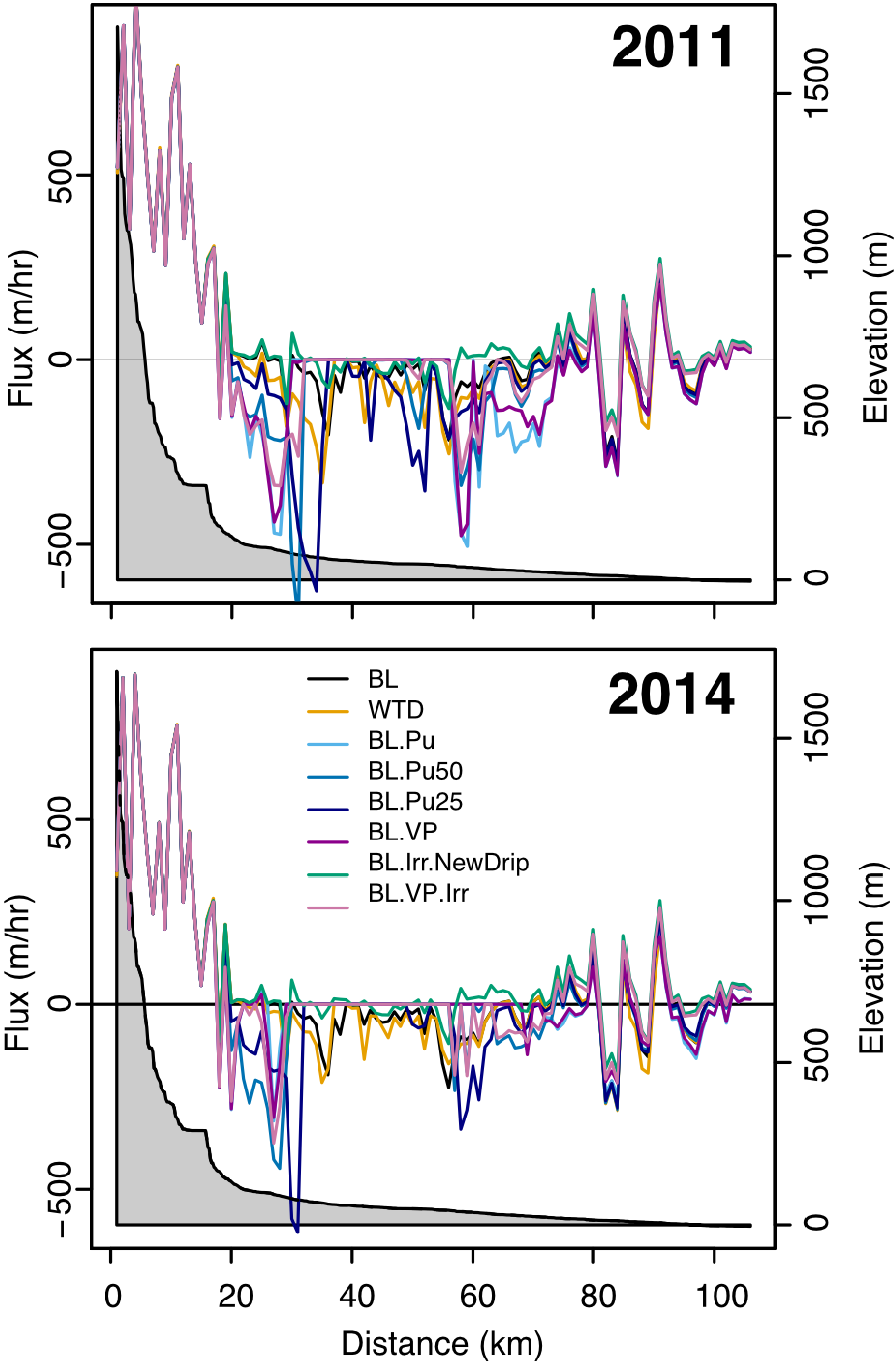


Total Water Storage,Difference from Initial
equivalent depth over domain (cm)
40
20
0
-20
-40
-60
-80
2010
2011
2012
2013
2014
2015
2016
BL
WTD
BL.Pu
BL.Pu50
BL.Pu25
BL.VP
BL.Irr
BL.VP.Irr
GRACE



BL
BL.Pu
BL.VP
BL.Irr
BL.VP.Irr
2011
2014
Equivalent Depth over Domain (cm)
Grace Month
PF-TS
PF-GW
PF-SM
PF-SW
PF-SWE
GRACE Average
GRACE Mascon Range
GRACE Leakage Error


Evapotranspiration
Surface Flow
A
B
C
D
E
F
G
H
2011
2014
Annual Accumulated ET, km³
% Difference from Baseline
Annual Accumulated Flow, km³
Accumulated ET, km³
Accumulated Flow, km³
Oct
Dec
Feb
Apr
Jun
Aug
BL
WTD
BL.Pu
BL.Pu50
BL.Pu25
BL.VP
BL.Irr
BL.VP.Irr
San Joaquin R. at Vernalis
MODIS



2011
2014
BL
WTD
BL.Pu
BL.Pu50
BL.Pu25
BL.VP
BL.Irr.NewDrip
BL.VP.Irr
Flux (m/hr)
Elevation (m)
Distance (km)
500
0
−500
1500
1000
500
0
20
40
60
80
100