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Simulating the pre-development hydrologic conditions in the San Joaquin Valley, California

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SUMMARY

The San Joaquin Valley (SJV) in central California has significant water management concerns given the high water demand for an increasing state population and for intense irrigation. The groundwater-surface water system in the area has undergone drastic changes since the employment of groundwater and surface water extractions for irrigation and mining, and is still responding to past and present stresses. In this study, we develop a pre-development hydrologic model of the SJV to serve as an appropriate initial state to analyze the influence of historic anthropogenic stresses. Specifically, the physically-based surface–subsurface numerical HydroGeoSphere model is used to examine the regional-scale hydrologic budget of the SJV at pre-development conditions, constrained by available historical data. As a result, complex hydrologic processes, including groundwater-surface water interaction along the major rivers and within wetland areas formed by flooded surface water, as well as evapotranspiration (ET) and impacted root zone processes were identified in the area. The presence and path of the major rivers in the domain are well defined in the model output. The general location and formation of the major wetlands simulated by the model, and the hydrologic processes that occurred within them have a fair agreement with historical records. There is also a fair match between simulated and estimated water table elevations. ET is a significant sink of both surface water and groundwater (44.8% of the water balance input). Successful simulation of the complex hydrologic processes and features, and the water balance of the natural system underscores the importance and necessity of using an integrated model, especially when available data is limited for input and calibration. This pre-development hydrologic condition should serve as a reasonable initial state for future transient runs that bring the model up to current hydrologic conditions capable of estimating present and future water budgets.

1. Introduction

The San Joaquin Valley (SJV), part of the Great Central Valley of California, has been subjected to evolving hydrologic and hydrogeologic conditions since the development of irrigated agriculture began in the 1800s and since the Gold Rush of 1849. Presently the SJV is highly developed, with the majority of the land being used for agriculture. The SJV can be thought of as 'the nation's salad bowl' (CERES, 2007), supplying a significant proportion of all food consumed in the United States (University of California Agricultural Issues Center, 2009). The proportion of water supply derived from either groundwater or surface water has varied throughout time and has been dependent on various factors such as climate conditions, new technology, land development, population growth, water policy and law, water transport methods, and government initiatives/projects (Williamson et al., 1989). Agriculture and highly populated areas make reliability of the groundwater and surface water resources of the SJV a major issue at a regional scale. Water quality and ecosystem health are also significant issues that emphasize the need for a high level of regional-scale water resource management and planning. The onset of climate change as well as uncertain population growth underscores the value of predicting the future availability of water resources.

In the SJV, the groundwater and surface water flow system has undergone considerable change since the development of irrigated agriculture. The present-day flow system is responding to both the past and the present anthropogenic stresses and alterations (Belitz and Heimes, 1990). Significant land subsidence has occurred, changing the surface topography and subsurface setting in the SJV, primarily due to massive groundwater pumping for irrigation (Williamson et al., 1989). The surface water system of the valley has changed drastically as well. Due to the dynamic and ever changing nature of the groundwater and surface water systems of the valley, it is necessary to understand the hydrologic conditions of the natural system before large-scale mining and irrigation, and before major surface water and groundwater extractions were enacted. A pre-development hydrologic condition can be a reasonable initial

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state in order to understand transient conditions up to the present day, and for estimating present and future water budgets.

Evapotranspiration (ET), groundwater and surface water interaction, groundwater recharge and discharge rates and patterns, and wetland formation and distribution are important processes in the SJV river valley system. Thus, in order to establish a pre-development hydrologic model for the SJV, simultaneous analysis of surface and subsurface water flow, including their interactions, is crucial. Numerous hydrologic modeling studies that concern the SJV or the entire Central Valley have been completed by others (Williamson et al. 1989; Phillips and Belitz, 1991; Belitz and Phillips, 1995; Burow et al., 1999; Weissmann et al., 1999; Quinn et al., 2001, 2004; Brekke et al., 2004; Brush et al., 2004; Burow et al., 2004; Lee et al., 2007; Phillips et al., 2007). While these studies have provided useful conceptual and physical data, they either do not incorporate a true pre-development condition, do not consider as large an area, or do not use a physically-based surface–subsurface hydrologic model that meets the Freeze and Harlan (1969) blueprint, as in this study. Therefore, the objective and novel contribution of this study is to: (1) develop a regional-scale integrated surface–subsurface model of a large portion of the SJV at a pre-development hydrologic condition that can provide an appropriate initial state to analyze the influence of past, present, and future anthropogenic stresses imposed on the system; and (2) characterize the water balance of the pre-development hydrologic system, consistent with historical data concerning river flows, recharge and discharge of both groundwater and surface water, precipitation, ET, and the nature of wetlands. To meet the objectives of this investigation, a physically-based surface–subsurface hydrologic HydroGeoSphere simulator (Therrien et al., 2007) was applied to the SJV study area. HydroGeoSphere meets the Freeze and Harlan (1969) blueprint of a physically-based surface–subsurface hydrologic model and is capable of addressing regional-scale groundwater and surface water management issues.

This study focuses on the combined surface water and groundwater regimes to identify and simulate important hydrological processes and features at a watershed scale, with no calibration efforts due to the limited amount of data that is available for parameterization and calibration of the model. The fully-integrated hydrologic modeling approach provides a simple and effective framework to capture the complex behavior of the hydrologic system based on pre-established constitutive relationships, and constrained by watershed-scale estimates of material balance components of the historic hydrologic cycle.

2. San Joaquin Valley at pre-development conditions

The SJV is more than 400 km long, 40–90 km wide, and makes up the southern two-thirds of the Central Valley of California, with the other third in the north being the Sacramento Valley (Phillips et al., 2007). The SJV is bounded by the delta of the Sacramento and San Joaquin Rivers on the north, the Tehachapi Mountains on the south, the Coast Ranges on the west, and the Sierra Nevada on the east. The location and boundary of the study area are shown in Fig. 1a along with a topography map of San Joaquin Valley in Fig. 1b. Fig. 1 shows that the domain boundary corresponds with surface water flow divides and topographic features such as mountain ranges. The area is about 17,232 km^2 and partly contains edges of the Sierra Nevada and the Coast Ranges.

The pre-development conceptual model for the groundwater and surface water system in the SJV describes the topographic, climatic, hydrological, hydrogeologic, and geological factors that influence groundwater and surface water flow within the system before the anthropogenic perturbations. In this study, it is assumed that the influence of the water resource development on the SJV climate is negligible. Therefore, the long-term average climatic condition within the SJV is a reasonable input to analyze the historic influence of the anthropogenic perturbations associated with the development. Thus, this model incorporates: (1) a long-term average climatic condition involving estimates of precipitation and potential ET, (2) a pre-development topography and subsurface hydrostratigraphy which has been corrected to account for land subsidence caused by massive groundwater pumping and irrigation, (3) a pre-development hydrologic condition such as river flow before the implementation of highly regulated water management or conveyance structures, and (4) pre-development land use and land cover that may be significant for overland flow, actual ET, and recharge/discharge patterns in the SJV. The following sections will describe the pre-development conditions estimated from the existing data and the way they are estimated.

2.1. Long-term average climatic conditions

The spatial distribution of annual average precipitation in the area was estimated using a PRISM (Parameter-elevation Regressions on Independent Slopes Model) data set (PRISM Group, 2008) (see Fig. 2a). PRISM is a climate analysis system that uses time-series data from meteorological stations, a digital elevation model (DEM), and other spatial datasets to generate gridded

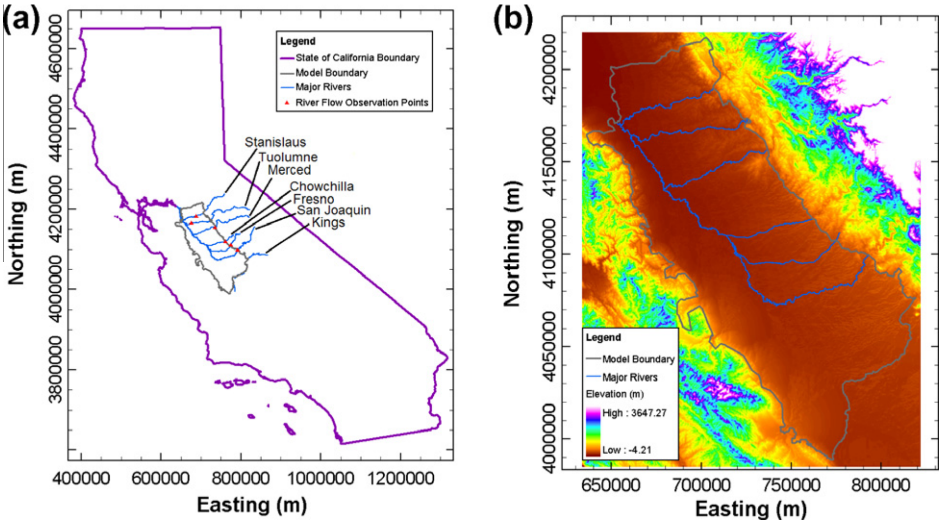

Fig. 1. (a) The location and boundary of the San Joaquin Valley study area and (b) present day topography for the San Joaquin Valley [spatial data from US Geological Survey (1999)].

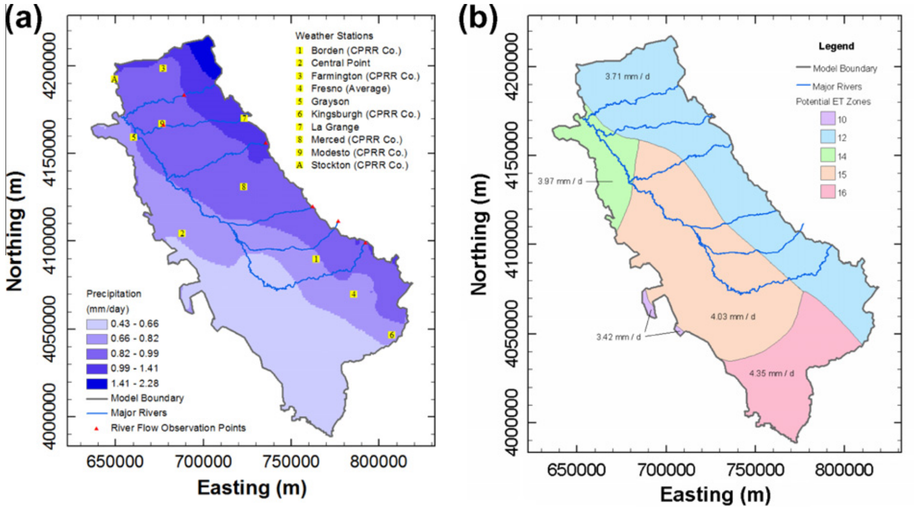

Fig. 2. The spatial distributions of (a) annual average precipitation (PRISM Group, 2008) and (b) potential evapotranspiration (California Department of Water Resources (DWR) et al. (1999)) in the study area at a pre-development condition.

estimates of annual, monthly and event-based climatic parameters (Daly et al., 1994). It employs a coordinated set of rules, decisions, and calculations, designed to approximate the decision-making process that an expert climatologist would invoke when creating a climate map (Daly et al., 1997). According to Schmidt and Lawrence (2000), PRISM data are the most detailed, highest-quality spatial climate datasets currently available.

Currently, PRISM provides precipitation data for the US from the late 1800s to present. In the SJV region, the longest period of averaged precipitation data available using PRISM is for the period 1971–2000. This recent 30-year data set is assumed to be representative of the pre-development climatic conditions in the absence of a more reliable representative data set, and under the assumption that simulated changes to the local hydrology of the SJV do not impact the local climate in terms of the amount and spatial distribution of precipitation. Using averaged precipitation data to establish an initial condition for a hydrologic model removes temporal and spatial details in the response of groundwater and surface water flow patterns to individual and even seasonal precipitation events. However, averaged precipitation data can be used to establish the hydrologic response of the system in a spatially-averaged sense, and provide a close characterization of groundwater and surface water flow patterns under normal climate conditions.

Precipitation values from the gridded PRISM data set were extracted to the two-dimensional model element centroid using a GIS tool involving interpolation of the values near the centroid. Comparison of the PRISM data set with historical station records (Hall, 1886: the oldest precipitation data readily available) implies that the PRISM data is generally representative of slightly wetter conditions compared to the historic records. Historical weather station (Hall, 1886) locations are plotted in the model domain (Fig. 2a), with values from the PRISM data set provided on Table 1 for comparison. This small sample comparison (10 points) shows the difference in the two data sets varies from 0.01 to 0.27 mm/d. In addition, the spatially-averaged rate of precipitation from the PRISM data set were compared to a mean annual precipitation map representing the period 1911–1960 (Gronberg et al., 1998, after Rantz, 1969). When the PRISM precipitation rates are multiplied by the receiving areas of the watershed to which they are applied, the resulting inflow is approximately 13,626,723 m^3/d. If one divides this precipitation inflow by the entire area of the model domain, the resulting spatially averaged rate of precipitation is 0.79 mm/d. Averaging the midpoints of the two precipitation zones that cover the Gronberg et al. (1998) mean annual precipitation map in roughly equal proportions yields a spatially averaged precipitation estimate of 0.78 mm/d. Consequently, the 30-year PRISM data set does appear representative of the long-term averaged precipitation conditions. In Fig. 2a, the least amount of precipitation falls in the southern portion of the San Joaquin Valley at roughly 0.43–0.66 mm/d, and the highest amount of precipitation falls in the northern portion of the San Joaquin Valley (north-eastern part of model domain) at roughly 1.41–2.28 mm/d.

Table 1
Comparison of PRISM and historical precipitation data.

Hall (1886)					PRISM Group (2008)[b]
Station name	Years used	County	Page no.	Precipitation (mm/d)	Precipitation (mm/d)
Fresno (average)	1877–1884	Fresno	185	0.60	0.81
Borden (CPRR Co.)	1875–1884	Fresno[a]	184	0.60	0.82
Kingsburgh (CPRR Co.)	1878–1884	Fresno	185	0.61	0.75
Merced (CPRR Co.)	1871–1884	Merced	188	0.73	0.87
Central Point	1879–1884	Merced	188	0.65	0.69
Stockton (CPRR Co.)	1870–1884	San Joaquin	194	0.96	0.97
Farmington (CPRR Co.)	1876–1884	San Joaquin	194	1.05	0.92
La Grange	1869–1884	Stanislaus	197	1.09	1.00
Grayson	1870–1884	Stanislaus	197	0.82	0.82
Modesto (CPRR Co.)	1870–1884	Stanislaus	197	0.65	0.93

(CPRR Co.) – Central Pacific Rail Road Company.

[a] County name used by Hall (1886), presently called Madera.

[b] Extracted from annual average (1971–2000).

ET is a significant component of the total water budget for the entire area. Actual ET is a function of the degree of soil saturation and the potential ET (PET), which is determined by climatic factors as well as land cover/vegetation type, and soil properties. The PET zones are delineated on Fig. 2b following California Department of Water Resources (DWR) (1999), with values based on spatial data from Jones et al. (1999). These PET values are assigned to model elements that have their centroid within a given PET zone. Jones et al. (1999) calculated PET using a modified version of the Penman–Monteith equation (Pruitt and Doorenbos, 1977) and a wind function developed by California DWR (2009). The PET rates within the model domain range from 3.42 to 4.35 mm/d on an average annual basis, and are similar to the PET value of 3.41 mm/d reported by Bertoldi et al. (1991), and the average annual pan evaporation for the central part of the western SJV of more than 4.2 mm/d as reported by Belitz and Phillips (1995). On an annual basis, PET exceeds the total precipitation for any given year throughout the valley.

2.2. Pre-development topography: land subsidence adjustment

The present day topography for the study area was taken from 30 m resolution US Geological Survey National Elevation Dataset digital elevation model (USGS, 1999), and subsequently adjusted by available land subsidence data to represent pre-development topography. Irrigation with groundwater in the SJV increased rapidly in the 1920s and the timing coincides with the beginning of aquifer compaction (including clay lenses) and subsidence in the SJV. By 1972, the maximum amount of observed subsidence within the SJV had reached 8.84 m (Poland et al., 1975), and 9.05 m in 1982 (Ireland, 1986).

A land subsidence map provided by Poland et al. (1975) was used to provide subsidence values for the period 1926 to end of 1971 with these values being interpolated using ordinary kriging to estimate a spatial grid of the subsidence in the study area prior to 1972 (Fig. 3a). Point measurements of subsidence that occurred from 1972 to 2004 were provided by the California DWR (personal communications, 2008) and they were combined with published point data of subsidence that occurred from 1972 to 1982 (Ireland, 1986) to provide point subsidence values for the period 1972 to present. The post 1972 point estimates were collectively interpolated by inverse distance squared weighting to estimate a second spatial grid of subsidence. Data were extracted from the two subsidence grids to the model nodes and were added to the present day ground surface elevations in order to estimate the elevations prior to groundwater development and land subsidence.

2.3. Pre-development hydrologic conditions

The major rivers that flow into and through the model domain start from the Sierra Nevada in the east, their source mainly being mountain rainfall and snowmelt (Fig. 1). The highest model elevation is 677 m. Snowpack occurs at higher elevations in the Sierra Nevada which outside the model domain. Snow processes are not explicitly simulated in this study. The San Joaquin River (SJR) is the major river draining the SJV, with major tributaries joining it within the model domain.

The annual-averaged river inflow rates over the period from 1878 to 1884 are summarized by Hall (1886). Surface water diversions on some of the rivers were present by or before the time these measurements were recorded. However, the naturalized flow was estimated by taking measurements at locations upstream of diversions or by using scaling methods (Hall, 1886). These estimates include seasonal flow increases due to snow melt. The river flow estimates documented by Hall (1886) are perceived to be the oldest, and assumed to be most representative of pre-development conditions in the SJV. Averaging all data from 1878 to 1884, Hall (1886) shows that the SJR has the highest annual-averaged inflow rate in the area of 7,531,777 m^3/d, while the Chowchilla River has the lowest at 373,423 m^3/d. The total inflow rate for the six major rivers in the study area is 23,695,008 m^3/d. Parts of minor intermittent stream courses occur within this SJV hydrologic model. However, these minor streams are not simulated nor do they form from applied precipitation in the model. Intermittent streams would only flow during the winter rainy season, and some only after storm events (Bull, 1964). The minor stream flow paths, extents, naturalized flow rates, and measurement locations are not readily available. Intermittent streams change course often, making them difficult to correctly map and simulate. From the perspective of water supply for the SJV, Mendenhall et al. (1916) indicates that the contributions from the minor west-side streams are negligible. Provided sufficient data were available to resolve and simulate the minor streams in this model, better resolution of the water table, wetlands, and surface–subsurface interaction may be achieved. Outflow to the Sacramento-San Joaquin Delta is the only mode of natural discharge of surface or ground water from the system (Gronberg et al., 1998, after Bertoldi et al., 1991).

2.4. Pre-development land use and land cover

In order to characterize the SJV under pre-development conditions, one must delineate the natural vegetation types comprising

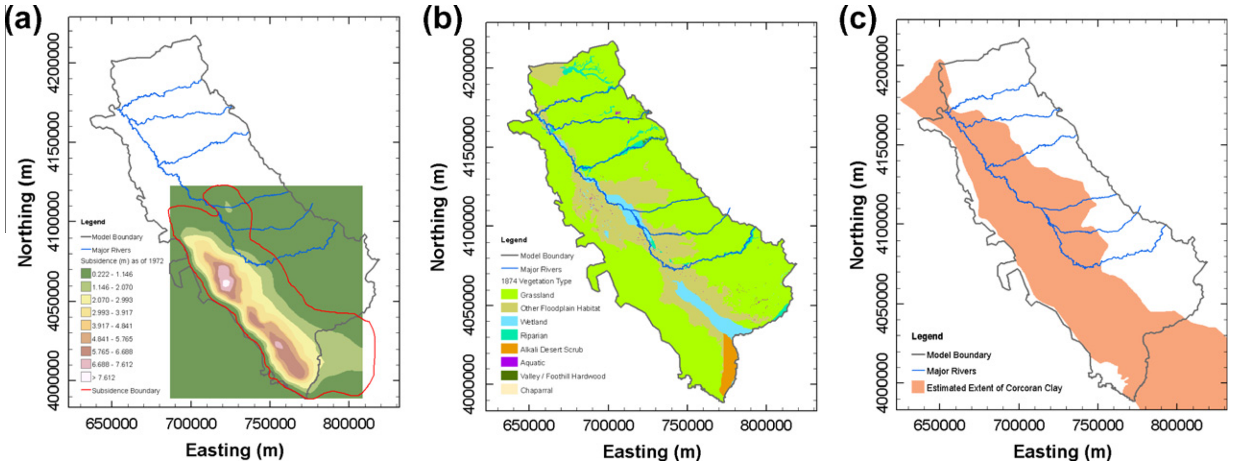

Fig. 3. The spatial distributions of (a) land subsidence estimated by collectively interpolating historical data sets and (b) vegetation type (mapped by California State University at Chico et al., 2003), and (c) the estimated extent of Corcoran Clay (Page, 1986).

the land cover. Pre-development natural vegetation types ca. 1874 were researched and mapped by California State University at Chico (2003) and they include (with% of land area covered); *grassland (70.4%)*, *other floodplain habitat (20.8%)*, *wetland (4.3%)*, *riparian (2.5%)*, *alkali desert scrub (1.5%)*, *aquatic (0.3%*, *valley/foothill hardwood (0.2%)*, and *chaparral (<0.01%)* (Fig. 3b). The distribution of *Wetland* vegetation type (covered roughly 749 km^2 in 1874) represents the distribution of wetland existing at a pre-development natural condition. This information will be used here to qualitatively validate the simulation results of the pre-development hydrologic condition, together with the distribution of the pre-development subsurface water table position.

2.5. Geology and hydrostratigraphy: land subsidence adjustment

Along the eastern part of the valley, the sediments are underlain by pre-Tertiary crystalline and metamorphic rocks of the Sierra Nevada (Davis and Poland, 1957). The sediments along the western portion of the eastern margin are thought to be underlain by a pre-Tertiary mafic and ultramafic complex (Cady, 1975). The Sierra Nevada is comprised of mainly granite and associated plutonic rocks, but also some metasedimentary and metavolcanic rocks (Bertoldi et al., 1991). The sediments on the western side of the valley are underlain by the folded and faulted, semi-consolidated to consolidated clastic sediments of the Coast Ranges. This sedimentary basement extends eastwards and thins out towards the Sierra Nevada (Page, 1986; Williamson et al., 1989). The geology of the overburden is characterized by unconsolidated and partially-consolidated lenses of sands and gravels interbedded with lenses of finer silts and clays. The upper part of the overburden deposits contains mostly fluvial deposits, some volcanic material, and some lacustrine deposits (Williamson et al., 1989). The most significant feature within the continental deposits is the Corcoran Clay, an extensive and well documented Pleistocene age lacustrine deposit. Spatial data concerning the extent, thickness, and depth to the top surface of the Corcoran Clay were provided by the US Bureau of Reclamation (BOR) based on maps by Page (1986; see Fig. 3c).

The hydrostratigraphy of the area contains two distinct units; the Corcoran Clay aquitard, and the main aquifer consisting of an upper zone (unconfined) and a lower zone (semi-confined to confined) with different hydraulic properties. The hydrogeological importance of appropriately accounting for the Corcoran Clay unit is well recognized, with its hydraulic properties being estimated in previous studies (Williamson et al., 1989; Phillips and Belitz, 1991; Phillips et al., 2007).

Because the land subsidence is primarily due to massive groundwater pumping, and because the upper aquifer zone materials and clay lenses represented by the Corcoran Clay unit have a much higher potential for compaction, subsidence is assumed here to influence the locations of the vertical boundaries between the upper aquifer and the Corcoran Clay unit. Therefore, the top surface of the Corcoran Clay as well as ground surface elevation were adjusted by the estimated land subsidence amount. Note that land subsidence is not simulated nor incorporated to dynamically adjust model elevations for modeling pre-development hydrologic conditions in SJV.

3. Numerical model

HydroGeoSphere is a comprehensive fully-integrated physically-based hydrologic model that accounts for three-dimensional variably-saturated subsurface flow and two-dimensional overland/stream flow, and that is capable of simulating ET in the root zone (Therrien et al., 2007). Two-dimensional triangular elements were used to discretize the surface domain of the study area, and then extended into the subsurface domain as 3D prism elements. The two-dimensional finite element mesh had a coarsest aerial dimension of approximately 3000 m, which was then refined along the centerline of the major rivers to approximately 60 m aerially to represent details of these main surface water features. The subsurface domain is discretized vertically to conform to the primary hydrostratigraphic units; surficial sediments in the unsaturated zone, upper unconsolidated aquifer zone, Corcoran Clay semi-confining unit, and lower unconsolidated aquifer zone. The upper and lower unconsolidated zones are part of one main aquifer, yet are distinguished based on their different material properties such as hydraulic conductivities and level of confinement. The model has a total of 11 layers; 5 layers to represent 5 m of surficial sediments, 3 layers to represent the upper unconsolidated aquifer zone, 1 layer to represent the Corcoran Clay, and 2 layers to represent the lower unconsolidated aquifer zone. Subsurface depth (total model thickness) ranges from 150 to 2215.5 m. The five 1 m thick surficial layers in the model are used to simulate the details of the root zone processes such as ET (Li et al., 2008), while having the same material properties as the upper aquifer zone. The remaining 6 model layers are of variable thickness. Layers in the upper aquifer zone range in thickness from 3 to 122 m. A pseudo thickness of 5 m was assigned to non-clay elements in the same layer as the Corcoran Clay, in order to represent the discontinuity (pinching out) of the clay. These non-clay pseudo elements were assigned material properties identical to that of the upper aquifer zone above the Corcoran Clay. The surface domain contains 36,138 nodes and 71,726 elements and the subsurface domain is made up of 289,104 nodes and 502,082 elements. The smallest elemental area is roughly 140.9 m^2 while the largest is roughly 7.54 km^2.

HydroGeoSphere utilizes a diffusion-wave approximation with a modified Manning's equation to simulate overland flow, based on parameters such as roughness coefficient (n), depression storage height (h_{ds}), and obstruction storage height (h_{os}) as summarized in Table 2. The model estimates actual ET based on the parameters for plant type (leaf area index (LAI), rooting depth (L_r), etc.) and soil type (wilting point (θ_{wp}), field capacity (θ_{fc}), oxic and anoxic limits (θ_o and θ_{an}), etc.) in conjunction with potential ET (E_p) values and water availability (moisture content, θ). Hydraulic parameters used to simulate overland flow and ET, and subsurface flow are taken from the literature and are summarized in Tables 2 and 3 (Chow, 1959; Abdul, 1985; Conley et al., 1991; Schroeder et al., 1994; Page, 1986; Hodgson, 2001; Sneed, 2001; White, 2003; Panday and Huyakorn, 2004; Jones, 2005; Steinwand et al., 2006; Nagler et al., 2007; Phillips et al., 2007). The theory behind HydroGeoSphere for simulating surface and subsurface flow and calculating ET is provided by Therrien et al. (2007).

In the model, water is not allowed to enter or exit the subsurface domain except via the land surface. The application of subsurface no flow boundary conditions is supported by the assumption that bedrock bounds the domain both along the east and west margins of the valley (east and west model bounds) and below the aquifer materials (model bottom), that the bedrock materials are essentially impermeable, and that the north and south ends of the model coincide with groundwater flow divides. The long-term (historical) mean inflow rates for the six major rivers were applied as a specified flux boundary condition at the centerline nodes where each river enters the surface of the model domain. A critical depth boundary condition was applied on part of the northern and southern perimeter of the model located in the central trough area of the valley to allow surface water to exit the system. In HydroGeoSphere, critical depth boundary conditions are non-linear third-type (Cauchy) boundaries. The advantage of this boundary condition is that it neither constrains the flow rate nor the surface water depth along the perimeter where it is applied. Instead,

Table 2
Overland flow and ET parameters used for the simulation of pre-development condition in the San Joaquin Valley.

Land cover	n (d/m$^{1/3}$)	h_{ds} (m)	h_{os} (m)	LAI	L_r (m)	RDF (m)	B_{soil} (m)	EDF	θ_{e1}	θ_{e2}	θ_{wp}	θ_{fc}	θ_o	θ_{an}	C_{int} (m)	C_1	C_2	C_3/E_p
									$\times$porosity									
Grasslands	4.05×10^{-7}	0.01	0	2	2.6	Linear	2.6	Linear	0.32	0.2	0.2	0.32	1	1	0	0.3	0.2	1
Other floodplain habitat	1.07×10^{-7}	0.01	0	2.71	5	Cubic	5	Cubic										
Wetlands	5.79×10^{-7}	0.01	0	2.64	0.76	Linear	0.76	Linear										
Riparian	1.74×10^{-6}	0.01	0	3.5	5	Cubic	5	Cubic										
Alkali desert scrub	5.79×10^{-7}	0.01	0	1.35	2	Linear	2	Linear										
River channel	4.05×10^{-7}	0.002	0	NA														

Symbols and abbreviations used: n (roughness coefficient), h_{ds} (depression storage height), h_{os} (obstruction storage height), LAI (leaf area index), L_r (maximum root depth), RDF (root density function), B_{soil} (maximum evaporation depth), EDF (evaporation density function), θ_{e1} (the moisture content at the end of the energy limiting stage above which full evaporation can occur), θ_{e2} (the limiting moisture content below which evaporation is zero), θ_{wp} (the soil moisture contents at wilting-point), θ_{fc} (the soil moisture contents at field capacity), θ_o (the soil moisture contents at oxic limit), θ_{an} (the soil moisture contents at anoxic limit), C_{int} (canopy storage parameter), C_1, C_2, C_3 (dimensionless fitting parameters), E_p (potential evapotranspiration).

Table 3
Subsurface flow parameters used for the simulation of pre-development condition in the San Joaquin Valley.

Material/Unit	K_{xx}, K_{yy} (m/d)	K_{zz} (m/d)	ϕ	S_s (m^{-1})	S_r	α (m^{-1})	β
Upper aquifer zone	33.9	0.09	0.35	3.05×10^{-6}	0.18	1.9	6.0
Corcorran clay	1.9×10^{-6}	1.9×10^{-6}	0.52	6.5×10^{-4}	NA		
Lower aquifer zone	26.43	0.08	0.35	3.05×10^{-6}			

K_{xx}, K_{yy} (hydraulic conductivity in the horizontal principal directions), K_{zz} (hydraulic conductivity in the vertical direction), ϕ (porosity), S_s (specific storage), S_r (residual saturation), α and β (van Genuchten parameters).

discharge leaving the domain is allowed to vary naturally throughout a given simulation period depending on the calculated depth of water along the perimeter (VanderKwaak, 1999; Panday and Huyakorn, 2004).

4. Results and discussion

4.1. Water budget

The total inflow into the SJV model domain is about 3.73×10^6 m^3/d and is comprised of spatially varying precipitation (36.5% of the total), and major river inflows (63.5% of the total). Simulation results show that at the pre-development condition, the river flow out of the system at the San Joaquin Delta area accounts for 55.2% of the total inflow with the remainder being evapotranspirated in the domain. As typically observed in the area, the spatially-averaged rate of actual ET (0.97 mm/d) is higher than the spatially-averaged rate of precipitation (0.79 mm/d), and the total river outflow at the downstream end of the drainage network is about 87% of the total river inflow.

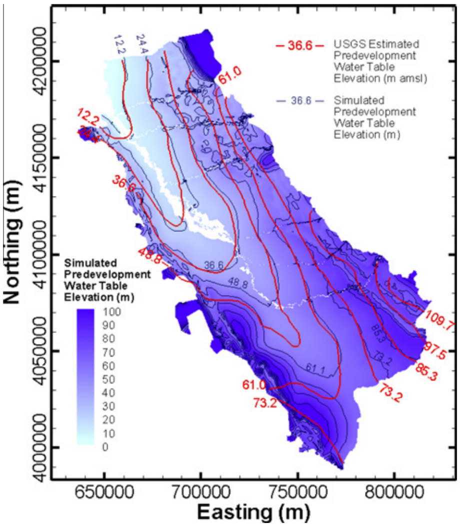

Fig. 4. Comparison of the distribution of simulated water table elevation with the estimates by the USGS in the study area at a pre-development condition.

4.2. Groundwater and surface water flow

In the SJV, the distribution of groundwater table elevations at a pre-development condition was estimated by the US Geological Survey (USGS), based on historical hydrologic and hydrogeologic data (Bertoldi et al., 1991, after Williamson et al., 1989; Planert and Williams, 1995). In Fig. 4, the simulated water table elevations are compared qualitatively with the USGS estimates. The higher water table elevations at the model margins and lower elevations in the central area are consistent with previous studies describing recharge as primarily occurring at high elevations in the Sierra Nevada and close to where the major rivers enter the valley, as well as the direction of groundwater flow mainly being towards and along the trough of the valley. The general trend of the simulated water table appears to follow the path of the lower SJR in the central part of the valley, gently sloping toward the model outlet. At the south-west margin of the model, it is interesting to note the three semi-circular patterns of higher water table elevation contours (Fig. 4). The shape of these three zones is quite similar to the shape of the alluvial fans in this same location. Considering the features described above, the model agrees with the basic concept that the pre-development water table would be a subdued reflection of the general surface topography.

The distribution of surface water depths simulated at the pre-development condition is shown in Fig. 5, along with outlines of the historic wetlands in the domain. The pool of surface water along the SJR in Fig. 5 indicates that the surface water from the SJR can flood the land surface south of where it meets the Merced River, confirming the presence and cause of large freshwater marshes in the trough of the valley (Katibah, 1984; Warner and Hendrix, 1985; Gronberg et al., 1998). The pools of surface water are also fairly consistent with the location of historical wetlands

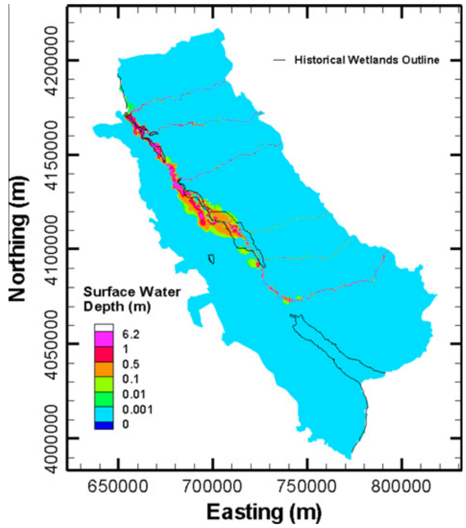

Fig. 5. The distribution of simulated surface water depth at a pre-development condition along with the historic wetlands outlines in the domain.

as shown in the historical map of natural vegetation ca. 1874 (California State University at Chico, 2003). Fig. 5 also exhibits pools of surface water along the SJR north of the Merced River towards the model outlet, which are also consistent with the historical presence of wetlands. The model was not able to reproduce the major axial wetland in the southern region of the study area.

Comparison of the simulated surface water and groundwater flow distributions with the estimates and historic records in the SJV indicates that the integrated model can help to qualitatively replicate and understand the general hydrologic conditions and features at a watershed scale with only limited inputs and no calibration efforts.

4.3. Groundwater and surface water interaction

The simulated surface–subsurface water exchange flux is shown in Fig. 6a and indicates that surface water is infiltrating into the subsurface across the majority of the modeled area at a rate of greater than 0.1 mm/d and less than 1 mm/d. Note that this amount of water entering the subsurface is evapotranspired as it enters the root zone, and therefore the exchange flux is not an estimate of groundwater recharge. A large proportion of the river reaches (where visible) in the model appear to be losing reaches (negative exchange flux: water in the river channel is infiltrated to the subsurface) at rates between about 10 mm/d and over 100 mm/d, while there are some significant portions of the river reaches that appear to be gaining reaches (positive exchange flux) at rates between 1 mm/d and 100 mm/d. The most visible areas of groundwater exfiltration are the middle reaches of the Tuolumne River, followed by the middle reaches of the Merced River, then the lower parts of the other tributary rivers where they meet the SJR, and finally small scattered portions of the SJR itself within the valley trough and near the model outlet. Note that the most significant areas of simulated water exchange flux at ground surface are generally consistent with the locations of simulated surface water features (defined as surface water depth >1 mm), and coincide with the areas where the water table intersects the ground surface. The region of intense precipitation in the north-eastern region of the model is responsible for the elevated water exchange flux in that region in the absence of surface water.

Fig. 6b and c show the simulated distributions of the vertical Darcy fluxes at the bottom of the root zone (5.5 m below ground surface) and the rate of ET from within the root zone, respectively. In Fig. 6b, the areas of downward flux along the banks of the SJR are generally consistent with the location of wetland areas, indicating that these areas serve to recharge the water table. The prominent presence of the moderate upward fluxes at the bottom of the root zone surrounding the lower SJR in Fig. 6b (red and pink[1] shaded areas) and the absence of these large areas of upward flux in Fig. 6a suggests that the water is being consumed before reaching ground surface. This water that is entering the root zone is being taken out of the subsurface domain through ET, as supported by the results in Fig. 6c. This confirms previous claims that most groundwater exiting the subsurface was discharged as ET in the trough of the valley, and to a lesser extent, to streams during the pre-development period (Gronberg et al., 1998). Note, however, that the SJR in the trough is actually recharging the water table (groundwater) and it is the broad region surrounding the SJR that is serving to discharge groundwater into the root zone for ET. The presence of large upward fluxes at the bottom of the root zone is consistent with claims that artesian conditions and upward vertical gradients were present in the trough of the valley at the pre-development condition (Hall, 1889; Mendenhall et al., 1916; Planert and Williams, 1995). Infiltration past the root zone into the subsurface appears to occur throughout the majority of the modeled area at very low rates between 0.01 and 0.1 mm/d, which is much less than the spatially averaged rate of precipitation (0.79 mm/d).

The simulated spatial distribution of actual ET in Fig. 6c shows the majority of actual ET rates ranges between 0.5 and 1 mm/d. The spatially averaged rate of actual ET is 0.97 mm/d which is much lower than the estimated PET for this area (see Fig. 2b) but higher than the spatially averaged rate of precipitation (0.79 mm/d). The higher rates of actual ET occur in areas of open water such as river channels and wetland areas. Noticeable rates of actual ET in the north-east region of the model occur where the rate of precipitation is more intense and infiltrates the ground surface. The complex role of actual ET as a major component in the water balance, and the significant impacts of ET on other hydrologic processes in the root zone (such as removing large amounts of water as it enters the root zone from above and below) has important implications for the overall model results. This affirms the decision to use vertical mesh refinement (1 m thick layers) within the root zone in order to resolve these complex processes.

It is clear from the overall model results (i.e. infiltration/exfiltration at the ground surface, ET in the root zone, and vertical flux at the bottom of the root zone, as shown in Fig. 6) that including hydrological processes at the interface between surface and subsurface flow regimes is essential to quantify the local and regional water balance for water resource management and planning. This emphasizes the utility of integrated surface and subsurface flow modeling. Strong ET in arid or semi-arid regions, as illustrated by the SJV simulation results, implies that hydrological processes in the root zone can have a significant impact on water quality through processes such as the salinization of soil and groundwater. This has raised sustainability issues for SJV agriculture practice of intense irrigation (Schoups et al., 2005).

4.4. Limitations of the hydrologic model

There are a few potential sources of discrepancy between the simulation results and documented historical hydrologic conditions. The major discrepancies include that between the simulated and estimated water table elevations, and that between the

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[1] For interpretation of color in Fig. 6, the reader is referred to the web version of this article.

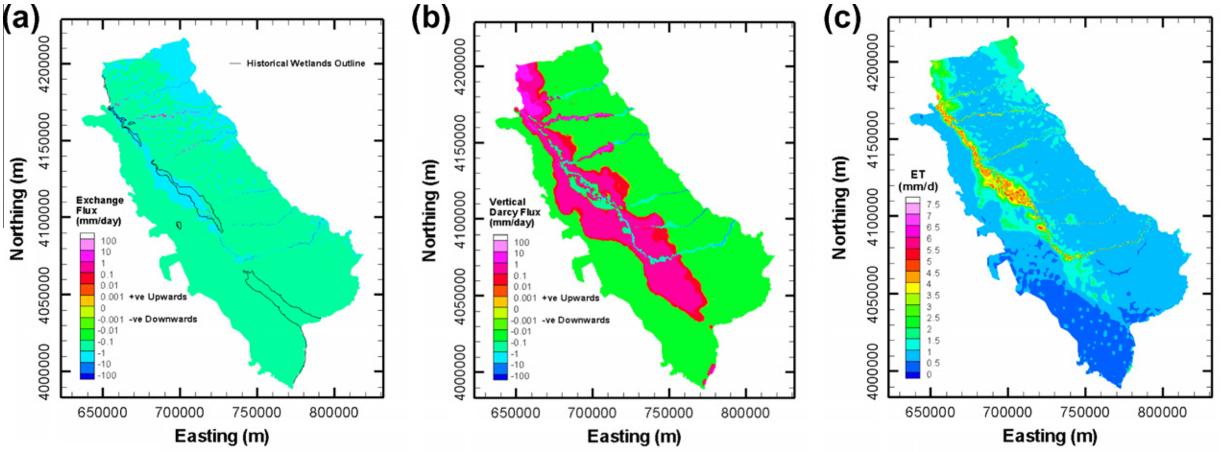

Fig. 6. The distributions of: (a) the simulated exchange flux at ground surface, (b) vertical Darcy flux at the bottom of the root zone, and (c) actual evapotranspiration in the study area at a pre-development condition.

simulated and mapped presence of historical wetlands. The quality of model assumptions, in particular the simplified and uniform hydraulic conductivity field applied to the subsurface units, as well as the southern model extent boundary conditions, may explain these discrepancies. Specifically, applying different boundary conditions at the southern model boundary (Kings River and the historical Tulare Lake) or adjusting the southern extent of the model may yield a better replication of historical wetlands and a better fit between simulated and estimated water table elevations. Other possible sources of discrepancy include averaging of data for model input (river flows, precipitation rates, ET rates, rooting depths, LAI), inaccuracies in forming river channel cross-sections from elevation data, not attempting to discretize the Fresno Slough (axial backwater feature/wetland between SJR and southern model boundary), adjustments to model elevations to account for large magnitudes of land subsidence, the empirical method of representing ET processes, and the appropriateness of ET parameters taken from the literature. Increasing the specified rooting depth to 5 m for zones assigned shallower depths (particularly wetland areas) may result in better replication of historical wetlands causing less water to be removed from the uppermost surficial layer. It is possible that inaccuracies in reproducing river channel cross-sections, such as overestimating the channel width due to the coarseness of the grid, may contribute to overestimation of evaporation from open water. To avoid temporal bias in long-term normal precipitation estimates, an alternative source would be to use PRISM to generate a 103-year record for the SJV. However, once averaged, there is no guarantee that this PRISM data set will be more representative of the long-term normal precipitation for the SJV than the current 30-year PRISM data set.

5. Summary and conclusions

The physically-based surface–subsurface HydroGeoSphere model was applied to examine the regional-scale hydrologic budget of a large portion of the San Joaquin Valley under pre-development hydrologic conditions. A steady-state model was developed, constrained by historical long term average climatic data assumed to be representative of the natural system, model elevations prior to land subsidence primarily due to massive groundwater pumping for irrigation, and hydrological conditions before the anthropogenic alteration in the last 150 years. With no calibration efforts, modeling results showed a fairly good agreement with the estimated and recorded pre-development surface water and groundwater distributions.

Simulation results indicate that the pre-development hydrologic condition in the San Joaquin Valley is a complex one. This hydrologic condition includes significant groundwater-surface water interaction along the major rivers and within wetland areas formed by flooded surface water, as well as ET and associated root zone processes in the shallow subsurface. Specifically, ET is a very significant sink of both surface water and groundwater (44.8% of the water balance input), and has a major impact on hydrologic processes in the root zone. The presence and path of the major rivers in the domain are well defined in the model output and agree well with their actual locations. The model simulates gaining and losing reaches of the major rivers, replicating the historic recharge–discharge relationship documented by others. The general location, formation, and hydrologic processes of some wetlands simulated by the model have a fair agreement with historical records. There is also a fair match between simulated and actual estimated pre-development water table elevations.

These results indicate that root zone processes, ET, and the interaction between surface and subsurface flow regimes are all essential processes for understanding the local and regional water balance and water quality. Successful simulation of these complex hydrologic processes and features that characterize the pre-development hydrologic condition of the SJV underscores the importance and utility of using an integrated hydrologic model, even when limited data is available for model parameterization and calibration. This model of the SJV should serve as a reasonable initial condition for future transient simulations that incorporate historic anthropogenic activities and capture the resulting response of the hydrologic system from pre-development to present-day conditions, and estimate present and future water budgets.

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