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Special Section:
Advancing process representation in hydrologic models: Integrating new concepts, knowledge, and data

An Integrated Approach Toward Sustainability via Groundwater Banking in the Southern Central Valley, California

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Key Points:
- How regional Ag-MAR projects can influence streamflows and surface diversions is demonstrated using an integrated management model
- The spatial distribution of agricultural lands for recharge is key to enhance groundwater storage
- Regional Ag-MAR projects may affect downstream water rights as well as increase the risk of waterlogging in the root zone

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2

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Abstract Intensive groundwater withdrawals in California have resulted in depletion of streams and aquifers in some regions. Agricultural managed aquifer recharge (Ag-MAR) initiatives have recently been piloted in California to mitigate the effects of unsustainable groundwater withdrawals. These initiatives rely on capturing wet-year water and spreading it on large areas of irrigated agricultural lands to enhance recharge to aquifers. While recharge studies typically consider local effects on aquifer storage, few studies have investigated Ag-MAR benefits and challenges at a regional scale. Here we used the Integrated Water Flow Model, to evaluate how Ag-MAR projects can affect streamflows, diversions, pumping, and unsaturated zone flows in the southern Central Valley, California. We further tested the sensitivity of three different spatial patterns of Ag-MAR, each chosen based on different thresholds of soil suitability, on the hydrologic system. This study investigates how the distribution of Ag-MAR lands benefit the regional groundwater system and other water balance components. The results suggest that Ag-MAR benefits vary as a function of the location of Ag-MAR lands. Stream-aquifer interactions play a crucial factor in determining the ability to increase groundwater storage in overdrafted basins. The results also indicate that Ag-MAR projects conducted during the November–April recharge season have implications for water rights outside of the Ag-MAR season. If not properly monitored, Ag-MAR can cause a rise of groundwater table into the root zone, negatively impacting sensitive crops. Our work also highlights the benefits of using an integrated hydrologic and management model to evaluate Ag-MAR at a regional scale.

1. Introduction

Advancing technology, climate change, and population growth have led to an increase in water demand and put the Earth's available surface and subsurface water resources under unprecedented pressure (Cosgrove & Loucks, 2015; Evans & Sadler, 2008; Gorelick & Zheng, 2015). To mitigate these pressure on water resources, policy makers have attempted to enhance the supply by developing water resources, with a focus on groundwater resources (Niswonger et al., 2017). Groundwater resources are widespread, are less vulnerable to quality degradation and droughts, and are often less regulated than are surface water resources. Over the past decades, groundwater has become an increasingly important source for water supply and currently is used in approximately 40% of the area equipped for irrigation globally (Siebert et al., 2010). This percentage is higher in lands with Mediterranean, semiarid to arid climates such as regions in the western and central United States, North Africa, the Middle East, southern Europe, and northwestern India, where there is a time lag between surface water availability (November to April) and irrigation demand (April to October). The Central Valley of California is an example where groundwater consumption has been estimated to be annually around 60% of the total water storage changes (snow water equivalent, surface water, soil moisture, and groundwater) in the basin (Famiglietti et al., 2011). Intensive groundwater withdrawals in the valley have contributed to depletion of streams (Fleckenstein et al., 2004), subsidence and irreversibly reducing storage (Farr & Liu, 2015; Faunt et al., 2016), drying up of wells and increased cost of pumping (Nelson et al., 2016), and disconnection of stream-aquifer systems (Bolger et al., 2011; Dogrul et al., 2016), among others. All these studies emphasize that the groundwater resources are under high pressure, their sustainability is at risk, and therefore, they need to be replenished as soon as possible.

Managed aquifer recharge (MAR) is a cross-cutting technology (Sprenger et al., 2017) and an increasingly common approach to improving groundwater resources. MAR is defined herein as diverting, conveying, recharging, and storing surplus surface water in wet periods and storing in the aquifer for extraction and use during dry periods. MAR can be accomplished through a variety of approaches such as using storm water via dry wells to recharge aquifers (Edwards et al., 2016), employing aquifer storage and recovery (Ebrahim et al., 2016; Hanson et al., 2014), using infiltration basins (Teatini et al., 2015), and flooding lands (Scherberg et al., 2014). Dry wells and aquifer storage and recovery require less land but require more design expertise, can be technically demanding to design, and may have high energy, construction, and maintenance requirements for the conveyance and pumping systems (Bouwer, 2002). Infiltration basins require less engineering and operating costs but may not be able to accommodate the substantial amounts of surface water during storm and flood events. When sufficiently large areas of land are available, the flooding approach lacks the drawbacks of the other techniques. It provides a potentially wide range of additional opportunities for MAR such as transferring water from ephemeral rivers into aquifers during storm events and at times when storage in surface water reservoirs exceeds capacity (e.g., end of spring and early summer) or when reservoir storage is released because of flood control measures (e.g., during and after heavy rainfalls). Flooding has proven to be beneficial in arid regions with wet seasons that are not far from mountain ranges (Hashemi et al., 2015; Pakparvar et al., 2018). California Department of Water Resources (DWR) has recently started a flood-MAR initiative, focusing on the use of flood water on aquifer recharge and sustainable use of water resources (California DWR, 2018).

While numerous studies exist regarding the delineation of suitable lands for flood MAR projects (Mahdavi et al., 2013; Mahmoud et al., 2014; Nohegar et al., 2016; Russo et al., 2015), the majority of those studies were performed within a geographic information system (GIS) framework and are based on the analysis of the surface land properties, such as land use, slope, and soil permeability. The scale of the geographic data that are used in GIS-based studies may not provide much information for the scale of flood MAR projects (Niswonger et al., 2017). One controlling MAR success factor, which is missing in GIS-based studies, is the lack of hydrogeologic data. Such data are important since any impeding layer that does not let the infiltrating water reach the water table or the existence of a thin aquifer/shallow groundwater that does not allow a considerable amount of the diverted water to be stored can lead to the failure of MAR projects. Two key factors that need to be considered for the proper design of flood MAR projects are (1) the existence of infrastructure to convey the diverted streamflows to participating lands and (2) the suitability and accessibility of the lands required for aquifer recharge projects. A promising approach that will address both is to practice MAR on irrigated agricultural lands, where recharge occurs naturally (Dahlke et al., 2018; Niswonger et al., 2017; Scanlon et al., 2007; Scanlon et al., 2016; van Roosmalen et al., 2009) and the infrastructure for irrigating already exists. This approach, herein referred to as agricultural managed aquifer recharge (Ag-MAR), focuses on utilizing lands that can be easily accessed via existing infrastructure, such as irrigation canals and irrigation systems.

Ag-MAR is here defined as the application of relatively low rates (L/T) of recharge over large areas, in contrast to traditional MAR aimed at achieving high recharge rates (L/T) at dedicated local recharge sites. Ag-MAR relies on the flexible management of surface and subsurface flow systems simultaneously to avoid undesirable effects (Karamouz et al., 2004; Marques et al., 2010; Petheram et al., 2008); however, the concept of off-season Ag-MAR is a new concept designed to increase the sustainable yield in overdrafting regions. Scherberg et al. (2014) applied the concept of Ag-MAR to the Walla Walla Basin, in Eastern Oregon, USA. Daily simulations over a 3-year period were used to evaluate the effectiveness of Ag-MAR in restoring the groundwater levels and sustaining the minimum river flow. Bachand et al. (2014) studied the effects of diverting water from Kings River in California to nearby farmlands on groundwater quality (nitrate and salinity). Their study results showed that while the root zone water quality constituents such as salts and nitrates migrated into deeper layers, electrical conductivity levels in the root zone decreased, and therefore, plant stress decreased. Using a simple conceptual model, they predicted that groundwater salinity concentrations would improve over time, as high-quality surface water would improve groundwater quality throughout the Kings Basin. Niswonger et al. (2017) applied the Ag-MAR concept to a hypothetical agricultural subbasin and developed a modeling methodology to simulate the benefits of Ag-MAR. They concluded that crop consumptive use and natural vegetation water consumption increased by up to 12% and 30%, respectively, due to the rise of the water table above well screens. These studies demonstrate that the concept can benefit a hydrologic system in multiple ways; thus, there is a need to put the Ag-MAR concept into an integrated modeling framework that considers all components of a

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hydrologic system, as well as their interactions. At present, to the best of our knowledge, there is no study to address the long-term pros and cons of Ag-MAR at the regional (county, catchment) scale rather than at the site or farm scale.

Our study attempts to provide insights into the long-term, regional benefits of Ag-MAR in a groundwater overdrafted region in a southeast portion of the Central Valley, California. We use an integrated hydrologic model (Brush et al., 2013) to simulate the benefits of Ag-MAR over the course of 88 years (1921 to 2009). The integrated model enables us to discuss the probable risks of Ag-MAR to agriculture. In addition, we investigate the impact of three different spatial patterns of Ag-MAR, each chosen based on different thresholds of soil suitability. We attempted to answer the question, "How does the distribution of Ag-MAR benefit the groundwater system as well as the change in streamflows, diversions, pumping, and unsaturated zone flows?"

2. Study Area

The study area is located in the Central Valley, California. The valley has a highly variable month-to-month and year-to-year climate; however, generally, the climate in the Central Valley is characterized by wet winters and dry summers. The average annual precipitation in the valley from 1921 to 2009 is 189 mm, which is far less than the average annual potential evapotranspiration (i.e., 984 mm) for the same period. Most rainfall occurs from November through April, while evapotranspiration occurs mainly from April through October. The distribution of precipitation varies dramatically across the valley, with about 70% of the precipitation falling in the northern part of the valley. Variability in the frequency, intensity, and type of precipitation produces large fluctuations in available water resources. Furthermore, climate change is leading to early snowpack melting, which limits the water from snowmelt available at the time of peak crop growth during late spring and early summer months (Dettinger & Cayan, 1995; Pagan et al., 2016). The population in the valley has had a fast-paced growth since 1920, reached nearly 8 million people in 2010, and is projected to grow to more than 11 million by 2050 (Brush et al., 2013). The inequality in the spatial and temporal distribution of precipitation and unconstrained access to groundwater in the valley have led to groundwater overdraft in the valley. This overdraft is posing a threat to the agricultural economy of the United States since market value of agricultural products grown in the Central Valley contributed up to 7% to the nation's $300 billion in agricultural revenue in 2007 (Scanlon et al., 2012).

The Central Valley (Figure 1) is a flat alluvial basin, which is bounded by the Sierra Nevada in the east, the Cascade Range and Klamath mountains in the north, the Coast Range and San Francisco Bay in the west, and the Tehachapi mountains in the south. The valley covers an area of roughly 51,000 km^2 with an approximate length of 640 km and varying width of 30 to 110 km. The Central Valley aquifer is mainly formed of unconsolidated sediments, such as alluvial fans, stream channel deposits, and flood plain deposits produced during the formation and retreat of the glaciers in surrounding mountains. The aquifer system is composed of interbedded sand, silt, and clay layers with some horizontally extensive lenses of clays sloped toward the center of the valley. It is noteworthy that aquifer sediments in the west of Central Valley are oceanic and finer grained, whereas the sediments in the east are more granitic and volcanic. **F1**

The California DWR has divided the Central Valley into 21 computational units (subregions) to resolve the water demand and supply relations and report the water budget (supporting information Figure S1). The focus of this study is subregion 18 (Figure 1a). Figure 1b shows the conceptual hydrogeologic model of the study area where the region has been divided into three aquifer layers vertically with a maximum thickness of 246, 316, and 710 m, respectively, from top to bottom. Layer 1 is unconfined, while layers 2 and 3 are assumed to be confined. Additionally, a clay layer named Corcoran clay with a maximum thickness of 35 m exists between the first and second layers. The Corcoran layer exists mainly on the western side of the study area and does not extend to the eastern boundary (supporting information Figure S2). Subregion 18 is intensively farmed, and the dominant land use is irrigated agriculture. The average annual potential evapotranspiration in this subregion for the 1921 to 2009 period is 807 mm, while the average annual precipitation for the same period is 231 mm. Therefore, the region relies on groundwater and diversions from the rivers in the region to meet agricultural demands.

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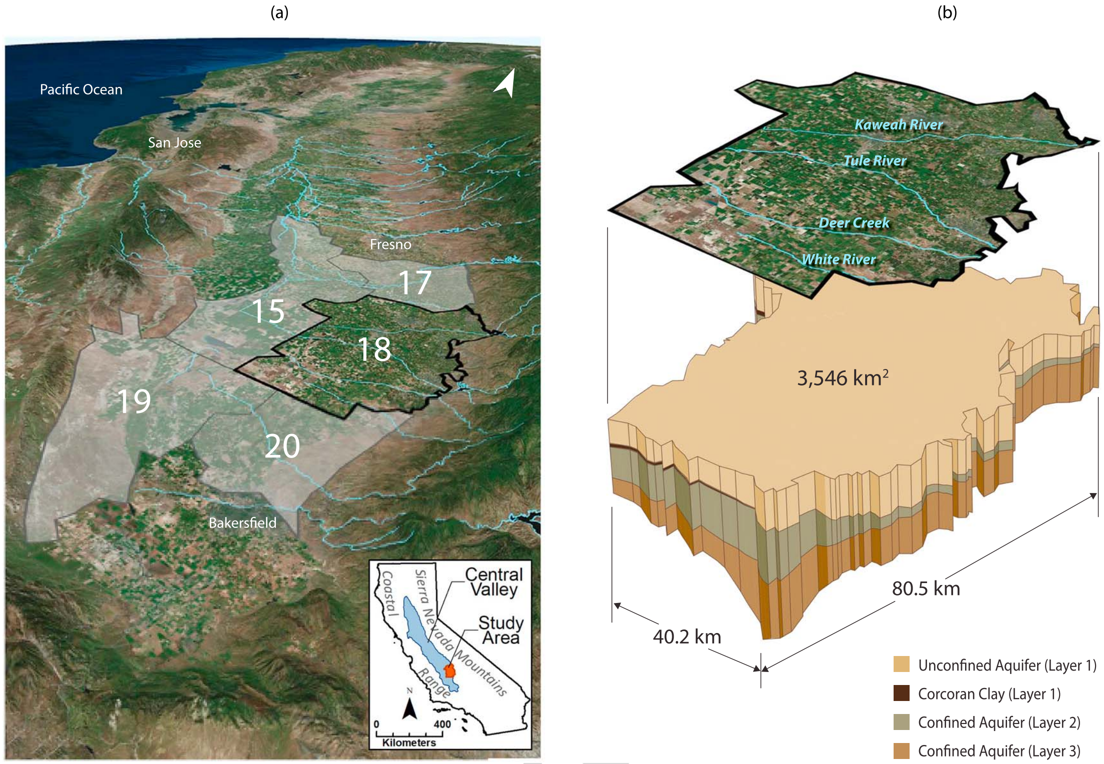

Figure 1. (a) Schematic of the study area (subregion 18) with the neighboring subregions (15, 17, 19, and 20) in the southern Central Valley in California (scaleless) and (b) conceptual model of the study area.

3. Methods

3.1. Flooding Agricultural Lands

There are four main rivers flowing through subregion 18, emanating from the Sierra Nevada to the east (Figure 2a). The locations of the major diversion points on these rivers are shown in the figure as well. The diversion points are named after the stream node numbers in the simulation model (Brush et al., 2013; see section 3.2.2). It is worth noting that the diversions are not used solely for irrigation purposes but also for recharging the aquifer when excess water is available. Availability of stream water for Ag-MAR projects is the single largest control on the amount of the annual recharge volume, highlighting the importance of a comprehensive assessment of available surface water resources. The amount of water diverted for recharge cannot violate environmental requirements or water rights along the rivers. The time series of diversion water for Ag-MAR in this study has been determined by statistical analysis of streamflow, as described in Kocis and Dahlke (2017), measured at the most upstream node of the Kaweah River, using a composite of U.S. Geological Survey gauges (11210500, 11209900, 11210100, and 11211300) and inflow data to Terminus Dam to create a time series from 1921 to 2009. This time series represents the water available for recharge at diversion point 514 with an exceedance probability of 95%. The Ag-MAR water, diverted during wet years between November and April in the 1921 to 2009 period, amounts to 2,089 million cubic meter (MCM) in total. It was assumed in this study that 95% of the diverted water can reach the water table and the remaining either is lost on the way to the recharge area (seeping from the canals) or is evapotranspirated. The November–April time window was chosen for Ag-MAR because in California most precipitation falls between November and April when agricultural water demand is at a minimum, and hence, excess water for Ag-MAR is available. Table 1 shows the monthly distribution of the total flow diverted for Ag-MAR as well as the number of months that the targeted diversions occurred during the 88-year (1,056-month) simulation period.

To identify the location and spatial extent of the Ag-MAR projects, we used an index developed by O'Geen et al. (2015). They developed the Soil Agricultural Groundwater Banking Index (SAGBI) to show the

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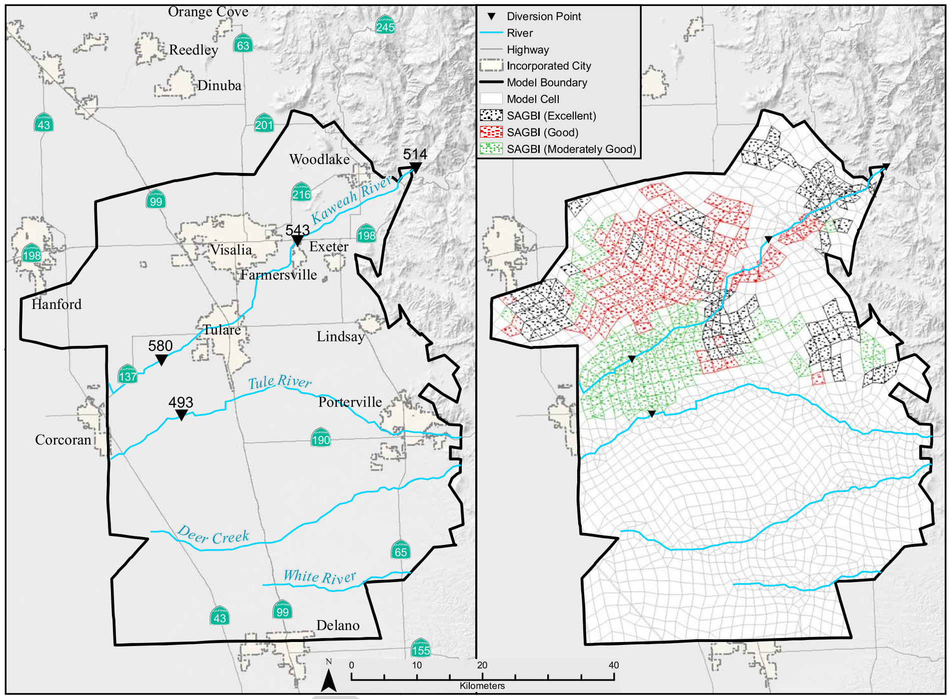

Figure 2. (a) Diversion points for irrigation and/or aquifer recharge in subregion 18 and (b) schematic of agricultural managed aquifer recharge land distribution scenarios A (excellent), B (excellent + good), and C (excellent + good + moderately good), based on Soil Agricultural Groundwater Banking Index (SAGBI).

suitability of agricultural lands in California for aquifer recharge projects. They analyzed five factors in a fuzzy logic and GIS framework to delineate the ideal locations for aquifer recharge. The factors they used were deep percolation rate (represented by the lowest saturated hydraulic conductivity of the soil profile), root zone residence time (harmonic mean of the saturated hydraulic conductivity within all horizons of the soil profile in addition to the soil drainage class), topography (surface slope), chemical limitation (depth-weighted average of electrical conductivity), and surface condition (erodibility factor and sodium adsorption ratio). The index ranks soils on a six-class scale ranging from very poor to excellent. In this study, we considered only soils ranked as either excellent, good, or moderately good as Ag-MAR lands. Using these three classes, we defined three Ag-MAR land scenarios, where A designates excellent soil suitability, B designates soils with excellent and good soil suitability, and C designates soils with excellent, good, and moderately good soil suitability for recharge. These land scenarios result in different areas and spatial distributions of the agricultural lands available for recharge. A has the most diffuse and patchy distribution pattern with an area of 313.3 km^2, whereas B covers an area of 685.4 km^2, and scenario C covers the largest area, 1,022.8 km^2 (Figure 2b). We note that the model cells in each scenario receive the same volume of water, independent of the cell area.

3.2. Modeling Water Flow in the Central Valley

3.2.1. Integrated Water Flow Model

The Integrated Water Flow Model (IWFM) has been developed, enhanced, and maintained by DWR since the early 2000s. Over the years, several major versions of IWFM have emerged, each version introducing

Table 1
The Distribution of the Targeted Diverted Flow for Agricultural Managed Aquifer Recharge (Ag-MAR) at Diversion 514 Q9

	Nov	Dec	Jan	Feb	Mar	Apr	Total
Percentage of total diverted flow for Ag-MAR	5	23	28	22	11	11	100
Number of months (within the 88-year simulation)	7	12	23	29	27	25	123

more simulation features to address more complex hydrologic and water resources management conditions. In this study, IWFM version 3.02 was used (California DWR, 2013a, 2013b).

IWFM is a fully integrated surface and subsurface flow model. IWFM simulates the hydrologic cycle, including simulation of streamflows, lake storage, land surface and root zone flow processes, vadose zone, and saturated groundwater flows (Figure 3). In addition to hydrologic flows, IWFM can calculate the agricultural **F3** and urban water demands, link these water demands to water supplies to quantify groundwater pumping and stream diversions, and optionally, adjust these water supplies to meet calculated water demands. These features allow users to dynamically calculate the stresses on the hydrologic system due to human activities within a basin. For this reason, IWFM is both a descriptive model (given the stresses on the hydrologic system, it simulates where and how fast the water flows within the basin) and a prescriptive model (given the parameters related to agricultural and urban development, it simulates the hydrologic stresses within the basin). The combination of these two modes of IWFM provides a powerful tool to simulate a wide variety of water management scenarios under future climate as well as agricultural and urban development conditions.

Precipitation and land-use-based evapotranspiration rates are user-defined time series input data for IWFM. Rainfall runoff is simulated using the curve number method developed by the U.S. Department of Q10 Agriculture (USDA) Natural Resource Conservation Service (USDA, 1972). The calculated runoff contributes to streams or lakes at user-specified locations. Remaining precipitation infiltrates into the root zone, contributing to the soil moisture storage in the root zone. The moisture in the root zone is routed vertically using a simplified, one-dimensional conservation equation (California DWR, 2013a), after accounting for precipitation, applied water, evapotranspiration, and deep percolation.

For saturated groundwater flow, IWFM solves the three-dimensional conservation equation using the Galerkin finite element method. Horizontal and vertical groundwater flows in complex, multilayered aquifer systems for both confined ad unconfined as well as the transition from confined to unconfined conditions, or vice versa, can be simulated. Effects of pumping, artificial recharge, tile drains, and subsidence can all be simulated.

Stream networks in IWFM are represented through a set of stream nodes that are connected to each other through stream segments. Each stream node is associated with an underlying groundwater node. IWFM version 3.02 simulates streamflows through the stream network using the assumption of instantaneous flow, meaning that the change in storage is negligible for a given time step within the stream network. In other words, the flow that enters the stream network at its most upstream node travels instantaneously through the network in that time step and flows out at the most downstream node. The length of the simulation time step is chosen in a way that exceeds the characteristic length of travel times of the flow within the modeled stream network. The inflows at a given stream node are the rainfall runoff, the agricultural and urban return flows, and the flows from upstream nodes. The outflows at a given stream node could be the diversions to meet the agricultural and urban water demands. Stream-aquifer interaction at each stream node is calculated as a Cauchy-type boundary condition, which is a function of the streambed conductance and the vertical head gradient between the groundwater and the stream surface elevation.

Lakes and large open water bodies and their interaction with surface and subsurface flows within a basin can also be simulated in IWFM. Streams can flow into lakes, and lake outflow can flow into the stream network. Changes in lake storages are simulated as a function of precipitation over the lake, surface evaporation, inflows from streams, rainfall runoff, and agricultural and urban return flows into the lake, lake-aquifer interaction, and the spills from the lake. Lake-aquifer interaction is simulated as a Cauchy-type boundary condition, which is a function of lake bed conductance and the vertical head gradient between the lake elevation and the groundwater.

Land surface and root zone flow processes as well as the stresses created on the hydrologic system due to agricultural and urban activities depend on several factors including climate, agricultural crop types and areas, soil types the crops are planted on, farm water management parameters, urban population and per capita water use, and distribution of urban water use between urban indoors and outdoors. Urban water demand is user input time series data for IWFM. It can be calculated outside IWFM as the product of population and per capita water use. Agricultural water demand is a function of crop type, planting and

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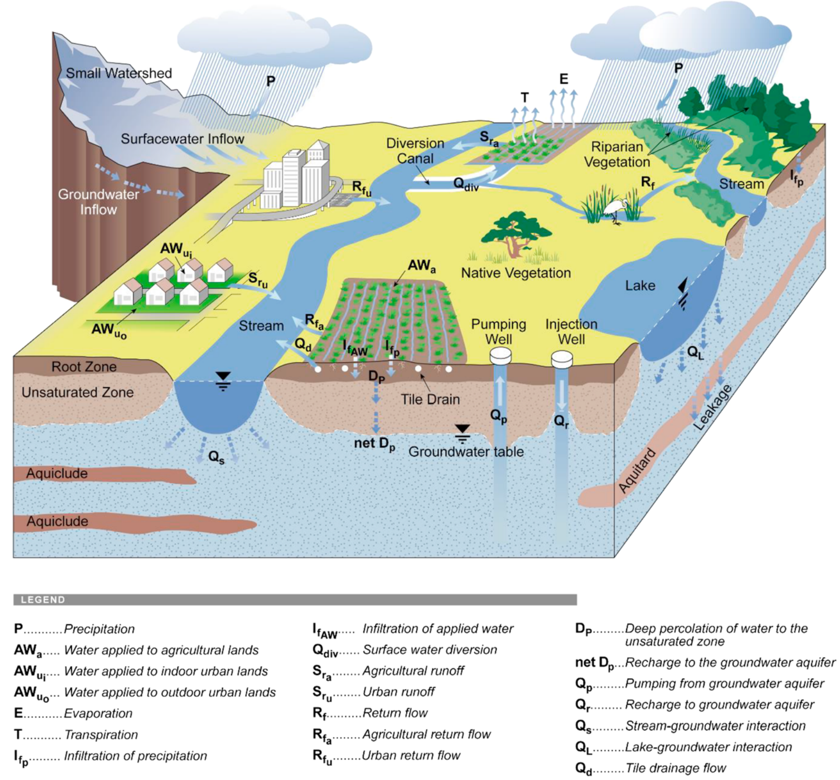

Figure 3. Hydrologic processes simulated by the Integrated Water Flow Model (IWFM; from the IWFM manual).

harvesting dates, properties of the soils that the crops are planted on, irrigation efficiency, and precipitation and evapotranspiration rates. IWFM defines the agricultural water demand as the amount of water to meet the evapotranspiration requirement of the crop that is not met by precipitation and stored moisture in a way to ensure that the moisture does not fall below a management soil moisture content (referred to as the "minimum soil moisture requirement"). During an irrigation period, IWFM first calculates the infiltration of precipitation into the soil. The infiltrated precipitation and the prestored moisture become the initial source of water to meet the crop water demand. Crop evapotranspiration is provided as time series input data to IWFM for each simulated crop by the user. If the initial source of moisture is not enough to meet the evapotranspiration and keep the moisture level at or above the minimum soil moisture requirement, then IWFM calculates the irrigation amount, assuming that there are no losses (farm return flows and losses due to deep percolation). To compensate for the losses, the initial irrigation estimate is divided by the irrigation efficiency to calculate the total irrigation requirement.

IWFM allows the user to simulate agricultural and urban water demands dynamically, link pumping and stream diversions, and, optionally, adjust them to meet these demands. As the water demand changes according to the changes in crop distribution, precipitation, and evapotranspiration rates, irrigation methods, and urban population, required pumping and stream diversions also change dynamically. Applied water (combination of pumping and diversions) leads to return flows that can flow back into streams and lakes, infiltrate into the root zone and a portion of it, aside from meeting crop water demands, and contribute to the vertical movement of the moisture through the root zone and recharge of the aquifer. Hence, IWFM provides a modeling platform where the water demand and the water flow within a basin are fully linked and interdependent. This makes IWFM a powerful modeling tool that can simulate a wide variety of water management scenarios and their impact on the water resources in a basin. Additionally, IWFM makes sure that pumping and diversions are limited by the available aquifer storage and streamflows, respectively, so water management scenarios that heavily strain the water resources in a basin can be addressed properly. These features of IWFM were heavily relied on in this study.

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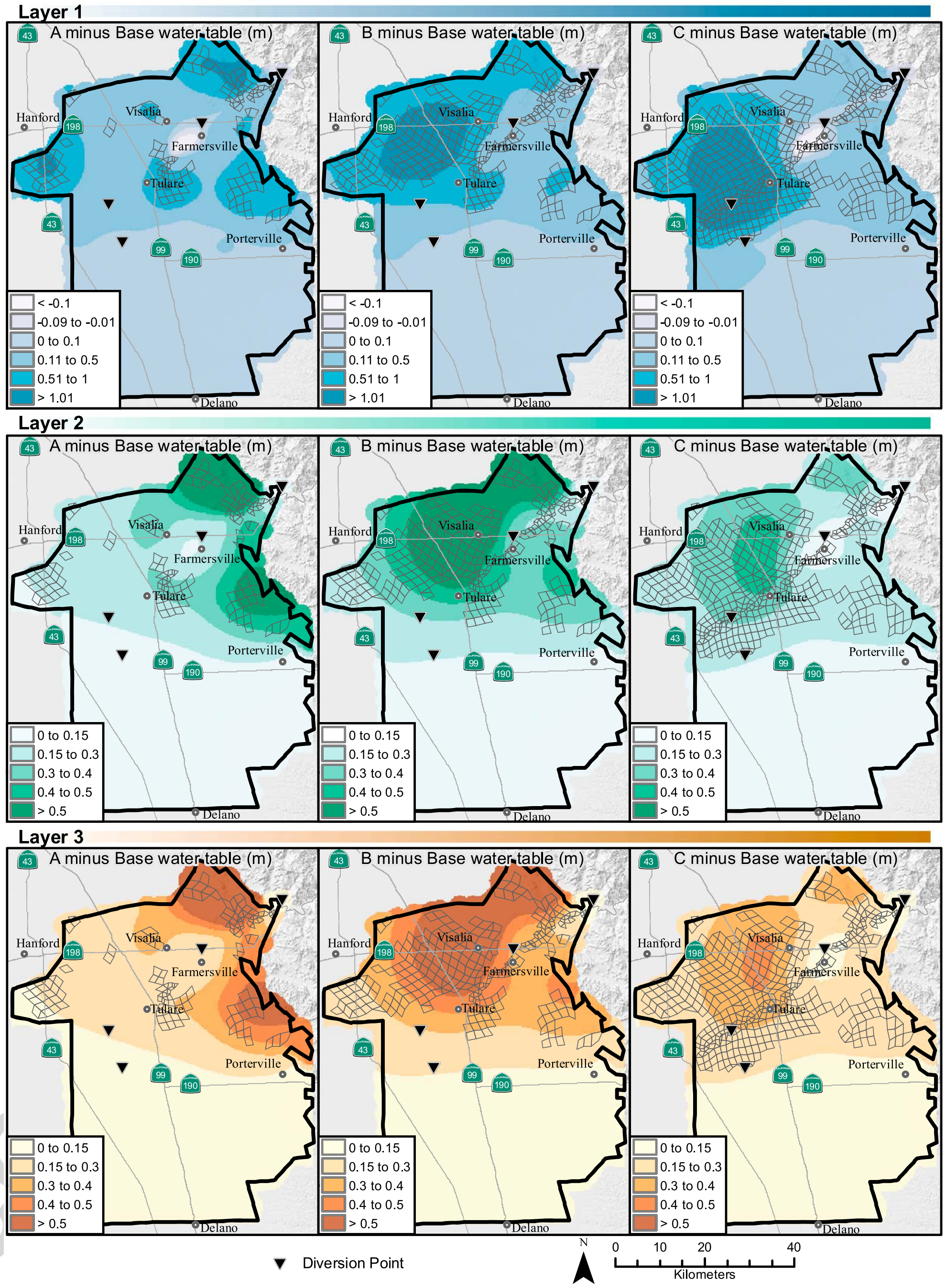

Figure 4. Spatial variation in the groundwater head change (m), relative to the base case, within (top row) layer 1 (blue color), (middle row) layer 2 (green color), and (bottom row) layer 3 (brown color) of the aquifer for all three recharge scenarios in subregion 18. Differences represent the average difference during the 88-year simulation period.

3.2.2. California Central Valley Groundwater-Surface Water Simulation Model

The California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) is the application of IWFM version 3.02, developed by DWR (Brush et al., 2013), to simulate the highly interactive system of surface and subsurface flows in the Central Valley. C2VSim is publicly available and can be downloaded from the DWR website (https://water.ca.gov/Library/Modeling-and-Analysis/Central-Valley-models-and-tools/C2VSim). Two versions of C2VSim exist to date: a coarse-grid C2VSim (C2VSim-CG) and a fine-grid C2VSim (C2VSim-FG). In this study, C2VSim-FG, referred to simply as C2VSim for the rest of the paper,

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Table 2
Relative Shortage in Million Cubic Meter of Water for Irrigation Purposes at the Diversion Points for Scenarios A, B, and C

	Diversion node				
Scenario	493	514	543	580	Total
A	−53.99	10.34	136.72	0.01	93.08
B	−55.47	10.34	−16.85	−3.21	−65.18
C	−108.19	10.34	209.59	1.75	113.48

was used because of its higher resolution. C2VSim contains a total of 32,536 grid cells with an average cell size of 1.6 km^2. The simulation period is from October 1921 through September 2009, and the simulation time step is a month. The Valley aquifer has been discretized into three vertical layers varying in depth. Additionally, surface and subsurface flows from 210 small watersheds bordering the Valley are simulated to estimate the flow entering the model domain from the lateral boundaries. The stream network is represented by 2,449 stream nodes with 246 diversion locations. C2VSim uses monthly historical surface water diversions, precipitation, land use, and crop acreages from October 1921 to September 2009 (supporting information Texts S2 and S3). Overall, C2VSim simulates the historical response of the Valley's groundwater and surface water flow system to historical stresses and can also be used in planning studies to simulate the response to projected future stresses. A complete description of C2VSim model development and characteristics is given by Brush et al. (2013).

4. Results

4.1. Groundwater Head and Storage Change

Results are presented relative to the base case reported in Brush et al. (2013). The base case does not include any Ag-MAR diversions but does include other real-world MAR schemes. The average differences in groundwater head were compared in all the three scenarios to examine the spatial variation of the groundwater head across subregion 18 due to Ag-MAR (Figure 4). As expected, the highest change occurs in layer 1 for all the three scenarios, and the change is in line with the pattern of land distribution in Ag-MAR. However, the targeted diversions have resulted in local groundwater head drop in layer 1 of scenarios A and C, near Farmersville, while that drop is missing in scenario B.

This is the result of the influence from upstream targeted diversions on downstream diversions, particularly on the diversions at node 543 (Figure 2). The relative changes in the shortage experienced at these diversions, used for irrigation and direct recharge, are compared separately (Tables 2 and 3). Here a shortage is defined as the volume of water that was planned to be diverted but is not available in the stream. Diversion 543 in scenario B has the most available (least shortage) amount of water among the three scenarios, particularly for irrigation (agriculture). The reason is that Ag-MAR scenario B resulted in higher groundwater table elevations in the vicinity of diversion node 543 (Figure 4) due to nearby recharge on lands not available in scenario A. In scenario C, recharge rates are less than those in scenario B due to the larger amount of land used for recharge. Scenario B (and less so in scenario C) results in a lower gradient between the water elevation in the stream and the groundwater head below. The lower gradient in a connected stream-aquifer system results in less seepage of water from the streambed to the underlying aquifer, allowing for more in-stream flow at diversion point 543 (see the supporting information and Table S1). The gradient difference (Table S1), is 0.3 for scenarios A and C as opposed to 0.07 for B at node 542. The diversion water for irrigation is affected because the change in the groundwater head below the streambed does not just occur during the Ag-MAR window (November to April) but also remains during the irrigation season (Table 2). Comparison of the relative shortages for direct recharge indicates that the major differences among total shortages (Table 3) are less than the values observed for irrigation (Table 2), implying that Ag-MAR effects on stream-groundwater interactions are more distinct during the irrigation season.

Table 3
Relative Shortage in Million Cubic Meter of Water for Direct Recharge Purposes at the Diversion Points for Scenarios A, B, and C

	Diversion node				
Scenario	493	514	543	580	Total
A	−38.42	183.58	162.73	3.43	311.32
B	−37.65	183.58	135.37	2.33	283.64
C	−77.68	183.58	216.18	4.18	326.26

To study the efficiency of Ag-MAR for increasing groundwater storage and therefore augmenting the sustainable yield, we evaluated the annual relative change in the groundwater storage over the course of 88 years (1921 to 2009; Figure 5). In all scenarios, the groundwater storage increased; however, the overall change in storage varied for the three scenarios: 296, 422, and 371 MCM for A, B, and C, respectively. This suggests that the total acreage of participating lands for Ag-MAR projects is not the only determining factor for increasing groundwater storage. Our analyses suggest that the storage in all the scenarios keep rising from the mid-1970s to the mid-1980s, although there is a decreasing trend in the

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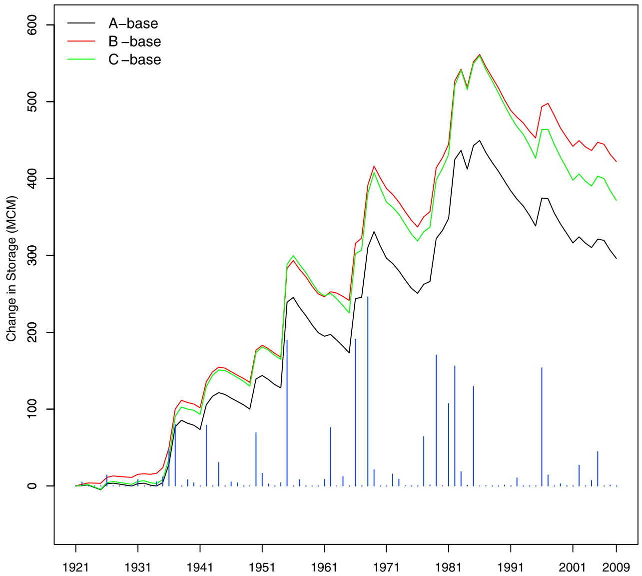

Figure 5. The annual relative change in groundwater storage in scenarios A, B, and C. The blue bar chart at the bottom shows the annual time series of the targeted diversions for agricultural managed aquifer recharge. MCM = million cubic meter.

amount of available water for diversions. Except for the drought years of 1976/1977 and 1986–1990 (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST) the 1970–1990 period had, on average, above-normal precipitation, which resulted in less pressure on groundwater reserves in the Central Valley despite the decrease in surface water diversions. Note that the changes in groundwater storage are far smaller than the amount of the targeted diversions (2,089 MCM), a difference that is explored next through a more detailed water budget analysis.

4.2. Water Budget Analysis

We analyzed the water budget components to understand the fate of the portion of the targeted diversions that does not end up in groundwater storage by 2009. For a more detailed analysis the change in the water budget components is split into surface and subsurface flow components. The relative change in the surface water components of the water budget for the three scenarios, over the entire period of simulation, is shown in Figure 6a. The targeted diversions in all the three scenarios lead to less **F6** downstream outflow from the subregion (accumulation of flow at the most downstream nodes of the four rivers in subregion 18). Scenario B leads to the least amount of downstream outflow in comparison with scenarios A and C (Figure 6a). Runoff and irrigation return flows in all the scenarios stay close to their counterparts in the base scenario, while the streams in all the scenarios gain more water from the underlying aquifer. In fact, a portion of the targeted diversions discharges back to the river in all the scenarios. There is, however, a decreasing trend in the streamflow gain from groundwater as the recharge area expands between scenarios A and C. How the three Ag-MAR scenarios affect the diversions at other diverting points over the course of 88 years is of importance to water managers (Figure 6a). While our targeted diversions at node 514 at the Kaweah River has led to less available water for diversions at downstream nodes 543 and 580, node 493 on the Tule River (an adjacent stream from which no Ag-MAR diversions were simulated) has gained more water. The nonhomogenous change in diversions is an indication of the nonlinearity of the system and highlights the importance of model applications to better understand the change in water balance components. The diversion shortage at node 514 is the portion of water that cannot be met (shown in Figure 6a).

The relative change in subsurface flow components over the entire course of the simulation was analyzed (Figure 6b). As shown in Figure 6b, scenario B is more effective in increasing groundwater storage. This is in line with the change in downstream flow (Figure 6a), suggesting that the bigger contribution of scenario B to increasing groundwater storage leads to less downstream flow. The net deep percolation is reduced in all the scenarios, compared with the base scenario, particularly in scenarios A and C (Figure 6b). This pattern is very similar to the reduction in groundwater pumping, where scenario B has led to significantly less pumping. To explain that pattern, we refer to the functionality of IWFM where any change in net deep percolation is related to the change in irrigation water. As shown in Table 2, scenario B has less water shortage for irrigation diversions than other scenarios; therefore, groundwater pumping in scenario B has been reduced by 65.18 MCM more than in other scenarios. Additionally, the model suggests there is a reduction in net subsurface inflow to subregion 18 (Figure 6b). The three Ag-MAR projects have all caused the groundwater heads to rise at the boundaries in subregion 18, leading to decreased groundwater inflows into subregion 18 from neighboring subregions.

4.3. Spatial and Temporal Stream-Aquifer Interaction

To investigate the long-term effect of recharge scenarios on streamflow, we analyzed the river-aquifer interaction along the Kaweah River since it is the river that is affected the most by the targeted diversions in the study area. Average monthly exchange flux (between the stream and the aquifer) from 1921 to 2009 along the river nodes for all the scenarios, including the base scenario, are compared in Figure 7. Values above **F7** the horizontal line represent a gaining stream, whereas the negative values represent a losing stream. Ag-MAR in scenarios A and C cause a very large increase in streamflow losses at the midstream nodes (541 to 543) (Figure 7). This large streamflow loss is congruent with the local groundwater head drop

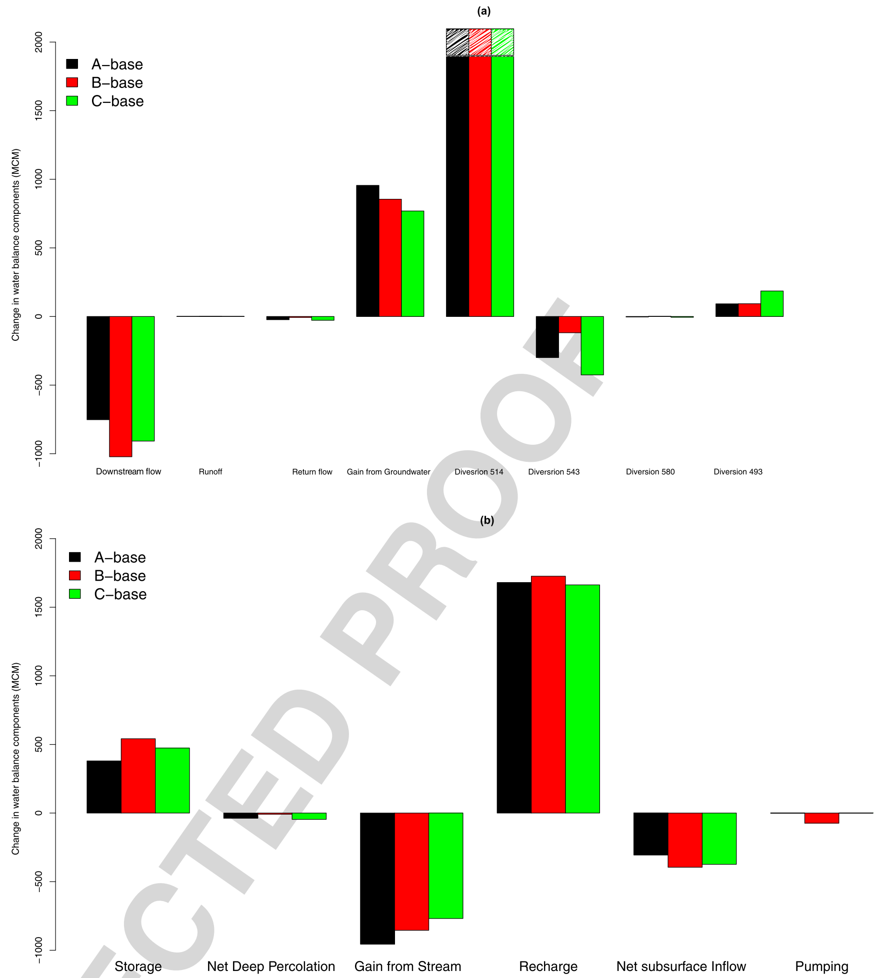

Figure 6. Total relative change in (a) surface and (b) subsurface water budget components of subregion 18 for scenarios A, B, and C from 1921 to 2009. MCM = million cubic meter.

(Figure 4). It is not an artifact of the model and is line with the discussion in section 4.1 on water shortage. The drop of the groundwater head causes a greater gradient between the stream water level and the groundwater head resulting in more loss of the streamflow (see supporting information and Table S1). Interestingly, the streamflow regime remains practically unchanged for a large section of the downstream Kaweah River (nodes 561 to 592; Figure 7). This is because the river bed conductivity drops 3 orders of magnitude, from 0.92 to 0.0003 m/day, in this part of the river compared with the upstream sections. Thus, the stream is practically disconnected from the aquifer in this section, and the change in the head gradient does not play a major role in the amount of stream-aquifer interaction.

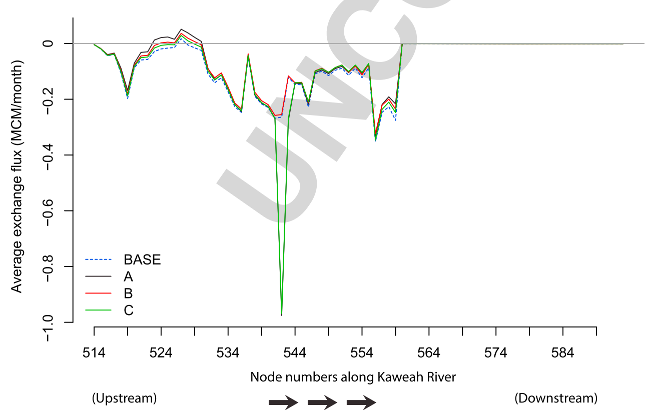

Figure 7. Average exchange flux between the Kaweah River and the underneath aquifer from 1921 to 2009. MCM = million cubic meter.

To analyze the temporal variability of the stream-aquifer interaction along the Kaweah River from 1921 to 2009, six different time periods were considered. First, drought years (1959–1961, 1975–1977, 1986–1992, and 2006–2009) and wet years (1981–1983, 1994–1998, and 2004–2005) were distinguished from normal years in California (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST). Second, we identified wet months (January, February, and March) and dry months (September and October). In the following, the average stream-aquifer exchange flux along the Kaweah River was computed for the wet and dry months of the wet, normal, and

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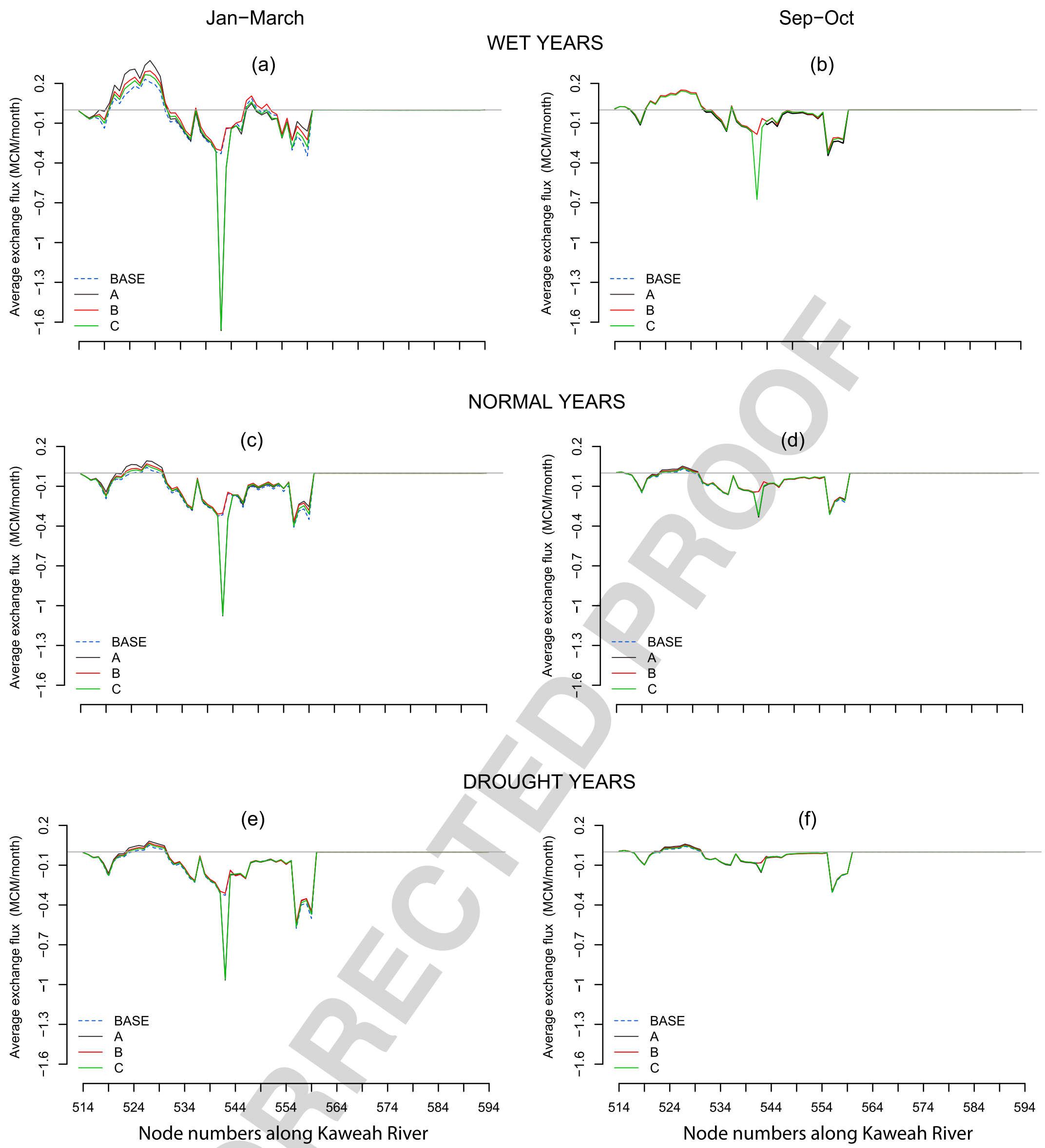

Figure 8. Temporal variation of the stream-aquifer interaction along the Kaweah River. Average exchange flux during (a) wet months of wet years, (b) dry months of wet years, (c) wet months of normal years, (d) dry months of normal years, (e) wet months of drought years, and (f) dry months of drought years from 1921 to 2009. MCM = million cubic meter.

drought years (Figure 8). We observe that the timing matters greatly in how much water is exchanged F8 between the stream and the aquifer, indicating that the Ag-MAR projects can significantly change the streamflow regimes. The streamflow loss along the middle nodes of the Kaweah River is increasingly larger during the wet months than during the dry months (compare Figures 8a, 8c, and 8e with Figures 8b, 8d, and 8f).

4.4. Risk of Ag-MAR to Agricultural Crops

One of the main concerns with Ag-MAR projects has been the rise of the water table into the root zone, which can create anoxic conditions in areas where groundwater levels rise substantially (SAGBI designates areas with very shallow water level—less than 3.3 m—and areas with hydric soils as not suitable for recharge). Therefore, it is very important to identify areas where the water table may potentially rise into the root zone and the length of time periods when the water table stays in the root zone. To identify areas

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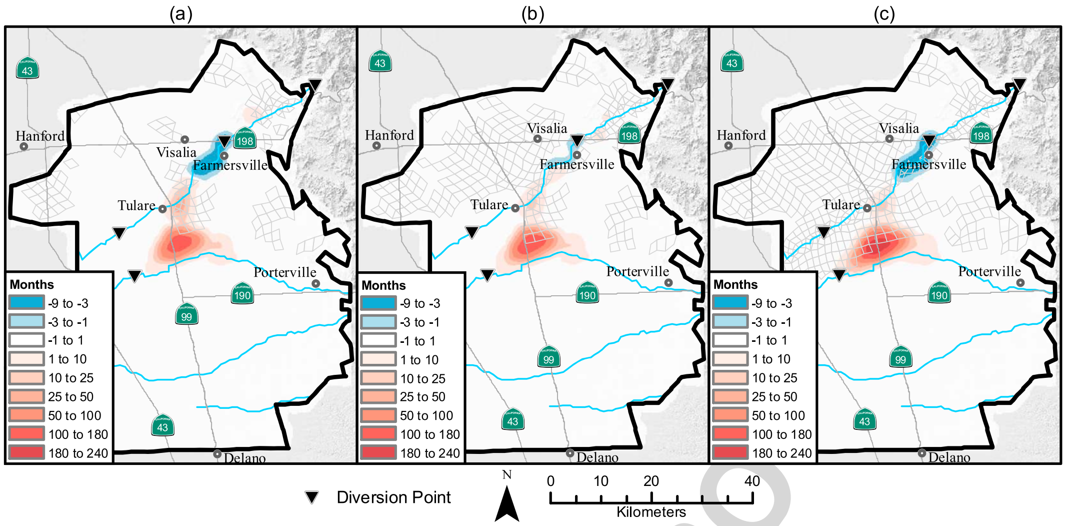

Figure 9. Difference in the number of months that the groundwater depth drops below 1.5 m in (a) scenario A, (b) scenario B, and (c) scenario C compared with the base scenario.

with shallow water tables, we set a 1.5-m threshold for the groundwater depth below land surface. If the water table rose to within 1.5 m from the ground surface elevation, it was assumed that agricultural crops will be damaged. The threshold was selected based on the average root depth for crops and trees farmed in subregion 18 (Brush et al., 2013). To quantify the water table rise into the root zone, first, the number of months that the groundwater depth dropped to less than 1.5 m at each node within the study area for all the scenarios, including the base scenario, was calculated. Second, we mapped the difference in the number of months at these nodes of the model and compared all the three scenarios with the base scenario (Figure 9). Positive values in Figure 9 represent the number of months that experience F9 waterlogging in the root zone due to Ag-MAR.

No additional waterlogging (relative to the base case) is observed throughout most of the recharge areas in all the three scenarios. In scenarios A and C, fewer months of waterlogging are observed than in the base scenario due to the lower water level near Farmersville. Scenarios A and C are therefore more effective in reducing the risk of waterlogging in the middle section of the Kaweah River (shown in blue in Figure 9). This conclusion is in line with the local groundwater head decline in scenarios A and C (Figure 4). Irrespective of the Ag-MAR scenarios, the center of the study region, mostly outside the recharge area near its southern margin, is the only area that experiences significantly more months with waterlogging in the root zone than in the base scenario, although it is not necessarily continuous (Figure 9). This area is fed by diversion node 493, and it was previously demonstrated that diversion 493 has the least shortage in all the scenarios, compared with the base scenario (Tables 2 and 3); therefore, more water is available at that point for diversion and recharging the nearby lands. This result appears counterintuitive, as this area is not the area with the largest water level rise, as it is mostly outside the recharge area. But the finding points to the interconnectedness of these regional water systems and the law of unintended consequences when operating with a highly nonlinear (water) system such as the study region: The regional rise in water level to north of the affected region leads to more irrigation water availability from surface water, less groundwater pumping, and either a decrease in the south-to-north hydraulic gradient and groundwater flow or an increase in the north-to-south hydraulic gradient and groundwater flow. This leads to a rising water table in the highlighted region (Figure 9), even though it is outside the actual recharge zone (especially in scenario A).

Another important concern that needs to be addressed in Ag-MAR projects is the magnitude and the time response of groundwater heads. The maximum groundwater head change across the entire study area at each time step of the model was analyzed for each scenario compared with the base scenario (Figure 10). F10 The magnitude of the groundwater response to the targeted diversions is 2 to 3 times higher in scenario A than in the other two scenarios, particularly at high diversions; the main reason for this is the larger

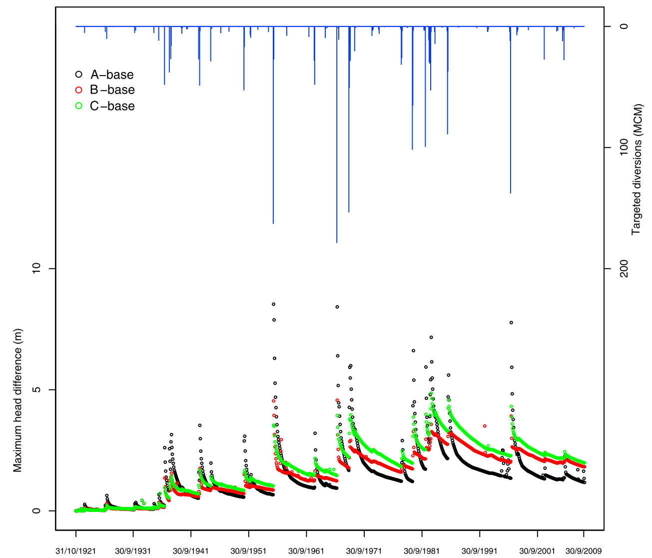

Figure 10. The maximum groundwater head change across the entire study area at each time step of the model for scenarios A (black), B (red), and C (green) with the base scenario.

volume of water per unit area in scenario A (remember that scenario A has the smallest Ag-MAR area) compared with the other scenarios. The largest simulated water table rise (relative to the base scenario) did not exceed 10 m (scenario A) and 5 m (scenarios B and C) and is located within the recharge areas. As water table depth across most of the region is more than 10 m, these increases in water table do not pose a significant problem to agricultural production. Another interesting point is the recession of the maximum change in the groundwater head response; the recession slows down as the peak change decreases from the smallest-area scenario (A) to the largest one (C; Figure 10). In addition, our analyses suggest that as the area for Ag-MAR becomes larger, the maximum groundwater table rise occurring due to the Ag-MAR remains higher than in B or A after the Ag-MAR event seizes (Figure 10). Extending Ag-MAR to large land areas is therefore an important consideration to manage dry years or time periods where diversions for Ag-MAR are minimal and local water agencies rely more on groundwater storage than on surface flows for water supply.

5. Discussion

The decline of groundwater levels and the resulting impacts, such as land subsidence, cost of groundwater use, and degradation of groundwater quality, have increased attention to MAR. Our study demonstrates that Ag-MAR is an innovative method that can successfully take advantage of large sections of agricultural lands to recharge winter runoff not stored or used prior to ocean discharge. Ag-MAR is shown to significantly expand the traditional scope of MAR. Ag-MAR utilizes in-place irrigation infrastructure to recharge excess water flows on agricultural lands. Typically, these excess flows comprise water currently not allocated by surface water rights or in-stream flow requirements (Kocis & Dahlke, 2017). Ag-MAR provides a framework to partially replenish aquifers at large scales in areas where irrigated agriculture is dominant without the need to change the land use of the region. Regional-scale aquifer recharge can significantly alter the hydrologic and agricultural conditions in the target area, such as retiming streamflow regimes (Ronayne et al., 2017), and affect surface water rights along a river (Niswonger et al., 2017), if not implemented properly. Therefore, Ag-MAR needs to be approached in a holistic framework. Our work is an attempt to assess the integrated hydrologic implications of long-term, extensive Ag-MAR.

Over the 88-year historic simulation period, groundwater storage increased by 21% to 26% of the targeted diversions, relative to the historic scenario (base scenario), depending on the choice of land used for recharge. Future conditions may significantly increase the relative benefits of Ag-MAR, since groundwater levels are considerably lower now than they were during the early decades of the 88-year historic simulation horizon. During the most recent drought in California, the increased groundwater levels would have provided substantial buffer capacity against the cost of additional pumping; crop revenue losses' negative impacts experienced during the drought, such as costs of additional pumping; and dairy and livestock revenue losses (Medellín-Azuara et al., 2016). Q12

In this study, diverting river water for Ag-MAR was shown to affect the available stream water at other surface water diversion points in two ways: (1) diversions limit the amount of water available for diversion downstream of the Ag-MAR diversion nodes and (2) diversions change the gradient between the stream water level and the groundwater head in the underlying aquifers due to the effect of recharge on the groundwater head in areas adjacent to the stream. We observed that this change in gradient affected the diversions along the streams during the irrigation season even though Ag-MAR diversions occurred outside the irrigation season. This seemingly nonintuitive result indicates that off-season diversions for aquifer recharge may affect water availability during the irrigation season.

In this study, water diversions for Ag-MAR occurred from the most upstream location on the Kaweah River. The diversion amount during high-flow events was designed not to impair water rights and other diversions along the river at the time of diversion. As shown by our integrated hydrologic assessment, the potential

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effects of the diversion on downstream flows later in the irrigation season creates downstream benefits, which should be considered in the permitting of Ag-MAR diversions. For the case presented here, potentially impacted beneficiaries are the Kaweah River water agencies and users in subregion 15 (Figure 1). Our analysis suggests that the Ag-MAR diversions have long-term benefits to subregion 15 that may outweigh the surface water effects of the diversion. Interestingly, our analysis also showed that the Ag-MAR diversions lead to higher water levels in subregion 18 and diminish the subsurface inflows to that subregion, including those from subregion 15. While this may be considered a benefit to the neighboring region (subregion 15), that region may benefit even more from increasing its own Ag-MAR efforts. The model results suggest that changes in these boundary fluxes between subregions are highly localized and dynamic in response to the recharge actions on both sides of the political boundary.

Our analysis further shows that the average increase in water table elevation was approximately 5 times higher below the Ag-MAR lands than in nonparticipating lands. The resulting elevated groundwater levels might help groundwater users reduce their groundwater pumping costs and could potentially prevent the need for drilling deeper wells (another cost saving to groundwater users). The prospect of these economic gains may further encourage agricultural land owners to engage in Ag-MAR projects.

One of the largest concerns to land owners, however, is the rise of the water table into the root zone, which must be properly addressed in the Ag-MAR planning phase. Our simulations suggest that Ag-MAR programs may lead to waterlogging of agricultural lands in unexpected places outside of the recharge zone. For the case presented here, we considered 1.5 m as the threshold for the groundwater depth, meaning that the risk to crop damage can increase if the depth to groundwater becomes less than 1.5 m. The threshold may differ from crop to crop depending on the rootstock depth. We also note that crop roots have different tolerance levels to saturated conditions and durations (Broughton et al., 2015; Colmer & Voesenek, 2009; Nishiuchi et al., 2012). The issue is particularly important for perennial crops and vines, because of the risk of losing high-value crops. In this regard, we note that soil conditions and water table depths within each of the 1.6-km^2 cells used in this study are unlikely to be homogeneous, and therefore, the spatial resolution of C2VSim is not sufficient to pinpoint local areas/farms where the water table encroaches into the root zone. A methodology that can avoid the rise of groundwater into the root zone is linking the groundwater models to optimization models in order to limit aquifer recharge where groundwater table crosses a predefined threshold (Ebrahim et al., 2016).

Enhancing groundwater recharge via flooding agricultural lands can pose a risk to contaminating groundwater resources in two ways: (1) pushing the accumulated salts in the root zone/shallow vadose zone down to the aquifer and (2) mobilizing contaminants such as nitrates and pesticides due to increased pressure gradients in the deep vadose zone. Salt contamination is more likely to occur in areas where groundwater is the dominant source of irrigation water and the unsaturated zone is relatively thick (Walvoord et al., 2003; Welch et al., 2011). Indeed, both conditions exist in the study area. The average thickness of the unsaturated zone across the studied area is 18.9 m, and groundwater is used intensively for irrigation in the study area (California DWR, 2013b). The SAGBI used here to differentiate the spatial land patterns already considers the presence of soil salinity (represented by the soil electrical conductivity) and a high sodium adsorption ratio as two major indicators of soil/vadose zone pollution. Therefore, this study intrinsically considered the most usable land, from a water quality perspective. Nitrate and pesticide contamination is mainly dependent on management history and the type of crops that are farmed within a region (O'Geen et al., 2015) and was not investigated in our study. A successful Ag-MAR project also requires high-quality water before spreading it on agricultural lands. Beganskas and Fisher (2017) conducted an Ag-MAR project in which storm runoff was collected from 40- to 400-ha drainage areas for recharge of a coastal alluvial aquifer in the Pajaro Valley, California, using a 1.7-ha infiltration basin. They realized that the fine-grained sediments in the storm water reduced soil hydraulic conductivity over time. This process can be mitigated with large sediment detention basins or source control (e.g., timing diversions to occur only after high sediment loads have passed).

Our analyses further indicate that the targeted diversion amounts were not completely met. In other words, a specified diversion amount could not always be taken from the source stream node due to the lack of incoming streamflow identified in C2VSim. We note that the surface water inflows to C2VSim are not identical to the streamflow data used in our high-flow events analysis. The discrepancy therefore may be a result of differences in the simulated streamflow data in C2VSim compared with historic U.S. Geological Survey streamflow data used by Kocis and Dahlke (2017) for the streamflow availability analysis for groundwater recharge. An alternative explanation for the shortage of the diversions can be the erroneous base diversions. In the past, many canals, pumps, and so on, did not have gauges, forcing modelers to assume that the diversion amount was equal to the water right. Where flumes are installed in canals, erroneous values will be observed if the canals change flow capacity due to land surface subsidence. Districts that have recently installed gauges have often found that the actual flow rates were significantly different (i.e., lower) from what they expected them to be (Kaweah Water District, personal communication).

6. Summary and Conclusion

The concept of recharging depleted aquifers by flooding of agricultural lands during the high-flow seasons (i.e., Ag-MAR) was investigated for the Kaweah groundwater subbasin, located in the southeastern Central Valley, California, to explore how a hydrologic system may benefit from these activities. We approached Ag-MAR comprehensively by employing an integrated hydrologic systems analysis, using the numerical simulation model C2VSim, which simulates the agricultural and urban demand for groundwater pumping where surface water cannot meet the demand. We investigated the effect of land suitability for aquifer recharge on the components of the water balance. Three spatial patterns of agricultural lands, each chosen based on different thresholds of a soil suitability index for groundwater recharge, SAGBI, were examined. The areas of the spatial land patterns named A, B, and C are 313.3, 685.4, and 1,022.8 km^2, respectively. The total amount of water diverted for each land scenario was equal. Streamflow for Ag-MAR was diverted from November to April during wet years, when streamflows at the most upstream point on the Kaweah River exceeded the 95th percentile flow.

Ag-MAR is shown to be effective in increasing the groundwater storage of the study region, irrespective of the spatial Ag-MAR land distribution; however, the overall highest increase in storage (26% of the targeted diversions) occurred when pattern B (soils rated as good and excellent) was used for Ag-MAR. This conclusion is somewhat nonintuitive as it indicates that for the same total volume of water applied the size of the area that is flooded for groundwater recharge is not the only determining factor in order to gain the largest increase in groundwater storage. Our analyses also indicate that the persistence of Ag-MAR benefits throughout the drought periods can depend on Ag-MAR land distribution. An analysis of the water dynamics in the region demonstrates, however, that the spatial pattern of the Ag-MAR lands can significantly influence not only total storage gains but also the amount of stream water available at other diversion points at later time periods. In fact, off-season diversions changed the gradient between the stream water level and the underlying aquifers by altering the groundwater head in the areas adjacent to the stream. That change was shown to be a crucial factor in changing the losing/gaining regime of the stream, which in turn affected surface water diversions along the river.

The undesirable effects and risks of Ag-MAR to agricultural crops are the factors that can lead to the failure of an Ag-MAR program. Our simulations show that Ag-MAR programs could lead to some waterlogging of agricultural lands, not necessarily within the Ag-MAR zone, which may damage certain crops sensitive to anoxic conditions in the root zone. We also addressed that Ag-MAR plans, performed in high-flow and wet seasons, can potentially negatively impact water rights and irrigation diversions during the growing season. Overall, this study provides significant insights into the application of integrated numerical models for aquifer recharge planning at regional scales. In the case of the Kaweah basin, we have identified a need for a more evenly distributed diversion and conveyance system to move surplus surface water to areas of greater subsurface storage potential. This information is valuable for developing an overview on how effective the long-term effectiveness of aquifer recharge plans in light of all water balance components.

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