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Special Section:
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Key Points:
- Agricultural managed aquifer recharge at low recharge rates over large areas offers benefits to groundwater storage and seasonal base flow
- Longer recharge periods allow for more recharge than short, fixed windows of recharge that accommodate high recharge rates
- Maximum groundwater level rise is sensitive to recharge timing and recharge locations

Supporting Information:
- Supporting Information S1

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Increasing Groundwater Availability and Seasonal Base Flow Through Agricultural Managed Aquifer Recharge in an Irrigated Basin

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Abstract Groundwater aquifers provide an important "insurance" against climate variability. Due to prolonged droughts and/or irrigation demands, groundwater exploitation results in significant groundwater storage depletion. Managed aquifer recharge (MAR) is a promising management practice that intentionally places or retains more water in groundwater aquifers than would otherwise naturally occur. In this study, we examine the possibility of using large irrigated agricultural areas as potential MAR locations (Ag-MAR). Using the California Central Valley Groundwater-Surface Water Simulation Model we tested four different agricultural recharge land distributions, two streamflow diversion locations, eight recharge target amounts, and five recharge timings. These scenarios allowed a systematic evaluation of Ag-MAR on changes in regional, long-term groundwater storage, streamflow, and groundwater levels. The results show that overall availability of stream water for recharge is critical for Ag-MAR systems. If stream water availability is limited, longer recharge periods at lower diversion rates allow diverting larger volumes and more efficient recharge compared to shorter diversion periods with higher rates. The recharged stream water increases both groundwater storage and net groundwater contributions to streamflow. During the first decades of Ag-MAR operation, the diverted water contributed mainly to groundwater storage. After 80 years of Ag-MAR operation about 34% of the overall diverted water remained in groundwater storage while 66% discharged back to streams, enhancing base flow during months with no recharge diversions. Groundwater level rise is shown to vary with the spatial and temporal distribution of Ag-MAR. Overall, Ag-MAR is shown to provide long-term benefits for water availability, in groundwater and in streams.

1. Introduction

Approximately 36% of the population worldwide relies on groundwater for drinking water supply, and 42% use groundwater for irrigated agriculture (Döll et al., 2012; FAO, 2011; Foster et al., 2013). In many groundwater-dependent regions, groundwater is often exclusively used to meet water demand during periods of surface water shortage or prolonged droughts (Scanlon et al., 2012; Siebert et al., 2010). Groundwater resources therefore provide an important "insurance" against climate variability and climate change (Grönwall & Oduro-Kwarteng, 2018; Scanlon et al., 2016). However, many groundwater-dependent regions, particularly arid and semiarid regions including the southwestern United States, India, Pakistan, the Middle East, the North China Plain, and North Africa, experience increasingly water scarcity and groundwater depletion due to water demand exceeding the sustainable yield of the groundwater aquifer and the local, renewable surface water supply from precipitation (Famiglietti et al., 2011; Konikow & Kendy, 2005; Scanlon et al., 2016; Taylor et al., 2013; Wada et al., 2012). In many groundwater-dependent regions, unsustainable groundwater use not only impacts human water supply and food security (USA: Scanlon et al., 2012; Konikow, 2015; Iran: Voss et al., 2013; India: Chinnasamy & Agoramoorthy, 2015; Australia: Chen et al., 2016) and groundwater-dependent ecosystems (Closas & Molle, 2016; Owen et al., 2019; Rohde et al., 2017) but also causes water quality degradation (Harter et al., 2012), land subsidence (Faunt, 2009), and seawater intrusion (Konikow & Kendy, 2005).

Recognition of worldwide depletion of groundwater resources and its adverse effects on human and environmental well-being has led to recent policy and legislative action toward sustainable water resources management in the European Union (European Commission, 2016), North-America (Cannon Leahy, 2015), New Zealand (Ministry for the Environment, 2018), and Australia (Water Act, 2007). Methods to achieve sustainable management of groundwater resources range from conservation (i.e., reduced groundwater pumping), conjunctive use (substituting surface water for groundwater to reduce groundwater use), and in-lieu recharge (supply surface water to users who normally use groundwater) to various managed aquifer recharge (MAR) methods, which intentionally place more water in groundwater aquifers than would otherwise naturally occur (Bouwer, 2002; Kocis & Dahlke, 2017; Scanlon et al., 2016). MAR approaches use a variety of water sources (e.g., river water: Scanlon et al., 2016; stormwater: Page et al., 2016; treated wastewater: Zekri et al., 2013; Bugan et al., 2016; or desalinated water: Kimrey, 1989) and methods (e.g., infiltration basins or channels, injection and recovery of groundwater through wells, induced bank filtration, off-season spreading of water on farmland; Dahlke, Brown, et al., 2018; Dillon, 2005; Russo et al., 2014) to intentionally replenish underlying aquifers.

Although most engineered MAR systems (e.g., infiltration basins, aquifer storage, and recovery) can achieve high recharge rates (>10 m per year) their small, localized footprint (few tens of square meters to a few hectares), high capital and maintenance cost along with requirements for creation and maintenance of conveyance and pumping systems and water quality permitting often limit their use for large-scale (e.g., regional) groundwater management (Bouwer, 2002; Dahlke, Brown, et al., 2018). More recently, the use of large areas of agricultural farmland as off-season spreading grounds of excess surface water, hereon referred to as Ag-MAR (Kocis & Dahlke, 2017; Niswonger et al., 2017), has emerged as a promising large-scale MAR approach. Ag-MAR can be practiced in any irrigated agricultural region with water conveyance and irrigation infrastructure in place, which can be used to move excess surface water or flood flows onto fields for replenishment of depleted groundwater aquifers (Kocis & Dahlke, 2017). Although agricultural fields may not support recharge rates of the same magnitude as achieved with carefully sited infiltration basins or injection wells (O'Geen et al., 2015), spreading water over large land areas (e.g., hundreds to thousands of square kilometers) at recharge rates of less than 1 m per month still allows capturing large amounts of water in short time periods (e.g., days to weeks) that would otherwise overwhelm localized systems such as well injections or infiltration basins. As such, Ag-MAR represents a particularly promising groundwater banking strategy for groundwater-dominated regions where large climate variability (e.g., annual rainfall derives from a few storm events; Dettinger et al., 2011) results in high volume rainfall-runoff events that could otherwise not be captured through traditional MAR approaches.

Because of its recent emergence, regional-scale water resources and environmental benefits of Ag-MAR have not yet been explored much through numerical modeling or quantitative analyses. Ag-MAR assessments have mainly focused on recharge projects implemented at individual sites (Bachand et al., 2014; Dahlke, Brown, et al., 2018). While a large majority of MAR modeling studies has focused on well, shaft, and borehole recharge (Ringleb et al., 2016), MAR spreading methods (e.g., infiltration basins or canals) have been mainly evaluated using site-specific unsaturated flow and groundwater flow models. Models have been used to assist in site selection (Jha & Pfeiffer, 2005; Rahman et al., 2013; Valley et al., 2005) and to assess the feasibility of MAR, the design and optimization of MAR systems (Maliva et al., 2015; Smith & Pollock, 2012), the estimation of recovery efficiency, the residence time of the infiltrated water (Tompson et al., 1999; Vandenbohede et al., 2008), and general changes to the groundwater system (e.g., groundwater level and groundwater storage changes; Dillon et al., 2009; Sheng, 2005). Even though there exist a few models that were specifically developed for MAR, most studies use widely available groundwater flow models such as MODFLOW (McDonald & Harbaugh, 1988; Mirlas et al., 2015), saturated flow models such as FEFLOW (Diersch & Kolditz, 2002) and SEAWAT (Langevin et al., 2008), or unsaturated flow models such as HYDRUS (Šimůnek et al., 2012) or MIKE-SHE (Sahoo et al., 2006).

Since Ag-MAR can be implemented over vast agricultural areas, regional- to large-scale modeling studies are needed to evaluate long-term benefits and impacts on groundwater supply, aquifer sustainability, and groundwater-dependent ecosystems. They would further allow optimizing the size and location of Ag-MAR programs with respect to regional hydrogeologic and climatic conditions. In regions with large precipitation and streamflow variability such as the southwestern United States, where increasing temperatures and changing precipitation patterns (Dettinger et al., 2011) are putting additional pressures on water resources, Ag-MAR may play a central role in efforts to optimize the use of surface water to bring depleted groundwater aquifers back into balance (SGMA (Sustainable Groundwater Management Act), 2014). While in many irrigated agricultural regions surface water resources have been mostly tapped, including water rights for environmental flow, recently Kocis and Dahlke (2017) identified significant unused surface

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water volumes from large runoff events (e.g., high-magnitude flows or flood flows) for the California Central Valley (CV). Ag-MAR and more integrated joint management of surface water reservoirs and groundwater storage capacity may allow for a significant fraction of this water to be captured prior to discharge into the ocean (California Department of Water Resources [DWR], 2018a; Dillon & Arshad, 2016; Pavelic et al., 2012). Nevertheless the diversion of large amounts of floodwaters may also lead to loss of water to estuary ecosystems (Grimaldo et al., 2009).

Widespread adoption of Ag-MAR programs hinges on uncertainty about the long-term effects on groundwater storage, levels and flow pathways, ecosystems services provided by potential increases in groundwater storage, and subsequently the potential benefits to stakeholders. As one of the few Ag-MAR modeling studies published to date, Niswonger et al. (2017) coupled the distributed hydrologic model MODFLOW-NWT (Niswonger et al., 2011) with the linked-network optimization and operations/planning model MODSIM (Labadie, 2010) to estimate potential benefits of Ag-MAR while considering heterogeneous hydrogeologic conditions, surface water diversions, reservoir releases, and stakeholder water rights, rules, and priorities. The coupled model was developed to represent the 698 km^2 (172,500 acres) semiarid Carson Valley in California and Nevada, USA in a simplified way, omitting some of the physiographic, land use, water infrastructure, and water rights complexities that often plague many larger irrigated agricultural regions such as the California CV. For the 1990–2014 modeling period recharge of excess surface water available only during seven years increased total groundwater recharge between 9 and 12%, resulting in groundwater level increases of up to 7 m, increased crop water consumption leading to greater crop yield, and increased drought resilience of the aquifer. However, the integrated model developed by Niswonger et al. (2017) focused on a very small study area, which would cover less than 1% of some of the most important groundwater-dependent agricultural regions in the United States such as the High Plains aquifer (111.4 million acres [450,657 km^2]), the Mississippi embayment alluvial aquifer (49.9 million acres [202,019 km^2]), and the California CV (16.1 million acres [65,000 km^2]). Nevertheless, the study illustrates that when simulating hydrologic conditions of Ag-MAR in developed groundwater basins with complex water use structures and conjunctive use of surface water and groundwater in place, estimating benefits of Ag-MAR is challenging, because enhanced water supply due to Ag-MAR changes the relative amounts of surface water and groundwater used for agriculture.

In this study, we use the California Central Valley Groundwater-Surface Water Simulation Model (California Central Valley Groundwater-Surface Water Simulation Model (C2VSim); Brush et al., 2013), a large-scale, integrated groundwater-surface water model that covers the entire CV of California, USA (model domain is 13.3 million acres [53,645 km^2]), to evaluate potential benefits and consequences associated with adopting different Ag-MAR practices in California's CV. We focus on a groundwater subbasin within the CV as a laboratory to quantify the impact of various Ag-MAR practices (e.g., different recharge locations, amounts, and timings) on local- and regional-scale, long-term benefits to groundwater storage, surface, and groundwater return flows (Sophocleous, 2007) within the full domain C2VSim model and how these benefits are distributed within the system. The study further aims to quantify the risk that Ag-MAR may pose for waterlogging the root zone of crops or shallow soils in urban areas and the effects that large surface water diversions for Ag-MAR may have on in streamflows. The modeling tool used in this study (C2VSim) has been developed by the California Department of Water Resources. C2VSim is frequently used by Water Districts, consultants, and other water agencies (Davids Engineering and West Yost Associates, 2018) for groundwater-related project assessments. In this study we also highlight some of the important assumptions and limitations of C2VSim pertinent to Ag-MAR assessments and illustrate a potential framework for how this tool can be used to extract valuable information for water resources managers.

2. Methods

2.1. Study Area

The Central Valley (16.1 million acres [65,000 km^2]) of California located between 35 and 41°N and 118 and 122°W is an irrigated, groundwater-dependent region overlying the second largest groundwater system in the United States. It is also one of the most agricultural productive regions in the world. Its 7.9 million acres (32,000 km^2) of irrigated agricultural lands are intensively farmed (Harter et al., 2017). Important crops include fruit, nuts, vegetables, rice, corn, citrus, and grapes. The CV is characterized by a semiarid

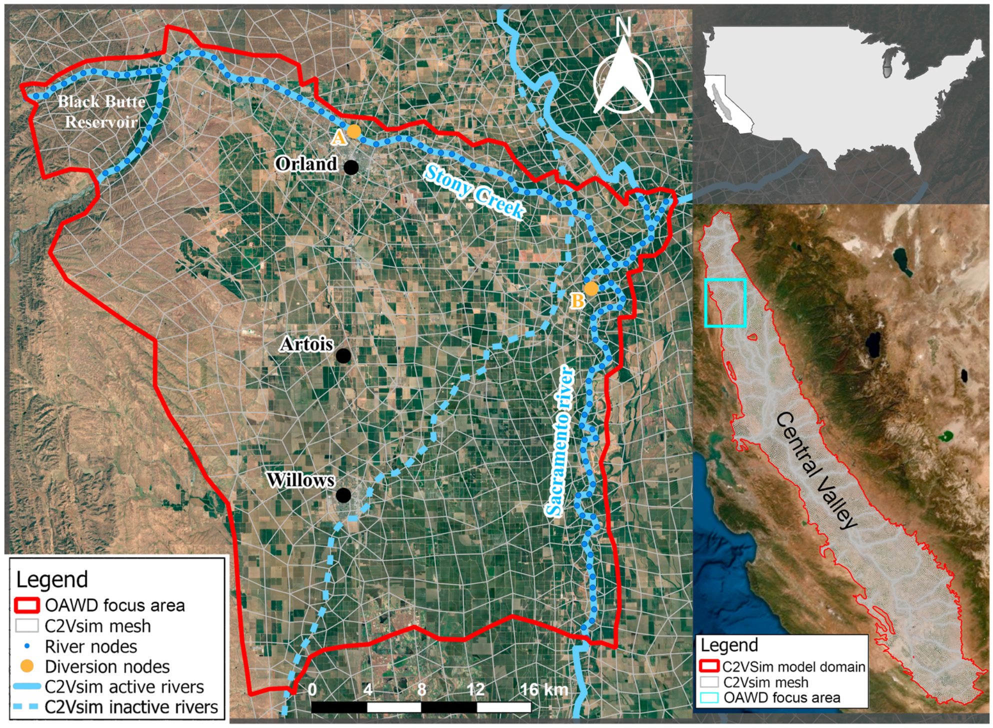

Figure 1. Orland-Artois Water Districts (OAWD), the study area, is located west of the Sacramento River in the northern part of the CV, California. Stony Creek and some smaller, ephemeral streams flow from the Coast Range, west of OAWD across the district to the Sacramento River. Stony Creek forms the northern boundary of the district and is the only major surface water feature besides the Sacramento River. A large diversion canal for irrigation within OAWD and south of OAWD runs diagonally through the district. Smaller canals run throughout the district, which currently have water rights to Stony Creek, but not to the Sacramento River (e.g., Tehama-Colusa canal).

Mediterranean climate with hot, dry summers and cool, wet winters. Annual precipitation in the valley ranges between 125 and 510 and over 1,000 mm/a in the Sierra Nevada mountains (1961–1990; DWR, (California Department of Water Resources), 2003), most of which falls as rain or snow between November and April. Mean annual temperature ranges between 16 and 19.5 °C across the valley (Kocis & Dahlke, 2017). Land use is dominated by irrigated, mostly high-value agricultural production. About 6.9 million acres (28,000 km^2) are connected to an extensive system of reservoirs, canals, and aqueducts (Hanak, 2011). While irrigation water is sourced from a mix of groundwater and surface water, many of the region's communities depend on groundwater for drinking water.

The CV comprises a large, high-yielding aquifer system formed from unconsolidated sedimentary basin deposits (Farrar & Bertoldi, 1988). Past or ongoing groundwater overdraft in some areas has created subsurface storage capacity and significantly degraded the groundwater-surface water connectivity, especially along the thalweg (Brush et al., 2013; Faunt, 2009). Large water conveyance systems such as the CV Project and the State Water Project link surface reservoirs in the foothills of the Cascade mountain range in Northern California to urban centers at the central and Southern California coast but also offer water trading opportunities throughout the state (Hanak & Lund, 2012). Similar climate, land use, and water resources conditions are found in other intensively farmed regions around the world, albeit some without extensive canal infrastructure (High Plains aquifer, North China Plain, agricultural regions in southern Europe, North Africa, South America, and the Middle East).

This study focuses on the Orland Artois Water District (OAWD), located in the Colusa groundwater subbasin in the north-western part of the CV and the CVSim model domain, to evaluate the impact of various Ag-MAR scenarios on the integrated groundwater-surface water system. The focus area of approximately 0.34 million acres (1,370 km^2) is bounded by the Coast Range to the west, the Sacramento River (thalweg) to the east, by Stony Creek—a Sacramento River tributary—to the north and the boundary between Glenn and Colusa County to the south (Figure 1).

The subsurface geology of OAWD, like elsewhere in the CV, consists of a mixture of unconsolidated late tertiary and quaternary continental deposits overlying a basement complex of granitic and metamorphic rocks (Davids Engineering, Inc., 2002; Davids Engineering, Inc., & MWH, 2006; West Yost Associates Consulting Engineers, 2012).

In OAWD, annual precipitation averages 585 mm/a (1981–2010) and the mean annual temperature is 16.7 °C. Precipitation occurs from November through April, while little or no rainfall is observed during summer and early fall. Stony Creek flows are managed by Black Butte Lake, located in the northwest corner of the study area. The Sacramento River has large upstream reservoirs (e.g., Lake Shasta, Lake Oroville), which store winter runoff and snowmelt for summer delivery via the Sacramento River, irrigation canals, and large water projects to irrigation districts and other water users throughout the CV.

OAWD delivers surface water from Stony Creek, an ephemeral stream north of Orland, CA. Irrigation canals deliver water to landowners within the district, irrigating approximately 28,918 acres (10,842 ha) in 2014 (California Department of Water Resources [DWR], 2018b) of predominantly deciduous tree orchards (15,780 acres [6,386 ha], mostly walnuts and almonds, north and northwest of the study area), field crops and pasture (4,495 acres [1,819 ha]), vineyards (1,048 acres [424 ha]), rice (867 acres [351 ha], eastern and southern part of the study area), and idle fields (4,596 acres [1,860 ha]). OAWD receives an annual allocation of 53 thousand acre-feet (TAF) (65.4 million cubic meter [Mm^3]) of surface water from the CV Project (i.e., U. S. Bureau of Reclamation), which equals 1.8 ft/acre (135 cm/ha) of irrigation water. The supplied surface water amount is not enough to grow most crops. Hence, in addition to private groundwater pumping, OAWD is supplementing surface water supplies with groundwater from two deep (>250 m) groundwater production wells (5,400 acre-feet (AF) [6.6×10^6 m^3]), every year as well as surface water transfers from other water districts (about 3,300 AF [4.0 Mm^3]; Orland-Artois Water District, 2014). Importantly, growers operate their own wells and pump as much as 58,600 AF (72.3 Mm^3) in a drought year (e.g., 2014).

Groundwater recharge occurs from streams, mostly along the upper alluvial fans in the western part of the study area away from the Sacramento River thalweg and from winter precipitation and irrigation return flows across the landscape (Brush et al., 2013). The regional groundwater tables are relatively stable despite supplemental groundwater pumping for irrigation. However, some local areas, which rely primarily on groundwater and recover more slowly after extended droughts periods, have experienced significant drawdown in recent years, especially west of the towns of Artois and Orland (north-central portion of the study area).

A key component in the CV and consequently the study area is the linkage between groundwater and surface water. In general, near the foothills of the CV the streams recharge the aquifer. Further downstream, some rivers receive significant inflow from groundwater that is an important component of summer base flow and contributes to low stream water temperatures, although streamflow is also significantly affected by upstream reservoir releases.

2.2. Model Description

This study, while focused on management actions and hydrologic responses in the region around OAWD, simulates the entire CV aquifer system. We employ the fine grid version of the Central Valley integrated groundwater-surface water simulation model C2VSim (Brush et al., 2013). C2VSim was developed using the Integrated Water Flow Model (IWFM) software (Dogrul, 2012; Dogrul et al., 2017). The IWFM software is designed as a basin-scale water resource management and planning tool, accounting for reservoir deliveries, streamflow, stream diversions, canal distribution systems, irrigation, runoff, crop water uses, vadose zone processes, and groundwater-surface water-irrigated landscape interactions typical of agricultural, irrigated basins. In California, IWFM is an important tool for decision makers and stakeholders (Harter & Morel-Seytoux, 2013). For local water districts and consulting firms it is often a first choice for developing an integrated groundwater-surface water modeling framework and for estimating water budget scenarios (Davids Engineering and West Yost Associates, 2018). C2VSim is an application of IWFM specifically to the CV aquifer system and its overlying land uses and surface water network. C2VSim and IWFM are publicly available and are documented and maintained and further developed by the California Department of Water Resources staff. For this study, the IWFM components of interest in the C2VSim application are primarily those related to groundwater flows, streamflows, and stream-groundwater interactions, which are briefly reviewed here, but documented in detail in the above references.

The groundwater flow is simulated by numerically solving the three-dimensional groundwater flow equation using a multilayer finite element grid subject to initial and boundary conditions detailed in Brush et al. (2013).

$$-\nabla(-K\nabla h) = S_s \frac{\partial h}{\partial t} \tag{1}$$

Briefly, C2VSim utilizes a three-layer system to represent the CV aquifer system. The CV aquifer domain is discretized into a two-dimensional grid of 32,537 finite elements that is extruded in the vertical direction. The OAWD study area is covered by 925 finite elements with an average element size of approximately 33 acres (13 ha; Figure 1). Assuming that storage is negligible in low-permeability zones, flow between layers is computed as a function of the vertical head difference between aquifer layers using a leakage coefficient (Brush et al., 2013). The Central Valley aquifer system is bounded by low-permeable bedrock simulated as no-flow or low-flow boundaries. Specified or general head boundary conditions are only found at the interface of the CV aquifer with the Bay-Delta region, over 200 km south of the study region. Groundwater flow dynamics are largely controlled by land surface recharge from precipitation and agricultural return flows, groundwater pumping, and groundwater-surface water interactions.

For stream-groundwater interactions, three conditions are often distinguished and accounted for in groundwater-surface water models like C2VSim: (i) gaining stream (water table near the stream is higher than the stream water elevation, (ii) losing stream (water table near the stream lower than the stream water elevation), and (iii) disconnected stream (an unsaturated zone separates the stream from groundwater). C2VSim also accounts for more complex interactions between streams, groundwater, and the irrigated landscape, that is, the diversion of stream water for irrigation, the increase of base flow from irrigation return flow to groundwater, or the decrease of base flow due to groundwater pumping and, hence, decreased discharge of groundwater to streams.

In IWFM, streams are represented as nodes. Their *x*-*y* node locations coincide with the element grid nodes used in the groundwater flow component. At each stream node the continuity equation is enforced such that inflows (the upstream flows, surface return flows from agricultural and urban areas, direct runoff, flows from tributaries, bypasses, and lakes) are equal to the outflows (diversions, water exchange between groundwater, and outflow to downstream node) plus storage changes due to changes in stream stage. Stream stage represents the discharge to the downstream node, that is, after diversions for recharge are subtracted from the stream inflow to the node (see page 14 in Brush and Dogrul (2016) for more details).

Streamflow and surface water (e.g., irrigation canals) diversions are user-defined time series of target diversions in the model. When target diversions cannot be met by streamflow, the model adjusts the diversion amount accordingly. In either case, the diverted amount affects the downstream groundwater-stream interaction, at the node of diversion and downstream from that node, due to lower instream flows and, hence, lower stream stage. The amount of water that is exchanged between the stream and groundwater depends both on the stream reach balance and the head gradient and streambed conductance (Cauchy boundary condition) between the groundwater head and stream water elevation; therefore, these two systems are solved simultaneously at each time step. In C2VSim, both, the Stony Creek tributary and the Sacramento River are explicitly simulated in this fashion, but none of the canals.

A fourth C2VSim model component of interest to recharge studies is the simulation of flow through the unsaturated zone (zone between ground surface and groundwater table). The IWFM software behind C2VSim includes a one-dimensional vertical unsaturated zone flow component that is divided into two layers: the root zone and the deep unsaturated zone. Both are operated based on a tipping bucket approach with transfer rates controlled by hydraulic properties of the unsaturated zone. Water routed for irrigation is applied to agricultural areas to meet irrigation demand and as such can re-enter the groundwater system through infiltration and vadose zone percolation. On the other hand, the software allows the user to route recharge diversions for MAR projects directly to one or several nodes in the groundwater system, bypassing the soil and deep unsaturated zone, when effects of recharge applied at the land surface on crop or vegetation ET, soil moisture, return flow, irrigation water demand, etc. are neglected. This provides computational efficiency and is adequate for our study, which focuses on the long-term (e.g., decadal) impacts of Ag-MAR on groundwater level rise and groundwater discharge to the stream network. The time required for recharge water applied on fields to percolate through the root and unsaturated zone as well is sufficiently short to be neglected for the analysis here. Similarly, additional evaporative or ET losses due to water storage in the vadose zone do not have significant impact on our overall analysis. Additional ET due to shallow groundwater would be undesirable in the agricultural landscape. In practice, Ag-MAR would be controlled to leave water levels well below the land surface. The exception is rice fields, where C2VSim already accounts for ET from flooding conditions.

C2VSim parameters were either estimated prior to model development or calibrated against observed groundwater heads, vertical head differences, and surface water flows for the period 1975–2003 and subsidence observations (Brush et al., 2013). For example, parameters related to soil properties, allocation rules, etc. were estimated, while parameters such as hydraulic conductivity, storage, curve numbers, river bed conductance, and other parameters of the C2VSim hydrologic components were adjusted during calibration using PEST (Doherty & Hunt, 2010). Details on C2VSim calibration can be found in Brush et al. (2013).

2.3. Scenarios

We developed several scenarios to assess the impact of Ag-MAR on local- and regional-scale, long-term benefits to groundwater storage, to instream flows, and to groundwater return flows. All Ag-MAR scenarios are developed as alternatives to the calibrated C2VSim baseline model. The C2VSim model simulates the entire CV surface water-groundwater system for water years 1922 through 2009 (88 years). Surface water for Ag-MAR is diverted starting in water year 1930 in the model, resulting in an 80-year recharge simulation in C2VSim. Each Ag-MAR scenario is mechanistically defined by several design parameters:

1. Diversion point: the point of diversion of streamflow;
2. Recharge locations: the spatial distribution of land where Ag-MAR is done; each recharge location scenario describes a selected array of finite elements that receive diverted streamflow as direct recharge to the topmost layer in the three-dimensional aquifer system (no routing through the vadose zone);
3. Recharge target amount: the targeted maximum annual amount of surface water to be diverted from the diversion point (e.g., stream node) and applied as recharge;
4. Recharge timing: the seasonal time period during which Ag-MAR is conducted.

Scenarios are developed to examine the response of the basin hydrology to these four Ag-MAR design parameters. Each design parameter is varied over a range of values reflecting varying potential agronomic, water rights, and infrastructure constraints. All surface water diversions considered in the Ag-MAR scenarios, in any given month, are limited by the actual amount of streamflow historically available in C2VSim at the point of diversion.

2.3.1. Diversion Point Scenarios

We test two surface water diversion points, both of which are upstream of irrigated lands used for Ag-MAR within the OAWD study area (Figure 1). The "Stony Creek" scenario (point A in Figure 1) diverts water from Stony Creek, a tributary to the Sacramento River along the northern boundary of the study area. The "Sacramento River" scenario (point B in Figure 1) uses a diversion located on the Sacramento River itself. In the base scenario (C2VSim model without modifications), neither location is a diversion point and the cumulative amount of stream discharge over 88 years is 34 million acre feet (MAF; 41.9 Mkm^3) at point A and 858 MAF (1058 Mkm^3) at point B.

2.3.2. Recharge Location Scenarios

While a rise in groundwater tables due to recharge is generally welcomed in overdrafted groundwater basins, a key concern in designing Ag-MAR operations is a rising groundwater table into the root zone, which can negatively impact agricultural crops grown in the vicinity or downgradient of the MAR operation. Depending on subsurface conditions, large amounts of recharge may locally create a groundwater mound that rises into the root zone, potentially causing waterlogged and anoxic conditions that damage commercial crops or other overlying land uses. Minimizing the risk for such root zone flooding from groundwater mounds is a critical design goal to be considered in the selection of Ag-MAR sites. Ag-MAR adds potential challenges as the design inherently involves large amounts of land and potentially large amounts of recharge. On the other hand, Ag-MAR recharge rates per unit area are commonly lower compared to recharge rates achieved in more focused MAR designs, lowering the risk of large groundwater mounding.

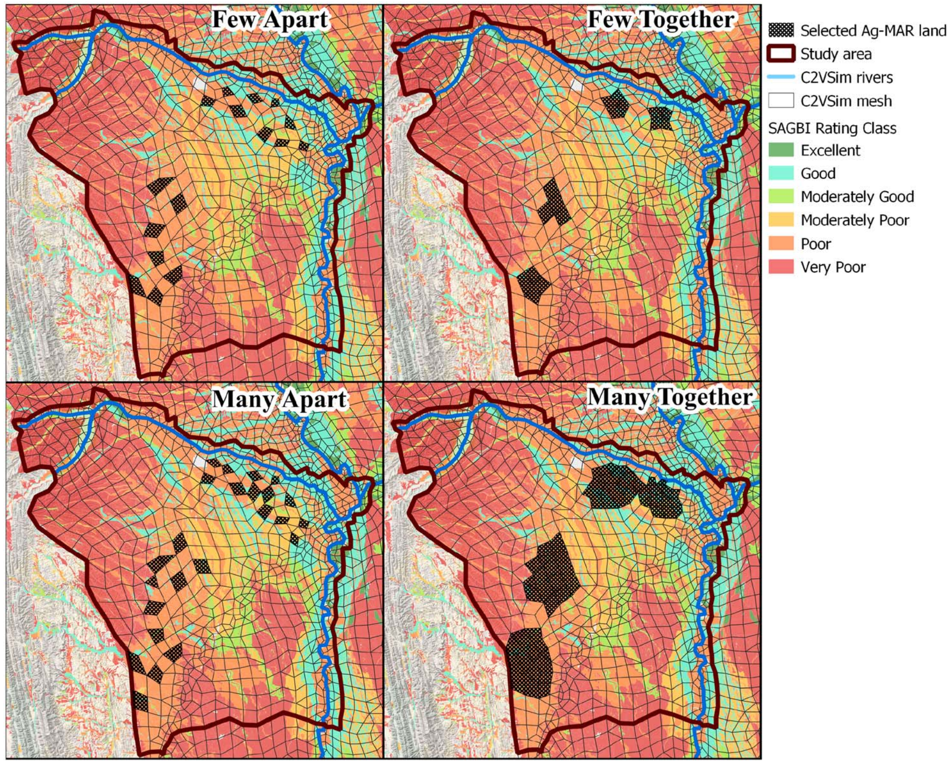

Figure 2. Irrigated land distributions to receive the diverted water.

In this study, we evaluate four spatial scenarios of winter Ag-MAR that reflect varying risks for groundwater mounding to occur: The “Few Apart” scenario considers relatively few parcels (18 finite elements total) for Ag-MAR, scattered widely across OAWD and not in close proximity to one another. The “Few Together” scenarios also represents a few parcels (17 finite elements) selected for Ag-MAR, but here parcels are in close proximity to each other, forming four localized clusters. Both scenarios assume that only limited amounts of irrigated lands are available for Ag-MAR; however, the second scenario represents the highest risk for large water level rise due to the regionally focused nature of recharge. The third and fourth scenarios assume that a large number of farms are available for Ag-MAR, and hence, recharge can be spread across a larger area. The “Many Apart” scenario consists of 26 elements, nearly 50% larger than the Few Together and Few Apart scenarios. They broadly spread across the study area. The “Many Together” scenario consists of 62 elements that form four widely spaced, larger clusters (Figure 2 and Table 1). The Many Together scenario represents more than twice as much recharge area than the Many Apart scenario.

Soil and aquifer properties are critical to recharge. The aquifer properties across the upper layer in the study area were determined by model calibration. Hydraulic conductivities vary from 3 to 30 m/day (median 25 m/day). Soil properties are more variable and are critical for accommodating recharge. In Ag-MAR particularly, the resilience of the current or future crop to the additional water application is another important consideration. In all four recharge location scenarios, elements were selected based on soil characteristics that are suitable for recharge, selected from the Soil Agricultural Groundwater Banking Index (SAGBI; O'Geen et al., 2015), a California-wide soil assessment for recharge capability of soils. SAGBI is based on a fuzzy logic assessment of soil profile percolation rate, root zone residence time, chemical limitations, topography, and soil surface conditions. The index ranks soils on a six-class scale ranging from very poor to excellent (O'Geen et al., 2015; Figure 2). Ag-MAR locations here were constrained to areas with SAGBI ratings of Moderately Good, Good, or Excellent. Locations were further constrained by selecting sites with crops that are suitable

Table 1
Summary of Recharge Land Distribution Scenarios

Recharge land distribution scenario name	Number of finite elements	Total area acres (ha)	Percent of the study area
Few Apart	18	10,369 (4,196)	3
Few Together	17	11,010 (4,455)	3.2
Many Apart	26	15,519 (6,280)	4.5
Many Together	62	38,048 (15,397)	11.2

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Table 2
Summary of Recharge Target Amount Scenarios With Corresponding Volumes and Depths, Respectively, for the Four Ag-MAR Location Scenarios (Few Apart, Few Together, Many Apart, Many Together)

Recharge target depth (RTD) scenarios		Recharge target volume (RTV) scenarios	
Applied water annual target depth	Corresponding volume for each Ag-MAR location scenario (Few Apart, Many Apart, Few Together, Many Together)	Stream diversion (recharge) annual target volume	Corresponding water depth for each Ag-MAR location scenario (Few Apart, Many Apart, Few Together, Many Together)
ft/a (m/a)	TAF/a (Mm^3/a)	TAF/a (Mm^3/a)	ft/a (m/a)
2 (0.61) "RTD2"	20.7, 22, 31, 76 (25.5, 27.1, 38.2, 93.7)	10 (12.3) "RTV10"	1, 0.9, 0.6, 0.3 (0.30, 0.27, 0.18, 0.09)
4 (1.22) "RTD4"	41.5, 44, 62.1, 152.2 (51.2, 54.2, 76.6, 187.7)	30 (37.0) "RTV30"	2.9, 2.7, 1.9, 0.8 (0.88, 0.82, 0.58, 0.24)
6 (1.83) "RTD6"	62.2, 66.1, 93.1, 228.3 (76.7, 81.5, 114.8, 281.6)	60 (74.0) "RTV60"	5.8, 5.4, 3.9, 1.6 (1.77, 1.65, 1.19, .49)
10 (3.05) "RTD10"	103.7, 110.1, 155.2, 380.5 (127.9, 135.8, 191.4, 469.3)	100 (123.3) "RTV100"	9.6, 9.1, 6.4, 2.6 (2.93, 2.77, 1.95, 0.79)

Note that the target amounts are expressed as totals over the water year (October–September). These totals may be applied in a single month (e.g., December) or spread out over several months (e.g., November–April) depending on the recharge timing scenario.

for winter recharge. Only finite elements that had at least 50% of the area planted with alfalfa or almonds in 2014 were selected for Ag-MAR, following suggestion by Dahlke, Brown, et al. (2018) and Bachand et al. (2014, 2016). Land use was determined from the 2014 USDA NASS land use data (USDA National Agricultural Statistics Service Cropland Data Layer, 2014). We note that the average finite element size of the C2VSim model is much coarser than the resolution of SAGBI or the land use maps. For the actual implementation of Ag-MAR programs on farmland within the Orland-Artois Water District, site-specific field evaluations are recommended, guided by SAGBI and land use maps and, for example, deep soil corings to provide more accurate assessments of recharge response to irrigation.

2.3.3. Recharge Target Amount Scenarios

We test two sets of four recharge target amounts in our scenario analysis: the first set fixes the annual recharge target depth (RTD) of water applied uniformly across all Ag-MAR locations. Scenarios are developed with 2, 4, 6, and 10 ft/a (0.6, 1.2, 1.8, 3.1 m/a) of applied water. For a given RTD, each Ag-MAR location scenario requires a different volume of water diverted from the stream, because of the varying size of the four location scenarios—the larger the area is, the larger the amount of water recharged is.

The second set of recharge target amount scenarios uses a fixed recharge target volume (RTV) as the maximum amount of annual diversion for recharge from the stream. Four scenarios with RTVs of 10, 30, 60, and 100 TAF/a (12 to 123 Mm^3/a) are considered. In these scenarios, the recharge target depth (depth of applied water) will vary between Ag-MAR location scenarios, because of the difference in acreage between the Ag-MAR location scenarios (Table 2). Depending on the RTV and the location scenario, the target depth of water recharged varies from 0.3 to 9.6 ft/a (0.1 to 2.9 m/a).

Within the modeling framework only one constraint limits the actual diversions in all of these eight scenarios: in any given month, the maximum diversion volume cannot exceed the amount of streamflow available at the selected diversion point. While the recharge target scenarios considered in this study cover a wide range of targeted recharge volumes (10–381 TAF/a, 12–469 Mm^3/a; see Table 2), C2VSim automatically reduces the maximum diverted amount for recharge if streamflow is not sufficient to provide the target recharge amount in a given diversion month.

Other volumetric constraints facing actual Ag-MAR implementation are not considered here as our interest was to develop a "best case" scenario for recharge. For example, we do not consider minimum environmental flow requirements (Burke et al., 2004) or additional constraints imposed by stakeholders (e.g., downstream surface water rights), etc. (Deitch & Dolman, 2017). For practical applications, the latter would need to be considered and would reduce both the amount of recharge and the effects of recharge simulated in this study.

2.3.4. Recharge Timing Scenarios

Because of the Mediterranean climate in the study area, excess stormwater runoff is limited to winter and early spring months, which largely coincides with the fallow or crop dormancy season. Adoption of Ag-

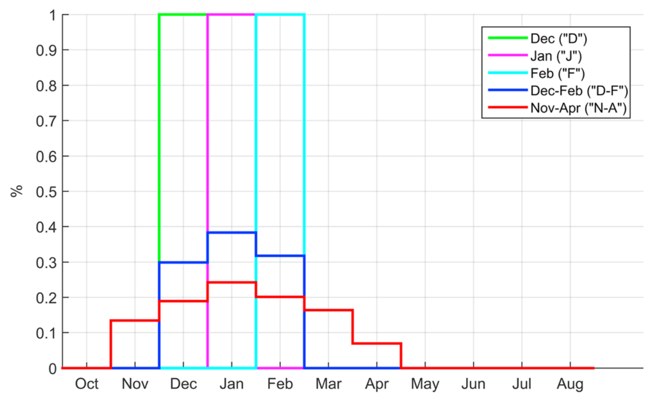

Figure 3. Relative seasonal distribution of target diversions as a fraction of the total annual target diversion.

MAR is limited not only by the availability of streamflow for groundwater recharge but also by agronomic and soil management considerations, such as the time when crops are sown, bloom or leaf out of perennial crops, or soil tillage. Other factors that potentially influence the timing of Ag-MAR include water conveyance limitations (e.g., due to canal maintenance during winter) or water rights restrictions.

Three Ag-MAR season scenarios assume that recharge, up to the full annual target amount, can only be applied in a single month each year: December ("D"), January ("J"), or February ("F"). The fourth Ag-MAR timing scenario distributes the total recharge target across three winter months (December to February, "D-F"). In the last scenario, recharge targets are split over a six-month period (November to April, "N-A"), with more weight given to the winter months (December to February), during which 65% of the target recharge is scheduled (Figure 3). This design conceptually reflects the increased evapotranspiration and crop water use in the shoulder months (e.g., November, March, and April), compared to the winter months. In all scenarios, the first year of recharge is 1930, continuing through 2009.

In summary, we evaluate two surface water diversion points (Stony Creek, Sacramento River), four Ag-MAR location patterns within OAWD (Few/Many Apart, Few/Many Together), eight different annual recharge target amounts specified either as recharge target volume (four scenarios: RTV10, RTV30, RTV60, RTV100) or as recharge target depth (four scenarios: RTD2, RTD4, RTD6, RTD10), and five different recharge timing scenarios (D, J, F, D-F, N-A), which are constraining the occurrence and length of the Ag-MAR season. While the selected scenarios are not exhaustive, they represent a wide range of plausible Ag-MAR practices for the CV. Across these four scenario parameters, a total of $2 \times 4 \times 8 \times 5 = 320$ different scenarios were considered.

3. Results and Discussion

Integrated hydrologic models such as the IWFM-based C2VSim are designed to perform multiple types of analysis; therefore, they produce a large number of output data. In our presentation and discussion of results we focus on the relative impact of the various Ag-MAR scenarios. Specifically, we analyze the impact that the different scenarios have on the groundwater budget, on the risk of creating waterlogged conditions in the root zone due to rising water table, and on instream flows in response to surface water diversions and to groundwater-surface water interactions.

3.1. Water Budget: Ag-MAR Design Impacts on Recharge Diversion

First we examine the amount of recharge achieved over the 80-year (1930–2009) recharge period, considering the smaller of the two diversion points, Stony Creek, with the smallest of the fixed recharge target depth, RTD2. For RTD2, the Few Apart scenario yields the smallest target recharge volume, at 1.6 MAF (2.0 km^3) for the 1930 to 2009 diversion period (Table 2). In RTD2, the Few Together, Many Apart, and Many Together scenarios would accommodate increasingly larger volumes of 1.7, 2.4, and 6 MAF (2.1, 3.0, 7.4 km^3) of recharge, respectively, over the same recharge diversion period.

3.1.1. Recharge Amount Relative to Target Amount

Actual recharge amounts are limited by available streamflows, which vary from month to month and from year to year. Simulation results demonstrate that even for this smaller project case, the total amount of recharge water actually diverted by the simulation never reaches the targeted recharge amounts, regardless of recharge timing or location pattern (Figure 4). Across all Stony Creek RTD2 scenarios, the actual amount of recharge varies from less than 40% to about 90% of the targeted amount. Targeted recharge is not achieved because the Stony Creek diversion point does not supply the amount of surface water targeted due to lack of sufficient flows, especially in dry winters, under any of these Ag-MAR scenarios.

3.1.2. Recharge Area

The effect that the size of the recharge area has on the amount of water that is effectively recharged is shown by considering the four different Ag-MAR location scenarios. The Many Together scenario offers the largest recharge area (38,048 acres [15,397 ha]). In the Stony Creek scenario, the much larger annual recharge target

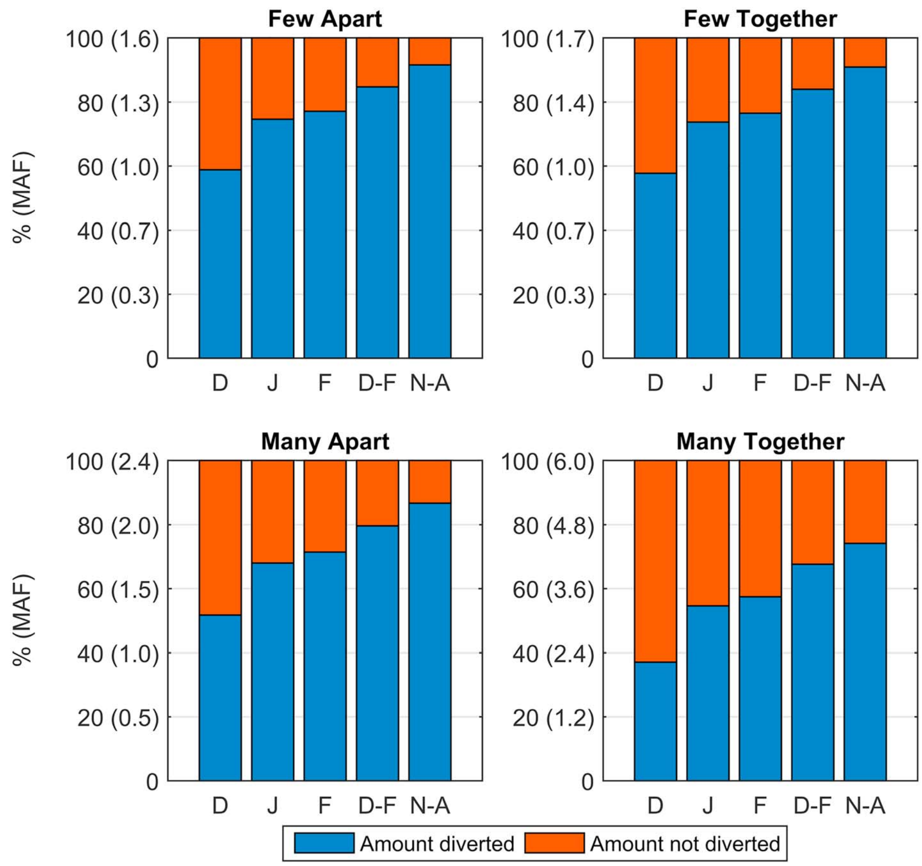

Figure 4. Recharge from the Stony Creek diversion point: total relative (and absolute) recharge target amounts (*y* axis) and actual amounts of water recharge (i.e., diverted, parentheses) for the recharge target depth scenario of 2 ft/a (RTD2). Results are shown for the four recharge location patterns and for the five recharge timing scenarios considered (D: December, J: January, F: February, D-F: December to February, N-A: November to April).

amount of the Many Together scenario is achieved less often than in the Few Apart scenario, resulting in an effective recharge amount of less than 40% to less than 80% of the long-term target depth, depending on the timing and length of the recharge season (recharge timing scenario; Figure 4). However, the Many Together location scenario still achieves significantly more recharge volume than the Few Apart and other scenarios, ranging from 2.2 MAF (2.71 km^3) in the December-only scenario to 4.3 MAF (5.3 km^3) in the November to April scenario over the 80-year recharge period (Figure 4).

Among the four location scenarios, a larger designated recharge area is advantageous during very large storm events or in wet years when large volumes of water are available for distribution across large Ag-MAR areas. Such events have a low probability to occur on an annual basis in the Sacramento River basin (Kocis & Dahlke, 2017). Only when these large storm events occur, recharge becomes limited by the targeted depth of recharge per unit area rather than by streamflow availability.

3.1.3. Recharge Timing

The timing of Ag-MAR also plays an important role in determining the amount of recharge achieved. If the recharge season must be limited to a single month (recharge timing scenarios D, J, F) due to infrastructure or agronomic conditions (e.g., canal maintenance, crop limitations), least recharge occurs in December, more in January, and most recharge would be achieved in February. For example, in the Few Apart RTD2 scenario, the actually diverted amount of water for Ag-MAR during December is 1 MAF (1.23 km^3) or 60% of the recharge target amount over 80 years (1.6 MAF [1.97 km^3]; Figure 4). When the diversion is allowed to take place in either of the other two winter months (J,F) the amount of diverted water is slightly higher, about 1.25 MAF (1.54 km^3) or nearly 85% of the targeted recharge amount. This pattern occurs because Stony Creek streamflow is lower in December compared to January and February, in most winters.

While the Stony Creek streamflow in December might not support diverting the full recharge target amount, any amount of surface water that is diverted early in the rainy season (November, December) helps to meet the overall recharge target. Hence, small early-season diversions increase the probability that remaining recharge requests toward the target amount are met by available flows in later months. For the most flexible recharge timing scenario, N-A, the amount of recharge therefore reaches nearly 90% of the recharge target amount, which is 50% higher than in the December scenario (Figure 4). Hence, significant groundwater gains are achieved over the long-term by designing Ag-MAR programs with flexible, longer recharge seasons that are more likely to capture peak flow events when they occur (Figure 4). We note that the D-F and N-A scenarios, while more accommodating of available recharge water over the season, are in fact also limited in flexibility: only a fraction of the annual target amount can be recharged in any given months (e.g., in the N-A scenario 25% of total RTD is diverted in January; Figure 3). A design that would further increase the amount of water recharged would allow for up to 100% of the annual target amount to be recharged in any month, until the target is achieved.

3.1.4. Recharge Target Depth

While peak flow events only occur in few years, the amount of surface water that can be diverted during these events results overall in significantly higher recharge if not limited by low RTD. For the largest RTD scenario, RTD10, and the Many Apart scenario, the total recharge target amount is 30 MAF, nearly the entire flow of Stony Creek. The actual recharge achieved with RTD10 varies from 3 MAF (3.7 km^3) to more than 4 times as much (about 13 MAF [16 km^3] or 45% of the target volume) depending on the recharge timing scenario. The least recharge is again achieved with D, when streamflows are limited, and the most with N-A, which provides the most flexibility (Table S3). Regardless of timing, this recharge outcome is more than an order of magnitude larger than can be achieved with the RTD2 Few Apart scenario. This result demonstrates that a recharge program that must limit recharge to a single winter month, especially early winter months (e.g., December), may still achieve significant recharge if it can accommodate large recharge target depths and volumes.

The small amount of recharge relative to the target amount in the RTD10 single-month timing scenarios (D, J, F) is due to the fact that Stony Creek delivers the full target amount for RTD10 within a single month only 5 times over the entire 80-year recharge period. However, when recharge can be done during the entire rainy season (N-A timing scenario), the recharge target volume of 380 TAF/a (0.47 km^3/a) can be accommodated in 35 out of 80 water years. From a water management perspective, it is also of interest that the largest amount of flow theoretically available in any given month at the Stony Creek diversion is 636 TAF/month (0.78 km^3/month) while the largest annual streamflow amount is 1,400 TAF/a (1.73 km^3/a), both far exceeding the maximum amount of recharge that can be accommodated in any of the 160 Stony Creek scenarios.

3.1.5. Recharge Location Distribution

The effect of the spatial distribution of recharge location (Few or Many Apart, Few or Many Together) is evaluated by considering a fixed RTV rather than a fixed RTD. In RTV scenarios, the recharge location scenario has no effect on the amount of recharge, as the RTV scenarios are all designed to recharge the same volume of water that can be diverted, constrained by the streamflow restriction in a given month. All scenarios neglect potential recharge rejection, that is, due to surface runoff (return flows to surface water) or other conditions, because the recharge water is directly injected into the first aquifer. But with a given RTV, the recharge location scenario affects water levels and water budgets, as described below.

3.1.6. Diversion From a Larger Stream

In contrast to the above Stony Creek scenarios, where Stony Creek represents a relatively small, but locally important tributary, the full amount of targeted recharge is obtained when diverting recharge water from the Sacramento River (Figure 1). Except for the largest recharge depth scenario with the shortest, one-month recharge timing (RTD10 D/J/F scenarios: 380 TAF/month [470 Mm^3/month]), the recharge amounts requested in the Sacramento River RTD and RTV scenarios (Table 2) are significantly lower than the actual Sacramento River flows observed in any given month, which typically exceed 240 TAF/month (290 Mm^3/month), even in dry years (USGS Water Resources, 2005). For example, in none of the Sacramento River RTV scenarios, including RTV100 (Table 2), streamflow diversion shortages are encountered (Figure 5). For RTV10, the total diverted volume over the 80-year recharge period (1930–2009) is 0.8 MAF (0.099 km^3). For RTV100, the total recharge volume is 7.9 MAF (9.74 km^3). In contrast, shortages

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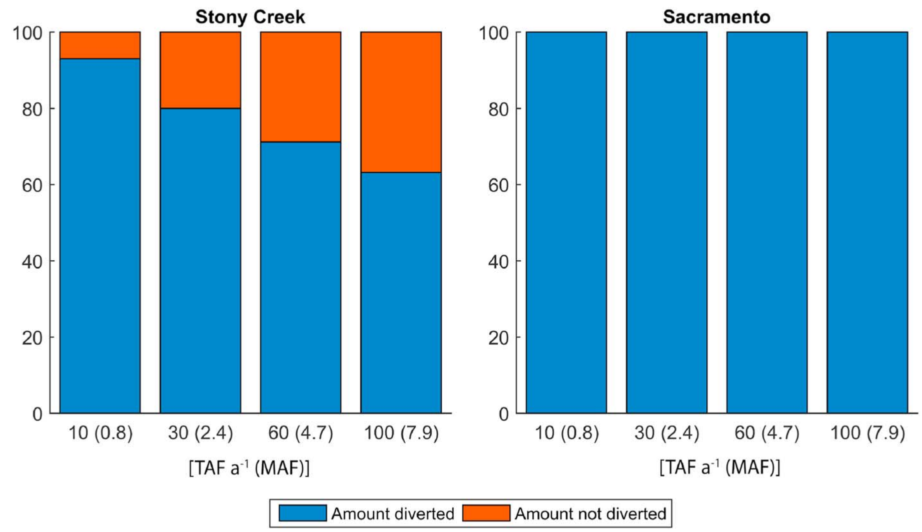

Figure 5. Comparison of effective recharge volumes between the Stony Creek and Sacramento River diversion points for four RTVs using the December–February recharge timing. Because the simulations are based on fixed target volumes, results are identical for all recharge locations. The numbers in parentheses on the *x* axis correspond to the total volume of diverted water over the entire simulation period.

occur in Stony Creek scenarios, even for the Few Apart RTV10, the scenario with the least recharge target amount among all scenarios simulated (Figure 5).

3.2. Water Budget: Ag-MAR Design Impacts on Groundwater Storage and Groundwater-Surface Water Interaction

To estimate the impact of the various Ag-MAR scenarios on groundwater fluxes, groundwater budget terms from the baseline model (original simulation, without Ag-MAR implementation) were compared against the Ag-MAR scenarios. In C2VSim, the groundwater module reports the changes in several groundwater budget components such as deep percolation, storage, and groundwater head. For illustration and discussion of results, we computed the difference in groundwater storage, and the difference in the cumulative volume of boundary fluxes from 1930 to year *t* (sum over monthly time steps) over all finite elements in the C2VSim model (entire model domain) using the following equation:

$$\Delta S_c(t) = \sum_{j=1}^{t}\sum_{k=1}^{N_{el}}\Delta S_{j,k} \tag{2}$$

where $\Delta S_c(t)$ is the difference in groundwater storage at time *t* between an Ag-MAR scenario and the base case and $\Delta S_{j,k} = S_{j,k}^{scenario} - S_{j,k}^{base}$ is the difference in the change in groundwater storage during month *j* at element *k* between a scenario and the base case. N_{el} is the number of elements of C2VSim and *t* is the number of months (time steps) since the start time of the recharge scenarios (October 1930). $\Delta S_{j,k} > 0$ indicates an increase in groundwater storage and $\Delta S_{j,j} < 0$ indicates a decrease in groundwater storage. Differences in the cumulative volume of boundary fluxes are obtained equivalent to equation (2). The exception is the difference in the cumulative discharge of groundwater to streams, which is computed as a change in base flow contribution from groundwater, a stream budget component. It is the negative value of the same flux term in the groundwater budget:

$$\Delta B_c(t) = -\sum_{j=1}^{t}\sum_{k=1}^{N_{el}}\Delta Q_{sa\,j,k} \tag{3}$$

where $\Delta Q_{sa\ j,k} = \left[Q_{sa\ j,k}^{scenario} - Q_{sa\ j,k}^{base}\right]$ represents the scenario to base case difference in the flux between stream and groundwater at element *k* during time step *j*.

Note that $Q_{sa,j,k} > 0$ indicates net groundwater gains (streamflow depletion) from an overlying stream node, while $Q_{sa,j,k} < 0$ indicates net groundwater discharge to an overlying stream node (streamflow accretion). We further note that total difference in streamflow, $\Delta F_{j,k}$, between the scenario and base case is

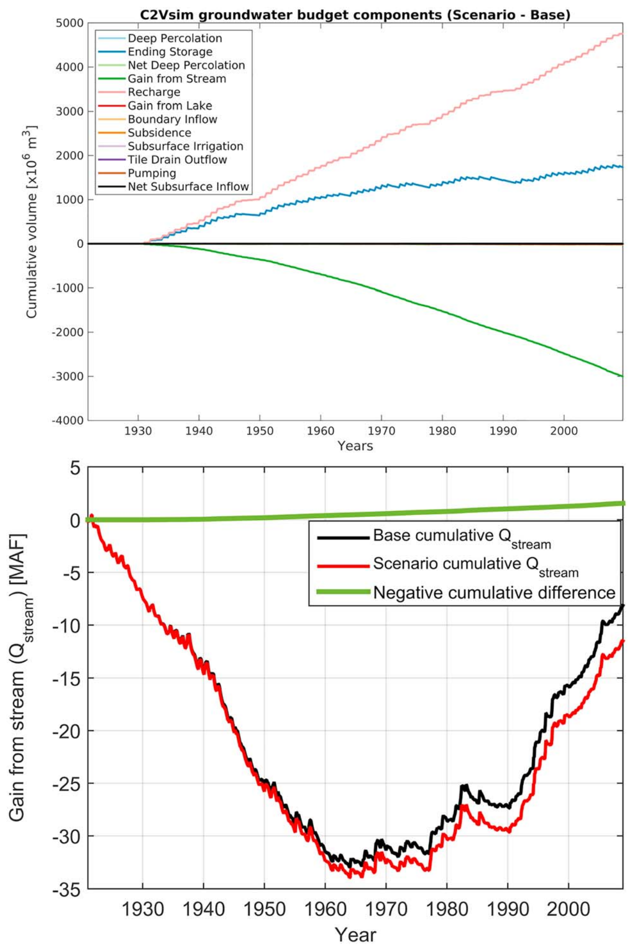

Figure 6. (top) Cumulative monthly volume difference between scenario and base case simulation for each groundwater budget component considered in the C2VSim model. The example shown is the Stony Creek Few Apart RTD10 N-A scenario. (bottom) Comparison of cumulative volume of net stream-aquifer water flux for the scenario (red) and the base case (black). Negative values indicate that the aquifer is discharging more water to the stream than it is gaining from the stream. Here the "negative cumulative difference" between the scenario and the base case (green; see equation (3)) represents the net gains in stream base flow due to additional net groundwater discharge to streams caused by the Ag-MAR diversions.

$$\Delta F_{j,k} = \left(-\sum\nolimits_k^{all\ upstream\ nodes} \Delta Q_{sa,j,k}\right) - R_{j,k} \tag{4}$$

where $R_{j,k}$ is the diversion volume for recharge. In this paper, "base flow gains" and "base flow losses" refer to the increase or decrease, respectively, in flux of groundwater to surface water due to Ag-MAR, relative to the base case, but not including the effects of $R_{j,k}$ on streamflow, unless otherwise mentioned.

All model elements are subject to groundwater storage change, but only some groundwater elements are subject to Ag-MAR recharge or to gains and losses from/to overlying streams (Figure 1). Furthermore, while equations (2) and (3) are applied to the entire Central Valley model domain, the groundwater budget changes can be shown to occur almost exclusively within the study area.

Among the various fluxes into and out of groundwater, only three fluxes are significantly affected in any of the scenario simulations: the recharge input discussed in the previous section, the amount of groundwater in storage, and the water flux across the groundwater-stream interface (Figure 6). Cumulative differences between the scenarios and the base case are negligible for all other groundwater budget components, including deep percolation from the landscape other than the added recharge, aquifer boundary inflows and outflows, subsidence storage, irrigation return flows, pumping, and tile drain outflow (Figure 6). Negative values for the cumulative difference in the net "gain from stream" groundwater budget component indicate that, across the model domain, more groundwater was discharged to streams or less water was recharged from streams to groundwater, when compared to the base case. Across all scenarios, recharge is observed to increase groundwater storage and to significantly increase base flow contributions from groundwater to the overlying stream system.

We note that Ag-MAR was here designed to support only historic and current land use and water demand conditions. The scenarios do not consider potential expansion of farmed lands that would have emerged as a result of the additional groundwater storage available under any of the Ag-MAR scenarios. Furthermore, the C2VSim model does not constrain pumping as a function of groundwater levels. Hence, changes in groundwater storage from Ag-MAR do not directly affect pumping. However, changes in streamflow due to diversions and due to the base flow gains available under the scenarios potentially affect the simulated water allocation decisions. Some water users are simulated in C2VSim with a flexible choice of water source, using stream diversions above a specified threshold streamflow level and pumping groundwater below that level. With the seasonal winter diversion for recharge and the added net base flow gains, water users may divert less or more streamflow, depending on time of year and location, which in turn affects their groundwater pumping. Figure 6 demonstrates that, for the diversion and recharge locations and amounts considered here, these latter effects remain negligible, even downstream of the study area, within the CV watershed. The largest cumulative difference in groundwater pumping observed across scenarios was 121.6 TAF (150 Mm^3), in the Sacramento Many Together RTD10 D-J scenario.

To further understand the impact of the various Ag-MAR scenarios on groundwater storage and cumulative base flow gains we again examine the four Stony Creek Ag-MAR location scenarios with the five recharge timing scenarios, using the RTD2 scenario for illustration. For the first few years after Ag-MAR was initiated, that is, in the 1930s, increases in groundwater storage correspond nearly 1:1 with the amount of water diverted for recharge (Figure 7). Already after 5 to 10 years, increases in groundwater storage begin to differ markedly from the cumulative amount of surface water diverted for Ag-MAR. Instead, we observe an

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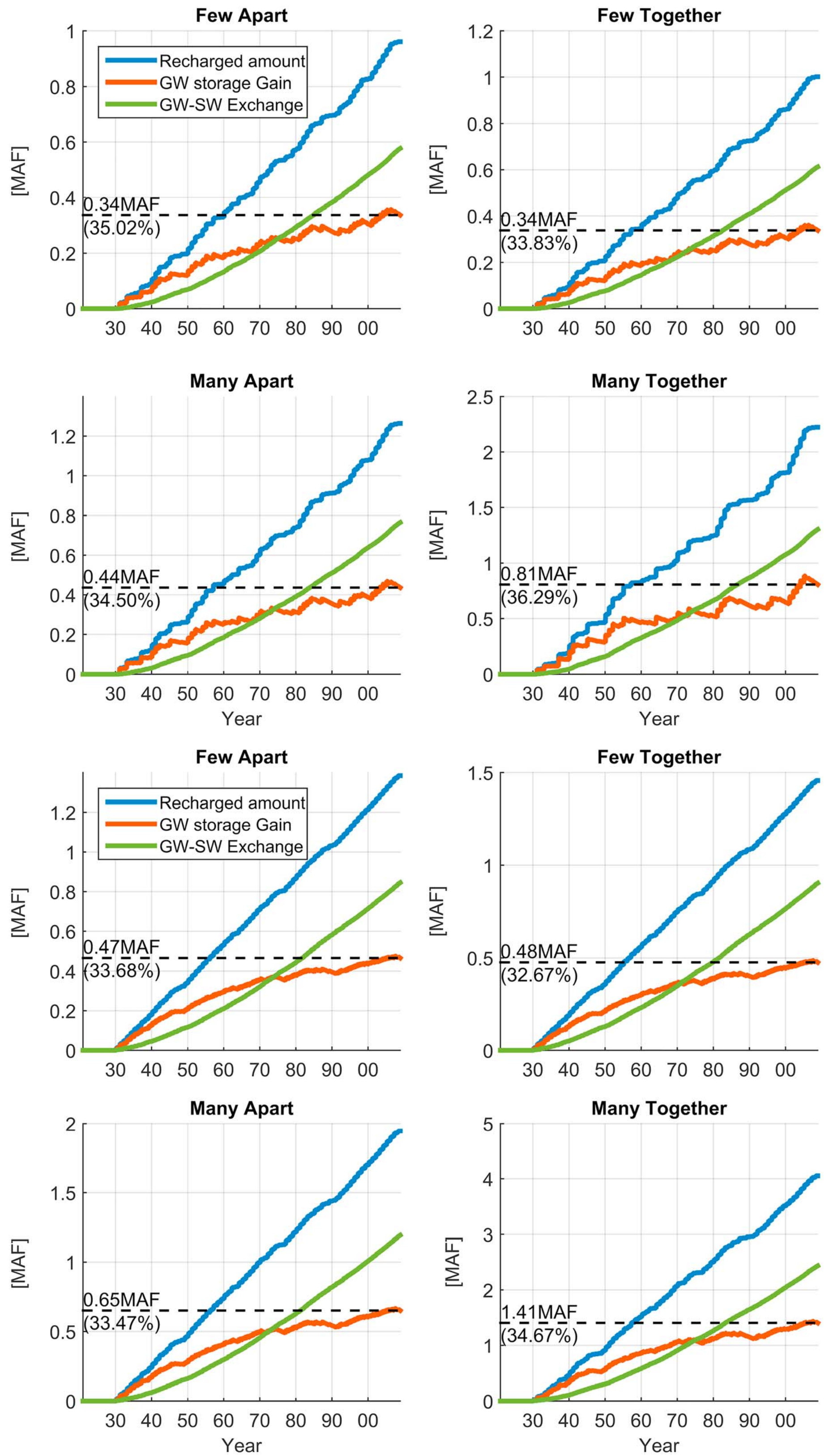

Figure 7. Difference in groundwater budget components for the four Stony Creek RTD2 location scenarios and two recharge timing scenarios (top four panels: D and bottom four panels: D-F). Note that the *y* axis has a different scale on each panel. The net difference in groundwater gain from streamflow is shown as base flow gain (positive).

increase in cumulative base flow gains due to additional net groundwater discharge to streams. The cumulative base flow gains equal the difference between cumulative recharge and groundwater storage change.

Until the 1970s, the percentage of cumulatively recharged water that contributes to groundwater storage in the aquifer is higher than the cumulative base flow gains. After the 1970s—nearly half a century after the beginning of the recharge scenarios—the increased cumulative base flow contribution from groundwater represents more than half of the cumulative recharge. Importantly, there are significant year-to-year variations in the cumulative recharge amount and in groundwater storage increases relative to the base case (Figure 7). In contrast, the cumulative base flow gains continuously increase, largely unaffected by seasonal and climatic variability. The intraannual and interannual variability in the cumulative recharge and groundwater storage reflect the monthly varying streamflow diversions for Ag-MAR as well as interannual climate variations that affect streamflow availability for recharge. Base flow gains, however, are buffered against these highly variable groundwater inflows by aquifer storage between the recharge area and the stream network (here, Stony Creek and the Sacramento River).

3.2.1. Recharge Area

Notably, the percentage of cumulative recharge that contributes to cumulative base flow gains at any time after Ag-MAR initiation, while changing over time, is shown to be almost independent of either the absolute amount of cumulative recharge applied or the spatial distribution of recharge between the four Stony Creek RTD2 location scenarios. By 2009, the amount of groundwater storage gained over the base case is 33–36% of the total amount diverted for recharge, regardless of location scenario (dashed lines in Figure 7). While the absolute diversion amounts for recharge varied, qualitatively similar temporal patterns to Figure 7 were observed in the time series of cumulative groundwater storage changes and base flow gains of other RTD and RTV scenarios simulated (see Table S1). The distribution of recharge locations also does not affect the amount of cumulative base flow gains and, hence groundwater storage, as illustrated for the Sacramento RTV100 scenarios in Figure 8. In the RTV scenarios, the volume of recharge is identical, regardless of the area of recharge (the area is smallest for the Few Apart, largest for the Many Together scenario). In both location scenarios, results are practically identical, across timing scenarios. The proportionally similar amount of groundwater storage and base flow gain across all scenarios is due to the generally similar distance between recharge areas and stream network.

3.2.2. Recharge Timing

A key difference between the different recharge timing scenarios is that larger oscillations are observed in the cumulative groundwater storage when the recharge season lasts only one month (timing scenarios D, J, F; see Figure 7) than when the timing allows for at least three months of recharge (D-F, N-A; see Figure 7). In the latter case, some recharge occurs each year, yielding a smoother cumulative streamflow diversion curve resulting in fewer years that witness no recharge than occurs in the single-month recharge timing scenario. In both cases, long drought periods lead to decreasing differences in groundwater storage between scenarios and base case.

Figure 8 illustrates the effects of recharge timing on the seasonal variations in groundwater storage changes, relative to the base case, for short (D), intermediate (D-F), and long (N-A) recharge seasons for the Sacramento scenario, which always provides 100% of the targeted recharge volume (RTV100). Even though the recharge volume is identical across the three timing scenarios, groundwater storage rises and declines more quickly, when the same volume is recharged over a shorter period of time. But again, regardless of the timing scenario, the buffer capacity of the aquifer system ensures that the effect on base flow gains remains nearly identical across the timing scenarios.

3.2.3. Recharge Efficiency

Often (but not always), a key goal of MAR design is to maximize groundwater storage and to minimize downstream losses to streamflow. The simulation results show that Ag-MAR in OAWD yields significant increases in groundwater storage, with most recharge initially remaining in groundwater storage. Once an Ag-MAR policy is exercised over a sufficiently long period, a new dynamic equilibrium is achieved, with the added recharge regime leading to stable water level dynamics at a higher level than prior to policy implementation. Under the new dynamic equilibrium—absent of additional pumping—long-term average increases in recharge are then matched by the increased base flow. The simulations show that the 90-year period is too short, in this large basin, for long-term groundwater storage gains to reach the dynamic equilibrium plateau. The simulations also demonstrate that the plateau will be a function of the average long-term

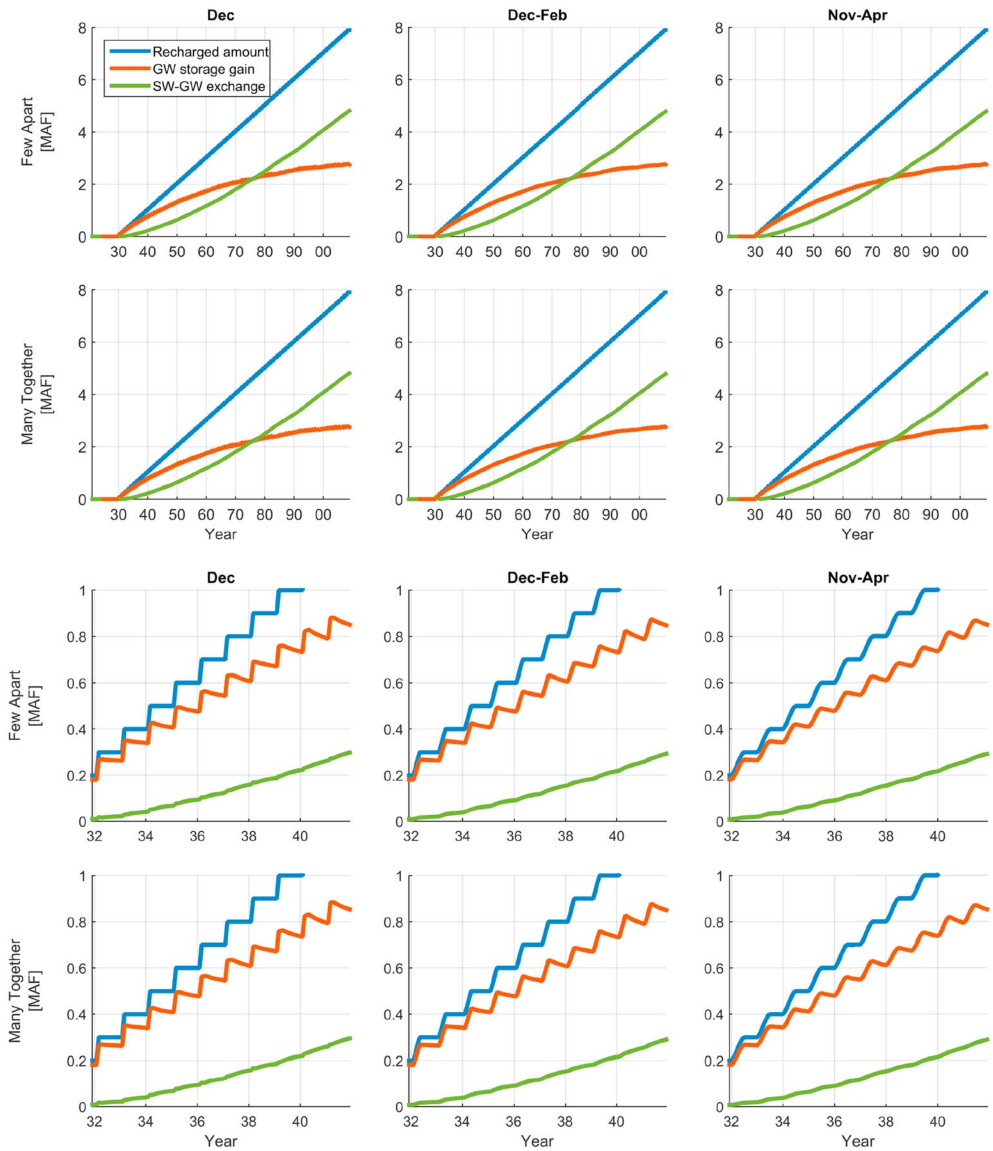

Figure 8. Difference in groundwater budget components for three Sacramento River RTV100 recharge timing scenarios (D, D-F, N-A) and for two of the four Ag-MAR location scenarios (Few Apart, Many Together). The net difference in groundwater gain from streamflow is shown as base flow gain (positive). The two top rows of panels show the monthly budgets for the entire simulation, while the two bottom rows display the first decade of the same simulation scenarios. In the RTV scenarios, the same volume is recharged regardless of location scenario (recharge area).

annual recharge, while the transient dynamics toward the new storage plateau are similar between scenarios. This is consistent with the underlying physics expressed in the so-called stream depletion function (Jenkins, 1968), where groundwater pumping (the inverse of recharge) is shown to affect stream depletion at exponential time scales. Depletion (here: repletion) time is a function of distance to stream, groundwater hydraulic conductivity, and groundwater specific yield and specific storage. Among scenarios, aquifer hydraulic properties are constant, and Ag-MAR distances to streams are rather similar, although patterns change. From a water management perspective, therefore, groundwater storage efficiency, that is, the ratio of groundwater storage increase to the cumulative recharge volume, declines over time. Using the Sacramento River Few Apart RTV scenarios as an example, results show that the cumulative groundwater storage efficiency at any given time is identical across different cumulative recharge volumes that exceed 0.7 MAF (0.86 km^3; Figure 9). For these larger volumes, and across the specific scenario designs considered here, the groundwater storage efficiency in OAWD is 72% after one

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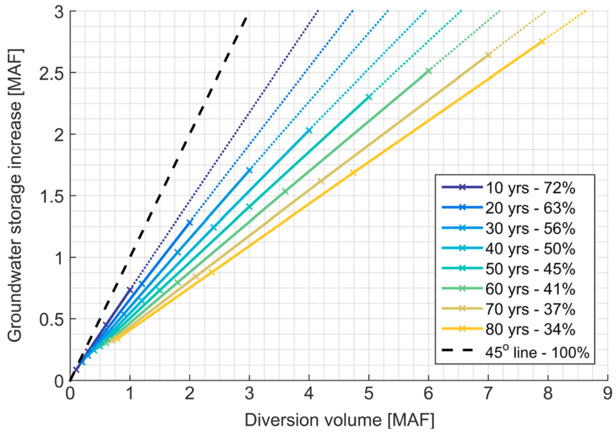

Figure 9. Change in groundwater storage efficiency, the ratio of groundwater storage change (relative to the base case) to the cumulative amount of recharge, as a function of Ag-MAR duration. Efficiency declines over time due to increasing base flow gains with time. The analysis uses results from four Sacramento Few Apart RTV scenarios.

decade, and exponentially decreases to 34% after 80 years (Figure 9). For other groundwater basins that are more depleted and lack a continuous groundwater-stream interface, Ag-MAR efficiencies might initially be higher, or even 100% over the time period until groundwater reconnects with surface water.

3.3. Ag-MAR Design Impacts on the Spatiotemporal Distribution of Groundwater Level Increases

3.3.1. Hydrographs of Water Level Rise

Temporal dynamics of the maximum groundwater table rise across the region are illustrated using the Sacramento Few Together RTV100 scenario, which has the most focused recharge among all location scenarios due to the proximity of recharge sites and the relatively small overall area to accommodate the fixed volume diversions. In the first recharge year, the largest seasonal head increase in the study area is as much as 20 ft (6.1 m) during the winter following recharge, but declines subsequently, although only by about 10 ft (3 m; Figure 10). In subsequent years, the maximum groundwater table change further increases at a relatively high rate and the cyclical annual pattern continues (Figure 10). After about 50 years, the rate of increase levels off. At the end of the recharge period, the largest groundwater level increase in this scenario is 90 ft (27.4 m; relative to the base case; Figure 10). For the single-month recharge timing scenarios the peak of the annual maximum water table rise is observed at the end of the recharge month (see inset in Figure 10). For longer recharge seasons (e.g., December–February, November–April), which mean lower monthly recharge rates, the annual maximum water table rise is smaller (e.g., November–April scenario; Figure 10). Distributing a fixed recharge target volume over a longer season therefore reduces groundwater mounding. However, after 80 years, the difference in the maximum groundwater table rise is only about 5% between the different recharge timing scenarios.

Besides recharge target amount, recharge location has the most prominent effect on localized groundwater table increases. The Few Together scenario leads to the largest seasonal increases in groundwater levels that are almost 25% higher during the recharge season than observed for the Many Apart location scenario, at the same recharge volume (Figure 11).

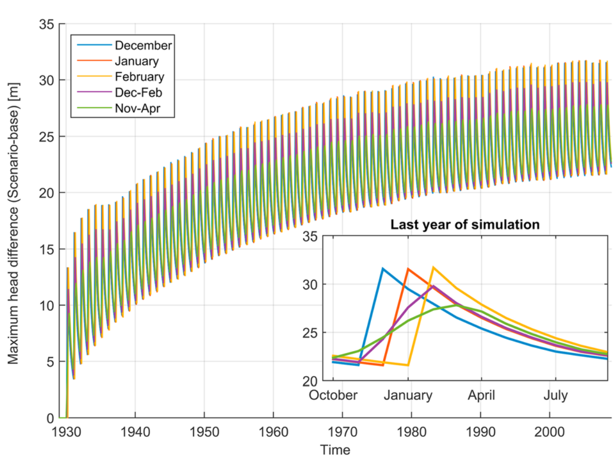

Figure 10. Maximum observed groundwater table (e.g., head) difference between the recharge scenarios and the base case across the study area. The figure shows the five recharge timing scenarios of the Sacramento Few Apart RTV100 simulations. The inset shows the intraannual variation during the last year of the simulation.

3.3.2. Spatial Distribution of Water Level Increases

Spatially, we observe that the maximum groundwater table difference in the relatively focused Few Together location scenario occurs at the shared node of four elements near the southwestern corner of the study area, upgradient of the shallow water table region on the valley floor (see arrow in Figure 12, compare to Figure 16). On the other hand, water table rise underneath the northern recharge locations, near Stony Creek, was much less than in the southwestern area, regardless of location scenarios. There, recharge dissipated more quickly, partly due to the nearby stream boundary, and partly due to higher aquifer K values than in the southwestern recharge region. Interestingly, the area with the deepest water table, in the north-central portion of the study area (Figure 16), does not accumulate a relatively larger amount of groundwater storage during the simulation period (Figure 12). Similar results were obtained in other scenarios (data not shown). At lower recharge target volumes, the maximum groundwater table increase was lower (compare to Figure 16).

3.3.3. Diversion Location

There is little difference in the regional distribution of water table change, for similar recharge volume, location, and timing scenarios, between the Stony Creek and the Sacramento scenarios. In contrast,

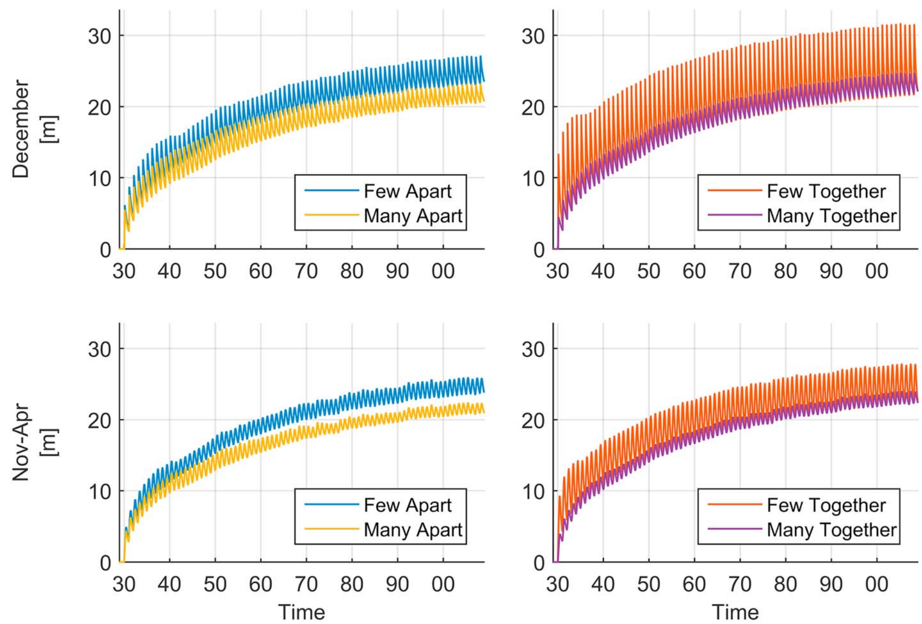

Figure 11. Maximum groundwater table differences between the recharge scenarios and the base case for two recharge timing and all four recharge location scenarios of the Sacramento RTV100 simulations.

the maximum decrease in groundwater table, observed downstream of the diversion point, depends highly on the location of the diversion (Figure 13). When water was diverted from Stony Creek (Figure 1, point A) the head decrease in groundwater immediately below the diversion is as high as 5 ft (1.5 m) due to reduced stage in the stream. On the other hand, when the same amount was diverted from the

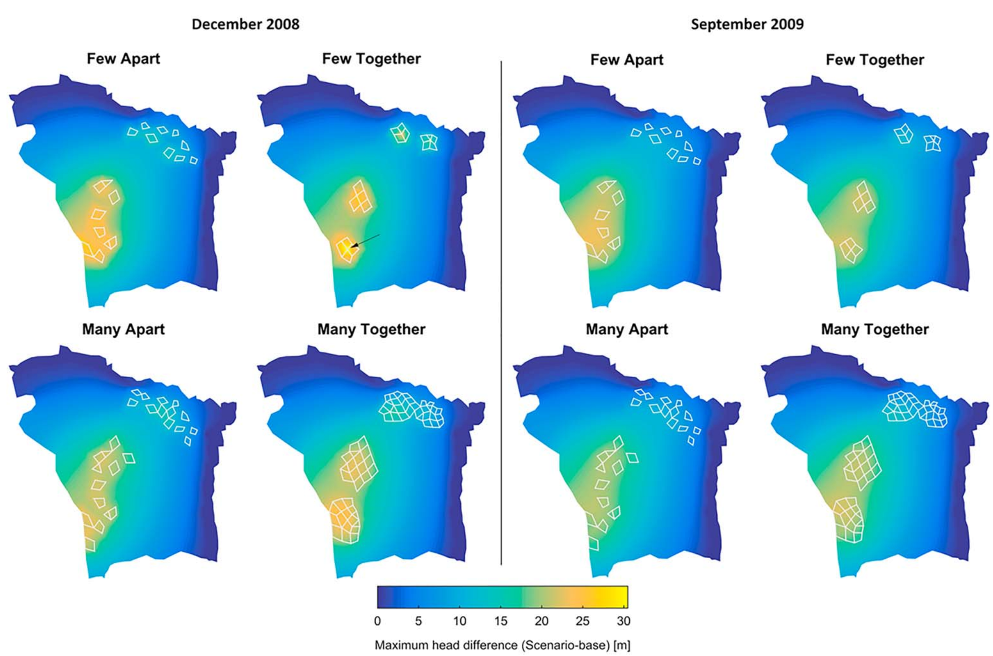

Figure 12. Maximum observed groundwater table difference over the simulation period, for all four location scenarios (Sacramento RTV100 D), using the December-only recharge timing. The left panel shows the maximum head difference for December 2008 (last time water was diverted in model) and the right panel for September 2009 (end of simulation period).

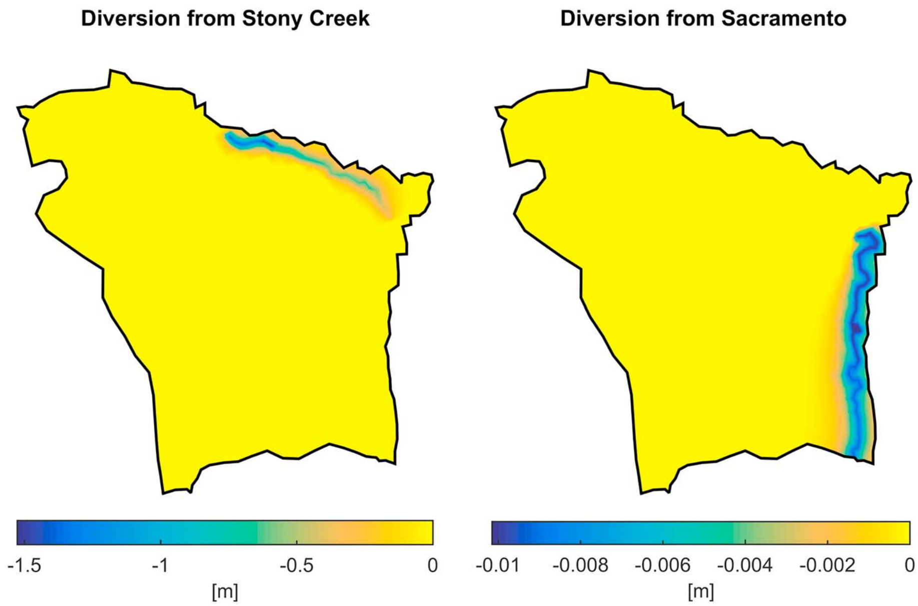

Figure 13. Maximum head decrease observed over the 78-year Ag-MAR period, relative to the base case. Results are shown for the Few Apart RTV10 D-F scenario. Water levels decrease due to lower stream stage below the diversion.

Sacramento River (Figure 1, point B), the maximum head decrease was negligible, on the order of 1–2 cm, due to the minor quantity of water diverted relative to instream flows in the Sacramento River.

To further illustrate the temporal dynamics of water level declines in the vicinity of the stream below the Ag-MAR diversion point, we consider the groundwater level hydrographs immediately below the diversion point for the Stony Creek Few Apart RTV10 and RTV100 D-F scenarios (Figure 14). Stony Creek is a mostly gaining river throughout the 88-year simulation period; that is, groundwater table elevations are higher than the stream water level. However, three dry periods are observed (1976/1977, 1987/1988, 1989/1991) during which the water table below the stream immediately downgradient of the diversion is shown to have dropped below the streambed, effectively disconnecting the stream from groundwater. The water level hydrographs for the recharge scenarios follow a similar pattern as the base case scenario, except during drier periods. In the RTV10 scenario, periods of intermediate and high groundwater levels are identical between scenario and base simulation. During dry periods, especially after 1970, water levels are 2–4 ft (0.6–1.2 m) lower than the base case. For RTV100, differences to the base case are apparent already in the 1930s, with groundwater levels as much as 0.5 ft (0.15 m) lower during the diversion period. After 1990, water levels in the RTV100 scenario fall below the bottom elevation of the streambed during the diversion period, unlike in the base scenario. On the other hand, the RTV100 scenario generates a small but notable increase in water table elevation near the stream, relative to the base case, during the nondiversion periods, including summer and fall—on the order of about 0.1 ft (few centimeters). This reflects the base flow gain discussed above, which increases overall streamflow and stream stage during the nonrecharge season (relative to the base case). Even during the extreme droughts, RTV100 water levels were higher than the base or RTV10 case, which indicates that the resilience of the aquifer to prolonged droughts has been improved.

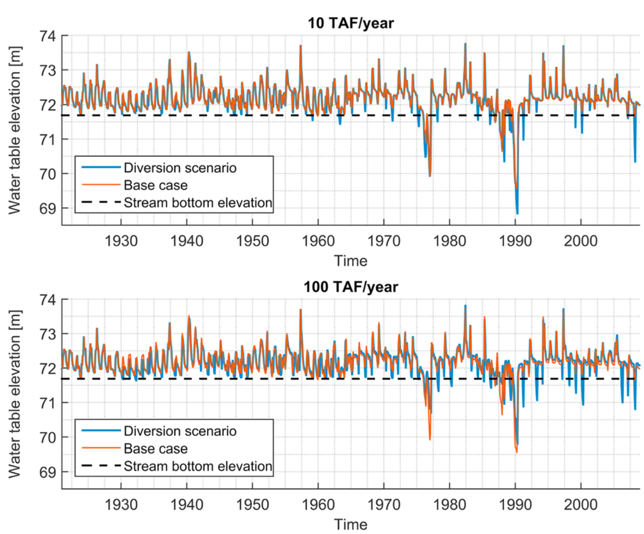

Figure 14. Water level hydrograph in groundwater immediately downstream of the Stony Creek diversion point (Figure 1, point A) for the base case and for the Stony Creek Few Apart (top) RTV10 and (bottom) RTV100 D-F scenarios. The dashed line indicates the stream bottom elevation at the location of the groundwater hydrograph.

3.3.4. Depth to Water Table

For MAR operations in agricultural areas, a major concern is the maximum groundwater table rise in response to recharge, especially in the

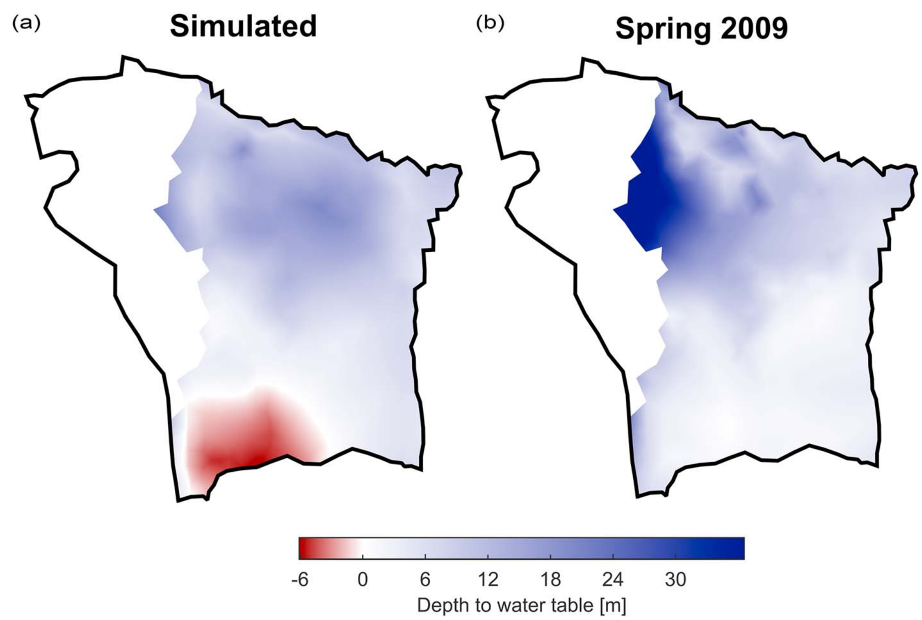

Figure 15. (a) Depth to the groundwater table for spring 2009 as simulated with C2VSim in the base case and (b) observed in spring 2009 through groundwater level measurements. White areas indicate no data availability for measured data.

period during and immediately after the recharge is conducted. Water levels reaching the root zone of commercial crops may significantly affect yields and economic output. In the study area, the actual depth to the groundwater table, measured in spring 2009, varies between 0 and 100 ft (30 m). To assess potential impacts of our Ag-MAR scenarios on crops, accurate prediction of depth to water table is needed, particularly in areas with shallow water table. However, given the large scale of C2VSim, the agreement between measured and simulated water table depth in the base case is somewhat limited: The range and general pattern of water table depth obtained in the base case simulation for April 2009 (last simulated month) are consistent with measured water table depths (Figure 15a). The shallowmost water table areas in the base case model (eastern and southern areas) mostly coincide with the rice growing region, where fields are frequently flooded and drained. However, in the southernmost part of the study area, the C2VSim base case simulation consistently shows water levels above the land surface, throughout much of the simulation period (Figure 15a). The shape of the “flooded” area expands and shrinks in response to climate conditions. The location of the area coincides with the areas in the study region that have the shallowest water table and are least suitable for recharge storage.

To avoid carrying forward the obvious mismatch between simulated and measured water levels of the base case, we interpret the scenario results with respect to their relative change in water level only. The relative water level change, instead of being added to the base-case water level results, is subtracted from the measured depth to groundwater. The measured depth to groundwater is interpolated surface from a large number (478) of water level measurements available for spring 2009 from regional monitoring programs (DWR, (California Department of Water Resources), 2016).

To calculate the effect of each diversion scenario on groundwater table rise, we calculated the relative simulated water level rise $WLR_{sim} = WT_{scenario} - WT_{base}$ by subtracting base case groundwater elevations WT_{base} from the groundwater elevations of the recharge scenarios $WT_{scenario}$. To highlight spatial patterns in these relative groundwater level changes, we then computed the depth to the groundwater table DWT using the following equation:

$$DWT = GSE - (WLR_{sim} + WT_{2009}) \tag{5}$$

where GSE is the ground surface elevation derived from a digital elevation model and WT_{2009} are the water table elevations measured during spring of 2009.

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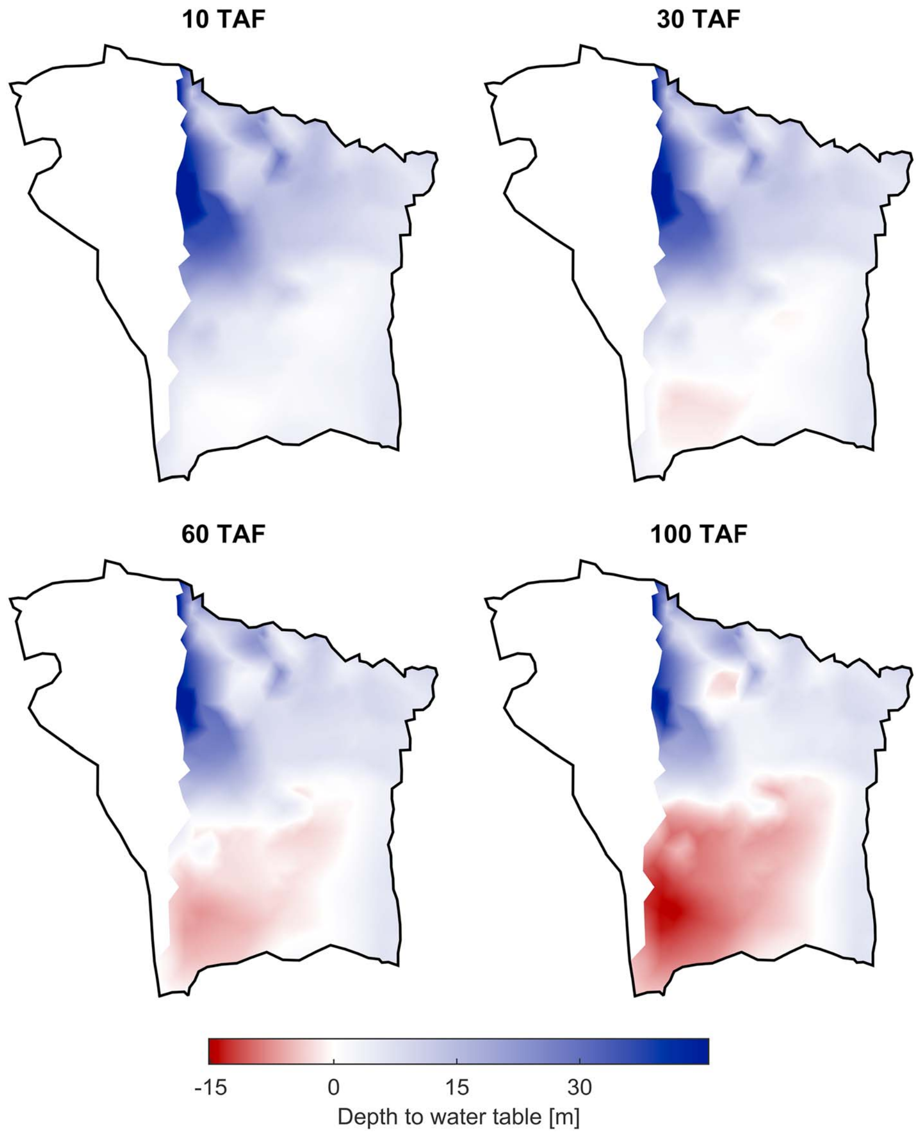

Figure 16. Modified depth to water table for the Sacramento Many Together RTV D-F scenarios for spring 2009. The recharge volume is identical across the location scenarios. The Many Together location scenario has by far the largest area; hence, results in the least water table rise compared to the other recharge location. Among the timing scenarios, only the N-A scenario (six months of recharge) would be somewhat less impactful.

To understand the full extent of the risk of root zone encroachment by the water table, we here focus on the results from the Sacramento RTV scenarios, which consistently delivered the targeted recharge volume and resulted in much larger groundwater storage change than Stony Creek scenarios. For the Sacramento Many Together RTV10 and RTV30 scenarios, the rise in the water table is relatively small and appears to not significantly affect the distribution of groundwater table depth. At RTV30, there is sufficient increase in water levels only in the southernmost area with the shallowest water table, leading to water levels just above the land surface (compare Figures 15 and 16).

However, for the larger diversion amounts simulated water levels in the southern portion of the study area can be as high as 50 ft (15.2 m) above the land surface in the Many Together RTV100 scenario, while the northwestern section of the area continues to experience large depth to groundwater. The area with water levels higher than the land surface mostly coincides with the low-elevation rice growing region, where flooding occurs regularly for agronomic reasons and drainage is already installed. Results indicate that

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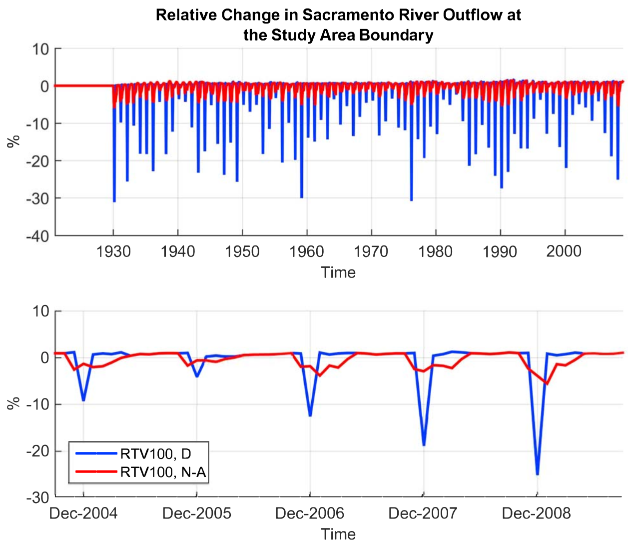

Figure 17. Relative change in Sacramento River flows at the model stream outflow boundary. The difference in flows between scenario and base case is shown as a percentage of base case flow for the RTV100 D (blue) and the RTV100 N-A (red) scenarios, among the largest recharge scenarios tested.

groundwater discharge into rice fields may increase, which would result in additional surface return flow to streams. However, the simulations here are not set up to handle that additional drainage.

3.4. Ag-MAR Design Impacts on Streamflow

The implementation of Ag-MAR has both potentially negative and positive effects on instream flows and instream flow-dependent ecosystem habitats: during the diversion period, instream flows are reduced below the diversion point. During nondiversion periods, the increase in water levels across the region relative to the base scenario leads to some additional instream flows. These additional instream flows are the result of both reduced stream leakage in losing stream sections and increased gains from groundwater in gaining stream sections.

From a long-term (annual, decadal) perspective, total instream flow volumes at the stream outlet of the study area (SE corner) are reduced by the amount of water added to groundwater storage during the period of interest. As groundwater storage increases and levels off to form a new dynamic equilibrium level that reflects the Ag-MAR policy, long-term average instream flows are again the same as in the base case. In this study, the 88-year period is not sufficient to reach that equilibrium and some groundwater storage increase is still observed (Figures 7–9).

Seasonally, the decrease in instream flow, relative to the base scenario, occurs during the diversion period, while instream flows are relatively higher (compared to the base case) at all other times. The largest relative change in Sacramento River outflow from the study area, measured as a fraction of the base case outflow, is −31% in December of 1930 and of 1976 for the Sacramento RTV100 D scenario, among the largest Ag-MAR scenarios and with the total annual diversion focused into a single month (Figure 17). Both years are drought years. For this scenario, in all but the driest winters, instream flow reductions due to diversion for recharge are less than 20%. In contrast, for Sacramento RTV100 N-A flow reductions on the Sacramento River during the diversion season are only 2% to 5%. Base flow increase during the lowest flow month, September, are on a similar order, from +1% to +2% for either scenario, after 80 years of Ag-MAR (Figure 17).

Given that winter months are among the highest runoff months, flow reductions of 100 TAF in below normal to wet years (between December and April) are not ecologically significant, since excess flows available for recharge during these months exceed, on average, at least 125 TAF along the Sacramento River (USGS gauge 11425500; Dahlke & Kocis, 2018; Kocis & Dahlke, 2017). However, RTV100 D could not be repeated in other subbasins that also impact Sacramento River flows without leading to severe cutbacks in December flows. Spreading diversions over a longer period during winter and spring (RTV100 N-A) is ecologically more appropriate, especially if similar scenarios play out in a handful of other subbasins, or if diversions occur off a smaller stream, as is the case in the Stony Creek scenarios (see section 3.1).

3.5. Comparison of Modeling Results to Other Ag-MAR Studies

In groundwater-dependent, irrigated agricultural areas management of surface water and groundwater supply for competing water uses, such as agriculture and environmental flows, remain an ongoing water management challenge. In California, this challenge is compounded by the recently passed SGMA (Sustainable Groundwater Management Act) (2014), which requires stabilizing (likely through reduction) groundwater pumping around the sustainable yield by the emerging application of the Public Trust doctrine to curtail existing surface water and groundwater rights for the protection of stream ecosystems (Owen et al., 2019; State Water Resources Control Board [SWRCB], 2018), as well as long-term climate change impacts, which are predicted to reduce surface water availability and to increase pressure on groundwater reserves in the coming decades (Connell-Buck et al., 2011; Mann & Gleick, 2015; Swain et al., 2018). Although climate projections differ in the timing and magnitude, many studies agree that California is predicted to experience longer, more frequent, and more spatially extensive heat waves and extended droughts (Lobell et al., 2011; Tebaldi et al., 2006), which can increase water demand (Chung, 2009; Mirchi et al., 2013). Total annual

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precipitation and precipitation frequency are expected to decrease (Dettinger et al., 2011; Pierce et al., 2013), while extreme events during wet years are expected to increase (Berg & Hall, 2015), leading to more frequent and more severe floods and droughts (Das et al., 2011, 2013; Dettinger et al., 2011), shifts in peak streamflow to winter and early spring away from summer and fall (Barnett et al., 2005), and earlier spring snowmelt (Stewart et al., 2005). Given these predictions, Scanlon et al. (2016) demonstrate that using depleted aquifers as reservoirs for capturing flood flows during the winter rainy season could increase long-term water supply by reducing groundwater overdraft by as much as 1.3 MAF/a (1.6 km^3/a; 2000–2014). In this study, we sought to illustrate how large-scale simulation modeling can provide a quantitative basis to evaluate different Ag-MAR management options with respect to their ability to influence long-term groundwater reserves and connected groundwater-dependent ecosystems.

Model predictions indicate that implementing Ag-MAR operations in the Orland-Artois Water District would have clear benefits for the long-term groundwater storage and base flow, both of which are important goals of water management in semiarid regions (Ronayne et al., 2017). Irrespective of the diversion amount for groundwater recharge considered in our simulations, about 34% of the recharged water remained in groundwater storage and about 66% returned to streams as base flow, indicating that Ag-MAR has the potential to stabilize and locally recover aquifer levels while increasing streamflow during summer low flow periods and the amount of groundwater available for irrigation. Similar groundwater storage gains were found by Niswonger et al. (2017) (e.g., 26–29% depending on aquifer hydraulic conductivity) for large-scale Ag-MAR simulations in the Carson Valley, NV and Ghasemizade et al. (2019) for the eastern San Joaquin Valley, CA. Other large-scale MAR modeling studies have seen lower gains in groundwater storage (e.g., Ronayne et al., 2017; Scherberg et al., 2014); however, most studies observed similar clear benefits of recharge for groundwater-dependent ecosystems and instream flows. Similar to findings of Kendy and Bredehoeft (2006) and Ronayne et al. (2017) recharge effects on seasonal streamflows and particularly summer low flows were greatest when MAR programs were extended over longer recharge seasons that allowed capturing more surface water excess flows. The recharge caused widespread increases in groundwater levels within the OAWD study area of as much as 90 ft (27.4 m) for some of the recharge scenarios. Ag-MAR benefits were sensitive to the diversion point and the timing of recharge, both of which influenced streamflow availability for recharge. Larger Ag-MAR recharge locations proved advantageous for capturing flood flows from very large storm events while moderating local groundwater mounding. Feedback mechanisms between recharge and crop water consumption, crop ET, and water consumption by natural vegetation from elevated soil moisture and groundwater levels could not be estimated in this study because the model does not support simulation of recharge through the root and unsaturated zone. Although such processes are important for enhancing ecosystem services of groundwater-dependent ecosystems (Bolund & Hunhammar, 1999; Dillon et al., 2009; Eamus & Froend, 2006; Fisher, 2015), Niswonger et al. (2017), Wu et al. (2016), and Ghasemizade et al. (2019) showed that the effect of recharge on crop water consumption and crop ET is modest (e.g., 3–6% increase in crop water consumption over the simulation period; Niswonger et al., 2017), but the increase in ET by natural vegetation can be significant (e.g., 20–30%; Niswonger et al., 2017) depending on soil moisture content.

In this study, we evaluated eight different recharge target amount scenarios ranging from a minimum annual diversion volume of 10 TAF (RTV10) to 380.5 TAF (RTD10). Using these recharge target amounts in potential Ag-MAR programs has both negative and positive effects on instream flows and instream flow-dependent ecosystem habitats. As shown in the results, larger recharge amounts resulted in a larger increase in groundwater levels across the region relative to the base scenario and increased instream flows, particularly during the summer base flow period. However, the results also show that diversion of some of the larger recharge target amounts (e.g., RTD6, RTD10, RTV100), particularly from the smaller Stony Creek tributary, is not feasible due to a lack of streamflow during the winter season. Adoption of such large diversion volumes might not even be feasible from a water management perspective, since the OAWD only delivers about 53 TAF of water during the irrigation season and might not have sufficient infrastructure to divert larger amounts (>100 TAF; Orland-Artois Water District, 2014). Hence, it is important to note that irrespective of the recharge amount a new dynamic groundwater-surface water equilibrium is achieved, leading to stable water level dynamics at a higher level than prior to policy implementation. Together these results illustrate how different Ag-MAR design factors can affect the benefits of Ag-MAR projects, and that large-scale simulation tools such as the C2VSim model can help decision makers determine how water resources and ecosystem benefits are distributed within a groundwater basin.

4. Conclusions

In this study we present the evaluation of different Ag-MAR practices (e.g., different recharge locations, amounts, and timings) using a large-scale integrated groundwater-surface water model that covers the entire CV of California, USA. The numerical modeling framework is used to evaluate local- and regional-scale, long-term benefits and consequences of Ag-MAR on groundwater storage, surface and groundwater return flows, and instream flows. Specific impacts are evaluated for one groundwater subbasin (530 mi^2 [1,370 km^2]) located in the northwestern part of the CV in the Sacramento River basin.

Our results highlight that the location or stream from which surface water is diverted is critical for Ag-MAR design. Diverting streamflow from a small stream will limit the diversion target amounts for recharge, and also increase the variability in the timing and length of the recharge season. Longer recharge seasons allow diverting larger total surface water amounts at much lower rates. Shorter diversion periods require higher recharge rates, in the amount of which surface water is less often available. On the other hand, if streamflow availability for recharge does not represent a limit, the recharge timing and recharge locations do not affect the amount of water recharged in the long term.

The water budget analysis revealed that among the different groundwater budget terms the groundwater storage and the stream-groundwater interaction term are by far the most affected by diversions in the study area. In all scenarios the diverted water was split into groundwater storage (about 34%) or return flow to streams (about 66%). During the first decades of Ag-MAR operation the diverted water contributed mainly to groundwater storage (60–70% in the first 20 years). In the OAWD study basin, given its size and hydrogeology, Ag-MAR takes over a century to reach a new dynamic groundwater storage equilibrium, regardless of recharge scenario. Ag-MAR contributes to maintaining the higher groundwater storage levels, while benefitting base flow during low-flow periods at a rate approaching the average recharge rate.

Analysis of the maximum short-term water table rise showed that the timing and duration of recharge is critical. Longer recharge seasons (e.g., December–February or November–April) support lower recharge rates and result in lower peaks in the maximum water table rise. In particular, spreading the recharge over a six-month season (November–April) resulted in 5 ft (1.5 m) less maximum water table rise compared to the single-month (e.g., February) recharge timing scenarios. The maximum groundwater table rise is also sensitive to the spatial distribution of recharge water applications. Larger and more widely distributed recharge areas result in a lower amplitude of the groundwater table response but do not change the effect that recharge has on base flow. The study area's major streams are gaining streams; that is, groundwater contributed to base flow except during a few dry periods. The simulated streamflow diversions for groundwater recharge, when taken from the smaller tributary, caused a significant groundwater level decline below the diversion point, mainly during dry and drought periods. We found that depending on the magnitude of the streamflow diversion, those groundwater level drops may become more frequent especially after long Ag-MAR operation.

In this study we used an integrated groundwater-surface water simulation framework; however, the movement of diverted water through the root and unsaturated zone was not taken into consideration. This study also did not considered additional drainage from rice fields due to increasing groundwater discharge into these low-lying land areas. But our work demonstrates the long-term dual benefit of Ag-MAR in the study region, more drought resilience, and increasing contributions to base flow.

Acknowledgments
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References

Bachand, P., Roy, S., Stern, N., Choperena, J., Cameron, D., & Horwath, W. (2016). On-farm flood capture could reduce groundwater overdraft in Kings River Basin. *California Agriculture*, *70*, 200–207. https://doi.org/10.3733/ca.2016a0018

Bachand, P. A., Roy, S. B., Choperena, J., Cameron, D., & Horwath, W. R. (2014). Implications of using on-farm flood flow capture to recharge groundwater and mitigate flood risks along the Kings River, CA. *Environmental Science & Technology*, *48*, 13,601–13,609. https://doi.org/10.1021/es501115c

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303–309. https://doi.org/10.1038/nature04141

Berg, N., & Hall, A. (2015). Increased interannual precipitation extremes over California under climate change. *Journal of Climate*, *28*, 6324–6334. https://doi.org/10.1175/JCLI-D-14-00624.1

Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological Economics*, *29*(2), 293–301. https://doi.org/10.1016/S0921-8009(99)00013-0

Bouwer, H. (2002). Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal*, *10*(1), 121–142. https://doi.org/10.1007/s10040-001-0182-4

Brush, C. F., & Dogrul, E. C. (2016). *User's manual for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), version 3.02-CG*, (p. 138). Sacramento, CA: Bay-Delta Office, California Department of Water Resources.

Brush, C. F., Dogrul, E. C., & Kadir, T. N. (2013). *Development and calibration of the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), version 3.02-CG*. Sacramento, CA: Bay-Delta Office, California Department of Water Resources.

Bugan, R. D., Jovanovic, N., Israel, S., Tredoux, G., Genthe, B., Steyn, M., et al. (2016). Four decades of water recycling in Atlantis (Western Cape, South Africa): Past, present and future. *Water SA*, *42*, 577–594. https://doi.org/10.4314/wsa.v42i4.08

Burke, S. M., Adams, R. M., & Wallender, W. W. (2004). Water banks and environmental water demands: Case of the Klamath Project. *Water Resources Research*, *40*, W09S02. https://doi.org/10.1029/2003WR002832

California Department of Water Resources [DWR] (2018a). FLOOD-MAR: Using Flood Water for Managed Aquifer Recharge to Support Sustainable Water Resources. 56 pp. https://water.ca.gov/Programs/All-Programs/Flood-MAR. Last accessed 4/3/2019.

California Department of Water Resources [DWR] (2018b). California Department of Water Resources Land Use Viewer. https://gis.water.ca.gov/app/CADWRLandUseViewer/. Last accessed 4/3/2019.

Cannon Leahy, T. (2015). Desperate times call for sensible measures: The making of the California Sustainable Groundwater Management Act, *9*. *Golden Gate U. Envtl. LJ*, 5.

Chen, J. L., Wilson, C. R., Tapley, B. D., Scanlon, B., & Güntner, A. (2016). Long-term groundwater storage change in Victoria, Australia from satellite gravity and in situ observations. *Global and Planetary Change*, *139*, 56–65. https://doi.org/10.1016/j.gloplacha.2016.01.002

Chinnasamy, P., & Agoramoorthy, G. (2015). Groundwater storage and depletion trends in Tamil Nadu State, India. *Water Resources Management*, *29*, 2139–2152. https://doi.org/10.1007/s11269-015-0932-z

Chung, F. (2009). Using future climate projections to support water resources decision making in California. California Energy Commission, Technical Report CEC-500-2009-052 F.

Closas, A., & Molle, F. (2016). Groundwater governance in Europe. IWMI Project Report No. 3, 98 p., http://gw-mena.iwmi.org/wp-content/uploads/sites/3/2017/04/Rep.3-Groundwater-governance-in-Europe_final_cover.pdf (accessed on April 4, 2019)

Connell-Buck, C. R., Medellín-Azuara, J., Lund, J. R., & Madani, K. (2011). Adapting California's water system to warm vs. dry climates. *Climatic Change*, *109*, 133–149. https://doi.org/10.1007/s10584-011-0302-7

Dahlke, H. E., Brown, A., Orloff, S., Putnam, D., & O'Geen, T. (2018). Managed winter flooding of alfalfa recharges groundwater with minimal crop damage. *California Agriculture*, *72*(1), 65–75.

Dahlke, H. E., & Kocis, T. (2018). Streamflow availability ratings identify surface water sources for groundwater recharge in the Central Valley. *California Agriculture*, *72*(3), 162–169. https://doi.org/10.3733/ca.2018a0032

Das, T., Dettinger, M. D., Cayan, D. R., & Hidalgo, H. G. (2011). Potential increase in floods in California's Sierra Nevada under future climate projections. *Climatic Change*, *109*(S1), 71–94. https://doi.org/10.1007/s10584-011-0298-z

Das, T., Maurer, E. P., Pierce, D. W., Dettinger, M. D., & Cayan, D. R. (2013). Increases in flood magnitudes in California under warming climates. *Journal of Hydrology*, *501*, 101–110. https://doi.org/10.1016/j.jhydrol.2013.07.042

Davids Engineering, Inc. (2002). Orland-Artois Water District Groundwater Management Plan. Prepared pursuant to the Groundwater Management Act (AB 3030), pp 25

Davids Engineering, Inc. and MWH (2006). Stony Creek fan conjunctive water management program feasibility investigation. Technical Memorandum No.3 Land Use, Water Demands and Supplies. pp 236.

Davids Engineering and West Yost Associates. (2018). Hydrogeologic Conceptual Model Report for County of Glenn and County of Colusa. Report #277-16-17-07, 69pp. https://www.countyofglenn.net/sites/default/files/Water_Resources/022318%20ac1%20Colusa%20Glenn%20HCM_w%20tab_fig_app.pdf (last accessed April 30, 2019).

Deitch, M. J., & Dolman, B. (2017). Restoring summer baseflow under a decentralized water management regime: Constraints, opportunities, and outcomes in Mediterranean-climate California. *Water*, *9*(1), 29. https://doi.org/10.3390/w9010029

Dettinger, M. D., Ralph, F. M., Das, T., Neiman, P. J., & Cayan, D. R. (2011). Atmospheric rivers, floods and the water resources of California. *Water*, *3*(2), 445–478. https://doi.org/10.3390/w3020445

Diersch, H. J., & Kolditz, O. (2002). Variable-density flow and transport in porous media: Approaches and challenges. *Advances in Water Resources*, *25*(8-12), 899–944. https://doi.org/10.1016/S0309-1708(02)00063-5

Dillon, P. (2005). Future management of aquifer recharge. *Hydrogeology Journal*, *13*(1), 313–316. https://doi.org/10.1007/s10040-004-0413-6

Dillon, P., & Arshad, M. (2016). Managed aquifer recharge in integrated water resource management. In A. J. Jakeman, O. Barreteau, R. J. Hunt, J. D. Rinaudo, & A. Ross (Eds.), *Integrated Groundwater Management* (Chap. 17, pp. 435–452). Cham: Springer. https://doi.org/10.1007/978-3-319-23576-9_17

Dillon, P., Pavelic, P., Page, D., Beringen, H., Ward, J. (2009). Managed aquifer recharge: An introduction. Waterlines Report Series No. 13. National Water Commission. Canberra, pp 65.

Dogrul, E. C. (2012). Integrated Water Flow Model (IWFM v3.02) Theoretical Documentation. Sacramento, CA: California Department of Water Resources.

Dogrul, E. C., Kadir, T. N., & Brush, C. F. (2017). DWR Technical Memorandum: Theoretical Documentation and User's Manual for IWFM Demand Calculator (IDC-2015), Revision 63, August 2017, Sacramento, 312 pages.

Doherty, J. E., & Hunt, R. J. (2010). *Approaches to highly parameterized inversion: A guide to using PEST for groundwater-model calibration*, *Scientific Investigations Report 2010-5169*, (). Reston, VA: U.S. Geological Survey.

Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., et al. (2012). Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics*, *59*, 143–156. https://doi.org/10.1016/j.jog.2011.05.001

DWR, (California Department of Water Resources) (2003). Groundwater: California's hidden resource, California's Groundwater Update (California: Department of Water Resources) pp. 20–30. https://water.ca.gov/LegacyFiles/pubs/groundwater/bulletin_118/california's_groundwater__bulletin_118_-_update_2003_/bulletin118-chapter1.pdf (last accessed April 30, 2019).

DWR, (California Department of Water Resources) (2016). California Statewide Groundwater Elevation Monitoring Database (California: Department of Water Resources). https://cadwr.databasin.org/maps/new#datasets=1f16180a077d4b79a701f4c2a1743237 (last accessed July 31, 2019).

Eamus, D., & Froend, R. (2006). Groundwater-dependent ecosystems: The where, what and why of GDEs. *Australian Journal of Botany*, *54*, 91–96. https://doi.org/10.1071/BT06029
European Commission (2016). Introduction to the new EU Water Framework Directive. http://ec.europa.eu/environment/water/water-framework/info/intro_en.htm. (Accessed on August 31 2018)
Famiglietti, J. S., Lo, M., Ho, S. L., Bethune, J., Anderson, K. J., Syed, T. H., & Rodell, M. (2011). Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters*, *38*, L03403. https://doi.org/10.1029/2010GL046442
FAO (2011). The state of the world's land and water resources for food and agriculture (SOLAW)—Managing systems at risk. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London.
Farrar, C. D., & Bertoldi, G. L. (1988). Region 4, central valley and pacific coast ranges. In *Hydrogeology*, (pp. 59–67). Boulder Colorado. 1988: The Geological Society of North America. 4 fig, 28 ref
Faunt, C. C. (Ed.) (2009). Groundwater availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766, 225 p.
Fisher, A. T. (2015). Groundwater provides and receives hydrologic system services. *Groundwater*, *53*, 671–672. https://doi.org/10.1111/gwat.12358
Foster, S., Chilton, J., Nijsten, G. J., & Richts, A. (2013). Groundwater—A global focus on the "local resource.". *Current Opinion in Environmental Sustainability*, *5*, 685–695. https://doi.org/10.1016/j.cosust.2013.10.010
Ghasemizade, M., Asante, K. O., Petersen, C., Kocis, T., Dahlke, H., & Harter, T. (2019). An integrated approach toward sustainability via groundwater banking in the southern Central Valley, California. *Water Resources Research*, *55*, 2742–2759. https://doi.org/10.1029/2018WR024069
Grimaldo, L. F., Sommer, T., Van Ark, N., Jones, G., Holland, E., Moyle, P. B., et al. (2009). Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary: Can fish losses be managed? *North American Journal of Fisheries Management*, *29*, 1253–1270. https://doi.org/10.1577/M08-062.1
Grönwall, J., & Oduro-Kwarteng, S. (2018). Groundwater as a strategic resource for improved resilience: A case study from peri-urban Accra. *Environmental Earth Sciences*, *77*, 6. https://doi.org/10.1007/s12665-017-7181-9
Hanak, E. (2011). Managing California's water: from conflict to reconciliation. *Public Policy Instit. of CA*.
Hanak, E., & Lund, J. R. (2012). Adapting California's water management to climate change. *Climatic Change*, *111*, 17–44. https://doi.org/10.1007/s10584-011-0241-3
Harter, T., Dzurella, K., Kourakos, G., Hollander, A., Bell, A., Santos, N., et al. (2017). Nitrogen fertilizer loading to groundwater in the Central Valley, Final Report to the Fertilizer Research Education Program Projects 11-0301 and 15-0454. Tech. rep., California Department of Food and Agriculture and University of California Davis, http://groundwaternitrate.ucdavis.edu, last access: 30 April, 2019.
Harter, T., Lund, J. R., Darby, J., Fogg, G. E., Howitt, R., Jessoe, K. K., et al. (2012). Addressing nitrate in California's drinking water. In *With a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature* (92 pp.). Davis, CA: UC Davis Center for Watershed Sciences.
Harter, T., & Morel-Seytoux, H. (2013). Peer review of the IWFM, MODFLOW and HGS model codes: Potential for water management applications in California's Central Valley and other irrigated groundwater basins, Final Report, California Water and Environmental Modeling Forum, Sacramento, http://www.cwemf.org, August.
Jenkins, C. T. (1968). *Computation of rate and volume of stream depletion by wells*. Washington: United States Government Publishing Office. TWRI Book 4, Chapter D1.
Jha, M. K., & Pfeiffer, O. (2005). Simulation modeling of salient artificial recharge techniques for sustainable groundwater management. In *Recharge Systems for Protecting and Enhancing Groundwater Resources, Proceedings of the 5th International Symposium on Management of Aquifer Recharge, ISMAR5* (pp. 11–16). Paris: United Nations Educational, Scientific and Cultural Organization 7.
Kendy, E., & Bredehoeft, J. D. (2006). Transient effects of groundwater pumping and surface-water-irrigation returns on streamflow. *Water Resources Research*, *42*, W08515. https://doi.org/10.1029/2005WR004792
Kimrey, J. O. (1989). Artificial recharge of groundwater and its role in water management. *Desalination*, *72*(1-2), 135–147. https://doi.org/10.1016/0011-9164(89)80031-1
Kocis, T. N., & Dahlke, H. E. (2017). Availability of high-magnitude streamflow for groundwater banking in the Central Valley, California. *Environmental Research Letters*, *12*, 084009. https://doi.org/10.1088/1748-9326/aa7b1b
Konikow, L. F. (2015). Long-term groundwater depletion in the United States. *Groundwater*, *53*, 2–9. https://doi.org/10.1111/gwat.12306
Konikow, L. F., & Kendy, E. (2005). Groundwater depletion: A global problem. *Hydrogeology Journal*, *13*, 317–320. https://doi.org/10.1007/s10040-004-0411-8
Labadie, J. W. (2010). *MODSIM 8.1: River basin management decision support system; User manaul and documentation*. Fort Collins, CO, USA: Colorado State University.
Langevin, C. D., Thorne Jr, D. T., Dausman, A. M., Sukop, M. C., & Guo, W. (2008). SEAWAT version 4: A computer program for simulation of multi-species solute and heat transport (No. 6-A22), Geological Survey (US).
Lobell, D. B., Torney, A., & Field, C. B. (2011). Climate extremes in California agriculture. *Climatic Change*, *109*, 355–363. https://doi.org/10.1007/s10584-011-0304-5
Maliva, R. G., Herrmann, R., Coulibaly, K., & Guo, W. (2015). Advanced aquifer characterization for optimization of managed aquifer recharge. *Environmental Earth Sciences*, *73*, 7759–7767. https://doi.org/10.1007/s12665-014-3167-z
Mann, M. E., & Gleick, P. H. (2015). Climate change and California drought in the 21st century. *Proceedings of the National Academy of Sciences*, *112*, 3858–3859. https://doi.org/10.1073/pnas.1503667112
McDonald, M. G., & Harbaugh, A. W. (1988). *A modular three-dimensional finite-difference ground-water flow model*, (Vol. 6, p. A1). Reston, VA: US Geological Survey.
Ministry for the Environment (2018). Development of the National Policy Statement for Freshwater Management. http://www.mfe.govt.nz/fresh-water/national-policy-statement/developing-2014-nps (accessed on April 30, 2019)
Mirchi, A., Madani, K., Roos, M., & Watkins, D. W. (2013). Climate change impacts on California's water resources. In *Drought in arid and semi-arid regions*, (pp. 301–319). Dordrecht: Springer.
Mirlas, V., Antonenko, V., Kulagin, V., & Kuldeeva, E. (2015). Assessing artificial groundwater recharge on irrigated land using the MODFLOW model: A case study from Karatal agricultural area, Kazakhstan. *Earth Science Research*, *4*, 16. https://doi.org/10.5539/esr.v4n2p16

Niswonger, R. G., Morway, E. D., Triana, E., & Huntington, J. L. (2017). Managed aquifer recharge through off-season irrigation in agricultural regions. *Water Resources Research*, *53*, 6970–6992. https://doi.org/10.1002/2017WR020458
Niswonger, R. G., Sorab, P., & Motomu, I. (2011). MODFLOW-NWT, A Newton formulation for MODFLOW-2005, U.S. Geol. Surv. Tech. Methods, 6-A37, 44 pp.
O'Geen, A., Saal, M., Dahlke, H., Doll, D., Elkins, R., Fulton, A., et al. (2015). Soil suitability index identifies potential areas for groundwater banking on agricultural lands. *California Agriculture*, *69*, 75–84. https://doi.org/10.3733/ca.v069n02p75
Orland-Artois Water District (2014). Water Management Plan: 2014 Criteria. Report to the U.S. Bureau of Reclamation. 122 pp. https://www.usbr.gov/mp/watershare/docs/2015/orland-artois-water-district.pdf (last accessed on April 30, 2019)
Owen, D., Cantor, A., Nylen, N. G., Harter, T., & Kiparsky, M. (2019). California groundwater management, science-policy interfaces, and the legacies of artificial legal distinctions. *Environmental Research Letters*, *14*, 045016. https://doi.org/10.1088/1748-9326/ab0751
Page, D., Vanderzalm, J., Dillon, P., Gonzalez, D., & Barry, K. (2016). Stormwater quality review to evaluate treatment for drinking water supply via managed aquifer recharge. *Water, Air, & Soil Pollution*, *227*, 322. https://doi.org/10.1007/s11270-016-3021-x
Pavelic, P., Srisuk, K., Saraphirom, P., Nadee, S., Pholkern, K., Chusanathas, S., et al. (2012). Balancing-out floods and droughts: Opportunities to utilize floodwater harvesting and groundwater storage for agricultural development in Thailand. *Journal of Hydrology*, *470-471*, 55–64. https://doi.org/10.1016/j.jhydrol.2012.08.007
Pierce, D. W., Das, T., Cayan, D. R., Maurer, E. P., Miller, N. L., Bao, Y., et al. (2013). Probabilistic estimates of future changes in California temperature and precipitation using statistical and dynamical downscaling. *Climate Dynamics*, *40*, 839–856. https://doi.org/10.1007/s00382-012-1337-9
Rahman, M. A., Rusteberg, B., Uddin, M. S., Lutz, A., Saada, M. A., & Sauter, M. (2013). An integrated study of spatial multicriteria analysis and mathematical modelling for managed aquifer recharge site suitability mapping and site ranking at Northern Gaza coastal aquifer. *Journal of Environmental Management*, *124*, 25–39. https://doi.org/10.1016/j.jenvman.2013.03.023
Ringleb, J., Sallwey, J., & Stefan, C. (2016). Assessment of managed aquifer recharge through modeling—A review. *Water*, *8*, 579. https://doi.org/10.3390/w8120579
Rohde, M. M., Froend, R., & Howard, J. (2017). A global synthesis of managing groundwater dependent ecosystems under sustainable groundwater policy. *Groundwater*, *55*, 293–301. https://doi.org/10.1111/gwat.12511
Ronayne, M. J., Roudebush, J. A., & Stednick, J. D. (2017). Analysis of managed aquifer recharge for retiming streamflow in an alluvial river. *Journal of Hydrology*, *544*, 373–382. https://doi.org/10.1016/j.jhydrol.2016.11.054
Russo, T. A., Fisher, A. T., & Lockwood, B. S. (2014). Assessment of Managed Aquifer Recharge Site Suitability Using a GIS and Modeling. *Groundwater*, *53*(3), 389–400. https://doi.org/10.1111/gwat.12213
Sahoo, G. B., Ray, C., & De Carlo, E. H. (2006). Calibration and validation of a physically distributed hydrological model, MIKE SHE, to predict streamflow at high frequency in a flashy mountainous Hawaii stream. *Journal of Hydrology*, *327*, 94–109. https://doi.org/10.1016/j.jhydrol.2005.11.012
Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., & McMahon, P. B. (2012). Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences*, *109*, 9320–9325. https://doi.org/10.1073/pnas.1200311109
Scanlon, B. R., Reedy, R. C., Faunt, C. C., Pool, D., & Uhlman, K. (2016). Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. *Environmental Research Letters*, *11*, 035013. https://doi.org/10.1088/1748-9326/11/3/035013
Scherberg, J., Baker, T., Selker, J. S., & Henry, R. (2014). Design of managed aquifer recharge for agricultural and ecological water supply assessed through numerical modeling. *Water Resources Management*, *28*, 4971–4984. https://doi.org/10.1007/s11269-014-0780-2
SGMA (Sustainable Groundwater Management Act) (2014). §§346-1-10, §§ 347-1-23, §§ 348-1–3. State of California
Sheng, Z. (2005). An aquifer storage and recovery system with reclaimed wastewater to preserve native groundwater resources in El Paso, Texas. *Journal of Environmental Management*, *75*, 367–377. https://doi.org/10.1016/j.jenvman.2004.10.007
Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation—A global inventory. *Hydrology and Earth System Sciences*, *14*, 1863–1880. https://doi.org/10.5194/hess-14-1863-2010
Šimůnek, J., Van Genuchten, M. T., & Šejna, M. (2012). The HYDRUS software package for simulating the two-and three-dimensional movement of water, heat, and multiple solutes in variably-saturated porous media. Technical manual, version, 2, 258.
Smith, A. J., & Pollock, D. W. (2012). Assessment of managed aquifer recharge potential using ensembles of local models. *Groundwater*, *50*, 133–143. https://doi.org/10.1111/j.1745-6584.2011.00808.x
Sophocleous, M. (2007). The science and practice of environmental flows and the role of hydrogeologists. *Groundwater*, *45*, 393–401. https://doi.org/10.1111/j.1745-6584.2007.00322.x
State Water Resources Control Board [SWRCB] (2018). Framework for the Sacramento/Delta Update to the Bay-Delta Plan, https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/comp_review.shtml (last accessed April 30, 2019),
Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward earlier streamflow timing across western North America. *Journal of Climate*, *18*, 1136–1155. https://doi.org/10.1175/JCLI3321.1
Swain, D. L., Langenbrunner, B., Neelin, J. D., & Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, *8*, 427–433. https://doi.org/10.1038/s41558-018-0140-y
Taylor, R. G., Todd, M. C., Kongola, L., Maurice, L., Nahozya, E., Sanga, H., & MacDonald, A. M. (2013). Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. *Nature Climate Change*, *3*, 374–378. https://doi.org/10.1038/nclimate1731
Tebaldi, C., Hayhoe, K., Arblaster, J. M., & Meehl, G. A. (2006). Going to the extremes. *Climatic Change*, *79*, 185–211. https://doi.org/10.1007/s10584-006-9051-4
Tompson, A. F., Carle, S. F., Rosenberg, N. D., & Maxwell, R. M. (1999). Analysis of groundwater migration from artificial recharge in a large urban aquifer: A simulation perspective. *Water Resources Research*, *35*(10), 2981–2998. https://doi.org/10.1029/1999WR900175
USDA National Agricultural Statistics Service Cropland Data Layer (2014). Published crop-specific data layer [Online]. Available at https://nassgeodata.gmu.edu/CropScape/ (accessed 5/14/2018; verified 5/14/2018), USDA-NASS, Washington, DC.
USGS Water Resources (2005). National Water Information System: Web Interface. Retrieved from https://nwis.waterdata.usgs.gov/ca/nwis/uv?cb_00060=on&format=gif_stats&site_no=11389500&period=&begin_date=1987-10-01&end_date=2019-04-10 (last accessed April 30, 2019).
Valley, S., Landini, F., Pranzini, G., Puppini, U., Scardazzi, M. E., & Streetly, M. J. (2005). Transient flow modelling of an overexploited aquifer and simulation of artificial recharge measures. In *Recharge systems for protecting and enhancing groundwater resources,*

Proceedings of the 5th International Symposium on Management of Aquifer Recharge, ISMAR5, (pp. 11–16). Paris: United Nations Educational, Scientific and Cultural Organization 7.

Vandenbohede, A., Van Houtte, E., & Lebbe, L. (2008). Groundwater flow in the vicinity of two artificial recharge ponds in the Belgian coastal dunes. *Hydrogeology Journal*, *16*, 1669–1681. https://doi.org/10.1007/s10040-008-0326-x

Voss, K. A., Famiglietti, J. S., Lo, M., De Linage, C., Rodell, M., & Swenson, S. C. (2013). Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. *Water Resources Research*, *49*, 904–914. https://doi.org/10.1002/wrcr.20078

Wada, Y., Van Beek, L. P. H., & Bierkens, M. F. (2012). Nonsustainable groundwater sustaining irrigation: A global assessment. *Water Resources Research*, *48*, W00L06. https://doi.org/10.1029/2011WR010562

Water Act (2007). An Act to make provision for the management of the water resources of the Murray-Darling Basin, and to make provision for other matters of national interest in relation to water and water information, and for related purposes. No 137, https://www.legislation.gov.au/Details/C2007A00137 (accessed on August 31 2018).

West Yost Associates Consulting Engineers (2012) Aquifer Performance Testing Report. Prepared for Stony Creek Fan Partners. pp. 329.

Wu, X., Zheng, Y., Wu, B., Tian, Y., Han, F., & Zheng, C. (2016). Optimizing conjunctive use of surface water and groundwater for irrigation to address human-nature water conflicts: A surrogate modeling approach. *Agricultural Water Management*, *163*, 380–392. https://doi.org/10.1016/j.agwat.2015.08.022

Zekri, S., Ahmed, M., Chaieb, R., & Ghaffour, N. (2013). Managed aquifer recharge using quaternary-treated wastewater: an economic perspective. *International Journal of Water Resources Development*, *30*(2), 246–261. https://doi.org/10.1080/07900627.2013.837370