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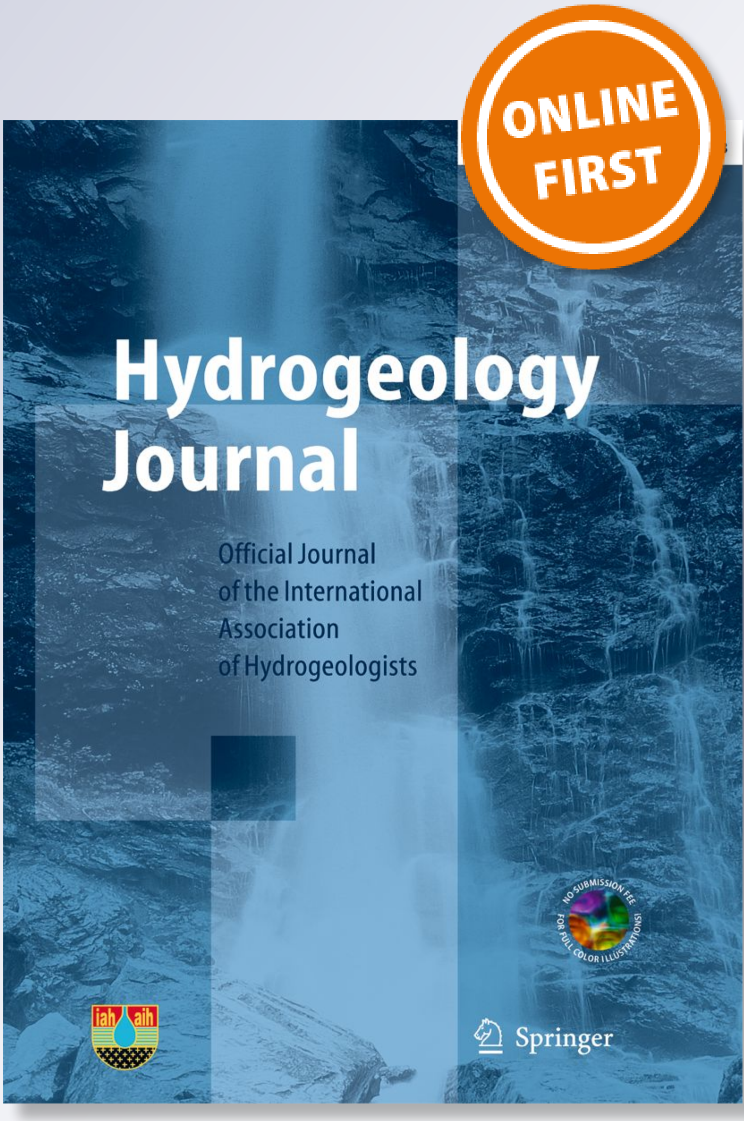

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PAPER

Maximizing on-farm groundwater recharge with surface reservoir releases: a planning approach and case study in California, USA

Robert M. Gailey[1,2] · Graham E. Fogg[3] · Jay R. Lund[1] · Josué Medellín-Azuara[4]

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Abstract

A hydro-economic approach for planning on-farm managed aquifer recharge is developed and demonstrated for two contiguous sub-basins in California's Central Valley, USA. The amount and timing of water potentially available for recharge is based on a reoperation study for a nearby surface-water reservoir. Privately owned cropland is intermittently used for recharge with payments to landowners that compensate for perceived risks to crop health and productivity. Using all cropland in the study area would have recharged approximately 4.8 km^3 (3,900 thousand acre-feet) over the 20-year analysis period. Limits to recharge effectiveness are expected from (1) temporal variability in recharge water availability, (2) variations in infiltration rate and few high-infiltration recharge sites in the study area, and (3) recharged water escaping from the study area groundwater system to surface water and adjacent sub-basins. Depending on crop tolerance to ponding depth, these limitations might be reduced by (1) raising berm heights on higher-infiltration-rate croplands and (2) creating dedicated recharge facilities over high-infiltration-rate sites.

Keywords Artificial recharge · Agriculture · USA · Hydro-economic modeling · Reservoir reoperation

Introduction

Groundwater is an important water supply for more than two billion people around the world (UNESCO 2012). It also provides more than 40% of the irrigation supply for global agricultural production (UNESCO 2015) on approximately 500 million ha of cropland (Portmann et al. 2010; GFSAD30 2017; World Bank 2018). Given such intense use, it is not surprising that depletion of the resource is occurring in many parts of the world (Wada et al. 2012; Döll et al. 2014) including the United States (Konikow 2013) and California (Famiglietti et al. 2011; Farr et al. 2015). Excessive groundwater extraction can decrease water levels, reduce surface-water flows, cause seawater intrusion, spread contaminants, and cause land subsidence (Foster and Chilton 2003; Barlow and Reichard 2010; Barlow and Leakey 2012; Konikow 2013; Sneed et al. 2013; Moran et al. 2014; USGS 2017).

Sustainable resource management requires a combination of reduced extraction and increased recharge (Scanlon et al. 2016). Some reduced extraction may occur by increasing water use efficiency (Howell 2001; Tindula et al. 2013); however, pronounced rates of extraction in many areas will likely necessitate modifying cropping patterns and fallowing cropland to address problems from over-pumping (Foster and Chilton 2003). Such changes will cause economic distress and likely bring political resistance. While avoiding strong measures to correct groundwater budget imbalances may not be possible, disruption might be reduced by increasing recharge where possible.

Elements for successful artificial recharge projects have been reviewed in detail (Bouwer 2000; Gale 2005; Dillon et al. 2009; Scanlon et al. 2016; Perrone and Rhode 2016; Hanak et al. 2018) and may be programmatic or site-specific. Programmatic elements include sourcing, conveyance and placement of recharge water. Sources of recharge water may include urban storm water runoff and recycled water as well

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as, notwithstanding water rights and permitting considerations (Miller et al. 2018), stormflows from streams and releases from reoperated surface-water reservoirs. Overcoming potential limitations regarding conveyance from source to recharge areas is essential. Considerations include access to either existing canals and ditches, or the land required to construct these structures, as well as routing and capacity specifications. Options for placing water in recharge facilities range from constructing dedicated basins to repurposing existing gravel pits. The recharge water could also be released to lands primarily used for other purposes but available on a seasonal basis such as sandy-bottomed drainage features, unlined canals and ditches, or croplands. Site-specific details include: (1) location relative to conveyance and favorable hydrogeology, (2) topography of the ground surface and presence of existing berms, (3) type of irrigation technology present, (4) timing of site availability relative to water available for recharge and (5) cost to use the land under purchase, rent or option arrangements.

Site-specific details regarding favorable hydrogeology directly relate to characteristics of the groundwater basin under consideration. Spatial variability of infiltration capacity is heavily influenced by the hydraulic conductivities of the soil and shallow geology (O'Geen et al. 2015) as well as interconnectedness of higher hydraulic conductivity deposits at depth (Fogg et al. 2000; Weissmann et al. 2004). Groundwater storage space is determined by the unsaturated zone thickness and its variations across the basin. The fate of recharged water over time relative to the recharge location can also be important (Niswonger et al. 2017). Recharge at some locations may offset local pumping and increase groundwater storage. At other locations, water entering the subsurface can quickly discharge from the groundwater system to surface water or flow across basin boundaries that are based on governance rather than physical characteristics.

Data on the performance of managed aquifer recharge (MAR) on croplands is limited and largely focuses on California and western USA. Dokoozlian et al. (1987) conducted a four-year pilot study flooding vineyards in the San Joaquin Valley of California during seasonal grapevine dormancy, observed no impact on crop yield, and concluded that the approach was viable for MAR. Bachand et al. (2014 and 2016) performed a single-season pilot study for on-farm flood flow capture and recharge, also in the San Joaquin Valley, with both perennial (vineyards and orchards) and annual crops. They observed no impacts to crop yield and estimated the unit cost for the on-farm recharge as ~3–30 times cheaper than surface-water storage or dedicated recharge basins. Dahlke et al. (2018) investigated effects of winter flooding on established alfalfa fields at two locations in the Sacramento Valley of California and found that significant amounts of water (2–26 ft, or 1–8 m) could be applied without decreasing crop yield. Additional unpublished studies indicate that (1) almonds may tolerate at least 2 ft (0.6 m) of cumulative applied recharge water in a season without detrimental effects (H. Dahlke, Hydrologic Sciences Graduate Group, University of California Davis, personal communication, 2018) and (2) some grapes have shown little to no productivity decline after more than 20 ft (6 m) of recharge in one season (D. Mountjoy, Sustainable Conservation, personal communication, 2018).

Some analysis on scaling up on-farm recharge for larger-scale groundwater management has also occurred. Harter and Dahlke (2014) discussed the potential for on-farm recharge projects to improve conditions in California where groundwater has been stressed by overuse and drought. O'Geen et al. (2015) considered requirements for successful projects and presented a spatially explicit soil-agricultural-groundwater-banking index (SAGBI) for recharge project suitability on agricultural lands in California. Niswonger et al. (2017) examined potential benefits from on-farm MAR (Ag-MAR) for a hypothetical groundwater sub-basin in the semi-arid western USA. They developed an integrated surface-water diversion and subsurface flow model to simulate recharge operations and benefits to the groundwater system over a 24-year period. Scenarios considered recharge water from snowmelt in excess of water rights during wet years applied to croplands during two winter months each year. Among other points, the work concluded that increases in groundwater storage from Ag-MAR operations (1) were spatially related to variations in groundwater depth and withdrawals across a basin as well as proximity to natural discharge areas and (2) supported greater pumping supplies for agriculture.

This work addresses planning-level analysis of Ag-MAR using water from reservoir reoperation for periodic flooding of croplands during winter months. Analysis in the following sections expands on previous work by including (1) consideration of recharge water from reservoir reoperation, (2) evaluation of recharge water sourcing, cropland characteristics and groundwater hydrology for a site-specific setting and (3) demonstrating a hydro-economic optimization approach that simulates separate decisions for land access and water delivery in the performance of Ag-MAR.

Study area and background

The regional-scale analysis is conducted for a semi-arid part of California, USA (Fig. 1) that has conditions fairly common for many parts of the globe. The two groundwater sub-basins in the study area are part of the much larger Central Valley groundwater system (Bertoldi et al. 1991) with an interfingered assemblage of alluvial and flood-basin deposits of local maximum depth exceeding 1,000 ft (300 m; Faunt 2009; RBI/WRIME 2011). Many of the sub-basin boundaries shown in Fig. 2a are arbitrarily based on surface-water features, and the southern boundary has recently been adjusted

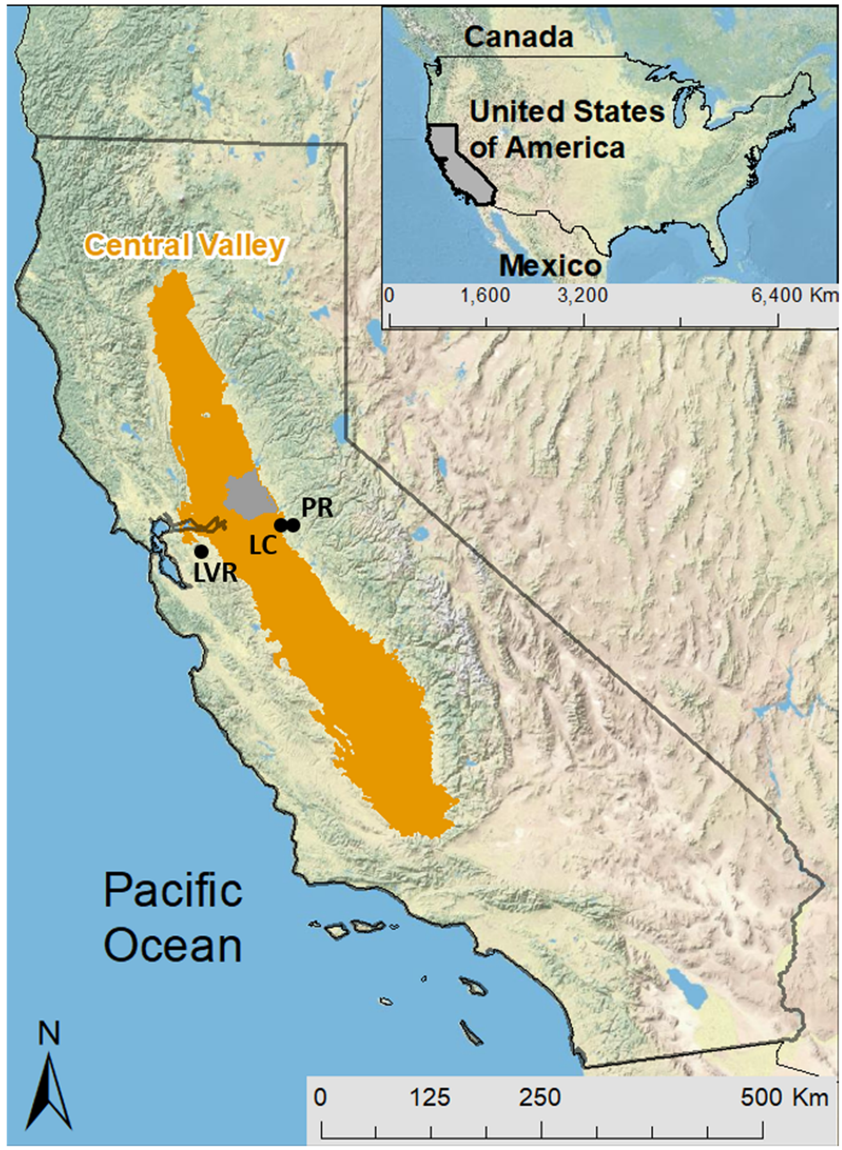


Fig. 1 Study area in California, USA. Gray shaded area indicates study area. LVR Los Vaqueros Reservoir, LC Lake Camanche, PR Pardee Resevoir

northward to accommodate governance considerations for current groundwater management efforts (CADWR 2016).

The 525,000-acre (ac; 212,000 ha) study area has a mix of urban (18%), agricultural (27%), wetland (4%) and undeveloped rangeland (51%) land uses (Fig. 2b). Over 90% of the total water use in the study area is supplied by groundwater (RBI/WRIME 2011). Moreover, approximately 41% of the agricultural acreage is planted as vineyards and orchards (calculations from data presented on Fig. 2b). This investment in perennial crops hardens water demand and intensifies groundwater extraction during droughts.

The spatial distribution of recent water levels indicates localized depressions from extractions far exceeding groundwater recharge (Fig. 3). Groundwater levels have dropped as much as 60 ft (20 m) over the past several decades so that surface water frequently becomes disconnected from saturated groundwater and drains into the subsurface. The lower reaches of the Cosumnes River, in the central part of the study area (Fig. 2a), are dry 85% of the time (RBI/WRIME 2011). New regulations for sustainable groundwater management in California require that this chronic lowering of groundwater levels and depletion of storage be addressed through active measures (Harter 2015; CADWR 2018a). While restoration of surface-water baseflow in the study area may not be required because impact occurred before implementation of the regulations, there is interest in maintaining, and possibly improving, groundwater support of surface-water flows (Hersh-Burdick 2008; RMC 2014).

Consistent with recent analysis (Kocis and Dahlke 2017; CADWR 2018b), local stakeholders are interested in harvesting runoff from high-precipitation events for recharging groundwater. One option is reoperation of Folsom Reservoir (Fig. 2a) to release extra water in advance of significant rain events (Goharian et al. 2016; E. Goharian, Hydrologic

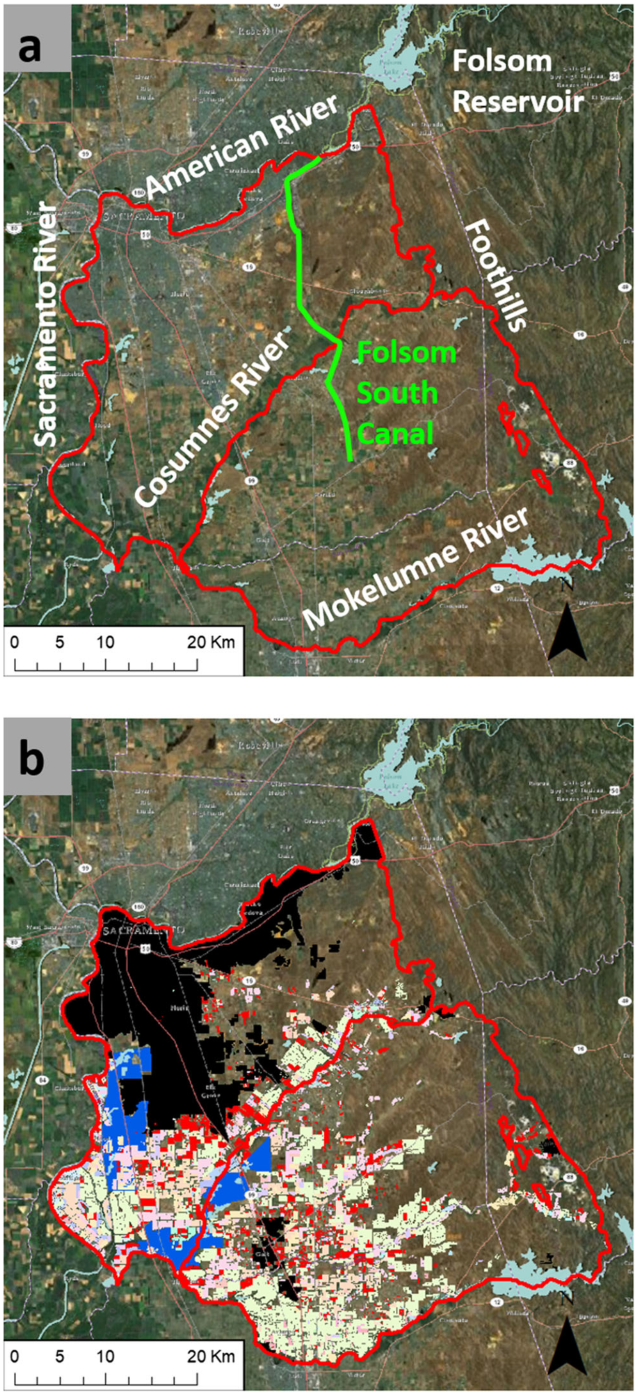


Fig. 2 Sub-basin characteristics: **a** boundaries and **b** land use. Land surface elevation ranges from approximately 0 ft relative to mean sea level (msl) in the southwest to 400 ft msl in the northeast (**a**). Land uses are indicated (**b**): black shading is urban, dark-blue shading is wetland, light-blue shading is surface water, lighter colors are agricultural, red shading is idle land during drought in 2014, unshaded areas are undeveloped rangeland. Data source: CADWR (2018d)

Sciences Graduate Group, University of California Davis, unpublished manuscript, 2018). The recharge water might be applied through a portfolio of the options noted previously; however, use of on-farm recharge (CADWR 2018c; RMC 2015) alone could achieve a potentially significant amount of aquifer recharge using some of the 140,000 ac (57,000 ha) of croplands in the study area (Fig. 2b). This work presents a planning-level analysis of what might be possible. While infrastructure construction costs are not considered, the results of this work might encourage further evaluation of necessary investments.

Methods of analysis

A retrospective analysis is conducted to evaluate the range of improvements in groundwater system state (i.e., groundwater elevations and storage as well as baseflow to surface water) that might have occurred for the study area from an Ag-MAR recharge program. Recharge water is from simulated reoperation of Folsom Reservoir with delivery through the Folsom South Canal (Fig. 2a) consistent with capacity limitations (Goharian et al. 2016; E. Goharian, Hydrologic Sciences Graduate Group, University of California Davis, unpublished manuscript, 2018) over a 20-year period that covers water years 1984 through 2003 (October 1983 through September 2003). The timing and amounts of surface water delivered to croplands for recharge application is prescribed by a linear programming model that combines available information regarding surface water and groundwater hydrology with the spatial distribution of croplands. Groundwater recharge is simulated with a groundwater/surface-water model that incorporates existing land uses, surface-water deliveries and groundwater demands over the period considered (Brush et al. 2013).

Identifying recharge application schedules

This analysis applies a formulation of simulation-optimization (Singh 2014) to MAR. Previous work includes Mushtaq et al. (1994) who simulated unsaturated flow from individual recharge basins and applied nonlinear programming to identify optimal loading schedules for maximizing recharge volume. Marques et al. (2010) included decisions for recharge area allocation and water volume application as part of a two-stage quadratic programming analysis that maximized crop profits. Hao et al. (2018) used a genetic algorithm to maximize recharge volume while meeting constraints on groundwater elevations. To the best of the authors' knowledge, the approach presented here is new in that it combines elements of recharge basin and groundwater hydraulics with economic considerations at a regional scale. The foundation of the linear programming approach is based on the study area hydrology which is adapted to include economic considerations regarding land use. A hydrologic formulation is presented as an explanatory step in developing the full hydro-economic formulation.

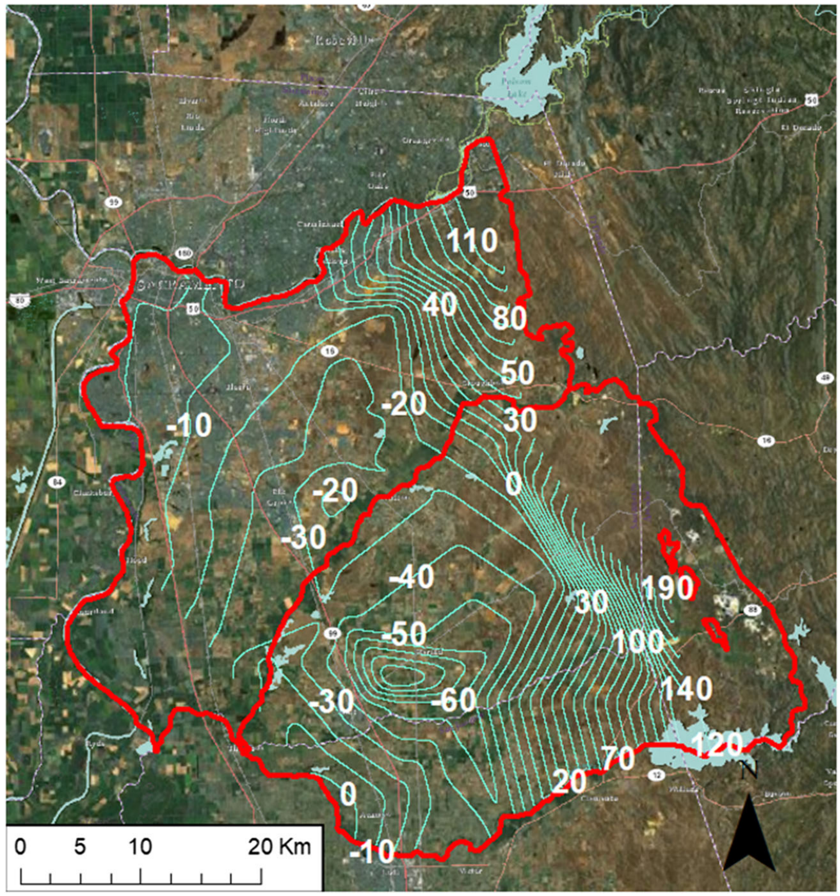


Fig. 3 Groundwater levels in the study area for Fall 2017. Contours are in ft. msl. Data source: CADWR (2018e)

Initial hydrologic formulation

Assuming that all cropland would be available to recharge groundwater and ignoring economic considerations, the recharge water application scheduling is determined with the following linear program:

$$\underset{\mathbf{RV}}{\text{Max}} \quad Z = \sum_{n=1}^{N} \sum_{t=1}^{T} \mathrm{RV}_{n,t} \tag{1}$$

subject to:

$$\sum_{n=1}^{N} \mathrm{RV}_{n,t} \le \mathrm{WAR}_t \quad \text{for all } t \tag{2}$$

$$\mathrm{RV}_{n,t} \le \mathrm{UB}_n \quad \text{for all } n, t \tag{3}$$

$$\mathrm{UB}_n = \left[(K_{\text{scale}} \mathrm{HB}_n A_n)(I_n/H_0 + \ln\{\varepsilon\}) \right] / \left[1 - e^{-(I_n/H_0 + \ln\{\varepsilon\})} \right] \quad \text{for all } n \tag{4}$$

$$\mathrm{GWE}_{i,t} < \mathrm{GSE}_i - \mathrm{FB}_i \quad \text{for all } i, t \tag{5}$$

$$\mathrm{GWE}_{i,t} = H_{i,t} + \sum_{n=1}^{N} \sum_{\tau=1}^{T} M_{n,i,\tau} (\mathrm{RV}_{n,\tau}/\mathrm{RVu})(\mathrm{FD}_1/\mathrm{FD}_0) \quad \text{for all } i, t \tag{6}$$

$$\mathrm{RV}_{n,t} > 0 \quad \text{for all } n, t \tag{7}$$

where:

RV is the matrix of recharge volumes to be optimized over space and time

Z is the total recharge volume over the planning horizon

n is the spatial index corresponding to a potential recharge location

N is the total number of potential recharge locations in the study area

t is the temporal index corresponding to the month within the planning period

T is the total number of months in the planning period

$\mathrm{RV}_{n,t}$ is the recharge volume at a location and time

WAR_t is the water available for recharge at a time

UB_n is the upper bound on recharge volume at a location

K_{scale} is a scaling factor that accounts for effective vertical hydraulic conductivity of the soil and underlying geology

HB_n is the berm height for a potential cropland recharge location

A_n is the area of cropland at a potential recharge location

I_n is the reference infiltration rate at a potential recharge location

H_0 is the ponding depth associated with the reference infiltration rate
$\mathcal{E}$ is a small increment greater than zero
i is the spatial index corresponding to a groundwater elevation control location
$\mathrm{GWE}_{i,t}$ is the groundwater elevation at a control location and time
GSE_i is the ground surface elevation at a control location
FB_i is the required groundwater freeboard at a control location
$H_{i,t}$ is the background groundwater transient head response to unmanaged stresses at a control location and time
$M_{n,i,t}$ is the expected groundwater transient head response (mounding) at control location i and time t in response to potential recharge at location n
RVu is the unit recharge volume used to generate M
FD_1 is the fraction of recharge water delivered net of evaporation during conveyance considered for a particular scenario
FD_0 is the fraction of recharge water delivered net of evaporation during conveyance assumed when generating M

The formulation objective, Eq. (1), maximizes the volume of water recharged over the planning horizon subject to a set of operational constraints. The total volume of water recharged in any period t cannot exceed the water available for recharge (WAR; Eq. 2), which is derived from a reoperation of Folsom Reservoir to provide additional water during November through March each year. The reoperation is performed by maximizing reservoir releases during the aforereferenced months while maintaining expected levels of service for flood control, water supply and hydropower generation (Goharian et al. 2016; E. Goharian, Hydrologic Sciences Graduate Group, University of California Davis, unpublished manuscript, 2018). The levels of service are maintained with a set of optimization constraints that include downstream requirements for minimum environmental flows and water supply as well as the reservoir operation rule curve. The analysis is based on a perfect foresight formulation which provides an upper bound for recharge water available from the reservoir. A static upper bound on the volume of water recharged at a particular location (Eqs. 3 and 4), is based on local infiltration capacity and field berm height through an analytical ponding and drainage model described in the Appendix. Equations (5) and (6) dynamically constrain the magnitude of recharge decisions as a result of a cap on groundwater elevation to avoid water-logging of soil. This constraint is tied to the buildup and redistribution of recharged water as a result of groundwater flow and is described further in the Appendix. Negative recharge decisions are prevented with Eq. (7).

There are 67 potential recharge locations ($N = 67$) corresponding to the number of groundwater model elements in the study area, 240 monthly time periods ($T = 240$) over the 20-year planning horizon and 18 groundwater elevation control locations ($i = 1$ to 18). The groundwater elevation control locations are shown in Fig. 4. While additional groundwater control locations could be considered, initial work with the optimization model indicated that the groundwater mounding constraints would not be binding. These constraints are merely added for completeness since they may be important for application to different project locations. No pertinent information is lost by using a lower density of groundwater elevation observation locations in the current work.

Hydro-economic formulation

Using cropland for groundwater recharge operations results from two separate sets of decisions made by the groundwater management agency: (1) acquiring access to specific lands for recharge operations and (2) subsequently delivering certain volumes of water to those lands. Land access decisions are made based on costs of use (rents) required by private landowning farmers, funds available to the groundwater management agency and the infiltration capacity of different parcels. Deliveries of water to specific parcels are decided based on (1) lands made available through financial transactions between the groundwater management agency and private land owners and (2) infiltration capacities of the different lands. From this perspective, the previously noted decision variable RV becomes the product of a constant and two decision variables and is generally expressed as:

$$\mathrm{RV} = A\ \mathrm{RA}\ D \tag{8}$$

where:

A is the area potentially available for recharge at a location (a constant)
RA is the relative area, a fraction of A ranging in value from 0 to 1, acquired for use in recharge operations through financial transaction
D is the amount of water, expressed as depth over the area A RA, delivered to a location by the water agency

The hydrologic formulation is supplemented with economic constraints as follows:

$$\underset{\mathbf{RA},\mathbf{D}}{\mathrm{Max}}\quad Z = \sum_{n=1}^{N}\sum_{t=1}^{T} D_{n,t} \sum_{j=1}^{J} \mathrm{RA}_{n,t,j} A_{n,j} \tag{9}$$

subject to:

$$\sum_{n=1}^{N}\sum_{j=1}^{J} C_j \mathrm{RA}_{n,x,j} A_{n,j} \le F_y \quad \text{for all } n, j, t \quad x \in t : \mathrm{mod}(t, 12) = 2 \quad y = 1 \text{ to } T/12 \tag{10}$$

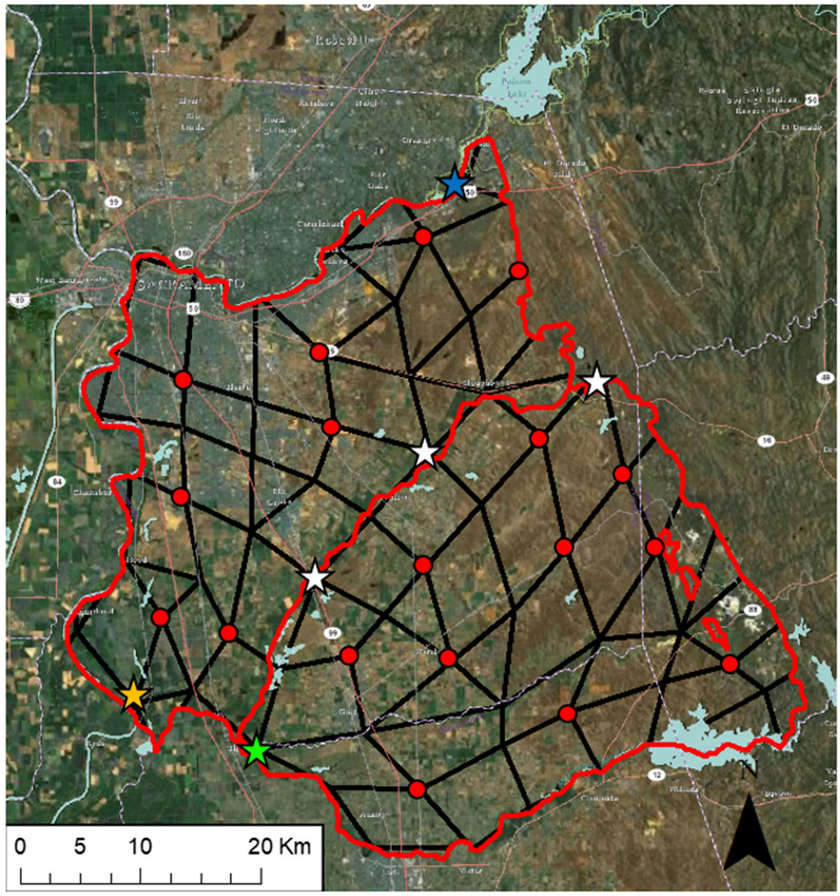


Fig. 4 Groundwater model elevation control and surface-water flow locations. Black lines are model element boundaries, red dots are groundwater elevation control locations, stars are surface-wter flow evaluation locations (blue star: American River, white star: Cosumnes River, gold star: Sacramento River, green star: confluence of Cosumnes and Mokelumne rivers)

$$\mathrm{RA}_{n,x,j} - \mathrm{RA}_{n,w,j} = 0 \quad \text{for all } n, j, t \quad x \in t : \mathrm{mod}(t, 12) = 2 \quad w \in t : x + z, z = 1 \text{ to } 5 \tag{11}$$

$$\mathrm{RA}_{n,t,j} < K \quad \text{for all } n, t, j \tag{12}$$

$$K = 0 : \mathrm{mod}(t, 12) = 1, 8 \text{ to } 12 \text{ or } A_{\mathrm{n,j}} = 0 \quad 1 \tag{13}$$

$$\mathrm{RA}_{n,t,j} > 0 \quad \text{for all } n, t, j \tag{14}$$

$$\sum_{n=1}^{N} D_{n,t} \sum_{j=1}^{J} \mathrm{RA}_{n,t,j} A_{n,j} \le \mathrm{WAR}_t \quad \text{for all } t \tag{15}$$

$$D_{n,t} < \left[(K_{\mathrm{scale}} \mathrm{HB}_n)(I_n/H_0 + \ln\{\varepsilon\})\right] / \left[1 - \mathrm{e}^{-(I_n/H_0 + \ln\{\varepsilon\})}\right] \quad \text{for all } n, t \tag{16}$$

$$\mathrm{GWE}_{i,t} < \mathrm{GSE}_i - \mathrm{FB}_i \quad \text{for all } i, t \tag{17}$$

$$\mathrm{GWE}_{i,t} = \mathrm{H}_{i,t} + \sum_{n=1}^{N} \sum_{\tau=1}^{T} M_{n,i,\tau} \left(\mathrm{RA}_{n,x,\tau} A_{\mathrm{n}} D_{n,\tau} / \mathrm{RVu}\right)(\mathrm{FD}_1/\mathrm{FD}_0) \quad \text{for all } i, t \quad x \in t : \mathrm{mod}(t, 12) = 2 \tag{18}$$

$$D_{n,t} > 0 \quad \text{for all } n, t \tag{19}$$

where:

RA is the array of relative areas to be optimized over space, time and crop category

D is the matrix of water delivery depths to be optimized over space and time

$D_{n,t}$ is the water delivery depth at a location and time

j is the crop category for a potential recharge location

J is the total number of crop categories

$\mathrm{RA}_{n,t,j}$ is the relative area at a location and time for a crop category

$A_{n,j}$ is the area potentially available for recharge at a location for a crop category

C_j is the annual cost per unit area to use land containing crop j for recharge operations

F_y is the annual funding available to pay for using land for recharge

As before, the formulation objective (Eq. 9) maximizes the volume of water recharged over the planning horizon subject to a set of operational constraints. The total expenditure for renting land for recharge during any year y cannot exceed the available funds for that year (F; Eq. 10). The right-hand side of this constraint is varied in a parametric analysis (Wagner 1969) on the total funding available to rent land. The costs for using land in different crop categories are assumed to be determined by farmers bidding in a reverse auction, varying based on the possibility of increased financial risk from winter recharge operations. Simplifying assumptions of (1) uniform land use cost for each crop category and (2) constant cropping patterns are applied. (There is no simulation of changes in cropping decisions or farm profits as a result of flooding decisions.) However, the selection of land is not based on cost alone, since infiltration capacity influences the land use decisions through the objective function values D.

While the formulation is general enough to allow monthly variation in land rental decisions, a practical adjustment is made to reduce computational and solution time requirements. The terms of **RA** are tied together for six winter months each water year (months 2–7; Eq. 11). An upper bound on the land use decision (Eqs. 12 and 13) is based on the total land available at particular locations and times. No land is available ($K = 0$) during the growing season (months 1 and 8–12 each water year as an assumption of this work) or where there is no agricultural land ($A = 0$). (The assumed seasonal availability of cropland for recharge could be relaxed and recharge performed during the growing season by over-irrigation if water was available for recharge during the growing season.) Otherwise, all land is available for recharge ($K = 1$). Equations (11)–(13) reduce the solution space to the minimum needed for the problem at-hand. Negative land use decisions are prevented with Eq. (14). Five crop categories ($J = 5$) may be present in any single groundwater model element. Equations (15)–(19) are a version of Eqs. (2)–(7) modified through substitution of Eq. (8) and simplification where appropriate.

Because there is a product of decision variables, in the objective function and constraints represented by Eqs. (15) and (18), the optimization problem is nonlinear and more difficult to solve than the previously presented hydrologic formulation. This nonlinear programming formulation can be decomposed into a two-part linear programming formulation and solved by iteration. The same objective function is used for both parts and the constraint set is split between Eqs. (14) and (15).

Part 1: land allocation

$$\underset{\mathbf{RA}}{\text{Max}}\, Z = \sum_{n=1}^{N} \sum_{t=1}^{T} D_{n,t} \sum_{j=1}^{J} \text{RA}_{n,t,j} A_{n,j} \tag{20}$$

subject to:

$$\sum_{n=1}^{N} \sum_{j=1}^{J} C_j \text{RA}_{n,x,j} A_{n,j} \leq F_y \quad \text{for all } n, j, t \quad x \epsilon t : \text{mod}(t, 12) = 2 \quad y = 1 \text{ to } T/12 \tag{21}$$

$$\text{RA}_{n,x,j} - \text{RA}_{n,w,j} = 0 \quad \text{for all } n, j, t \quad x \epsilon t : \text{mod}(t, 12) = 2 \quad w \epsilon t : x + z, z = 1 \text{ to } 5 \tag{22}$$

$$\text{RA}_{n,t,j} < K \quad \text{for all } n, t, j \tag{23}$$

$$K = \begin{matrix} 0 : \text{mod}(t, 12) = 1, 8 \text{ to } 12 \text{ or } A_{n,j} = 0 \\ 1 \end{matrix} \tag{24}$$

$$\text{RA}_{n,t,j} > 0 \quad \text{for all } n, t, j \tag{25}$$

The water depths (**D**) in Eq. (20) are taken as constants and either assumed as an initial condition on the first iteration (set to the static upper bounds described in the preceding) or taken from solution of the following part 2 in the previous iteration. They become objective function weights.

Part 2: water allocation

$$\underset{\mathbf{D}}{\text{Max}}\, Z = \sum_{n=1}^{N} \sum_{t=1}^{T} D_{n,t} \sum_{j=1}^{J} \text{RA}_{n,t,j} A_{n,j} \tag{26}$$

Subject to:

$$\sum_{n=1}^{N} D_{n,t} \sum_{j=1}^{J} \text{RA}_{n,t,j} A_{n,j} \leq \text{WAR}_t \quad \text{for all } t \tag{27}$$

$$D_{n,t} < \left[(K_{\text{scale}} \text{HB}_\text{n})(I_n/H_0 + \ln\{\varepsilon\}) \right] / \left[1 - \text{e}^{-(I_n/H_0 + \ln\{\varepsilon\})} \right] \quad \text{for all } n, t \tag{28}$$

$$\text{GWE}_{i,t} < \text{GSE}_i - \text{FB}_i \quad \text{for all } i, t \tag{29}$$

$$\text{GWE}_{i,t} = H_{i,t} + \sum_{n=1}^{N} \sum_{\tau=1}^{T} M_{n,i,\tau} \left(\text{RA}_{n,x,\tau} A_n D_{n,\tau} / \text{RVu} \right) (\text{FD}_1/\text{FD}_0) \quad \text{for all } i, t \quad x \epsilon t : \text{mod}(t, 12) = 2 \tag{30}$$

$$D_{n,t} > 0 \quad \text{for all } n, t \tag{31}$$

The land rental decisions (**RA**) are taken as constants from solution of part 1. If convergence of optimal objective function values from parts 1 and 2 has not occurred, the decision variables (**D**) from part 2 are used in part 1 as constants and another iteration of the two-part optimization procedure is performed.

This solution scheme is analogous to Benders' decomposition (Geoffrion 1972):

1. The decision variables in the original problem are separated by forming two sub-problems that each contain only one variable. (Where both variables remain in a sub-problem, variable separation is accomplished by converting the second variable to a constant.)
2. Solution of the two sub-problems is performed in series with the results of one sub-problem used to upgrade information used in the next sub-problem. The values of variables held constant are updated based on solution of the preceding sub-problem.
3. Iteration is applied until a satisfactory approximation to solution of the original problem is indicated by convergence of the results between iterations.

The approach used here is not as rigorous as Benders' decomposition since cuts to the solution space are not represented as functions of the variable held constant. It is also simpler than alternative approaches demonstrated by Cia et al. (2001) or Afshar et al. (2010). Initial work with the hydrologic formulation (section 'Initial hydrologic formulation') established that, when water is available for recharge, there is more than can be accommodated by the available land with the short berms assumed in this work. This insight allowed identification of an appropriate initial condition. The values of **D** in Eq. (20) of part 1 can be set to their maxima at the beginning of the solution procedure based on Eq. (28). This allows solution for **RA** constrained by financial limitations in Eq. (21). Solution for **D** in part 2 using **RA** from part 1 is then possible.

The information needed to specify equation constants and coefficients is preprocessed in spreadsheets and passed to a linear programming solver. Experience with the example presented in the following indicates that the approach encounters no infeasibilities and converges in two iterations because the original hydro-economic formulation is not so complex. Moreover, reversing the order of solution for the two-part optimization yields the same ultimate results but with a slightly different path towards convergence. (Solving part 2 first involves setting the **RA** decision variables to 0.5 during initial solution for **D**.) These results suggest that global, rather than local, minima are identified.

Simulating recharge application and evaluating groundwater system improvements

After solution of the linear programming model, recharge volume schedules are calculated for each of the 67 groundwater model elements from the optimal values for the decision variables **D** and **RA**.

$$\mathrm{RV}_{n,t} = D_{n,t} \sum_{j=1}^{J} \mathrm{RA}_{n,t,j} A_{n,j} \quad \text{for all } n, t \tag{32}$$

Unsaturated flow is not simulated because the groundwater model does not address addition of water to ponds during the run period (Brush et al. 2013). As a result, a different capability of the simulation model is used and the recharge water is added directly to the saturated zone. Post-processing the model output creates information to evaluate changes in groundwater storage and stream flow relative to a base case of no recharge operations. The locations for stream flow evaluation are indicated on Fig. 4.

Limitations

Four limitations of the approach are described here. The first three are related to the linear programming formulation and the fourth relates to the scope of analysis.

1. Because unsaturated flow cannot be simulated in the groundwater model during recharge operations and all recharge water is applied directly to the saturated zone, no time lags for groundwater elevation responses or partitioning of water between unsaturated and saturated zone storage occurs. This limitation could lead to overestimation of recharge effects from operating decisions. However, this limitation is not expected to be significant since the depth to groundwater is generally less than 100 ft (30 m) near the crop lands.
2. The linearized representation of groundwater head responses to recharge could over-estimate increases in groundwater elevations near rivers that are in contact with groundwater because the discharge of groundwater to surface water is not included in the responses M of Eq. (30). Because final evaluation of improvements to the groundwater system are made with the groundwater model and not the linear programming formulation, this limitation does not affect the ultimate predictions of changes in groundwater system state. Moreover, this final evaluation with the groundwater model shows that the limitation matters most when a groundwater elevation control

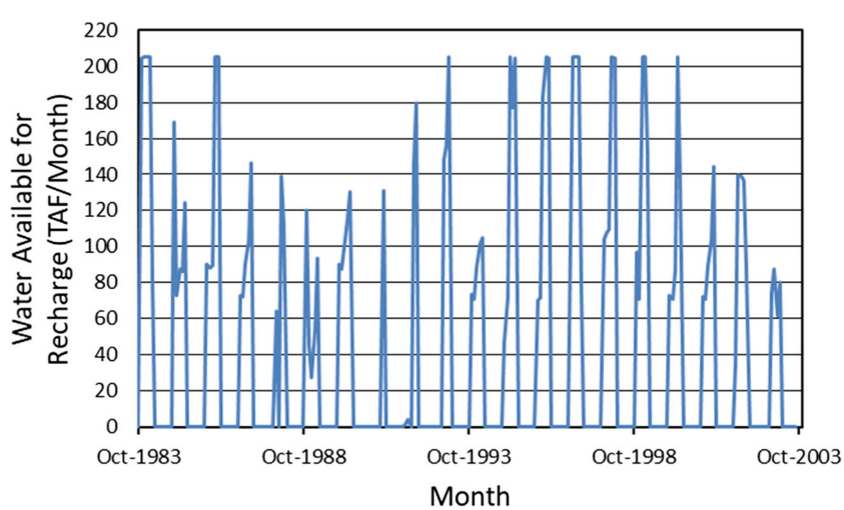


Fig. 5 Water available for recharge. 1 TAF = 1.2×10^6 m^3, TAF thousand acre-feet

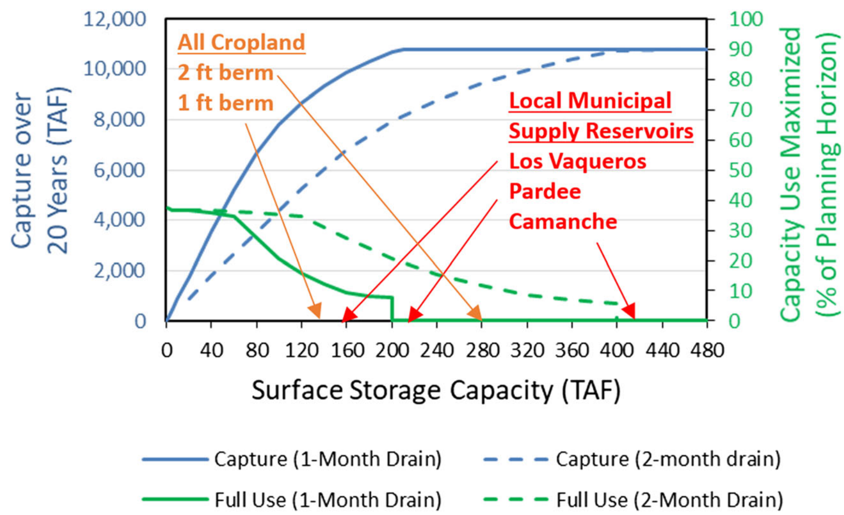


Fig. 6 Conditions for capturing water available for recharge using recharge basins

constraint is binding and that this condition occurs infrequently because of the initial depth to groundwater.

3. All cropland is represented as available for recharge operations at a stated rental price and the land is assumed to be flat and horizontal such that ponded recharge water distributes uniformly. These conditions will not be met at all locations in the study area. Moreover, costs to distribute water from the Folsom South Canal, including any lift costs required to overcome topographic variations, are not considered in this planning-level analysis. As a result, this work presents an optimistic estimate of what might be possible.
4. Potential effects on groundwater quality are not considered in this analysis. Studies have shown the presence of potential pollutants in the unsaturated zone beneath lands used for a range of purposes, including irrigated

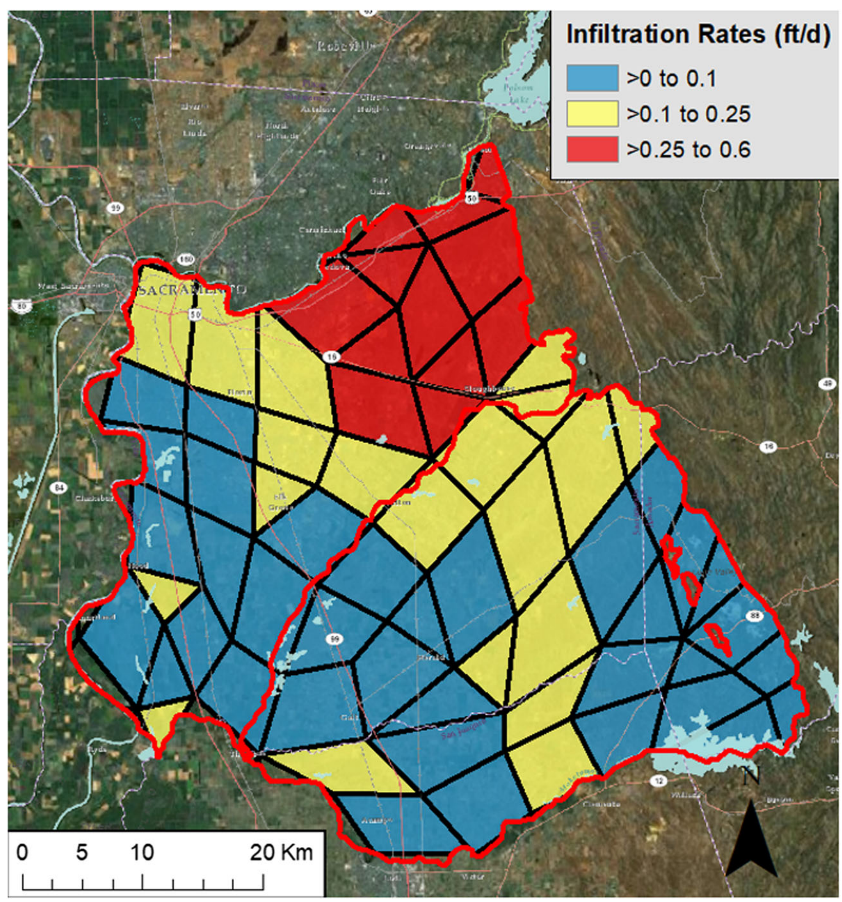


Fig. 7 Study area infiltration rates

agriculture, and considered the potential for groundwater contamination from recharge (Böhlke 2002; Walvoord et al. 2003; Scanlon et al. 2005; McMahon et al. 2006; Jurgens et al. 2010; Harter and Lund 2012; Ascott et al. 2017). In some cases, chemical reactions in the unsaturated zone during recharge reduce the potential for groundwater contamination (Schmidt et al. 2012). Bachand et al. (2014) considered potential groundwater quality impacts for their pilot study by estimating the volume of recharge water required to flush constituents from the unsaturated zone and also dilute resulting water quality impacts in the saturated zone. Gailey (2013) presents data for a different area in the Central Valley where conversion of cropland to a recharge basin caused nitrate concentrations to increase above the maximum contaminant level and more than a decade was needed for water quality impacts to subside. The potential for water quality impacts from on-farm recharge appears to vary among sites and consideration of the factors involved (Green et al. 2008; Liao et al. 2012) should be part of recharge site selection. Economic

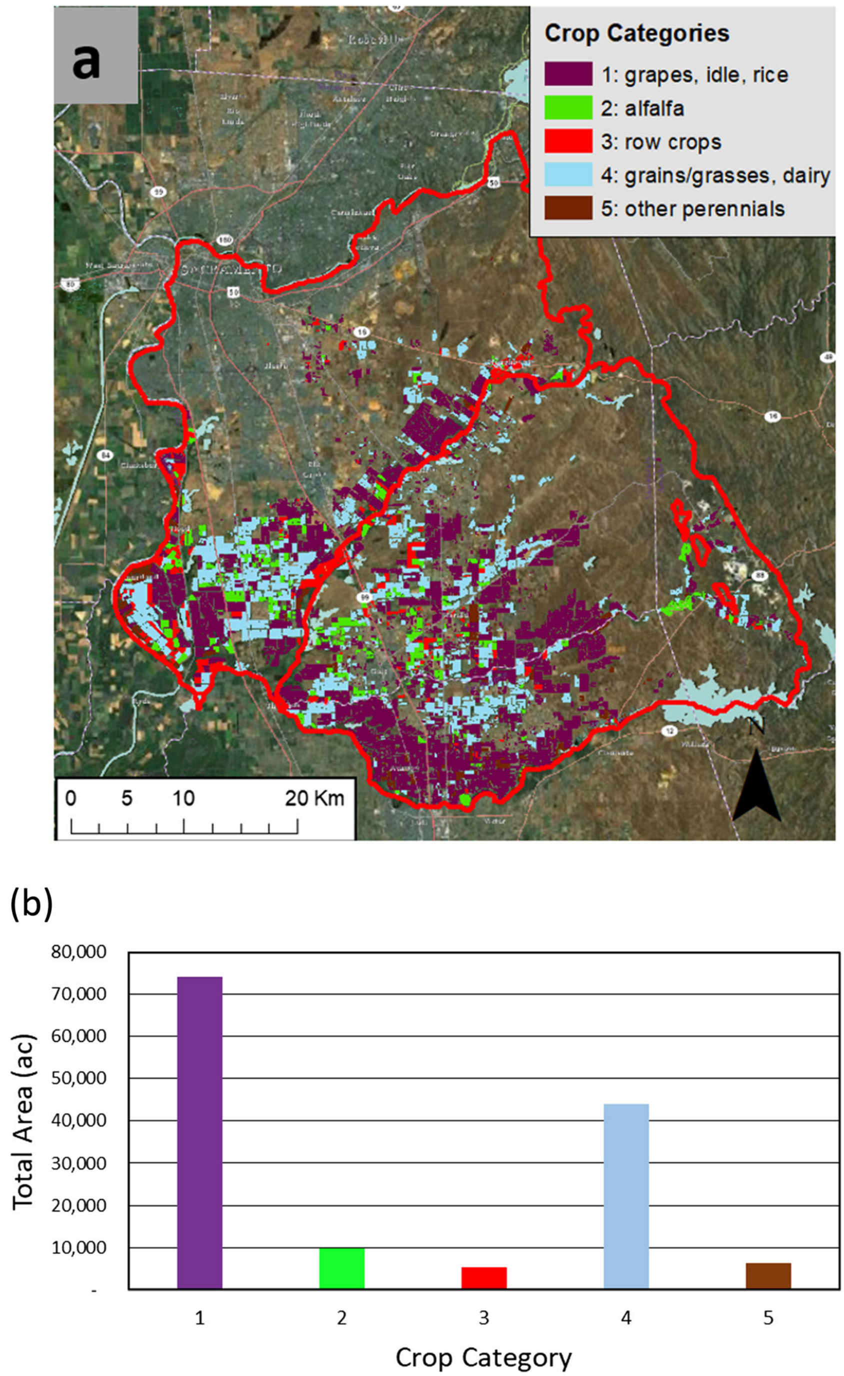


Fig. 8 Crop categories for costs to use land for recharge: **a** spatial distribution of categories and **b** categories and total acreages (ac). 1 acre = 0.4 ha

incentives may be applied to promote recharge on lands that are less likely to cause impact (i.e., alfalfa; Dahlke et al. 2018). This is an ongoing area of inquiry and additions to the approach presented here may be possible in the future.

Notwithstanding these limitations, this approach extends inquiry regarding Ag-MAR allowing for flexibility in future application and adds reasonable insight on the topic.

Results and discussion

Data development and preliminary analysis

Water available for recharge is estimated from simulated reservoir reoperation (Goharian et al. 2016; E. Goharian, Hydrologic Sciences Graduate Group, University of California Davis, unpublished manuscript, 2018) and occurs at some point during each of the 20 years in the planning period (Fig. 5). While a significant total volume is available over the planning period (10.8 million ac-ft or 13.3 km^3), the distribution in time is quite irregular. Simple spreadsheet simulation of WAR capture in recharge basins indicates the total surface-water storage capacity needed to capture different amounts of water when it is available (Fig. 6). Capture of all available water would require approximately 205,000 ac-ft (TAF; 253 × 10^6 m^3) of surface-water storage capacity assuming the recharge basins drained every month (solid blue curve on the plot) and double that storage capacity if drainage required twice as long (dashed blue curve on the plot). Because the water is available seasonally and large amounts of water are available only infrequently, the capture curve has diminishing returns to scale and facility utilization is low (green curves on plot).

The significant amount of surface-water storage capacity required to implement this traditional approach for groundwater recharge is placed into context by considering the capacities of nearby municipal supply reservoirs (Lake Camanche and Pardee Reservoir operated by the East Bay Municipal Utility District at 417 and 198 TAF, or 514 and 244 × 10^6 m^3; Los Vaqueros Reservoir operated by the Contra Costa Water District at 160 TAF, or 197 × 10^6 m^3; Fig. 6). By comparison, use of all 140,000 ac (57,000 ha) of crop land

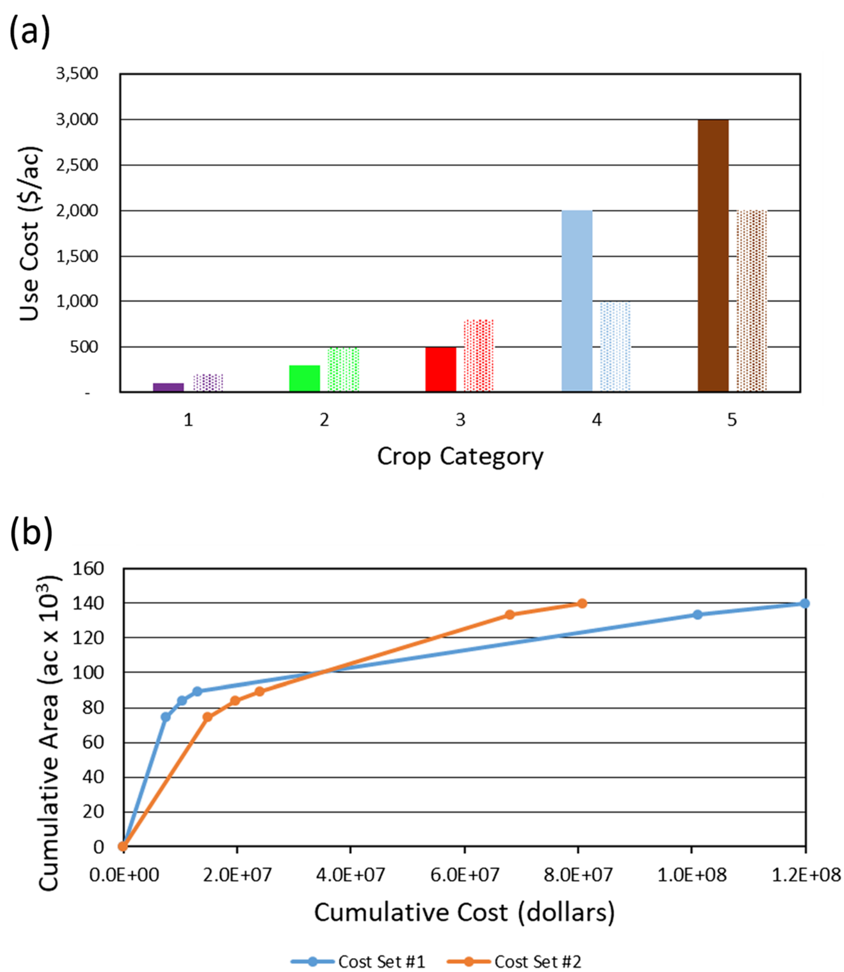


Fig. 9 Cropland use costs: **a** unit annual costs and **b** cumulative annual costs without consideration of spatially variable infiltration rates. Solid colors (**a**) correspond to cost set No. 1 and stippled colors correspond to cost set No. 2

Table 1 Parameter values

Parameter	Value
HB	1 ft (0.3 m)
H_0	0.3 ft (0.1 m)
FB	2 ft (0.6 m)
FD_0	0.95
FD_1	1.0
F	0.5–120 million dollars

Parameter definitions provided in sections 'Initial hydrologic formulation' and 'Hydro-economic formulation'

with berms between 1 and 2 ft (0.3–0.6 m) high would result in similar amounts of surface-water storage capacity (Fig. 6). Therefore, it might be reasonable to evaluate using croplands to meet at least some recharge opportunities for the study area.

Information for infiltration rates in the study area is mapped to the groundwater model elements (Fig. 7) and applied in the ponding model (Appendix) used to derive Eqs. (4), (16) and (28). The rates are derived from simulating ponding at ground surface and transient unsaturated/saturate flow into a fine-scale (200-m resolution in all three spatial dimensions) representation of the spatially variable hydrogeology (Maples et al. 2017; S. Maples, Hydrologic Sciences Graduate Group, University of California Davis, unpublished manuscript, 2018). Average infiltration rates are calculated over the 120-day simulations for a variety of assemblages of sediments. These values are applied to zones (proximal, intermediate and distal parts of the alluvial fan deposits in the study area) in the coarser-resolution groundwater flow model used here. It is assumed that any shallow hardpan has been breached consistent with the SAGBI rating for conditions where sites have been modified by deep tillage rating (O'Geen et al. 2015); however, observations of ponded water in parts of the study area suggest that hardpan may be present at some locations.

Crop categories for annual costs to use land in recharge operations are developed to be generally consistent with

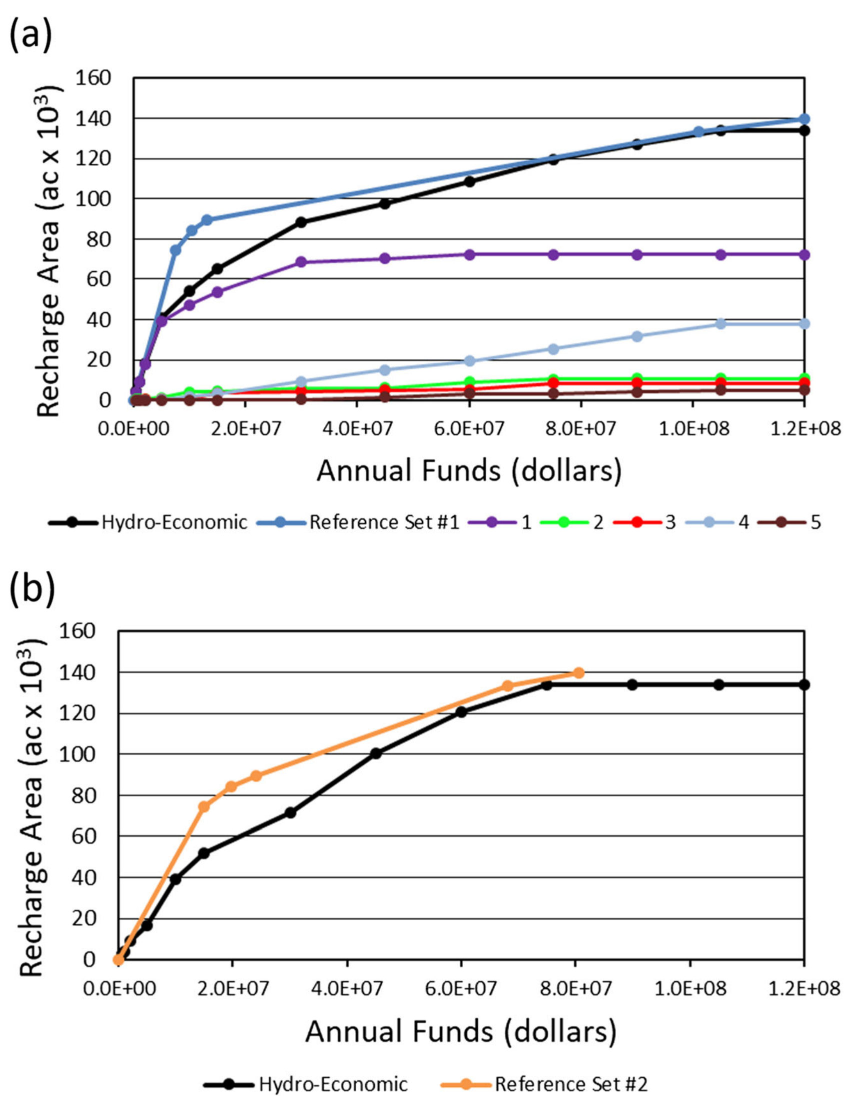


Fig. 10 Variation of cropland used for recharge with annual funding: **a** cost set No. 1 and **b** cost set No. 2. Reference curves based on cost only from Fig. 9b are presented for comparison. Numbered curves (**a**) indicate land use for recharge by individual crop categories. Slight differences in the maximum recharge areas attained for the "Hydro-Economic" and "Reference Set" curves occur because the groundwater model elements do not conform to the sub-basin boundaries. The cropland area not accounted for in the model, approximately 6,000 ac (3,000 ha), is evident by comparing Figs. 7 and 8a

discussion of risks to crop health and productivity presented by Dahlke et al. (2018) as well as Hanak et al. (2018). The categorization in Fig. 8a,b is based on discussions with a variety of people working in the study area (i.e., land managers, Sacramento County Agriculture Commissioner staff, other county staff and researchers). The unit costs applied to the categories (Fig. 9a) are quite preliminary (exploratory) and could be improved with survey data on land manager perceptions of crop risk and attitudes towards financial risk tolerance. Combining the cumulative areas and unit costs for each category provides a view of total land area used for recharge as a function of potential total cost (Fig. 9b). These curves are based on an assumption that land is selected solely on unit price; however, infiltration rates must also be considered when attempting to maximize recharge. To the extent that locations of the cheapest land are not correlated with the highest infiltration rates, the curves will be different than those shown. The linear programming method described in the preceding allows performance of the required analysis. Table 1 summarizes the values of the hydro-economic model parameters not addressed elsewhere.

Potentially achievable recharge

Cropland area use for recharge as a function of funding is presented in Fig. 10a,b. These are the results of parametric analysis using Eq. (21). Differences between the results for hydro-economic analyses and the reference curves occur because, as indicated by the curves for individual crop categories (Fig. 10a), some of the more expensive land is brought into use before all of the least expensive land has been used. This result is driven by variation in infiltration rate across the study area which is controlled by the shallow geology and the interconnectedness of high conductivity sediments at depth (Maples et al. 2017; S. Maples, Hydrologic Sciences Graduate Group, University of California Davis, unpublished manuscript, 2018) used in the ponding model of Eq. (28). Figure 11 shows the spatial distribution of land use for two different levels of funding. For low amounts of funding, land is brought into use where there is a combination of cheaper land (Fig. 8a) and higher infiltration rates (Fig. 7) in an effort to maximize the product of decision variables **RA** (scaled by area potentially available for recharge, *A*) and **D**. This observation is consistent with the steep slope of recharge volume as a function of funding for land use at low funding levels (Fig. 12). Spatial distribution of the recharge water cumulative depth per year is presented for the maximum funding and land use in Fig. 13. The values are generally within a reasonable range based on currently available information on crop inundation tolerance; however, constraints could be added to control cumulative water application as necessary.

Figure 14 indicates the increase in groundwater storage from recharge using all of the cropland (high level of funding). Recharging over the 20-year planning period used 36% of the

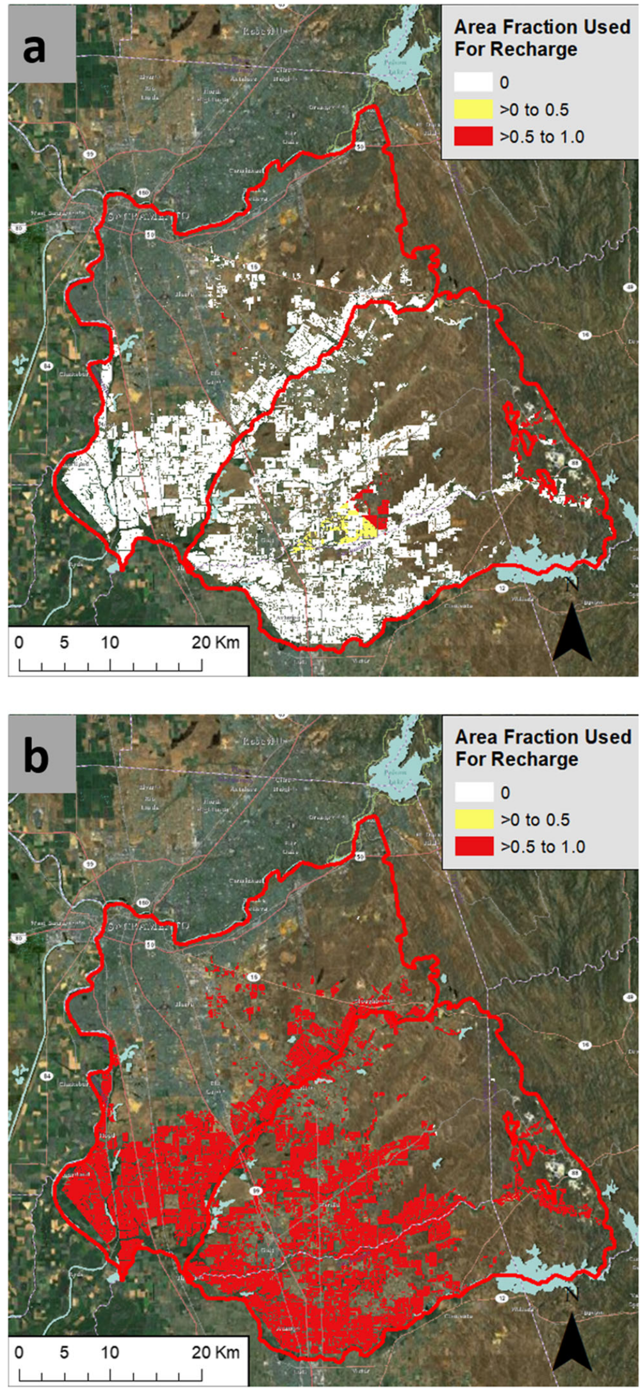


Fig. 11 Spatial distribution of land used for recharge with different amounts of annual funding (F): **a** F = $500,000 and **b** F = $120,000,000. Results for cost set No. 1. Area fraction plotted is the decision variable RA

WAR (3,921 TAF or 4.8 km^3). Simulation of the optimal recharge scenario with the groundwater model indicates the most of the water remains in the groundwater system (2,419 TAF or 62% of the total volume recharged); however, appreciable amounts exit to surface water (718 TAF, 18%) or flow across sub-basin boundaries (764 TAF, 20%). Additionally,

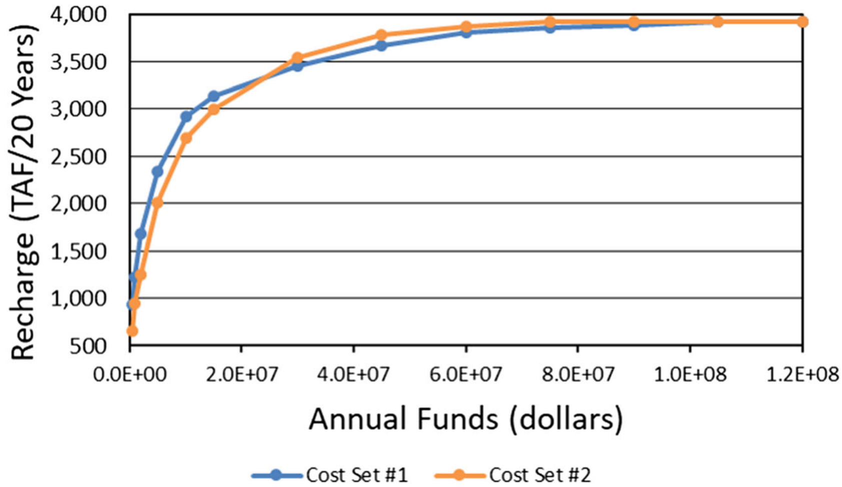


Fig. 12 Variation of recharge volume with annual funding

the recharge provides enough baseflow to support flow in the Cosumnes River throughout the 20-year simulation except during a 5-year drought from 1987 through 1992. Table 2 presents results for a range of recharge funding levels. Volumes discharging to surface-water and flowing to other sub-basins increase with the volume recharged since head buildup from adding water to the system (the driving force for groundwater flow) is more pronounced.

Comparison of the recharge volume results from the hydro-economic analysis for cost set No. 1 (Fig. 12) with reference curves from the initial capture analysis (Fig. 6) indicates the effect of including study area hydrogeology (spatial variation in infiltration rate) in the analysis (Fig. 15a). High infiltration rate sites are selected preferentially, even when the amount of recharge area is limited by funding, and plot on the left side of the hydro-economic curve. These sites drain quickly and the

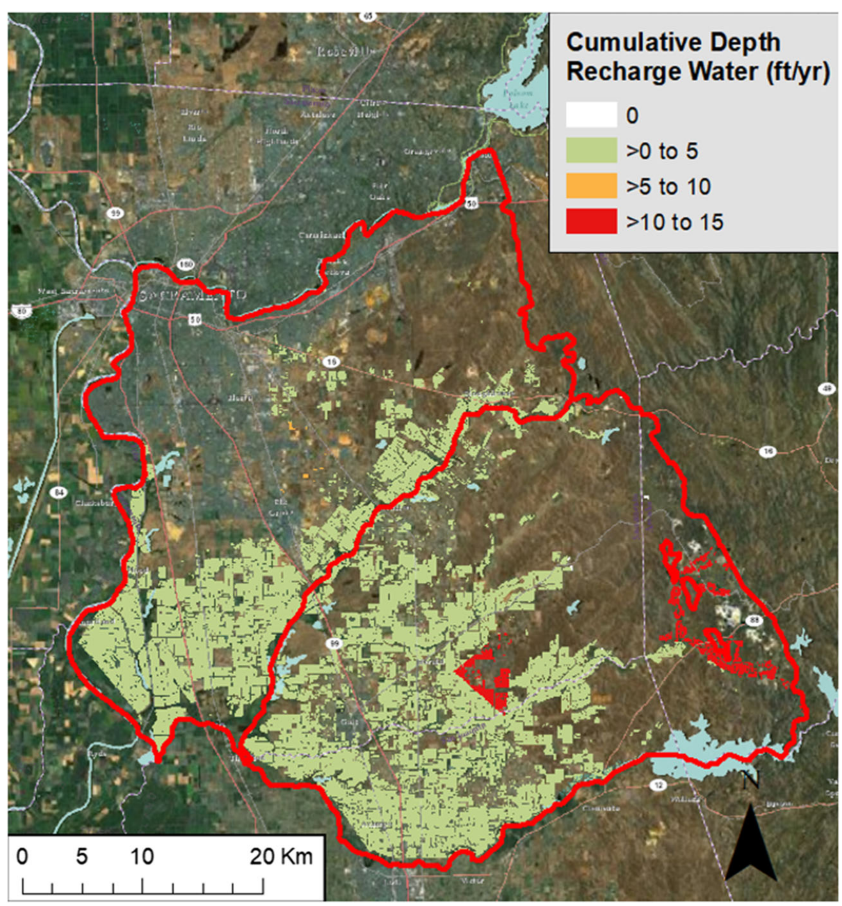
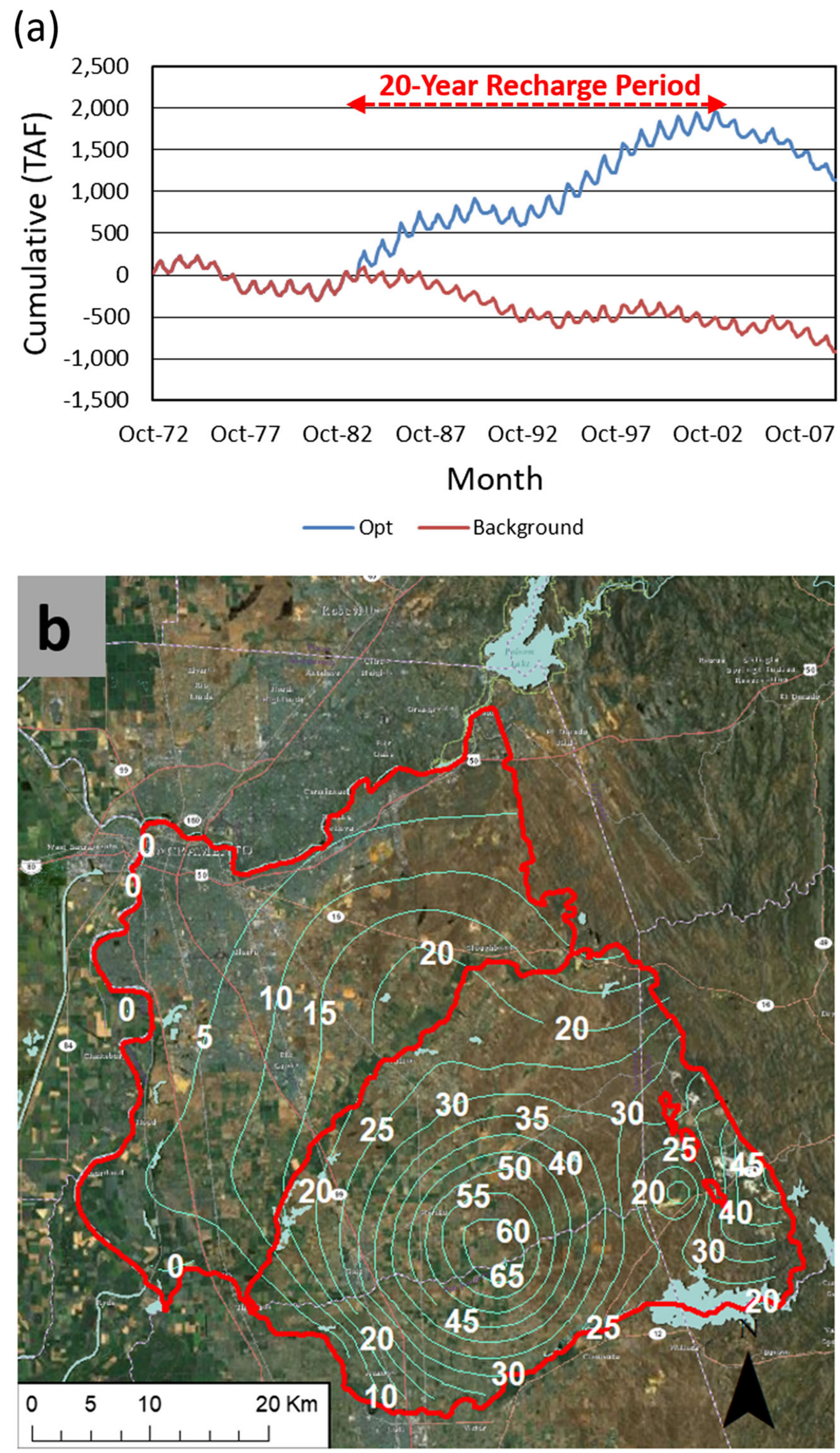


Fig. 13 Cumulative depth of applied recharge water for maximum land use funding using cost set No. 1

Fig. 14 Increase in groundwater storage using all cropland: **a** storage accumulation over time and **b** spatial distribution of elevation increases. Red line (**a**) indicates change in storage resulting from continued groundwater pumping and no recharge operations, blue line (**a**) indicates change in storage resulting from addition of optimized recharge operations



results (shown in black) plot above the reference curves (shown in blue). Only few such sites are within the footprint of the cropland and, when greater amounts of land are used for recharge, the additional sites drain slower and plot below one or both of the reference curves. The result is a recharge capture curve for the study area that is shallower in slope than the reference curves. Therefore, the spatial variability in infiltration rate magnifies the diminishing returns to scale already occurring as a results of the temporal variability of the water source.

More recharge could be achieved, and the study area capture curve moved higher on the plot, if the berm heights around the cropland were increased. The linear programming results obtained can help develop guidance on where such

Table 2 Results for different levels of land use funding (cost set No. 1). *gw* groundwater, *TAF* thousand acre feet

Parameter	Land-use-funding level		
	\$500,000	\$5,000,000	\$120,000,000
Land use area	4×10^3 ac (1,600 ha)	41×10^3 ac (17,000 ha)	134×10^3 ac (54,000 ha)
Recharge volume	937 TAF (1.2 km^3)	2,335 TAF (2.9 km^3)	3,921 TAF (4.8 km^3)
Increased gw storage	628 TAF (0.8 km^3)	1,551 TAF (1.9 km^3)	2,419 TAF (3.0 km^3)
Discharge to surface water	203 TAF (0.3 km^3)	359 TAF (0.4 km^3)	718 TAF (0.9 km^3)
Flow to other sub-basins	107 TAF (0.1 km^3)	425 TAF (0.5 km^3)	764 TAF (0.9 km^3)

capital investment might be most valuable. Reformulating the Lagrange multiplier for Eq. (28) in terms of the berm height (see Appendix) indicates where and how much additional water could be recharged over the planning horizon if berms were raised from 1–2 ft (0.3–0.6 m; Fig. 15b). This result provides a high estimate of what might be possible since some perennial crops may be unable to accommodate the increased ponding depth; nevertheless, this information provides guidance for where efforts might be best spent increasing berm heights.

The values for Lagrange multipliers based on increasing berm height by 1 ft (0.6 m) are low in the northern portion of the study area (Fig. 15b) because little cropland is present (Fig. 2). Given the high infiltration rates of the deeper geology in the north (Fig. 7), recharge potential would be much better for a gravel pit since it would provide additional land area and also penetrate the low hydraulic conductivity soil layer included in this analysis. Cropland present in one of the northern model elements with high-infiltration rate was used to simulate the potential effect of repurposing a gravel pit for recharge. A total of 570 ac (230 ha) in crop categories 2, 3 and 4 were used to simulate gravel pits by increasing the hydraulic conductivity of the soil layer to match the underlying geology and increasing the berm height to 20 ft (6 m).

Figure 16a,b summarizes the results of gravel pit simulation at the maximum annual funding level. Recharging over the 20-year planning period uses 50% of the WAR (5,412 TAF or 6.8 km^3). Most of the water remains in the groundwater system (3,651 TAF or 68% of the total volume recharged) with amounts similar to the previously presented results exiting to surface-water (869 TAF, 16%) and flowing across sub-basin boundaries (889 TAF, 16%). Allocation is skewed towards the gravel pits (31% of the total volume recharged) and provides enough baseflow to support continuous flow in the Cosumnes River throughout the 20-year simulation including during the previously mentioned 5-year drought.

Potential extensions

The method and analysis for the study area could be extended to include net metering (Kiparsky et al. 2018). This approach could entail representing cropland managers as individual profit-maximizing agents along with the groundwater management agency charging fees for groundwater pumping and providing rebates for recharge. This approach would relax the assumption of uniform land use rents for each crop category and include a more likely dispersion of land use costs across the study area.

It is unclear if the aggregate effect of net metering with modest pumping fees would significantly differ from the work presented here since the influence on rational profit maximizers of a net rebate, rather than a payment for using land for recharge, may be similar. However, the effect of net metering combined with a cash flow constraint applied to water management operations (revenue from groundwater pumping minus a financial friction for management must equal or exceed payments for recharge) could impose limits on a program for improving groundwater system conditions. Given the regulatory requirement for improved groundwater system state, these changes could drive pumping fees higher and influence the behaviors of profit maximizing land managers.

It may also be possible to explore improving groundwater conditions through water banking operations where capital investments (i.e., construction of distribution canals from Folsom South Canal) and operations costs would be paid by a client, or clients, external to the sub-basins. Management policy questions would include: (1) how much water would be left in-place to benefit the groundwater system (recharged but not withdrawn at a later time) and (2) the longevity of withdrawal rights (ability to withdraw water decreases with time since recharge event). Details of the policy decisions would likely have implications for the amount of infrastructure investment a water banking client might be willing to make.

Either the cash flow or water banking approach might be modified to encourage recharge in areas where it is most needed. Lower bound constraints for groundwater elevations at control locations could be added in parts of the basin with the greatest cumulative drawdowns. It might also be possible to evaluate policies to avoid potential water quality degradation from flushing undesirable constituents (i.e., nitrate, pesticides and salts) from the unsaturated zone and shallow groundwater by including subsidies (reducing costs to use certain lands for recharge) to focus recharge on more desirable lands (i.e., alfalfa fields as suggested by Dahlke et al. 2018).

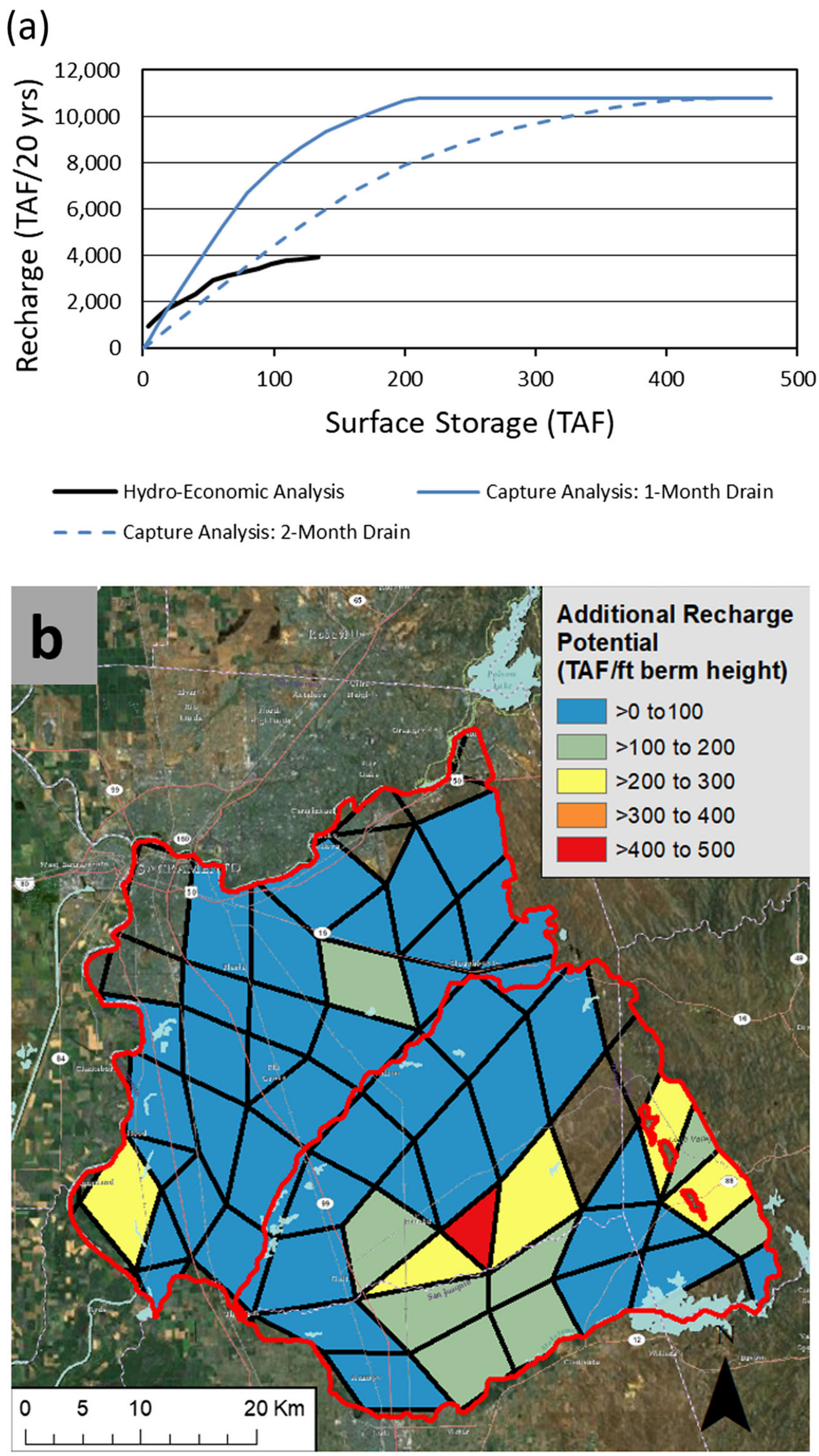


Fig. 15 Effect of spatial variation in infiltration rate on recharge volume potential: **a** capture curves and **b** Lagrange multipliers

Recharge at locations important for supporting and increasing surface-water baseflow could also be emphasized. The simplest way to achieve this benefit would be to set lower bound constraints for groundwater elevations at control locations near the surface-water bodies (i.e., Cosumnes River). However, this approach would require experimentation with lower bound values and locations because, as previously indicated, the linearized approach for representing the groundwater response to recharge does not account for exchange between groundwater and surface water. A more thorough approach would entail reformulating the planning problem as a nonlinear program where the groundwater flow model is called on each iteration of the solver to evaluate baseflow constraints.

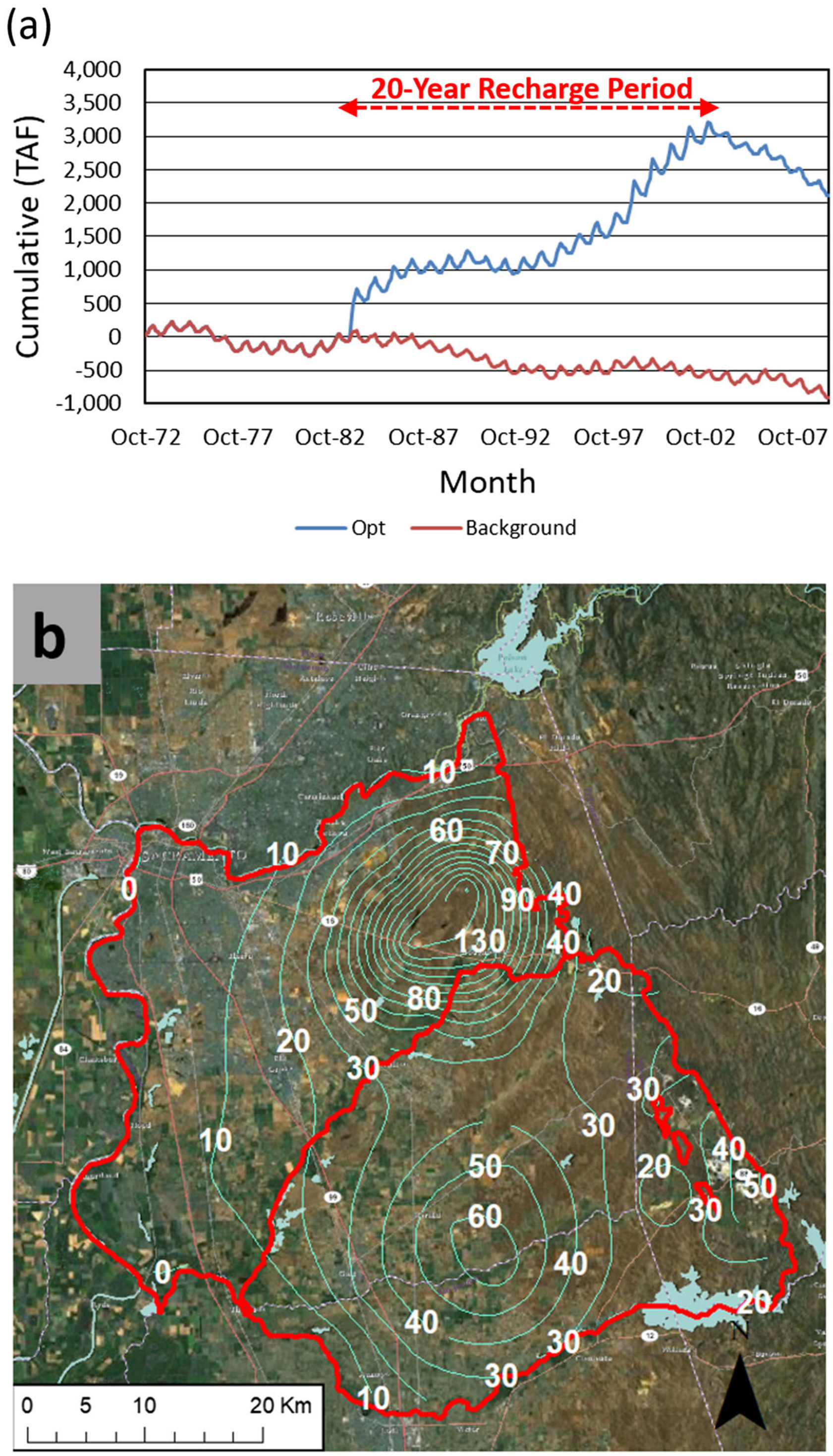


Fig. 16 Increase in groundwater storage using all cropland and repurposed gravel pits in north: **a** storage accumulation over time and **b** spatial distribution of elevation increases. Red line (**a**) indicates change in storage resulting from continued groundwater pumping and no recharge operations. Blue line (**a**) indicates change in storage resulting from addition of optimized recharge operations

Finally, a portfolio of recharge projects that includes a mix of croplands and dedicated facilities could be considered. This extension would be desirable since croplands in the study area are concentrated in the south, while the higher hydraulic conductivity deposits are in the north (cf. Figs. 2 and 7). Not coincidentally, potential properties that could be repurposed as dedicated facilities (gravel excavations) are in the north. To control the number of potential facilities considered, upper bound infiltration capacity constraints for the gravel pits could be manipulated to include/exclude the potential facilities in the formulation by toggling the bound value between zero and an estimated capacity (a form of parametric analysis). Alternatively, the linear programming model could be reformulated as a mixer-integer linear program and parametric analysis could be performed on a funding constraint for gravel pit repurposing.

Conclusions

On-farm recharge appears to be promising for the study area. Using all of the 134,000 ac (54,000 ha) of cropland modeled in the study area would have allowed approximately 3900 TAF (4.8 km^3) of recharge over the 20-year period considered (October 1983–September 2003). Analysis indicates that there would be decreasing returns to scale as a result of (1) temporal variability of water available for recharge, (2) variations in infiltration rate and a limited number of high-infiltration rate sites across the study area and (3) recharged water exiting the study area groundwater system to surface water and adjacent sub-basins. Depending upon crop tolerance to ponding depth, these limitations might be reduced by raising berm heights on higher-infiltration rate croplands. Additional efforts to recharge high-infiltration rate sediments to the north through pits that penetrate lower-infiltration rate topsoil could significantly increase total recharge volume. Preliminary results indicate approximately 5,400 TAF (6.8 km^3) of recharge could occur over the 20-year period by adding 570 ac (230 ha) of gravel pits to the land available for recharge.

The method applied in this work is general enough that it can accommodate additional information that may be gathered including:

1. Characterization of potential recharge sites
   a. Soil hydraulic conductivity measurements
   b. Geology
   c. Infiltration pilot testing results
   d. Observations from land managers regarding field drainage rates
2. Flooding tolerance for different crops
   a. Acceptable date ranges
   b. Maximum durations
   c. Total volumes
3. Costs for specific sites
   a. Annual use fees
   b. Infrastructure improvement requirements

Extensions of the work could readily address related considerations such as (1) financial considerations regarding investment and operations, (2) measures to safeguard groundwater quality, (3) support for baseflow to the Cosumnes River and (4) portfolios of recharge facility types and approaches. Continued collaboration with stakeholders in the study area may provide future insights.

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Appendix

Details regarding formulation of the linear programming model are presented in the following sections.

Ponded water drainage

The upper bound for recharge water applied is specified as Eqs. (4, 16 and 28) and based on a requirement that water ponded on the field not overtop an assumed perimeter berm of height HB. A series of steps are taken to develop an expression for the maximum allowable recharge volume.

An ordinary differential equation and initial condition for water mass balance in a recharge pond during filling is formulated and solved:

$$A\ dh/dt = Q – A\ (I/H_0)\ h \tag{33}$$

$$h(0) = 0 \tag{34}$$

$$h = [(Q\ H_0)/(I\ A)]\left[1 – e^{-(I/H_0)t}\right] \tag{35}$$

where:

A is the ponding area
h is the ponding depth
t is time
Q is the rate of inflow
I is the reference rate ponded water infiltrates the subsurface
H_0 is ponding depth associated with I

The quantity (I/H_0) in Eq. (33) normalizes the infiltration rate by the ponding depth used to estimate the quantities summarized in Fig. 7 (Maples et al. 2017; S. Maples, Hydrologic Sciences Graduate Group, University of California Davis, unpublished manuscript, 2018) and allows scaling by h to simulate variation in infiltration rate with ponding depth. Evaporation is not considered in the pond mass balance because recharge operations are considered during the winter when evaporative losses are expected to be small.

Filling the pond at a constant rate until the maximum ponding depth is reached at a specified time is represented by substituting $h = \mathrm{HB}$, $Q = Q_{\max}$ and $t = T$ into Eq. (35). Rearrangement yields:

$$Q_{\max} = (I\,A\,\mathrm{HB}/H_0)/\left[1 - \mathrm{e}^{-(I\,T/H_0)}\right] \quad (36)$$

An ordinary differential equation for water mass balance in a recharge pond during draining is formulated and solved for the general condition:

$$\mathrm{d}h/\mathrm{d}t = -(I/H_0)\,h \quad (37)$$

$$h = \mathrm{e}^{-(I/H_0)t+K} \quad (38)$$

Substituting $t = t - T$ into Eq. (38) so that Eqs. (35) and (38) initiate at the same time and rearranging yields:

$$h = K\,\mathrm{e}^{-(I/H0)\,(t-T)} \quad (39)$$

Equating Eqs. (35) and (39) at time $t = T$, solving for K and substituting into Eq. (39) yields:

$$h = [(Q\,H_0)/(I\,A)]\left[1 - \mathrm{e}^{-(I/H_0)T}\right]\mathrm{e}^{-(I/H_0)\,(t-T)} \quad (40)$$

Substituting Eq. (36) for Q and rearranging yields an expression for filling to time T and then draining thereafter:

$$h = \mathrm{HB}\,\mathrm{e}^{-(I/H_0)\,(t-T)} \quad (41)$$

Assume that the pond must be filled and drained within 1 month to allow operational flexibility such that the land could be used for purposes other than recharge during the following month. A 1-month filling and draining cycle is represented by introducing a terminal boundary condition for Eq. (41): $h(1) = \varepsilon\,\mathrm{HB}$, where ε is a small increment. Solving for T yields:

$$T = 1 + (H_0/I)\,\ln(\varepsilon) \quad (42)$$

Substituting Eq. (42) into Eq. (41) and the result into Eq. (36) yields an expression for $Q_{\max}$:

$$Q_{\max} = (\mathrm{HB}AI/H_0)/\left[1 - e^{-(I/H_0 + \ln\{\varepsilon\})}\right] \quad (43)$$

Multiplying this expression for $Q_{\max}$ by the Eq. (42) for T results in an expression for the maximum recharge volume that can be added to a pond in a single month:

$$\mathrm{RV}_{\max} = [(\mathrm{HB}A)(I/H_0 + \ln\{\varepsilon\})]/\left[1 - e^{-(I/H_0 + \ln\{\varepsilon\})}\right] \quad (44)$$

Equation (44) is based on an infiltration rate derived for water ponded on the deeper geologic materials. Because a lower hydraulic conductivity soil overlays the geology, the expression is scaled by a factor that accounts for the effective vertical hydraulic conductivity of the layered porous medium:

$$K_{\mathrm{scale}} = K_{\mathrm{eff}}/K_{\mathrm{geol}} \quad (45)$$

$$K_{\mathrm{eff}} = (b_{\mathrm{soil}} + b_{\mathrm{geol}})/\left[(b_{\mathrm{soil}}/K_{\mathrm{soil}}) + (b_{\mathrm{geol}}/K_{\mathrm{geol}})\right] \quad (46)$$

where:

- K_{eff} is the effective vertical hydraulic conductivity calculated as the harmonic mean of the conductivities of the soil and geologic layers
- K_{geol} is the averaged vertical hydraulic conductivity of the deeper geologic materials (Maples et al. 2017; S. Maples, Hydrologic Sciences Graduate Group, University of California Davis, unpublished manuscript, 2018)
- K_{soil} is the vertical hydraulic conductivity of the soil (taken as 3×10^{-2} ft/day, or 10^{-5} cm/s, based on Brush et al. 2013)
- b_{geol} is the thickness of the unsaturated zone in the geologic materials (Maples et al. 2017; S. Maples, Hydrologic Sciences Graduate Group, University of California Davis, unpublished manuscript, 2018)
- b_{soil} is the thickness of the soil layer (taken as 1 ft or 0.3 m)

Applying the scaling factor to Eq. (44) yields the general expression used for Eq. (4).

$$\mathrm{RV}_{\max} = [(K_{\mathrm{scale}}\,\mathrm{HB}\,A)(I/H_0 + \ln\{\varepsilon\})]/\left[1 - \mathrm{e}^{-(I/H_0 + \ln\{\varepsilon\})}\right] \quad (47)$$

Dividing Eq. (47) by A yields a general expression for the maximum recharge depth that can be added to a pond in a single month. This is used for Eqs. (16) and (28).

$$D_{\max} = [(K_{\mathrm{scale}}\,\mathrm{HB})(I/H_0 + \ln\{\varepsilon\})]/\left[1 - \mathrm{e}^{-(I/H_0 + \ln\{\varepsilon\})}\right] \quad (48)$$

The formulation is somewhat sensitive to the value chosen for ε with smaller values reducing the upper bound. Using a value of 0.01 appeared reasonable for this analysis. Finally, the assumed 1-month filling and drainage cycle could be adjusted by extending the approach described here to simulate pulsed flooding for crop root health (Dahlke et al. 2018).

Groundwater elevation calculation

The upper bound on groundwater elevation is specified as Eqs. (6), (18 and (30) based on ground surface elevation and an assumed required freeboard to avoid waterlogging of soil. This consideration can be important for down-flow parts of basin where recharge might not be applied but water levels may rise as a result of recharge water redistribution by means of groundwater flow (Niswonger et al. 2017). The groundwater elevation itself is based on a linearized representation of groundwater head response to addition of water to the system at a particular location and time (Reilly et al. 1987; Gorelick et al. 1993; Ahlfeld and Mulligan 2000). The representation is most accurate for confined systems but works well for unconfined conditions when the head change in response to the addition of water is small relative to the saturated thickness, as is the case for this work.

The groundwater simulation model used in this work (coarse-grid version of C2VSim; Brush et al. 2013) was manipulated to generate the background groundwater heads (H) as well as the mounding responses (M) for the control locations. The background heads were based on running the original model. Information for M was generated through a series of steps: (1) altering the model by stripping out all unmanaged hydrologic stresses, (2) making a suite of runs with the altered model separately simulating a managed stress for each potential recharge location using a unit recharge volume (RVu) in the first time step of the model, (3) running the altered model once with no managed stresses and (4) calculating the differences in heads at control locations between the runs from steps 2 and 3. The resulting information for M is a set of vectors containing transient mounding responses at each control location for each potential recharge location. The vectors are then arranged in tableaus as described by Gorelick et al. (1993) to create a matrix $\mathbf{M}$ for each control location.

The information developed for $\mathbf{M}$ is used as a groundwater elevation simulator that represents increases in elevation over time as a linear combination of responses to monthly recharge volumes. The responses (1) are produced by recharge events simulated for single time steps in any model element within the study area and any time step over the planning horizon, (2) scale with the magnitude of recharge volume and (3) can be summed to simulate combinations of recharge events over space and time.

Reformulation of Lagrange multiplier for berm height

A generalized form of constraint Eq. (28) is as follows:

$$D \leq [(K_{\text{scale}}\text{HB})(I/H_0 + \ln\{\varepsilon\})]/\left[1 - e^{-(I/H_0 + \ln\{\varepsilon\})}\right] \qquad (49)$$

When this constraint is binding in the linear programming solution, the Lagrange multiplier will be non-zero and indicate the change in the optimal value of the objective function for an increase of 1 in the right-hand side (RHS). If HB in Eq. (49) were increased by 1, the RHS would increase by $[K_{\text{scale}}\ (I/H_0 + \ln\{\varepsilon\})]/[1 - e^{-(It/H0 + \ln\{\varepsilon\})}]$. Multiplying the Lagrange multiplier value from Eq. (49) by this quantity converts the original linear programming result, Lagrange multiplier for Eq. (49), into a Lagrange multiplier for HB. Summing the converted Lagrange multipliers for each model element over all time steps in the planning horizon provides a location-specific estimate for total increase in recharge over the planning horizon for a unit increase in berm height.

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