Gerenday SP, Perrone D, Clark JF, Ulibarri N. 2023. Recycled water could recharge aquifers in the Central Valley. Calif Agr 77. https://doi.org/10.3733/ca.2023a0005

## Contents

# 1 A note about units

Metric units are used in the modeling and calculations done in this study for consistency with scientific standards and existing models. Surface distances and tabulated areas are presented in feet, miles, or square miles, as these are standard when discussing United States geography.

# 2 Well locations

## 2.1 Determining well locations from state databases

For the sake of modeling, wells are located based on the latitude and longitude assigned to them in the Well Completion Reports dataset published by the California Natural Resources Agency (CNRA 2021). Wells completed in 2019 or later are located by their actual latitude and longitude. Those completed earlier but following the rollout of the Online System for Well Completion Reports (OSWCR) in October 2015 are located primarily by latitude and longitude, address, or assessor's parcel number. The majority of earlier records are located only by public land survey system and are assigned the coordinates of the center of the section in which they are located (Benjamin Brezing, California Department of Water Resources, personal communication). This introduces an uncertainty of up to 0.7 miles (~1.1 km, the distance from the section center to the corner) to earlier well locations and causes wells located in different parts of the same section to be assigned the same coordinates. The methods of determining the coordinates included in the database for wells in the Central Valley are shown in Figure A *1*.

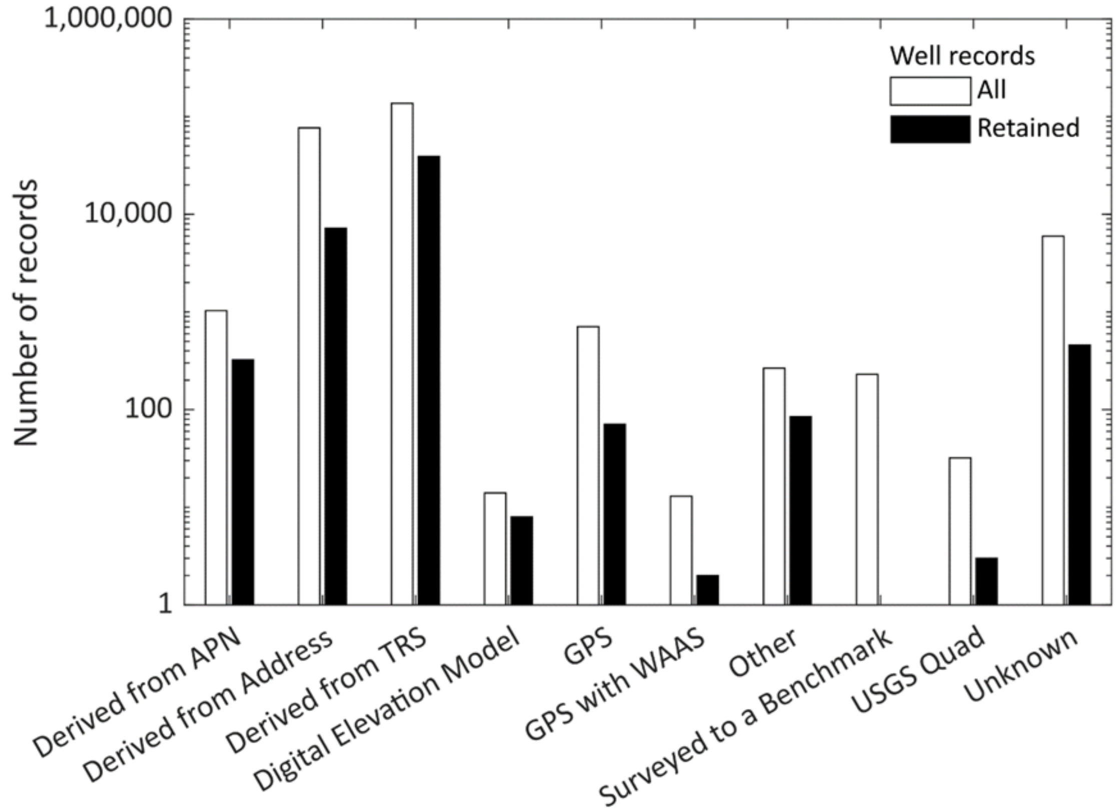


Figure A 1: Method of determining well coordinates for records within the Central Valley. Retained records are those that remain after cleaning as described in sections 2.2 and 2.3. (APN - Assessor's Parcel Number, TRS – Township, Range, Section, GPS – Global Positioning System, WAAS – Wide Area Augmentation System, USGS – United States Geological Survey)

## 2.2 Reasons for discarding well reports

Reasons for discarding well reports are indicated below. Single records are reports that do not refer to the same well as any other report (or cannot be proven to refer to the same well). Clustered records refer to a set of two or more reports determined to refer to the same well on the basis of latitude, longitude, depth, and possibly legacy log number. Single records are discarded if they do not refer to a new well, the work was completed prior to January 1, 1970, they are missing latitude or longitude, they were missing depth, or the primary use is not for human consumption (Figure A *2*). Clustered records are discarded if the cluster did not contain a new well report, the cluster contained an abandonment report, the most recent report is dated prior to 1970, or the primary use is not for human consumption (Figure A *3*). Since records are matched by location in three dimensions, missing positional data is not a relevant criterion for discarding clustered records. Note that due to the different ways in which single and clustered records are processed, the single records plot shows all reasons that a given well report would be ineligible, while the clustered records plot shows only the first reason. Clusters are evaluated first by whether they contained a new report, secondly whether they have been abandoned, thirdly by date, and lastly by whether they were intended for human consumption. The most common reasons for records to be excluded were lack of depth data (for single records) and primary use not for human consumption.

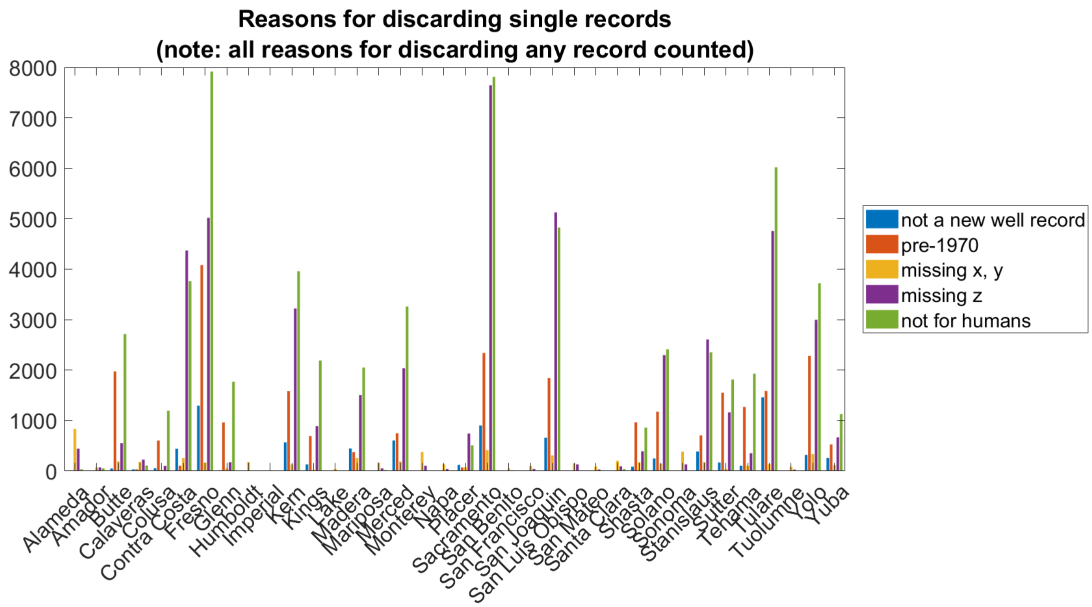


Figure A 2: Reasons for discarding single well records

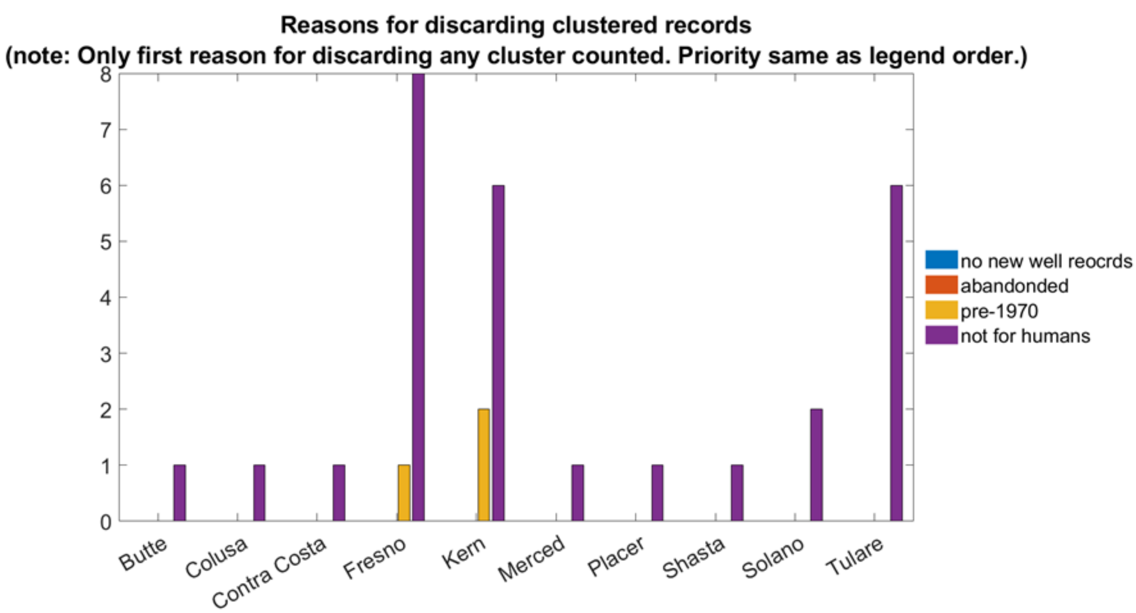


Figure A 3: Reasons for discarding clustered well records

# 3 Estimating missing screen depths

Approximately 45% of the retained well reports are missing depths for the tops and bottoms of their screens. In order to fill in the missing bottom depths, wells are divided by bulletin 118 subbasins, and a linear regression of screen bottom depth as a function of total completed depth is fitted to all wells for which both numbers are defined. Subbasins containing fewer than 75 retained well records are grouped with adjacent basins until their combined number of retained wells is at least 75, and the data for the whole group is used for the regression (Table A *1*, Figure A *4*). In some cases, subbasins with 75 or more wells are included in a group; however, the combined regression is used only for the subbasins in the group with fewer than 75 wells. The regression for basins with 75 or more wells is based solely on data from that subbasin.

Table A 1: Retained wells by subbasin with regression groups

| Name | Retained Wells | Group |
|---|---|---|
| Arroy del Hambre Valley* | 0 | |
| Clayton Valley | 24 | C |
| Pittsburg Plain | 16 | C |
| Redding Area - Anderson | 1107 | |
| Redding Area - Bowman | 940 | |
| Redding Area - Enterprise | 828 | |
| Redding Area - Millville | 410 | D |
| Redding Area - South Battle Creek | 16 | D |
| Sacramento Valley - Antelope | 531 | |
| Sacramento Valley - Bend | 113 | |
| Sacramento Valley - Butte | 475 | |
| Sacramento Valley - Colusa | 1617 | |
| Sacramento Valley - Corning | 1247 | |
| Sacramento Valley - Los Molinos | 492 | |
| Sacramento Valley - North American | 1018 | |
| Sacramento Valley - North Yuba | 255 | |
| Sacramento Valley - Red Bluff | 2428 | |
| Sacramento Valley - Solano | 1206 | |
| Sacramento Valley - South American | 931 | |
| Sacramento Valley - South Yuba | 261 | |
| Sacramento Valley - Sutter | 1042 | |
| Sacramento Valley - Vina | 1727 | |
| Sacramento Valley - Wyandotte Creek | 415 | |
| Sacramento Valley - Yolo | 1225 | |
| San Joaquin Valley - Chowchilla | 272 | |
| San Joaquin Valley - Cosumnes | 1338 | |
| San Joaquin Valley - Delta-Mendota | 1354 | |
| San Joaquin Valley - East Contra Costa | 827 | C |
| San Joaquin Valley - Eastern San Joaquin | 5193 | |

| | | |
|---|---|---|
| San Joaquin Valley - Kaweah | 1958 | |
| San Joaquin Valley - Kern County | 783 | A |
| San Joaquin Valley - Kettleman Plain | 6 | B |
| San Joaquin Valley - Kings | 7759 | |
| San Joaquin Valley - Madera | 2670 | |
| San Joaquin Valley - Merced | 2310 | |
| San Joaquin Valley - Modesto | 1689 | |
| San Joaquin Valley - Pleasant Valley | 5 | B |
| San Joaquin Valley - Tracy | 997 | |
| San Joaquin Valley - Tulare Lake | 941 | B |
| San Joaquin Valley - Tule | 845 | |
| San Joaquin Valley - Turlock | 2454 | |
| San Joaquin Valley - Westside | 27 | B |
| San Joaquin Valley - White Wolf | 5 | A |
| Suisun-Fairfield Valley | 249 | |
| Ygnacio Valley | 25 | C |

*Not included in further analysis due to lack of retained well records.

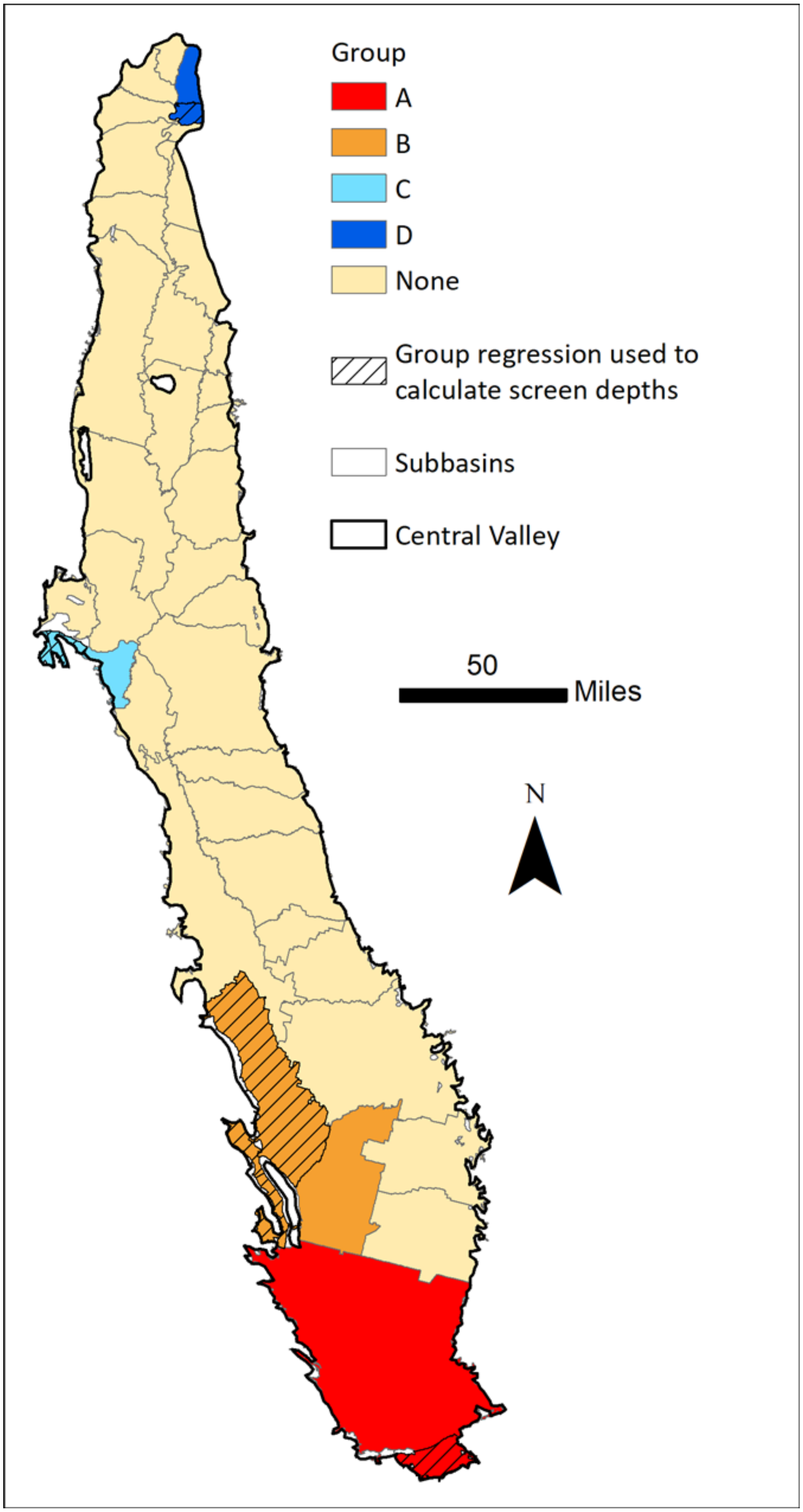


Figure A 4: Subbasins with groups used for calculating regressions.

## 4 C2VSimFG

Simulated groundwater heads and velocities were generated using version 1.0 of C2VSim fine grid (C2VSimFG) (Hatch et al. 2020). C2VSimFG simulates all pumping original to the model on an element level, except for groundwater substitution transfer pumping, which is simulated by individual well. The water supply wells identified from OSWCR were added to the model as additional individual wells. The OSWCR wells were divided into domestic and public supply wells. The two that did not fit directly into either category (described as "Other Agricultural/Domestic" and Other TNC well") were assumed to have the same pumping patterns as a domestic well, as they are not expected to support large amounts of potable use on a regular basis. Since the goal of the C2VSimFG modeling was to produce a multiyear average water table and velocity field, the OSWCR wells were assumed to continuously pump the same amount of water. Domestic wells were assigned a pumping rate of 0.020 acre-feet per month based on average California per capita residential water use in 2015 (California State Water Resources Control Board 2022) and 2010 average California household size (US Census Bureau 2011). Public supply wells were assigned a pumping rate of 5.272 acre-feet per month based on the same per capita water use, average number of people served and average number of wells per water system in the San Joaquin Valley (the largest hydrologic province in the Central Valley) (Bostic 2021) and average proportion of urban demand met by groundwater in the Central Valley (Springhorn et al. 2021).

Sixty-five wells had a screen top or bottom outside the model domain and were modeled in C2VSimFG with shortened screens to fit inside the domain. Six wells were not included in C2VSimFG modeling, as their screens were completely outside the model domain.

C2VSimFG can output a file of groundwater velocities at cell centers, though it is not produced by default. This option was enabled before running the model. The output units for groundwater velocity are set using a conversion factor (referred to as FACTVROU in the specification file) and a label (UNITVROU). The default settings for these is 0.000022957 (converting from cubic feet to acre feet) and AC-FT/MON; however, the velocity units should actually be linear (Tyler Hatch, CA DWR, personal communication). FACTVROU is therefore changed to 1000.0 such that the output unit is thousand feet per month. Additionally, each element is designated as its own zone for the Z-budget calculation.

## 5 ICHNOS

ICHNOS version 2.10 was used for backwards particle tracking from wells to find the areas where recharging water would reach them within a year. The input files were prepared using the boundary shapefile, node file, and stratigraphy file which come with C2VSimFG. Additionally, the velocity and groundwater head files produced by running C2VSimFG were used. The outline, top and bottom (single file), processor polygon, velocity files were prepared according to the Getting Started guidance on the ICHNOS GitHub page for C2VSimFG single processor steady state (Kourakos 2022). In contrast to the published example, the average groundwater head in the top layer of the C2VSimFG model, as opposed to the top of the aquifer unit, was used as the top of the model domain for ICHNOS. In order to account for downward movement of water from the unsaturated zone to the saturated zone, an additional layer was added to the top of the model with the same horizontal velocity as the original top layer and a vertical velocity determined from the Z-budget calculated for each element by C2VSimFG. The net flux in each element to the groundwater zone from streams, deep percolation, diversions, bypasses, and small watersheds, and that required by constant head boundaries (used in C2VSimFG to represent certain water bodies), was divided by the element area to produce an element average vertical velocity. The surface layer was assigned 25% of the thickness of the original top layer, while the top layer of the saturated zone receives 75% of the original thickness. Groundwater levels and velocity from October 2005 through September 2015 were averaged to allow a steady state simulation.

## 5.1 Wells

Particles for tracking were released from 46,125 wells (all of those identified in OSWCR which passed the cleaning stage, minus 3,906 which were too shallow or too deep for the modified ICHNOS domain). Eighteen particles were released from each well, divided into six layers, at a distance of 1 meter from the well. Tracking was ended at 365 days, and any particles exiting the model domain via the top were determined to represent locations where recharge would reach a well within a year.

## 5.2 Rivers

Buffer areas for rivers were generated in a similar manner to buffers for wells. C2VSimFG nodes intersected by rivers delineated the shapefiles accompanying the model were selected. Flow lines from NHDplusV2 with associated bankfull depth estimates were also selected (US EPA and USGS 2012; Wieczorek et al. 2018). Selected nodes falling within 10 meters of selected NHDplusV2 flow lines were retained and given the bankfull depth associated with the line. These points were treated as fully screened wells in ICHNOS with 6 particles released per well from 3 layers at a distance of 1 meter from the virtual well. Given that the river beds are shallower than the water table in many locations, the surface was used as the top of the model domain instead of the water table. Backwards particle tracking was conducted for 365 days. For each virtual well, the exit location of the farthest particle reaching the surface (if any) was selected to be used to calculate buffer distances as described in Section 6.2.

## 5.3 ICHNOS model configuration parameters

[Velocity]

XYZType = CLOUD

Type = STEADY

[Domain]

TopRadius = 3000

TopPower = 3

[StepConfig]

Method = RK45

Direction = -1

StepSize = 50

StepSizeTime = 100

nSteps = 10

nStepsTime = 0

minExitStepSize = 0.1

[AdaptStep]

MaxStepSize = 1000

MinStepSize = 0.1

increaseRateChange = 1.5

limitUpperDecreaseStep = 0.15

Tolerance = 1

[StoppingCriteria]

MaxIterationsPerStreamline = 3000

MaxProcessorExchanges = 50

AgeLimit = 365

StuckIter = 10

[InputOutput]

ParticlesInParallel = 5000

GatherOneFile = 0

[Other]

Version = 0.2.10

Nrealizations = 1

## 5.4 ICHNOS velocity configuration parameters

[Velocity]

Type = STEADY

Multiplier = 0.000001

Scale = 1

Power = 3.5

InitDiameter = 1500000

InitRatio = 20

[Porosity]

Value = 0.1

[General]

OwnerThreshold = 0.15

Threshold = 0.1

FrequencyStat = 100

# 6 Suitability Mapping

## 6.1 Land cover

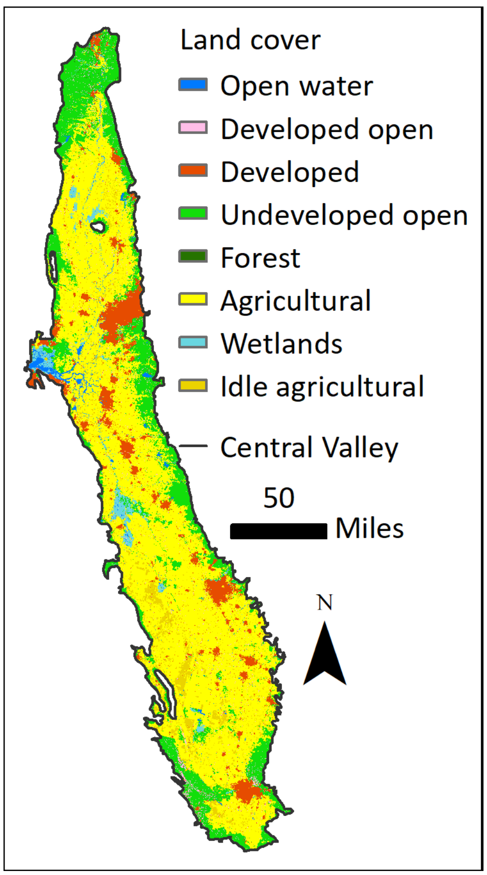


Figure A 5: Basic land cover classes. For detailed classes, see Table A 2 - Table A 5.

Land cover was determined based on the Land IQ 2018 map for 61% of the study area. Land cover for the remaining area, which the Land IQ map does not cover, was determined based on the National Land Cover Dataset 2016 data for the contiguous United States (Figure A 5) (Land IQ and DWR 2021; USGS 2021). Land covers were divided into those potentially compatible with recycled water MAR and those which are incompatible and therefore excluded from analysis. The map was converted to a raster with a value of 1 in all areas to be included and a value of 0 in all areas to be excluded. Land covers present in the study area are listed in Table A 2 - Table A 5, divided into those classes included in further analysis and those that are excluded.

Table A 2: Land IQ classes included in analysis

| Class 2 | Class 2 description | Subclass 2 | Subclass 2 description |
|---|---|---|---|
| C | Citrus and subtropical | | |
| G | Grain and hay crops | | |
| T | Truck, nursery, and berry crops | | |
| V | Vineyards | | |
| X | Unclassified fallow (Idle status could not be determined solely within the 2018 calendar) | | |
| YP | Young Perennial | | |
| C | Citrus and subtropical | 4 | Dates |
| C | Citrus and subtropical | 5 | Avocados |
| C | Citrus and subtropical | 6 | Olives |
| C | Citrus and subtropical | 7 | Miscellaneous subtropical fruit |
| C | Citrus and subtropical | 8 | Kiwis |

| | | | |
|---|---|---|---|
| D | Deciduous fruits and nuts | 1 | Apples |
| D | Deciduous fruits and nuts | 3 | Cherries |
| D | Deciduous fruits and nuts | 5 | Peaches and nectarines |
| D | Deciduous fruits and nuts | 6 | Pears |
| D | Deciduous fruits and nuts | 10 | Miscellaneous deciduous |
| D | Deciduous fruits and nuts | 11 | Mixed deciduous |
| D | Deciduous fruits and nuts | 12 | Almonds |
| D | Deciduous fruits and nuts | 13 | Walnuts |
| D | Deciduous fruits and nuts | 14 | Pistachios |
| D | Deciduous fruits and nuts | 15 | Pomegranates |
| D | Deciduous fruits and nuts | 16 | Plums |
| F | Field crops | 1 | Cotton |
| F | Field crops | 2 | Safflower |
| F | Field crops | 10 | Beans (dry) |
| F | Field crops | 11 | Miscellaneous field |
| F | Field crops | 12 | Sunflowers |
| F | Field crops | 16 | Corn, Sorghum or Sudan grouped for remote sensing only |
| G | Grain and hay crops | 2 | Wheat |
| G | Grain and hay crops | 6 | Miscellaneous grain and hay |
| I | Idle | 2 | new lands being prepared for crop production |

| | | | |
|---|---|---|---|
| P | Pasture | 1 | Alfalfa and alfalfa mixtures |
| P | Pasture | 3 | Mixed pasture |
| P | Pasture | 4 | Native pasture |
| P | Pasture | 6 | Miscellaneous grasses |
| R | Rice | 1 | Rice |
| R | Rice | 2 | Wild Rice |
| T | Truck, nursery and berry crops | 4 | Cole crops (mixture of broccoli, cabbage, cauliflower, and Brussels sprouts) |
| T | Truck, nursery and berry crops | 6 | Carrots |
| T | Truck, nursery and berry crops | 9 | Melons, squash, and cucumbers (all types) |
| T | Truck, nursery and berry crops | 10 | Onions and garlic |
| T | Truck, nursery and berry crops | 12 | Potatoes |
| T | Truck, nursery and berry crops | 15 | Tomatoes (processing) |
| T | Truck, nursery and berry crops | 16 | Flowers, nursery and Christmas tree farms |
| T | Truck, nursery and berry crops | 18 | Miscellaneous truck |
| T | Truck, nursery and berry crops | 19 | Bush berries |
| T | Truck, nursery and berry crops | 20 | Strawberries |
| T | Truck, nursery and berry crops | 21 | Peppers (chili, bell, etc.) |
| T | Truck, nursery and berry crops | 27 | Greenhouse |
| T | Truck, nursery and berry crops | 30 | Lettuce or Leafy Greens grouped for remote sensing only |

| | | | |
|---|---|---|---|
| T | Truck, nursery and berry crops | 31 | Potato or Sweet potato grouped for remote sensing only |

Table A 3: Land IQ classes excluded from analysis

| Class 2 | Class 2 description | Subclass 2 | Subclass 2 description |
|---|---|---|---|
| U | Urban - residential, commercial, and industrial, unsegregated | | |

Table A 4: NLCD classes included in analysis

| Class | Description |
|---|---|
| 21 | Developed, Open Space- areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes. |
| 31 | Barren Land (Rock/Sand/Clay) - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover. |
| 52 | Shrub/Scrub- areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions. |
| 71 | Grassland/Herbaceous- areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing. |
| 81 | Pasture/Hay-areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation. |
| 82 | Cultivated Crops -areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled. |

Table A 5: NLCD classes excluded from analysis

| Class | Description |
|---|---|
| 11 | Open Water- areas of open water, generally with less than 25% cover of vegetation or soil. |
| 22 | Developed, Low Intensity- areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units. |
| 23 | Developed, Medium Intensity -areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units. |
| 24 | Developed High Intensity-highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover. |
| 41 | Deciduous Forest- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change. |
| 42 | Evergreen Forest- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage. |
| 43 | Mixed Forest- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover. |
| 90 | Woody Wetlands- areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water. |
| 95 | Emergent Herbaceous Wetlands- Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water. |

## 6.2 Well buffers

For residence time-based buffers, the vertices of streamlines that exited from the top of the domain in ICHNOS were imported to ArcGIS. Buffer zones were created from the point features using the minimum bounding geometry tool with the convex hull option, grouped by well number. The resulting polygons represent the area within which surface recharge would reach a well within a year and are thus to be excluded from consideration for recycled water MAR. The shapefile was then converted to a raster with a value of 0 for all of the buffer zones and a value of 1 everywhere else.

For distance-based buffers, each domestic well was given a circular buffer with a 100-ft radius. The buffer shapefile was then converted to a 100 m x 100 m raster for analysis consistent with other layers. Since the buffers were smaller than the raster pixels, the rasterization process gave buffer pixels to an apparently random selection of wells (Figure A *6*). Therefore, the area excluded should be considered a minimum estimate.

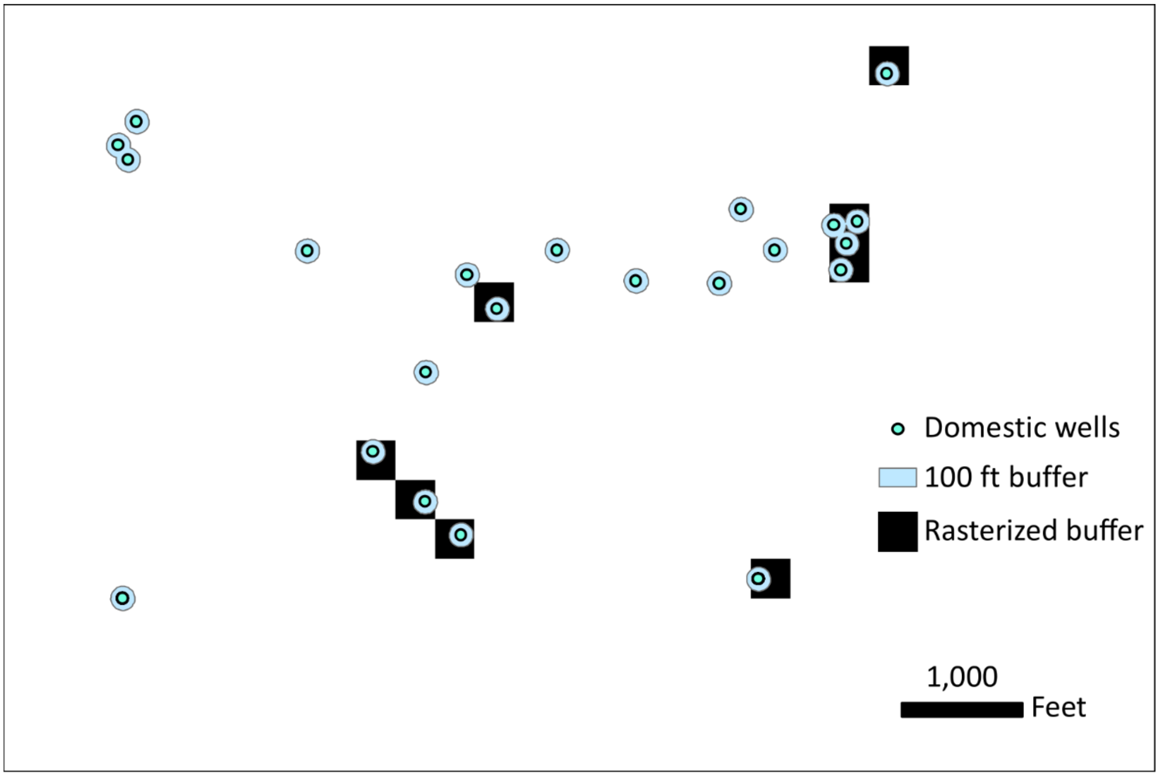


Figure A 6: Example of domestic wells with 100-ft buffers in original and rasterized form.

## 6.3 River buffers

Nodes from which backward tracked particles in ICHNOS reached the surface within a year were considered part of gaining reaches of rivers and therefore in need of protective buffers. A buffer distance was calculated at each of these nodes as:

$$B = 0.5W + D$$

where

B is the buffer distance.

W is the bankfull width.

D is the maximum distance travelled by a particle which was released from the node and reached the surface.

C2VSimFG river lines were split where they coincide with nodes. The resulting segments were given a buffer equal to the average of the values calculated for the nodes at either end.

## 6.4 Source water proximity

### 6.4.1 Previous studies

MAR suitability mapping studies often use a cutoff of 3 or 5 miles for source water proximity, generally citing cost to transport (Table A *6*). These studies tend to cite previous studies using the same distance. The earliest sources in the chains of references are Reed and Crites (1984) and Brown et al. (2005). Brown et al. (2005) justifies the 3 mi cutoff based on cost of transport but does not give a reason for the specific number. Reed and Crites (1984) offers suitability scores for a range of distances, and it is not clear where the citing literature obtains the 5 mi (~8 km) cutoff. Several other works are cited for distance limits but do not actually contain any distance criteria.

In order to determine what distance is realistic, 31 MAR projects infiltrating reclaimed water were identified from the INOWAS global MAR map (Table A *7*). Assuming that on-site infiltration had a distance of 0 miles, the average distance from reclaimed water source to infiltration site was 3 mi (~4.8 km) (Figure A *7*).

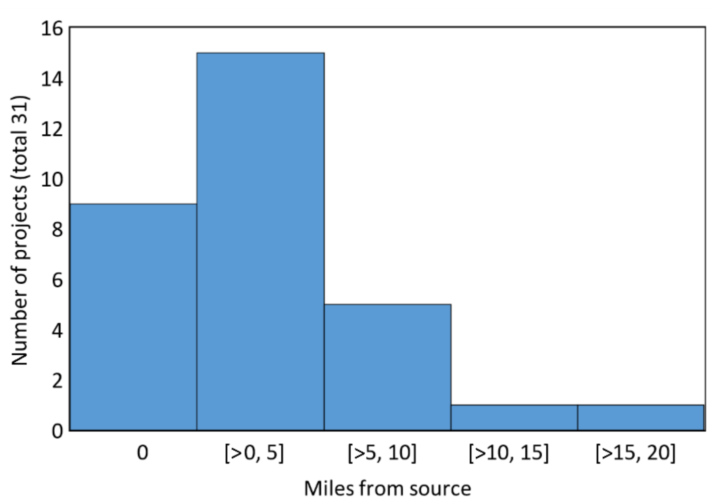


Figure A 7: Distance from reclaimed water source to infiltration locations in 31 MAR projects worldwide.

Table A 6: Review of literature pertaining to or referenced by others regarding maximum distance to source water

| Study | Max distance (mi) | Reasoning | References |
|---|---|---|---|
| Gibson et al. (2018) | 3 | Assumes farther is cost prohibitive | Brown et al. (2016); Brown (2005)<br>References also include Brown et al. (2005) |
| Tsangaratos et al. (2017) | 5 | Cost | US EPA (2004) |
| Smith et al. (2017) | 20 | None given, but also mentions feasible cities 32 km from aquifers, so the number might have some significance | None given |
| Ahmadi et al. (2017) | 5 | EPA guidance | US EPA (2006) |
| Brown et al. (2016) | None | States that source water availability and distance to surface water are important. | NA |
| Gdoura et al. (2015) | Stretched | Cost | None cited in text, but references include<br>Anane et al. (2008); US EPA (1984); Kallali et al. (2007); Pedrero et al. (2011); Rahman et al. (2013) |
| Gibson and Campana (2014) | 3 | Following Woody (2007) | Woody (2007) |
| Rahman et al. (2013) | Indirect, probably stretched | Mentions cost of effluent transfer as subcriterion | None cited in text, but references include<br>Anane et al. (2008) |
| Pedrero et al. (2011) | 5 | EPA guidance | US EPA (2006) |
| Anane et al. (2008) | Stretched | Cost | None cited in text, but references include<br>US EPA (1984) |
| Woody (2007) | 3 | Cost. Notes that pipelines or canals could be expanded in future | Brown et al. (2005) |
| Kallali et al. (2007) | 5 | Cost. Notes that decision makers could choose to go farther | None cited in text, but references include<br>US EPA (1984) |
| US EPA (2006) | Offers a range of scores. No maximum distance | Cost | Taylor (1981) |
| Brown et al. (2005) | 3 | Cost. Also allows 3 miles to canal, which could imply that the presence of conveyance would also satisfy requirement. | None given |

| | | | |
|---|---|---|---|
| Brown (2005) | None | Evaluates decision making process for aquifer storage and recovery projects. States that distance to source water is relevant. | NA |
| US EPA (2004) | None | Does not mention distance | NA |
| US EPA (1984) | Offers a range of scores. No maximum distance | Cost | Reed and Crites (1984) |
| Reed and Crites (1984) | Offers a range of scores. No maximum distance | Cost | None given |
| Taylor (1981) | None | Does not include table attributed to it by US EPA (2006) | NA |

Table A 7: Reclaimed water infiltration projects with source water distance from INOWAS Global MAR Portal (Stefan and Ansems 2018)

| Project | Location | Country | Dist. (mi) | Citation |
|---|---|---|---|---|
| Alice Springs SAT | -23.846, 133.857 | Australia | 3.7 | Page et al. (2010) |
| Yanchep WWTP | -31.543, 115.648 | Australia | 0 | McFarlane (2019) |
| Gordon Road WWTP | -32.503, 115.754 | Australia | 0 | McFarlane (2019) |
| Caddadup WWTP | -32.617, 115.631 | Australia | 0 | McFarlane (2019) |
| Floreat | -31.949, 115.791 | Australia | 0.3 | Toze and Bekele (2009) |
| Halls Head | -32.54, 115.693 | Australia | 0 | Toze and Bekele (2009) |
| Torreele/St-André | 51.125, 2.666 | Belgium | 1.6 | Van Houtte and Verbauwhede (2012) |
| ETE Ponta Negra | -5.897, -35.178 | Brazil | 0 | Lopes and dos Santos (2012) |
| Gaobeidian WWTP | 39.894, 116.526 | China | 0 | Pi and Wang (2006) |
| Abu Rawash | 29.669, 31.26 | Egypt | 0.1 | El-Fakharany (2013) |
| Soreq-1 | 31.96, 34.764 | Israel | 1.2 | Kanarek and Michail (1996) |
| Soreq-2 | 31.954, 34.769 | Israel | 1.2 | Kanarek and Michail (1996) |
| Yavne-1 | 31.893, 34.724 | Israel | 4.0 | Kanarek and Michail (1996) |

| | | | | |
|---|---|---|---|---|
| Yavne-2 | 31.867, 34.72 | Israel | 6.2 | Kanarek and Michail (1996) |
| Yavne-3 | 31.854, 34.713 | Israel | 6.8 | Kanarek and Michail (1996) |
| Yavne-4 | 31.848, 34.706 | Israel | 7.8 | Kanarek and Michail (1996) |
| Sulaibyia | 29.282, 47.8 | Kuwait | 0 | Al-Otaibi and Al-Senafy (2004) |
| Ben Sergao | 30.386, -9.609 | Morocco | 0 | Bennani et al. (1992) |
| Atlantis Water Resource Management Scheme (AWRMS) | -33.59, 18.369 | South Africa | 2.2 | Towers and Hugman (2021) |
| Sedgefield | -33.907, 22.793 | South Africa | 0.6 | Murray et al. (2010) |
| Blanes | 41.674, 2.772 | Spain | 0.4 | Sendrós et al. (2021) |
| Korba | 36.639, 10.884 | Tunisia | 0.2 | Chaieb (2014) |
| Nabeul-Hammamet | 36.415, 10.635 | Tunisia | 17.4 | Chaieb (2014) |
| LOTT Hawks Prairie | 47.095, -122.813 | USA | 2.2 | Washington Department of Ecology (2017) |
| Cochrane Park Rehabilitation Project | 46.955, -122.666 | USA | 1.2 | City of Yelm, WA n.d. |
| Whittier Narrows Water Reclamation Plant | 34.036, -118.071 | USA | 2.5 | Johnson (2009) |
| Brooks Street Basin* | 34.061, -117.714 | USA | 8 | Campbell (2020); Campbell and Fan (2021) |
| 7th and 8th Street Basins | 34.09, -117.635 | USA | 8 | Campbell (2020); Campbell and Fan (2021) |
| Turner Basins | 34.071, -117.6 | USA | 8 | Campbell (2020); Campbell and Fan (2021) |
| San Sevaine Flood Control Basins | 34.146, -117.491 | USA | 8 | Campbell (2020); Campbell and Fan (2021) |
| Victoria Basin | 34.128, -117.508 | USA | 8 | Campbell (2020); Campbell and Fan (2021) |
| Hickory Basin | 34.092, -117.512 | USA | 8 | Campbell (2020); Campbell and Fan (2021) |
| Banana Basin | 34.096, -117.499 | USA | 8 | Campbell (2020); Campbell and Fan (2021) |
| IEUA RP3 Ponds | 34.047, -117.477 | USA | 8 | Campbell (2020); Campbell and Fan (2021) |
| Ely Basins | 34.037, -117.615 | USA | 8 | Campbell (2020); Campbell and Fan (2021) |
| Kraemer Basin | 33.862, -117.857 | USA | 13 | Hutchinson (2013) |
| Mesa Northwest Water Reclamation Plant (NWWRP) | 33.427, -111.68 | USA | 6.8 | Salt River Project n.d. |

| | | | | |
|---|---|---|---|---|
| Fort Dix Land Application Site Infiltration Basin Project | 39.976, -74.601 | USA | 0 | Bouwer et al. (2008) |
| Honouliuli WWTP, OSC Field No. 049 – Sugarcane | 21.329, -158.049 | USA | 0.6 | Lau et al. (1989) |

*Inland Empire Utilities Agency basin distances estimated. Considered one project for the purposes of average distance to avoid biasing result with uncertain numbers.

### 6.4.2 This study

The locations of water treatment facilities were determined from the 2019 Volumetric Annual Report of Wastewater and Recycled Water (California State Water Resources Control Board 2021). Facilities report volumes of effluent produced along with treatment levels, which can be "Full Advanced Treatment", "Disinfected Tertiary", "Disinfected Secondary-2.2", "Disinfected Secondary-2.3", "Undisinfected Secondary", "Tertiary Treatment", "Secondary Treatment", or "Primary Treatment". Out of these treatment levels, the first five are considered recycled water under Title 22 (California State Water Resources Control Board 2020). Eight facilities were flagged for review because they were designated as not producing recycled water in the Facility table of the report but reported some volume of recycled water in the Effluent table. At two of the flagged facilities, WDR100034219 and WDR100037211, it was observed that each reported 11 months of a single type of non-recycled water effluent and one month of recycled water, suggesting that the one month of recycled water was an error. These two entries were adjusted to match the effluent type for the other months from the respective facilities. All other effluent data was used as is. Facilities were classified by the highest treatment level of effluent that they produced in 2019, as indicated in Table A *8*. Four facilities in the CV produced no effluent in 2019 and were excluded from further analysis.

Table A 8: Classification of treatment facilities

| Classification | Highest treatment level | Facilities in Central Valley |
|---|---|---|
| Disinfected tertiary | Full Advanced Treatment | 0 |
| | Disinfected Tertiary | 20 |
| Other recycled water | Disinfected Secondary-2.2 | 3 |
| | Disinfected Secondary-23 | 6 |
| | Undisinfected Secondary | 11 |
| Wastewater | Tertiary Treatment | 26 |
| | Secondary Treatment | 58 |
| | Primary Treatment | 52 |

The Euclidean distance tool was used to create a raster containing the distance from every location in the Central Valley to the nearest disinfected tertiary facility in the Valley. A second analysis was done including both disinfected tertiary and other recycled water, treating both the same. A third was conducted for all recycled water and wastewater facilities. Any location 3 or more miles (≥ 4.8 km) away from a facility was reassigned a value of 3 miles, as this is assumed to be the farthest that water could be feasibly transported. The locations in both rasters were then scored based on relative distance to the nearest facility with 1 being the farthest and 100 being the closest. Scores were assigned to points by:

$$\text{score} = (\text{maximum distance} - \text{distance at point})/\text{maximum distance} * 99 + 1$$

## 6.5 Compiling maps

A raster of the modified SAGBI for the Central Valley was averaged with the distance score for reclaimed water, giving both layers equal weight. This produced a numeric suitability score for recycled water MAR for the whole Valley. This raster was then multiplied by the land cover, well buffer, and river buffer exclusion rasters to remove areas that are off limits. All rasters had a cell size of 100 m by 100 m. Areas with a value of 0 are removed with the Set Null tool. The result is a raster with suitability scores for all potentially available areas in the Central Valley covered by the modified SAGBI (12% of the Valley does not have a modified SAGBI score). The same analysis was repeated with the distance raster containing both WWTP's and WRF's to evaluate potential for recycled water MAR if existing WWTP's are upgraded or replaced.

# 7 Required land areas and water volumes for MAR

Land areas required for each GSA to meet its stated recharge goals were estimated from the MAR project descriptions in the GSPs. Of the 207 proposed physical MAR projects in the Central Valley, 125 (60%) provided concrete estimates for the amount of land required. If a range of possible areas was provided, we used the minimum estimate. For projects without land areas stated in the GSP, we calculate the mean land area required for that MAR project type (as defined in Ulibarri et al. 2021) from other proposed projects. Lower and upper bounds were calculated for these projects with the formula:

$$\text{lower or upper bound} = \text{mean} \pm 1.96 \text{ standard error}$$

If 1.96 standard error was greater than the mean, then the minimum and maximum areas stated for that type of project were used as lower and upper bounds.

As some projects included multiple recharge approaches, we disaggregated areas where available (e.g., listing separate acreages for basins versus on farm recharge). For creekbed recharge, the GSPs estimated the miles of river, creek, or ditch along which recharge would take place. To convert this to an area, we estimated an average width of 10 ft. (likely an underestimate); the river miles were multiplied by 10 ft. and then converted to acres. Area required for projects intending to recharge with floodwater were calculated but not included in total land requirements used in the main analysis, as these projects would probably not have a need for recycled water. See GSP_MAR_land_area_water.xlsx

Planned average annual recharge volumes were also determined from GSPs with unstated volumes calculated in the same manner as unstated land areas, classifying projects by recharge type. Projects were also classified by water source. If more than one source was listed but disaggregated volumes were not given, the recharge volume associated with the project was assumed to come equally from all sources mentioned.

# 8 Additional results

## 8.1 Wells with residence time greater than one year

Out of the 46,125 wells included in the particle tracking model, 1,086 received surface recharge within one year, and 45,039 did not. Wells at which water had greater than one year of underground residence time are found at high density throughout the Valley except in areas such as the Western San Joaquin Valley, where wells in general are more scarce (Figure A *8*).

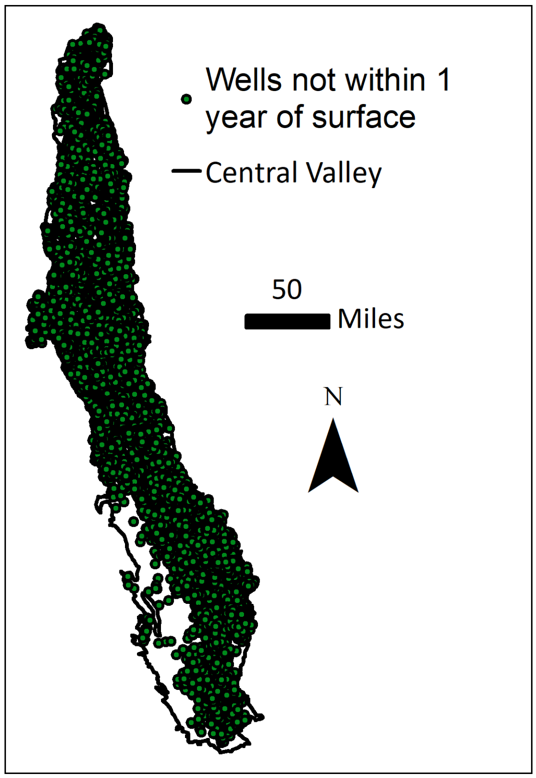


Figure A 8: Wells not receiving surface recharge within a year of its infiltration

## 8.2 Suitability classes shown to scale

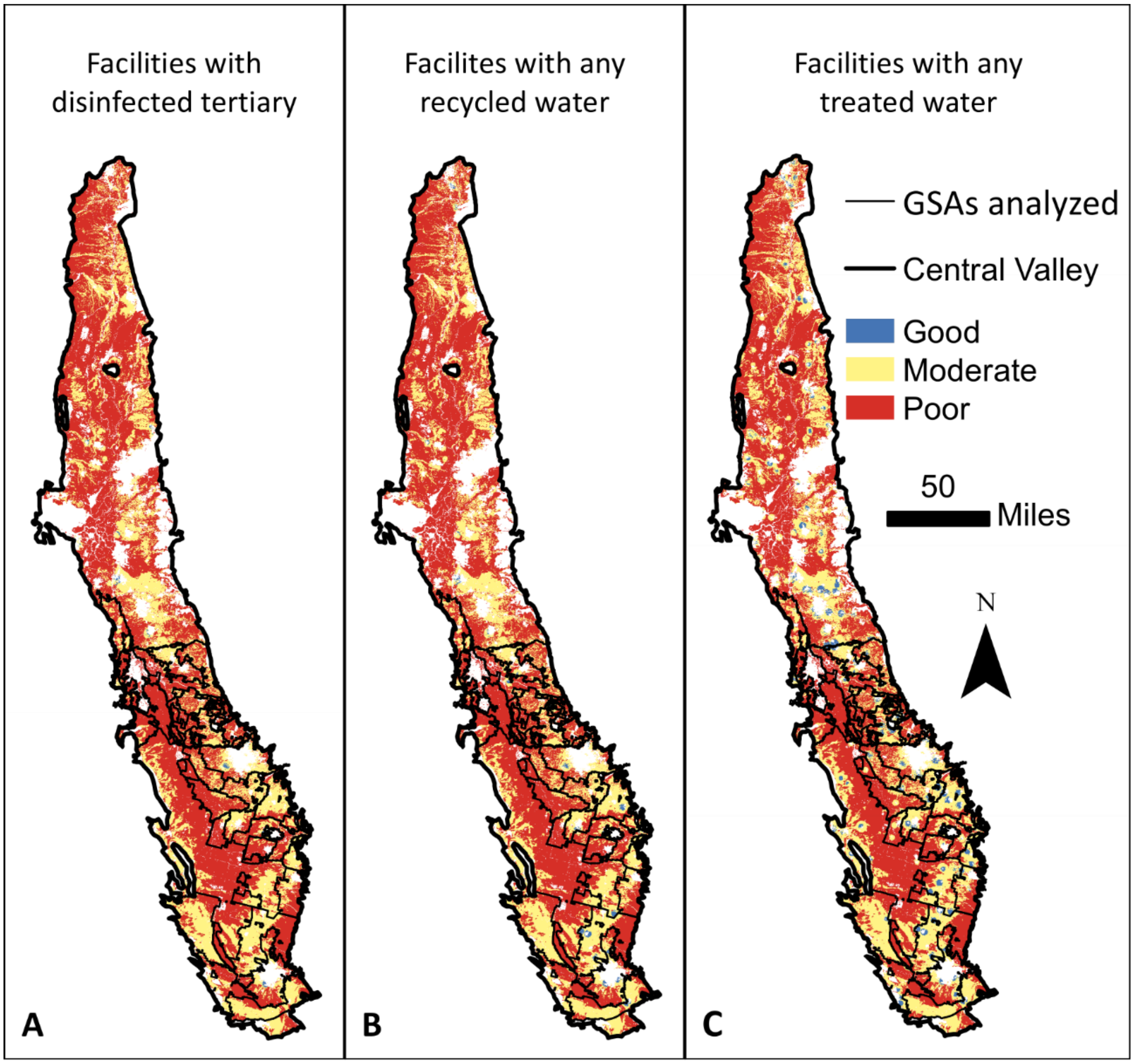


Figure A 9: Suitability of potentially available land considering (A) only facilities producing disinfected tertiary, (B) any facility with recycled water, (C) any treatment facilities, including those with only wastewater. This is the same map as Fig. 5 of the main text without highlighting. All areas are shown to scale.

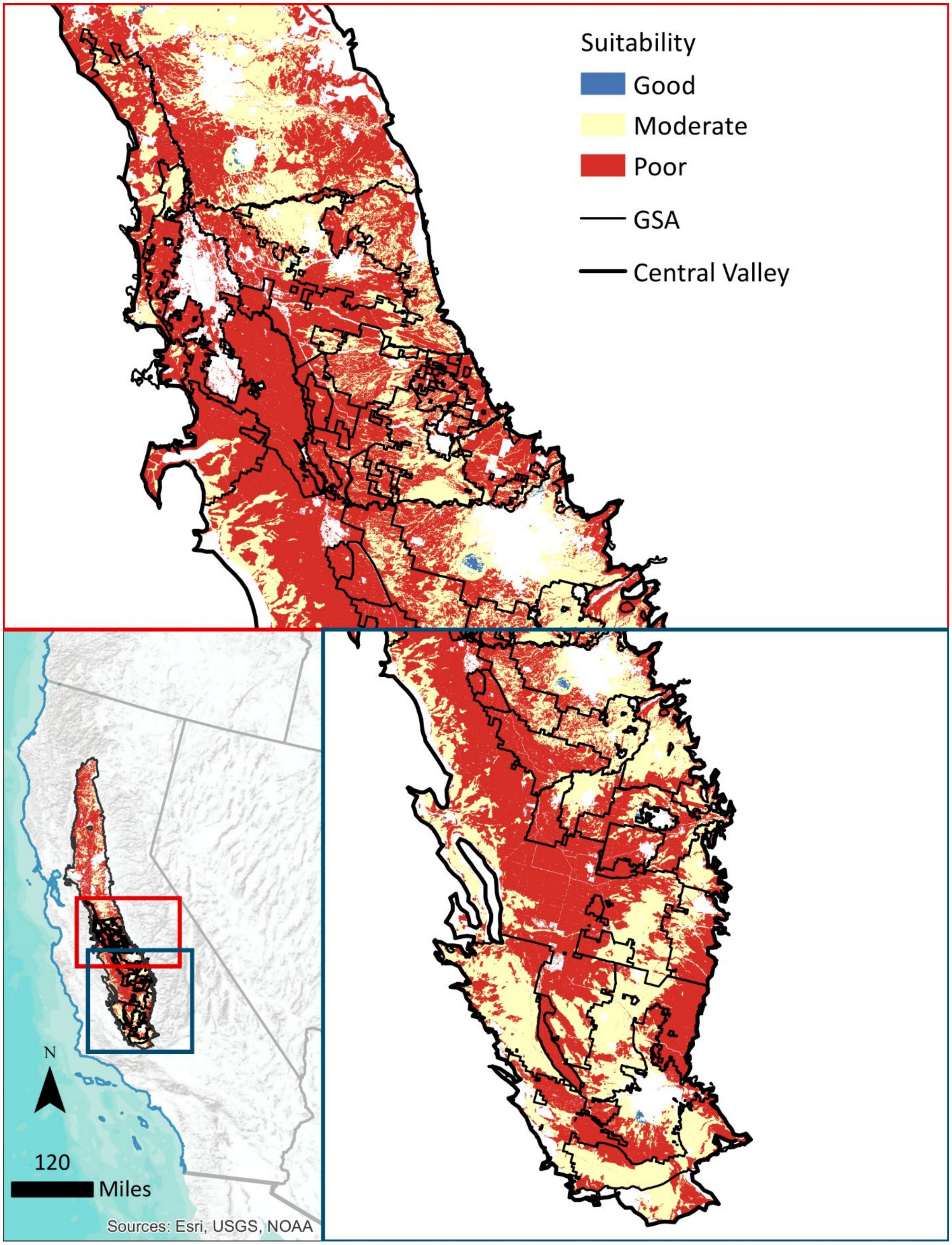


Figure A 10: Close up of suitability considering only treatment facilities producing disinfected tertiary water as potential sources of recharge water

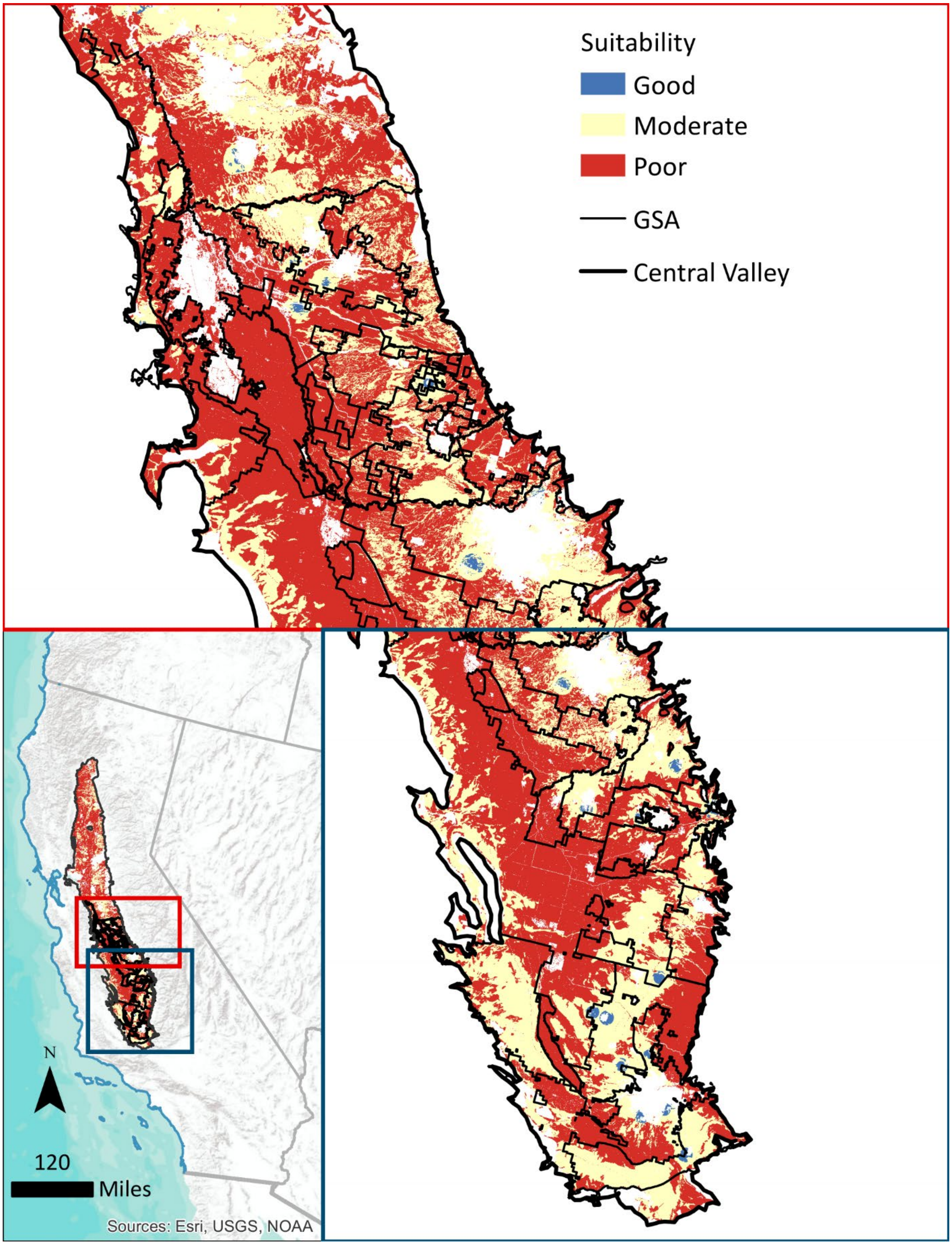


Figure A 11: Close up of suitability considering treatment facilities producing any kind of recycled water as potential sources of recharge water

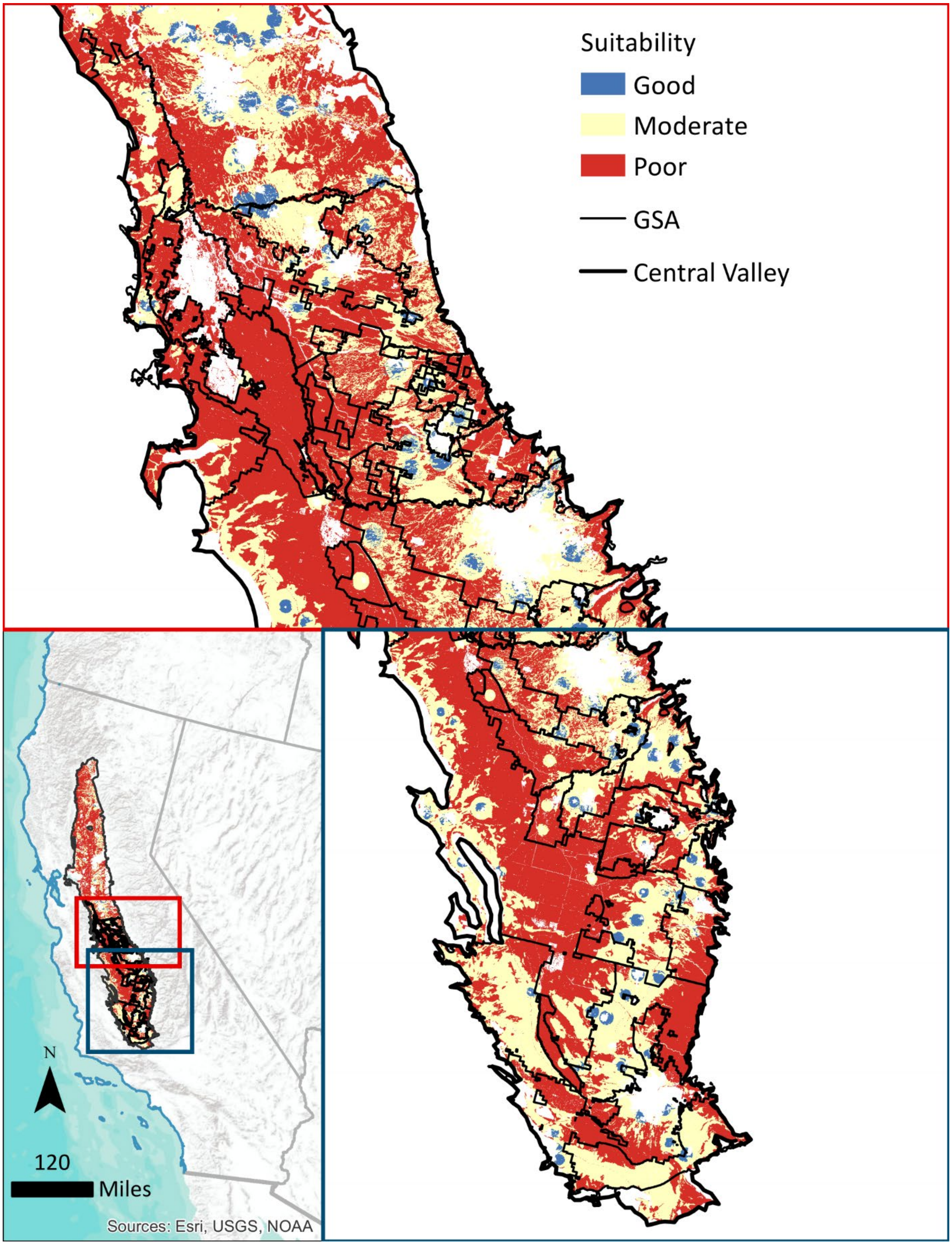


Figure A 12: Close up of suitability considering any treatment facilities, including those only producing wastewater, as potential sources of recharge water

Gerenday SP, Perrone D, Clark JF, Ulibarri N. 2023. Recycled water could recharge aquifers in the Central Valley. Calif Agr 77. https://doi.org/10.3733/ca.2023a0005

## 8.3 Land use

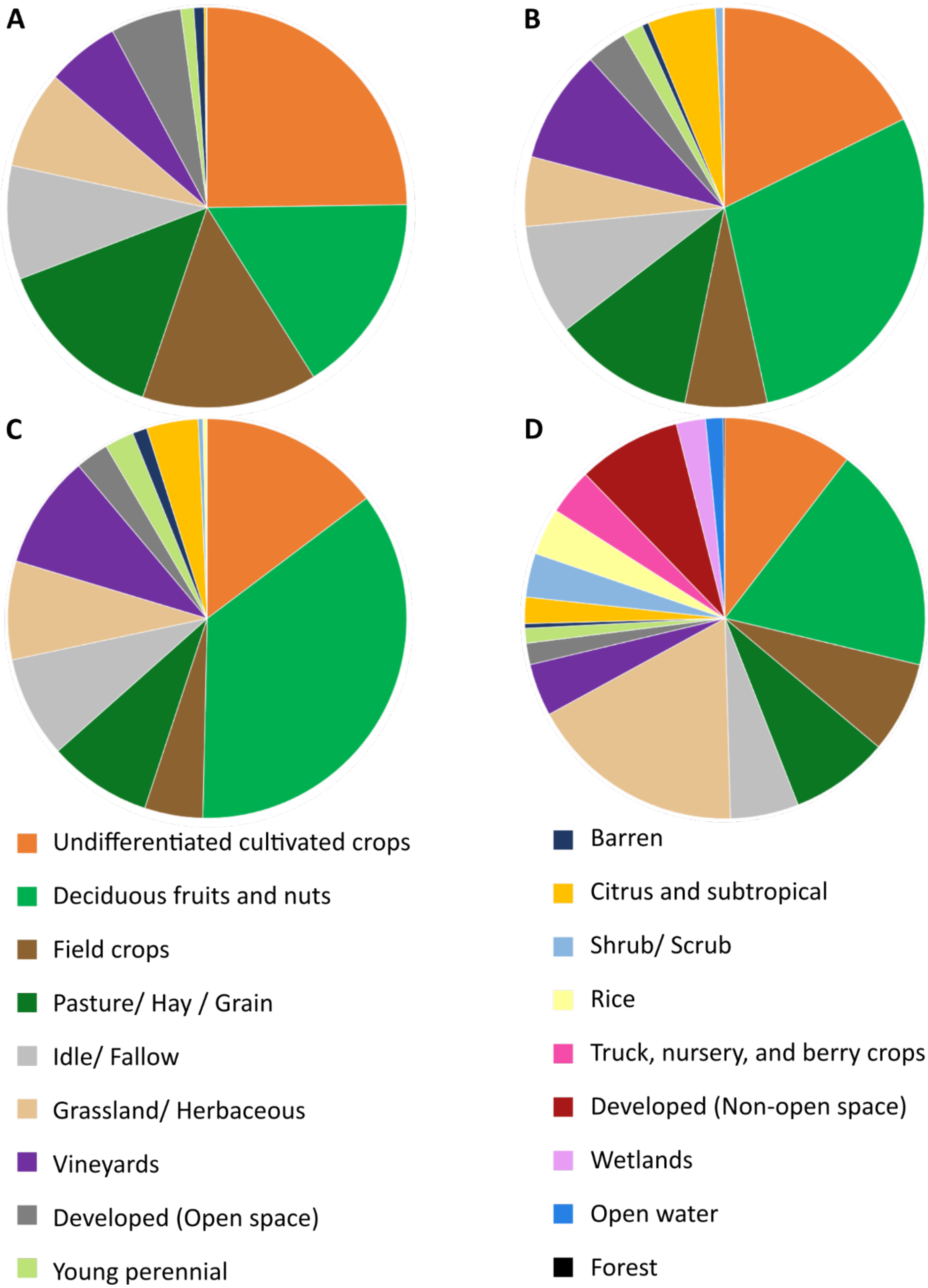


Figure A 13: Land use in good suitability areas considering facilities with (A) disinfected tertiary only (B) any recycled water (C) any effluent. (D) Shows the entire Central Valley. Legend items are listed clockwise. Developed (Non-open space), Wetlands, Open water, and Forest are present in the Central Valley but not in good suitability areas as they were excluded from consideration.

# 9 Alternatives

## 9.1 Chemical contaminants

A version of the suitability analysis was conducted including estimated arsenic and nitrate concentrations in groundwater using data from the USGS (McKinney 2012). Concentrations in the USGS geospatial dataset were given as ranges for 3 km x 3 km (1.8 mi x 1.8 mi) cells (Figure A *13*). Lower concentrations of both chemicals are better, and neither is acceptable above its respective drinking water maximum contaminant level (MCL) (10 ug/L arsenic, 10 mg/L nitrate - N). Numerical suitability scores were assigned to each cell based on its concentration range. The lowest concentration range received a score of 100. Any concentrations greater than or equal to the MCL were given a score of 1. Intermediate scores were assigned proportionally to other cells based on the midpoint of their range (Table A *9*). The arsenic and nitrate scores were then averaged for a combined chemical contaminant score. The chemical contaminant score was then averaged with the SAGBI and source water proximity scores to determine relative suitability. Additionally, any cell for which either compound was predicted to be present above its MCL was excluded as unsuitable. The remaining steps were conducted in the same manner as the main analysis. Results are shown below. Due to the lower resolution and less extensive coverage of the arsenic and nitrate geospatial data, the resulting map is less detailed and includes 20% less area than that produced by the main analysis (Figure A *14*, **Error! Reference source not found.**).

Table A 9: Concentration ranges for arsenic and nitrate with assigned suitability scores

| Arsenic range (ug/L) | Arsenic score | Nitrate range (mg/L as N) | Nitrate score |
|---|---|---|---|
| <1.0 | 100 | <0.50 | 100 |
| 1.0 – 1.9 | 95 | 0.50 – 0.99 | 97 |
| 2.0 – 2.9 | 84 | 1.0 – 1.9 | 90 |
| 3.0 – 4.9 | 68 | 2.0 – 4.9 | 69 |
| 5.0 – 9.9 | 29 | 5.0 – 9.9 | 28 |
| 10 – 24 | 1 | ≥10 | 1 |
| ≥25 | 1 | | |

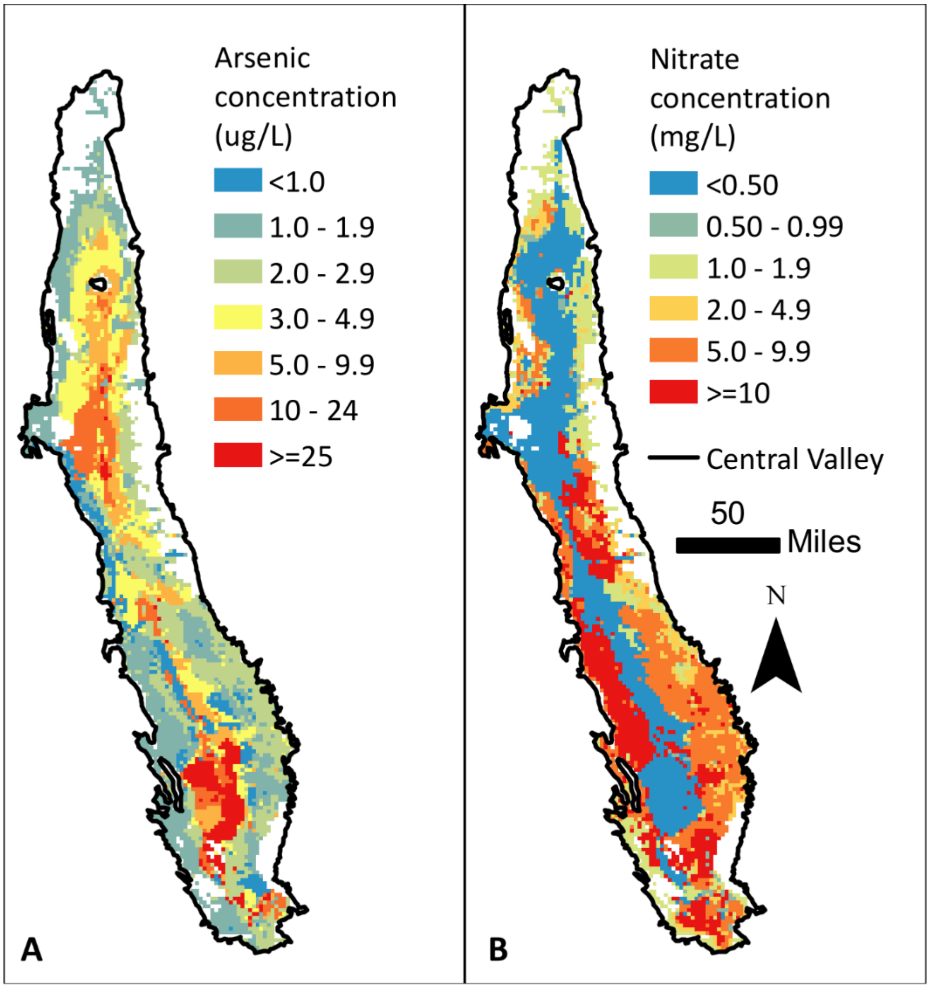


Figure A 14: Arsenic and nitrate concentrations predicted in Central Valley groundwater by McKinney (2012).

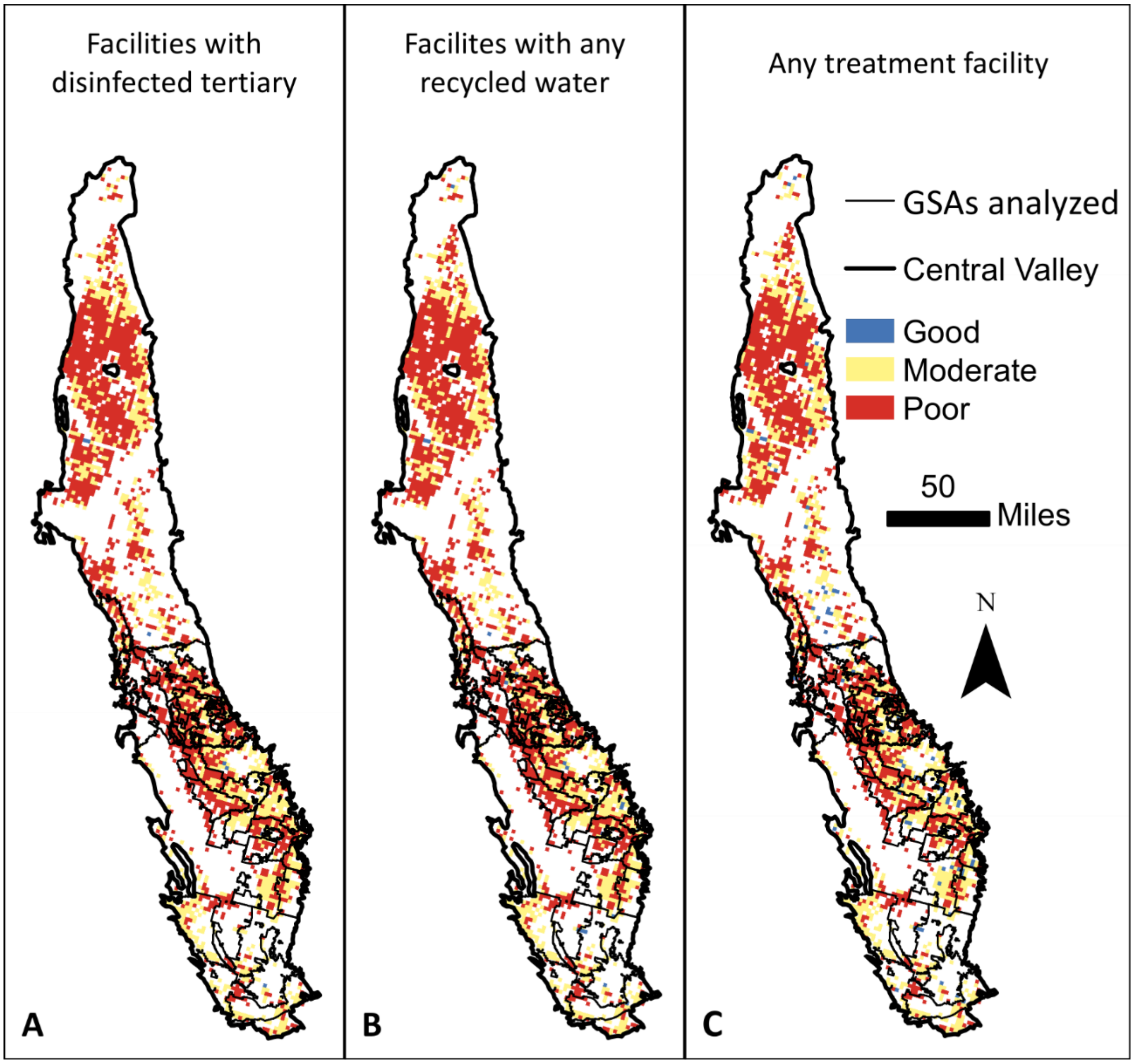


Figure A 15: Suitability of potentially available land considering chemical contaminants. (A) Only facilities producing disinfected tertiary, (B) any facility with recycled water, (C) any treatment facilities, including those with only wastewater as water sources.

Table A 10: Area ($mi^2$) available to each GSA by suitability considering chemical contaminants. (1 $mi^2$ = 2.6 $km^2$)

| GSA | Disinfected tertiary | | | Any recycled water | | | Any effluent | | |
|---|---|---|---|---|---|---|---|---|---|
| | Good | Moderate | Poor | Good | Moderate | Poor | Good | Moderate | Poor |
| Aliso Water District | 0 | 3.5 | 28 | 0 | 3.5 | 28 | 0 | 3.5 | 28 |
| Buena Vista | 0 | 3.5 | 17 | 0 | 3.5 | 17 | 0 | 6.9 | 14 |
| Central Kings | 0 | 140 | 45 | 0 | 140 | 45 | 35 | 100 | 42 |
| Chowchilla Water District | 0 | 42 | 73 | 0 | 42 | 73 | 3.5 | 42 | 69 |
| East Kaweah | 0 | 76 | 59 | 3.5 | 73 | 59 | 10 | 73 | 52 |
| Eastern Tule | 0 | 76 | 42 | 0 | 80 | 38 | 6.9 | 73 | 38 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Gravelly Ford Water District | 0 | 3.5 | 10 | 0 | 3.5 | 10 | 0 | 3.5 | 10 |
| Greater Kaweah | 3.5 | 49 | 150 | 3.5 | 56 | 140 | 3.5 | 63 | 140 |
| James Irrigation District | 0 | 0 | 45 | 0 | 0 | 45 | 0 | 6.9 | 38 |
| Kern Groundwater Authority | 0 | 410 | 160 | 10 | 410 | 150 | 10 | 410 | 150 |
| Kings River East | 0 | 160 | 80 | 6.9 | 150 | 80 | 14 | 150 | 76 |
| Madera County - Chowchilla | 0 | 14 | 56 | 0 | 14 | 56 | 0 | 17 | 52 |
| Madera County - Madera | 0 | 73 | 170 | 0 | 87 | 160 | 3.5 | 97 | 140 |
| Madera Irrigation District | 0 | 87 | 94 | 0 | 90 | 90 | 6.9 | 100 | 73 |
| Madera Irrigation District, City of Madera | 0 | 0 | 3.5 | 0 | 0 | 3.5 | 0 | 3.5 | 0 |
| McMullin | 0 | 56 | 120 | 0 | 56 | 120 | 0 | 69 | 100 |
| Merced County | 0 | 0 | 3.5 | 0 | 0 | 3.5 | 0 | 0 | 3.5 |
| Merced Subbasin | 0 | 80 | 180 | 3.5 | 87 | 170 | 6.9 | 90 | 170 |
| Mid Kaweah | 0 | 28 | 56 | 0 | 28 | 56 | 0 | 38 | 45 |
| Mid Kings River | 0 | 73 | 24 | 0 | 73 | 24 | 6.9 | 66 | 24 |
| New Stone Water District | 0 | 0 | 6.9 | 0 | 0 | 6.9 | 0 | 0 | 6.9 |
| North Fork Kings | 0 | 42 | 160 | 0 | 42 | 160 | 3.5 | 49 | 150 |
| North Kings | 6.9 | 170 | 110 | 6.9 | 170 | 110 | 14 | 170 | 110 |
| Northern & Central Delta-Mendota | 0 | 49 | 130 | 0 | 49 | 130 | 3.5 | 56 | 120 |
| San Joaquin River Exchange Contractors Water Authority | 0 | 28 | 170 | 0 | 28 | 170 | 6.9 | 28 | 160 |
| South Fork Kings | 0 | 10 | 21 | 0 | 10 | 21 | 0 | 10 | 21 |
| South Kings | 0 | 10 | 0 | 0 | 10 | 0 | 3.5 | 6.9 | 0 |
| Tri-County Water Authority | 0 | 10 | 0 | 0 | 10 | 0 | 0 | 10 | 0 |
| Triangle T Water District | 0 | 3.5 | 17 | 0 | 3.5 | 17 | 0 | 3.5 | 17 |
| Central Valley | 24 | 3400 | 5600 | 63 | 3500 | 5500 | 300 | 3600 | 5100 |

## 9.2 Porosity

The default porosity used by ICHNOS is 10%. The model was also run with porosities of 20% and 30% for sensitivity analysis. Increasing porosity decreased the number of particles exiting the model domain within one year (Figure A *15*). This is in agreement with Darcy's law, which states that linear velocity is inversely proportional to porosity. The total number of wells receiving surface recharge within a year decreased from 1086 with 10% porosity to 408 with

20% porosity and 227 with 30% porosity. None of the scenarios change which of the GSA's have enough suitable land to meet their recharge goals with recycled water MAR.

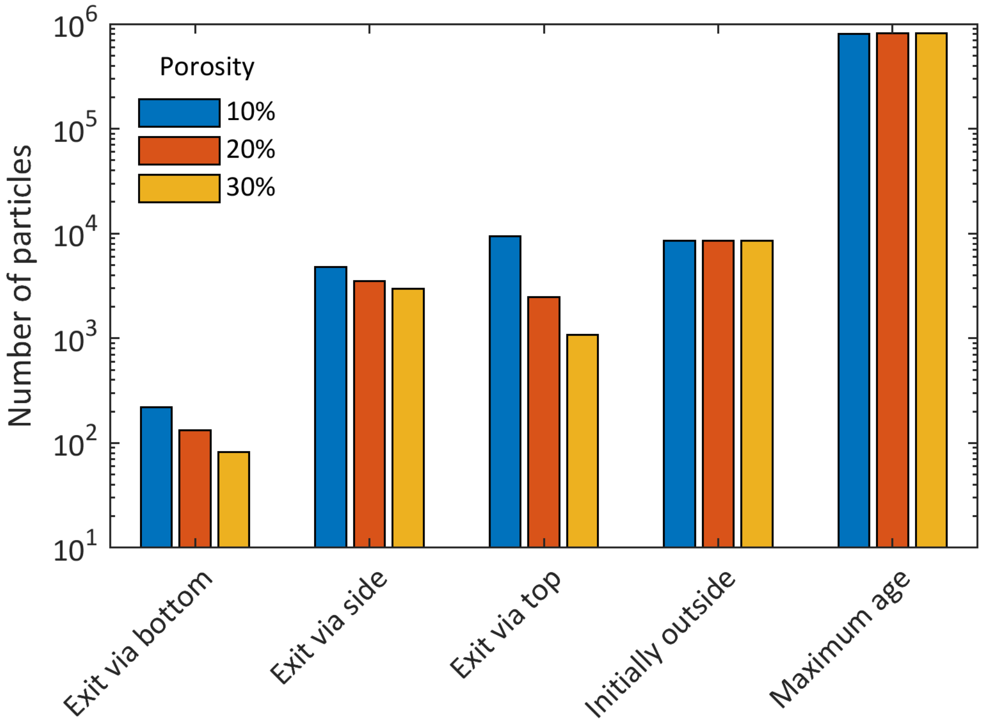


Figure A 16: Fate of particles in ICHNOS model runs with varying porosity. Particles exiting via the top of the model indicate a path along which a well receives surface recharge. A total of 830,250 particles were modeled.

## 9.3 Fully screened wells

The screen depth of a well plays a significant role in determining when water is captured (McDermott et al. 2008). Nevertheless, leaks in the casing could result in water entering the well from units in which it is not screened. To account for this, a scenario was modeled in ICHNOS in which all wells were assumed to have screens starting one meter below the top of the model domain and continuing down to the recorded or estimated screen bottom depth. The one meter offset from the top reduces the likelihood of errors from particles being released outside of the model domain.

Under this scenario, 11,271 wells received surface recharge within a year, resulting in an additional 2 $mi^2$ (5.1 $km^2$) of buffered area after the 100-ft default buffers for domestic wells are considered for both scenarios.

## 9.4 Natural breaks classification

*Classification of recycled water MAR suitability scores was done by both equal intervals and natural breaks, with equal intervals ultimately being selected and reported in the main text. Breaks are shown in* ***Error! Reference source not found.****, and results of the natural breaks classification are shown in*

Table A 12: Area (mi$^2$) available to each GSA of good, moderate, and poor recycled water MAR suitability using natural breaks. (1 mi$^2$ = 2.6 km$^2$)

| GSA | Facilities with disinfected tertiary | | | Facilities with any recycled water | | | Any treatment facility | | |
|---|---|---|---|---|---|---|---|---|---|
| | Good | Moderate | Poor | Good | Moderate | Poor | Good | Moderate | Poor |
| Aliso Water District | 5.4 | 12 | 24 | 5.4 | 12 | 24 | 0.9 | 17 | 23 |
| Buena Vista | 0.11 | 0.37 | 79 | 0.11 | 0.37 | 79 | 1.8 | 10 | 67 |
| Central Kings | 160 | 59 | 9 | 150 | 63 | 9.0 | 150 | 59 | 13 |
| Chowchilla Water District | 30 | 48 | 48 | 31 | 47 | 48 | 24 | 58 | 44 |
| East Kaweah | 73 | 50 | 46 | 46 | 80 | 43 | 53 | 76 | 41 |
| Eastern Tule | 72 | 26 | 120 | 38 | 62 | 120 | 29 | 82 | 110 |
| Gravelly Ford Water District | 3.2 | 3.5 | 6.4 | 3.2 | 3.5 | 6.4 | 1.3 | 5.4 | 6.4 |
| Greater Kaweah | 83 | 100 | 130 | 82 | 110 | 130 | 35 | 170 | 110 |
| James Irrigation District | 0.43 | 0.62 | 42 | 0.43 | 0.62 | 42 | 1.9 | 12 | 29 |
| Kern Groundwater Authority | 640 | 430 | 400 | 630 | 450 | 400 | 330 | 710 | 420 |
| Kings River East | 150 | 47 | 76 | 120 | 69 | 76 | 100 | 95 | 68 |
| Madera County - Chowchilla | 6.9 | 27 | 32 | 8.5 | 25 | 32 | 5.7 | 28 | 32 |
| Madera County - Madera | 32 | 120 | 88 | 43 | 110 | 88 | 38 | 120 | 86 |
| Madera Irrigation District | 60 | 110 | 34 | 67 | 100 | 34 | 70 | 110 | 21 |
| Madera Irrigation District, City of Madera | 1.6 | 1.8 | 0.63 | 1.6 | 1.8 | 0.63 | 3.5 | 0.63 | 0.019 |
| McMullin | 36 | 110 | 44 | 33 | 110 | 44 | 40 | 91 | 55 |
| Merced County | 1.3 | 0.47 | 0.02 | 1.3 | 0.47 | 0.02 | 0.12 | 1.7 | 0.023 |
| Merced Subbasin | 50 | 200 | 210 | 57 | 210 | 200 | 58 | 210 | 190 |
| Mid Kaweah | 19 | 50 | 49 | 19 | 50 | 49 | 10 | 69 | 38 |
| Mid Kings River | 76 | 51 | 7.8 | 80 | 47 | 7.6 | 36 | 90 | 8.6 |
| New Stone Water District | 0.015 | 1.3 | 5.2 | 0.015 | 1.3 | 5.2 | 0 | 1.3 | 5.2 |
| North Fork Kings | 35 | 50 | 170 | 34 | 51 | 170 | 33 | 57 | 170 |
| North Kings | 140 | 130 | 42 | 120 | 150 | 42 | 110 | 170 | 37 |
| Northern & Central Delta-Mendota | 36 | 170 | 200 | 34 | 170 | 200 | 21 | 180 | 210 |
| San Joaquin River Exchange | 14 | 73 | 300 | 13 | 74 | 300 | 11 | 93 | 280 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Contractors Water Authority | | | | | | | | | |
| South Fork Kings | 17 | 8.1 | 77 | 17 | 8.1 | 77 | 7.5 | 43 | 51 |
| South Kings | 2.3 | 0.64 | 0.54 | 2.2 | 0.74 | 0.54 | 2.9 | 0.55 | 0.062 |
| Tri-County Water Authority | 18 | 24 | 52 | 18 | 24 | 52 | 17 | 25 | 52 |
| Triangle T Water District | 0.097 | 3.6 | 19 | 0.097 | 3.6 | 19 | 0 | 3.7 | 19 |
| Central Valley Total | 3900 | 5200 | 7600 | 3500 | 5600 | 7600 | 2800 | 6500 | 7400 |

. Natural breaks rates more areas as good and fewer as poor than equal intervals does (Figure A *16*). Additionally, natural breaks rates more land as good when the number of potential recharge sources is lower (i.e. plants with disinfected tertiary vs any facility). This result is not logical in context and demonstrates why the use of equal interval is a more suitable form of analysis.

Table A 11: Classification breaks for recycled water MAR suitability scores

| Facilities with disinfected tertiary | | Facilities with any recycled water | | Any treatment facility | |
|---|---|---|---|---|---|
| natural breaks | equal interval | natural breaks | equal interval | natural breaks | equal interval |
| 35.45 | 33.27 | 35.45 | 33.27 | 21.45 | 33.61 |
| 47.76 | 66.03 | 47.76 | 66.03 | 43.95 | 66.71 |

Table A 12: Area (mi$^2$) available to each GSA of good, moderate, and poor recycled water MAR suitability using natural breaks. (1 mi$^2$ = 2.6 km$^2$)

| GSA | Facilities with disinfected tertiary | | | Facilities with any recycled water | | | Any treatment facility | | |
|---|---|---|---|---|---|---|---|---|---|
| | Good | Moderate | Poor | Good | Moderate | Poor | Good | Moderate | Poor |
| Aliso Water District | 5.4 | 12 | 24 | 5.4 | 12 | 24 | 0.9 | 17 | 23 |
| Buena Vista | 0.11 | 0.37 | 79 | 0.11 | 0.37 | 79 | 1.8 | 10 | 67 |
| Central Kings | 160 | 59 | 9 | 150 | 63 | 9.0 | 150 | 59 | 13 |
| Chowchilla Water District | 30 | 48 | 48 | 31 | 47 | 48 | 24 | 58 | 44 |
| East Kaweah | 73 | 50 | 46 | 46 | 80 | 43 | 53 | 76 | 41 |
| Eastern Tule | 72 | 26 | 120 | 38 | 62 | 120 | 29 | 82 | 110 |
| Gravelly Ford Water District | 3.2 | 3.5 | 6.4 | 3.2 | 3.5 | 6.4 | 1.3 | 5.4 | 6.4 |
| Greater Kaweah | 83 | 100 | 130 | 82 | 110 | 130 | 35 | 170 | 110 |
| James Irrigation District | 0.43 | 0.62 | 42 | 0.43 | 0.62 | 42 | 1.9 | 12 | 29 |
| Kern Groundwater Authority | 640 | 430 | 400 | 630 | 450 | 400 | 330 | 710 | 420 |
| Kings River East | 150 | 47 | 76 | 120 | 69 | 76 | 100 | 95 | 68 |
| Madera County - Chowchilla | 6.9 | 27 | 32 | 8.5 | 25 | 32 | 5.7 | 28 | 32 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Madera County - Madera | 32 | 120 | 88 | 43 | 110 | 88 | 38 | 120 | 86 |
| Madera Irrigation District | 60 | 110 | 34 | 67 | 100 | 34 | 70 | 110 | 21 |
| Madera Irrigation District, City of Madera | 1.6 | 1.8 | 0.63 | 1.6 | 1.8 | 0.63 | 3.5 | 0.63 | 0.019 |
| McMullin | 36 | 110 | 44 | 33 | 110 | 44 | 40 | 91 | 55 |
| Merced County | 1.3 | 0.47 | 0.02 | 1.3 | 0.47 | 0.02 | 0.12 | 1.7 | 0.023 |
| Merced Subbasin | 50 | 200 | 210 | 57 | 210 | 200 | 58 | 210 | 190 |
| Mid Kaweah | 19 | 50 | 49 | 19 | 50 | 49 | 10 | 69 | 38 |
| Mid Kings River | 76 | 51 | 7.8 | 80 | 47 | 7.6 | 36 | 90 | 8.6 |
| New Stone Water District | 0.015 | 1.3 | 5.2 | 0.015 | 1.3 | 5.2 | 0 | 1.3 | 5.2 |
| North Fork Kings | 35 | 50 | 170 | 34 | 51 | 170 | 33 | 57 | 170 |
| North Kings | 140 | 130 | 42 | 120 | 150 | 42 | 110 | 170 | 37 |
| Northern & Central Delta-Mendota | 36 | 170 | 200 | 34 | 170 | 200 | 21 | 180 | 210 |
| San Joaquin River Exchange Contractors Water Authority | 14 | 73 | 300 | 13 | 74 | 300 | 11 | 93 | 280 |
| South Fork Kings | 17 | 8.1 | 77 | 17 | 8.1 | 77 | 7.5 | 43 | 51 |
| South Kings | 2.3 | 0.64 | 0.54 | 2.2 | 0.74 | 0.54 | 2.9 | 0.55 | 0.062 |
| Tri-County Water Authority | 18 | 24 | 52 | 18 | 24 | 52 | 17 | 25 | 52 |
| Triangle T Water District | 0.097 | 3.6 | 19 | 0.097 | 3.6 | 19 | 0 | 3.7 | 19 |
| Central Valley Total | 3900 | 5200 | 7600 | 3500 | 5600 | 7600 | 2800 | 6500 | 7400 |

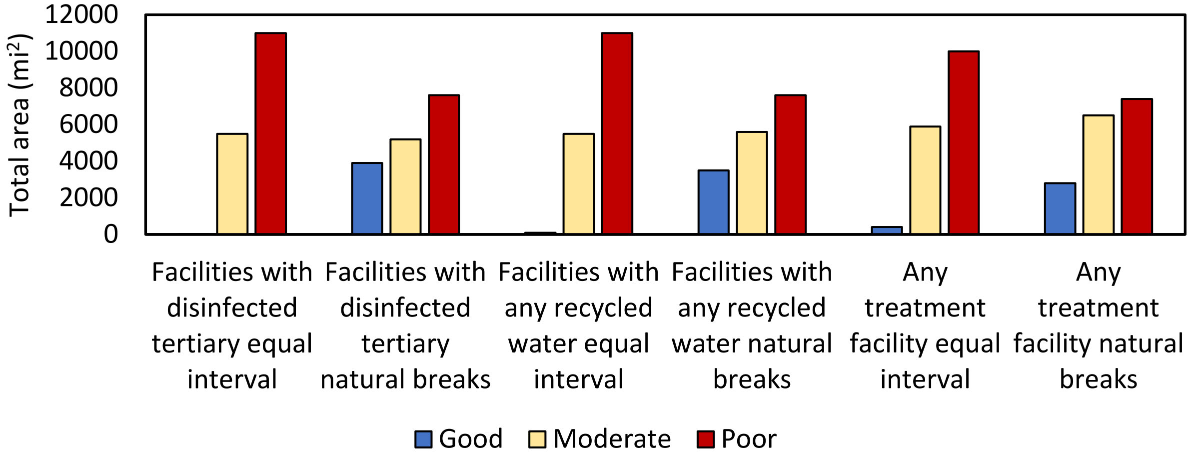


Figure A 17: Area of good, moderate, and poor recycled water MAR suitability for the whole Central Valley with classification by equal interval and natural breaks. (1 $mi^2$ = 2.6 $km^2$)

## 9.5 Darcy's law well buffers

Particle tracking results in residence time-based buffers for only some wells. These buffers are irregularly shaped and tend to trace a narrow track. For a simpler scenario in which all wells are buffered by approximate residence time, circular buffers can be created with Darcy's law.

$$v = \frac{K\frac{dh}{dl}}{n}$$

where *v* is linear velocity, *K* is hydraulic conductivity, *dh/dl* is hydraulic gradient, and *n* is porosity. For this scenario, hydraulic conductivity was taken from the top stratigraphic layer of C2VSimFG version 1.1. Water elevation point measurements from fall 2015 are taken from the SGMA data viewer and interpolated to form a water table (DWR n.d.). Unfortunately, measurements are not available for the entire study area, so the following analysis is restricted to the area where water level measurements are available. The slope of the water table at each well is used for the magnitude of the local hydraulic gradient, using the simplifying assumption that the slope of the overall water table is more significant than any cone of depression caused by the wells. Maximum and minimum shallow groundwater velocities are then calculated at each well location using the minimum and maximum porosities reported by Bertoldi et al. (1991). These velocities are multiplied by one year, and the resulting distances are used to create circular buffers around each well. The results are shown in Table A *13* and Table A *14*.

This method assumes that shallow groundwater reaching the horizontal location of a well could be captured by it regardless of screen depth. This assumption can be useful in the event of leaks in a well's casing or vertical transmission of water within the borehole, but it also excludes areas for the protection of wells that may not receive any local surface recharge. Under Title 22, basic conceptual models such as Darcy's law receive only 0.25 credits for virus removal (CCR 2018). Thus, to demonstrate that a desired area is truly suitable for recycled water MAR, either the travel time must be extended to two years, or more detailed analysis must be performed.

Table A 13: Suitable land by subbasin using Darcy's law for well buffers, assuming maximum porosity (note that only areas with water level measurements are included).

| GSA | Maximum porosity (0.65) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Facilities with disinfected tertiary | | | Facilities with any recycled water | | | Any treatment facility | | |
| | Good | Moderate | Poor | Good | Moderate | Poor | Good | Moderate | Poor |
| Aliso Water District | 0 | 7.6 | 33 | 0 | 7.6 | 33 | 0.03 | 7.8 | 33 |
| Buena Vista | 0 | 0.062 | 15 | 0 | 0.062 | 15 | 0 | 0.47 | 14 |
| Central Kings | 0 | 160 | 65 | 0 | 160 | 65 | 23 | 150 | 49 |
| Chowchilla Water District | 0 | 44 | 74 | 0 | 46 | 73 | 2.2 | 49 | 67 |
| East Kaweah | 0 | 83 | 43 | 0.87 | 84 | 41 | 9.8 | 78 | 38 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Eastern Tule | 0 | 54 | 36 | 0.32 | 54 | 36 | 4.1 | 54 | 33 |
| Gravelly Ford Water District | 0 | 3.5 | 9.5 | 0 | 3.5 | 9.5 | 0 | 3.5 | 9.5 |
| Greater Kaweah | 2.2 | 73 | 190 | 2.9 | 73 | 180 | 3.4 | 82 | 170 |
| James Irrigation District | 0 | 0.83 | 42 | 0 | 0.83 | 42 | 0 | 6.7 | 36 |
| Kern Groundwater Authority | 0 | 300 | 140 | 17 | 290 | 140 | 27 | 280 | 140 |
| Kings River East | 0 | 140 | 65 | 5.8 | 140 | 63 | 19 | 130 | 59 |
| Madera County - Chowchilla | 0 | 13 | 51 | 0 | 15 | 49 | 0.07 | 16 | 48 |
| Madera County - Madera | 0.11 | 37 | 120 | 1.3 | 46 | 110 | 4.4 | 52 | 110 |
| Madera Irrigation District | 0 | 100 | 88 | 0.93 | 110 | 83 | 14 | 120 | 62 |
| Madera Irrigation District, City of Madera | 0 | 1.9 | 2.1 | 0 | 1.9 | 2.1 | 1.7 | 2.1 | 0.15 |
| McMullin | 0 | 73 | 110 | 0 | 73 | 110 | 4.5 | 76 | 100 |
| Merced County | 0 | 1.7 | 0.13 | 0 | 1.7 | 0.13 | 0 | 1.7 | 0.13 |
| Merced Subbasin | 0.78 | 52 | 210 | 3.3 | 63 | 190 | 7.9 | 67 | 190 |
| Mid Kaweah | 0.88 | 18 | 97 | 0.88 | 18 | 97 | 1.4 | 25 | 89 |
| Mid Kings River | 0 | 7.2 | 5.2 | 0 | 7.2 | 5.2 | 0 | 7.2 | 5.2 |
| New Stone Water District | 0 | 0.31 | 6.2 | 0 | 0.31 | 6.2 | 0 | 0.31 | 6.2 |
| North Fork Kings | 0 | 35 | 220 | 0 | 35 | 220 | 1.1 | 43 | 210 |
| North Kings | 5.7 | 140 | 120 | 5.7 | 140 | 120 | 16 | 140 | 110 |
| Northern & Central Delta-Mendota | 0 | 57 | 170 | 0 | 57 | 170 | 0.40 | 68 | 160 |
| San Joaquin River Exchange Contractors Water Authority | 0 | 23 | 350 | 0 | 23 | 350 | 0.16 | 32 | 340 |
| South Fork Kings | 0 | 6.5 | 7.7 | 0 | 6.5 | 7.7 | 0 | 6.5 | 7.7 |
| South Kings | 0 | 2.9 | 1.1 | 0 | 2.9 | 1.1 | 1.6 | 2.0 | 0.4 |
| Tri-County Water Authority | 0 | 16 | 7.8 | 0 | 16 | 7.8 | 0 | 16 | 7.8 |
| Triangle T Water District | 0 | 0.84 | 22 | 0 | 0.84 | 22 | 0 | 0.84 | 22 |
| Central Valley Total | 20 | 3800 | 7000 | 66 | 3800 | 6900 | 330 | 4000 | 6400 |

Table A 14: Suitable land by subbasin using Darcy's law for well buffers, assuming minimum porosity (note that only areas with water level measurements are included).

| GSA | Minimum porosity (0.25) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Facilities with disinfected tertiary | | | Facilities with any recycled water | | | Any treatment facility | | |
| | Good | Moderate | Poor | Good | Moderate | Poor | Good | Moderate | Poor |
| Aliso Water District | 0 | 7.6 | 33 | 0 | 7.6 | 33 | 0.027 | 7.8 | 33 |
| Buena Vista | 0 | 0.062 | 15 | 0 | 0.062 | 15 | 0 | 0.47 | 14 |
| Central Kings | 0 | 160 | 66 | 0 | 160 | 66 | 23 | 150 | 50 |
| Chowchilla Water District | 0 | 47 | 77 | 0 | 49 | 75 | 2.8 | 52 | 69 |
| East Kaweah | 0 | 85 | 43 | 0.88 | 86 | 42 | 10 | 80 | 39 |
| Eastern Tule | 0 | 55 | 36 | 0.32 | 55 | 36 | 4.2 | 54 | 33 |
| Gravelly Ford Water District | 0 | 3.5 | 9.6 | 0 | 3.5 | 9.6 | 0 | 3.5 | 9.6 |
| Greater Kaweah | 2.2 | 74 | 190 | 2.9 | 74 | 190 | 3.4 | 84 | 180 |
| James Irrigation District | 0 | 0.83 | 42 | 0 | 0.83 | 42 | 0 | 6.7 | 36 |
| Kern Groundwater Authority | 0 | 300 | 140 | 17 | 290 | 140 | 27 | 280 | 140 |
| Kings River East | 0 | 140 | 65 | 5.9 | 140 | 63 | 19 | 130 | 59 |
| Madera County - Chowchilla | 0 | 13 | 52 | 0 | 16 | 50 | 0.069 | 16 | 49 |
| Madera County - Madera | 0.12 | 38 | 130 | 1.4 | 47 | 120 | 4.4 | 54 | 110 |
| Madera Irrigation District | 0 | 110 | 89 | 0.93 | 110 | 84 | 14 | 120 | 63 |
| Madera Irrigation District, City of Madera | 0 | 1.9 | 2.1 | 0 | 1.9 | 2.1 | 1.7 | 2.1 | 0.15 |
| McMullin | 0 | 73 | 110 | 0 | 73 | 110 | 4.5 | 77 | 100 |
| Merced County | 0 | 1.7 | 0.13 | 0 | 1.7 | 0.13 | 0 | 1.7 | 0.13 |
| Merced Subbasin | 0.78 | 52 | 210 | 3.3 | 63 | 200 | 8 | 67 | 190 |
| Mid Kaweah | 0.88 | 18 | 98 | 0.88 | 18 | 98 | 1.4 | 26 | 90 |
| Mid Kings River | 0 | 7.3 | 5.2 | 0 | 7.3 | 5.2 | 0 | 7.3 | 5.2 |
| New Stone Water District | 0 | 0.31 | 6.2 | 0 | 0.31 | 6.2 | 0 | 0.31 | 6.2 |
| North Fork Kings | 0 | 35 | 220 | 0 | 35 | 220 | 1.1 | 44 | 210 |
| North Kings | 5.9 | 140 | 120 | 5.9 | 140 | 120 | 17 | 140 | 110 |
| Northern & Central Delta-Mendota | 0 | 58 | 170 | 0 | 58 | 170 | 0.40 | 68 | 160 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| San Joaquin River Exchange Contractors Water Authority | 0 | 23 | 350 | 0 | 23 | 350 | 0.16 | 32 | 350 |
| South Fork Kings | 0 | 6.6 | 7.7 | 0 | 6.6 | 7.7 | 0 | 6.6 | 7.7 |
| South Kings | 0 | 2.9 | 1.1 | 0 | 2.9 | 1.1 | 1.6 | 2.0 | 0.4 |
| Tri-County Water Authority | 0 | 16 | 7.8 | 0 | 16 | 7.8 | 0 | 16 | 7.8 |
| Triangle T Water District | 0 | 0.85 | 22 | 0 | 0.85 | 22 | 0 | 0.85 | 22 |
| Central Valley Total | 20 | 3800 | 7000 | 66 | 3800 | 6900 | 340 | 4100 | 6400 |

## 9.6 On-farm versus not on-farm recharge

Seven GSAs have plans for recharge on farmland. The land required for these projects is included with all of the other land requirements in the main analysis; however, since on-farm recharge would not require land fallowing while other types would, it may be worthwhile to view them separately. Analysis was conducted considering all available land for all needs except on-farm recharge; this assumes that necessary land will be converted to basins regardless of current use (Figure A *17*). A second analysis was conducted considering only agricultural land and only on-farm recharge needs (Figure A *18*). While McMullin and Kern GSAs do not have enough suitable land to meet all of their recharge goals with recycled water MAR, they do have enough to meet either their on-farm *or* not on-farm goals. All of the GSAs planning on-farm recharge have enough suitable farmland except for North Fork Kings, but only Greater Kaweah and North Kings can meet their on-farm needs solely with land surrounding treatment facilities currently producing disinfected tertiary water.

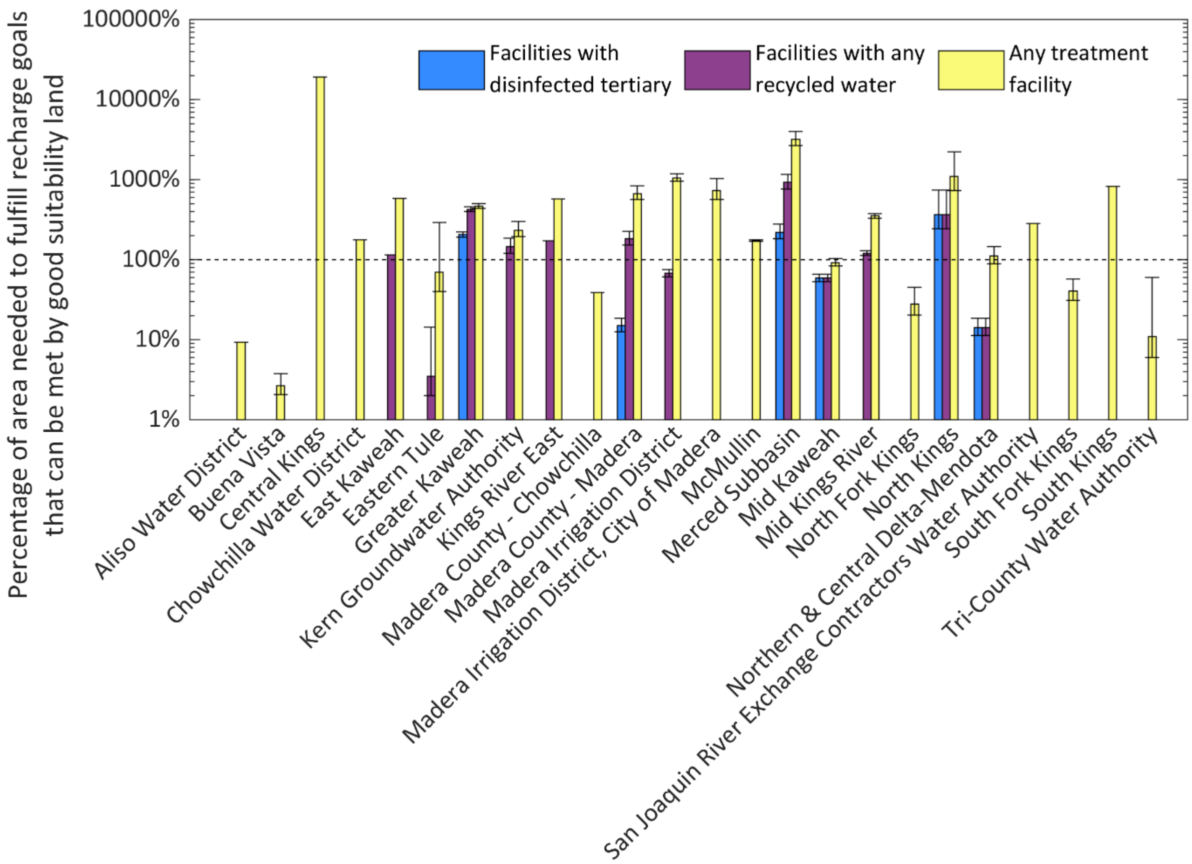


Figure A 18: Land with proximity to facility assessment, excluding on-farm needs. Percentage of area needed by each GSA to fulfill recharge goals for projects not classified as on-farm that can be met by good suitability land considering proximity to different types of treatment facilities (e.g., facilities with disinfected tertiary, facilities with any recycled water, and facilities with any treated water). Some Plans did not explicitly state land needs; for these Plans, we estimated a mean, min, and max amount of land based on proposed MAR projects. For these GSAs, bar represent the mean land; minimum and maximum estimated land requirements are shown with error bars. GSAs without suitable area not shown. Dashed line indicates 100% of area needed to fulfill recharge goals can be met by good suitability land within proximity to treatment facilities.

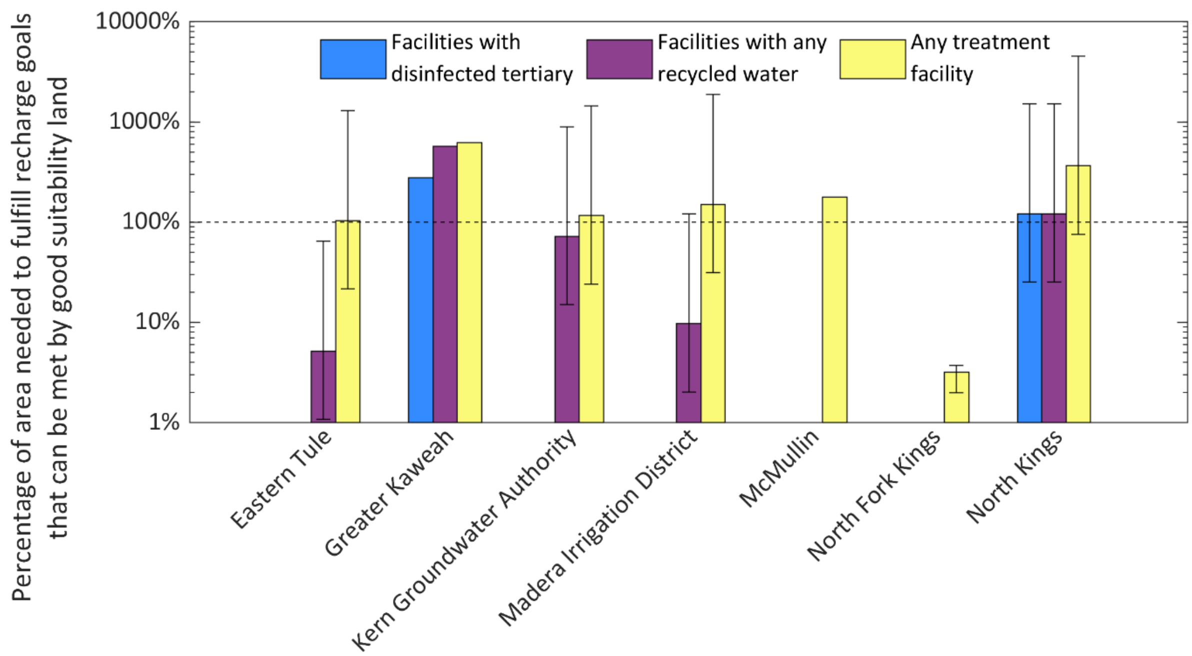


Figure A 19: Land with proximity to facility assessment for on-farm recharge. Percentage of area needed by each GSA to fulfill recharge goals for projects classified as on-farm that can be met by good suitability land considering proximity to different types of treatment facilities (e.g., facilities with disinfected tertiary, facilities with any recycled water, and facilities with any treated water). Some Plans did not explicitly state land needs; for these Plans, we estimated a mean, min, and max amount of land based on proposed MAR projects. For these GSAs, bar represent the mean land; minimum and maximum estimated land requirements are shown with error bars. GSAs without suitable area not shown. Dashed line indicates 100% of area needed to fulfill recharge goals can be met by good suitability land within proximity to treatment facilities.

## 9.7 Differentiating water needs by project

MAR projects described in GSPs were classified as ASR/injection, Banking, Basin, Basin and flood, Creek bed, Dry well, FloodMAR, On-Farm, Physical, Both in-lieu and physical, or No information. Water sources were classified as Central Valley Project, State Water Project, Local surface water, Imported water, Recycled water, Stormwater, or Other. The main analysis considers water needed for projects classified as anything other than ASR/injection, Dry well, or FloodMAR for consistency with the land needs analysis.

Alternative analyses were conducted considering different types of projects or water sources as a sensitivity analysis. For the first alternative, the same set of projects was considered except that on-farm recharge projects were also excluded, in order to only evaluate projects likely to require land fallowing (Figure A 20). The second alternative considers all water needs except those that the GSPs state will be met by stormwater, since stormwater projects are frequently intended to manage a sudden influx of water that will be problematic if not used, as opposed to competing for treated water for which there are many other possible uses (Figure A 21). The third alternative considers the total water needs for all projects, which is the most conservative evaluation (Figure A 22). All three alternatives give the same results as the main analysis in terms of which GSAs will have sufficient water based on explicitly stated water needs plus average needs assumed for projects that do not give a number (see Section 7 for water needs calculations). There is some variation in how close the GSAs come to meeting 100% of their needs.

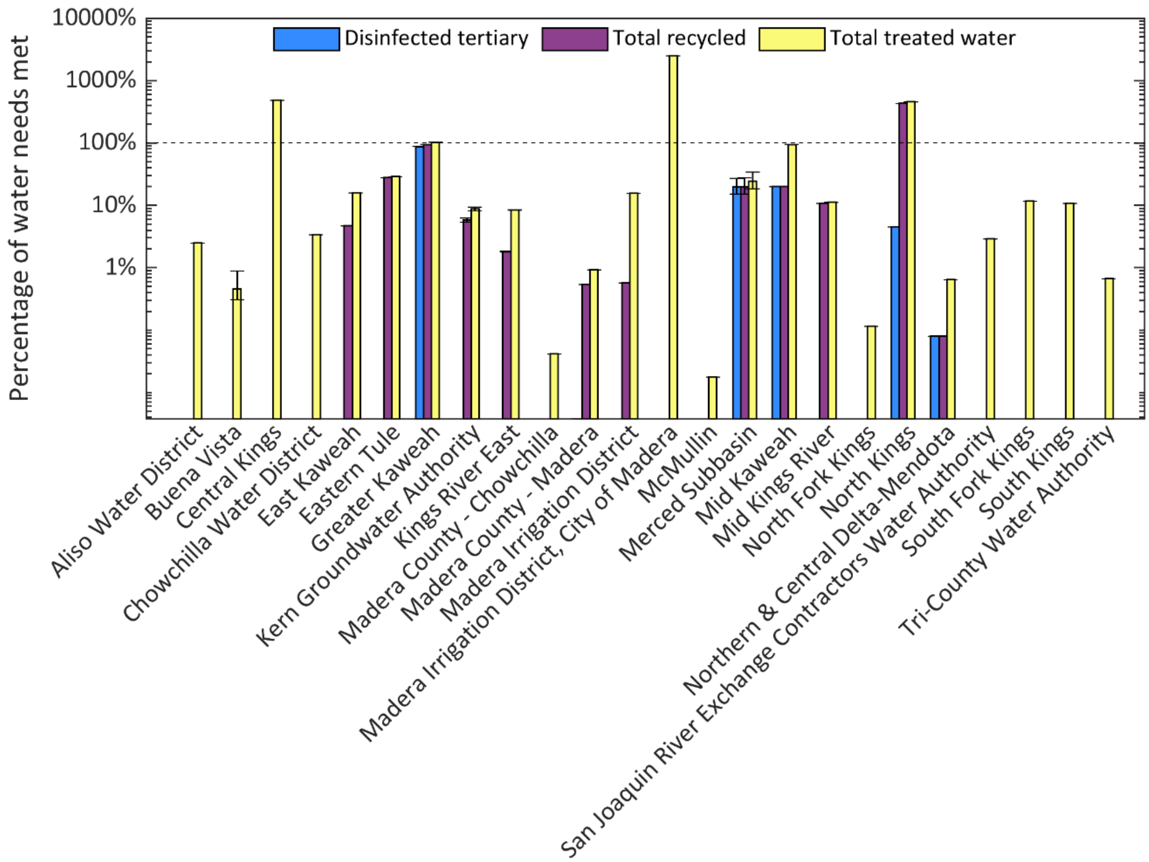


Figure A 20: Percentage of water needs met for surface recharge projects that are not considered on-farm.

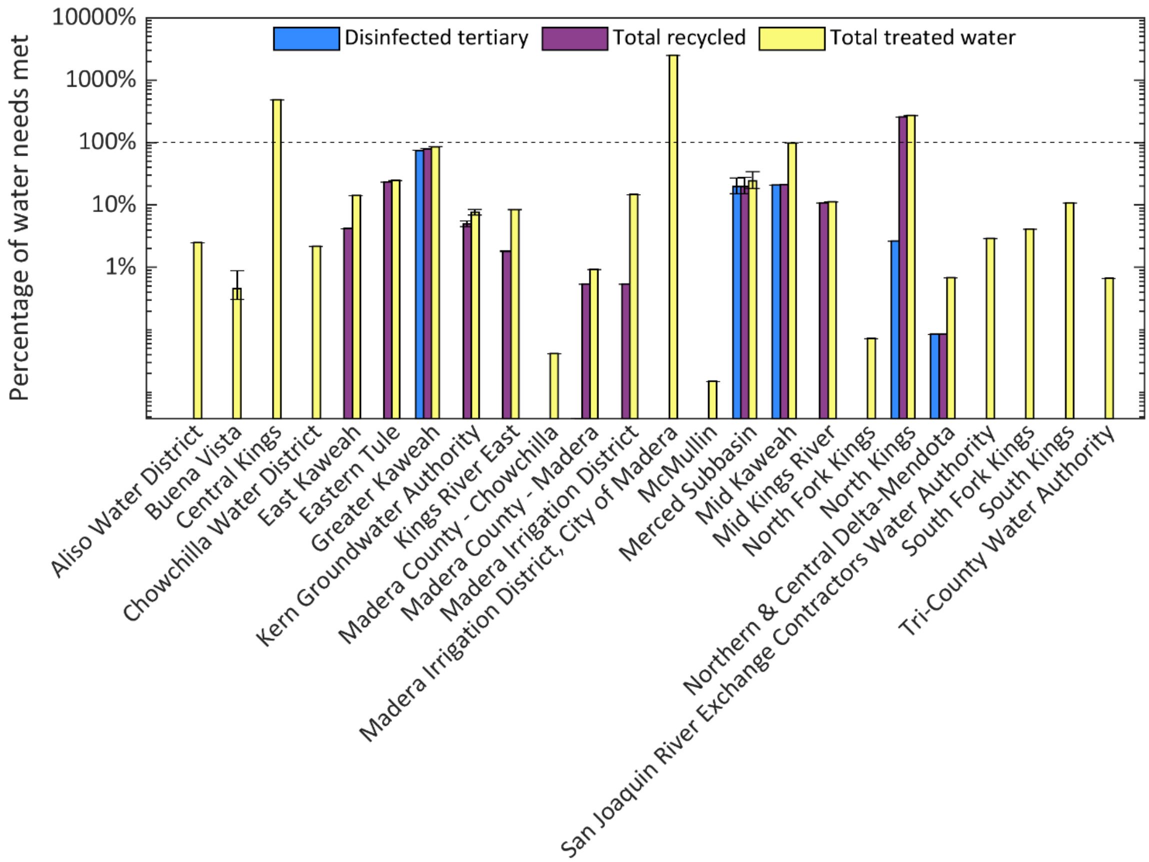


Figure A 21: Percentage of water needs met excluding stormwater needs.

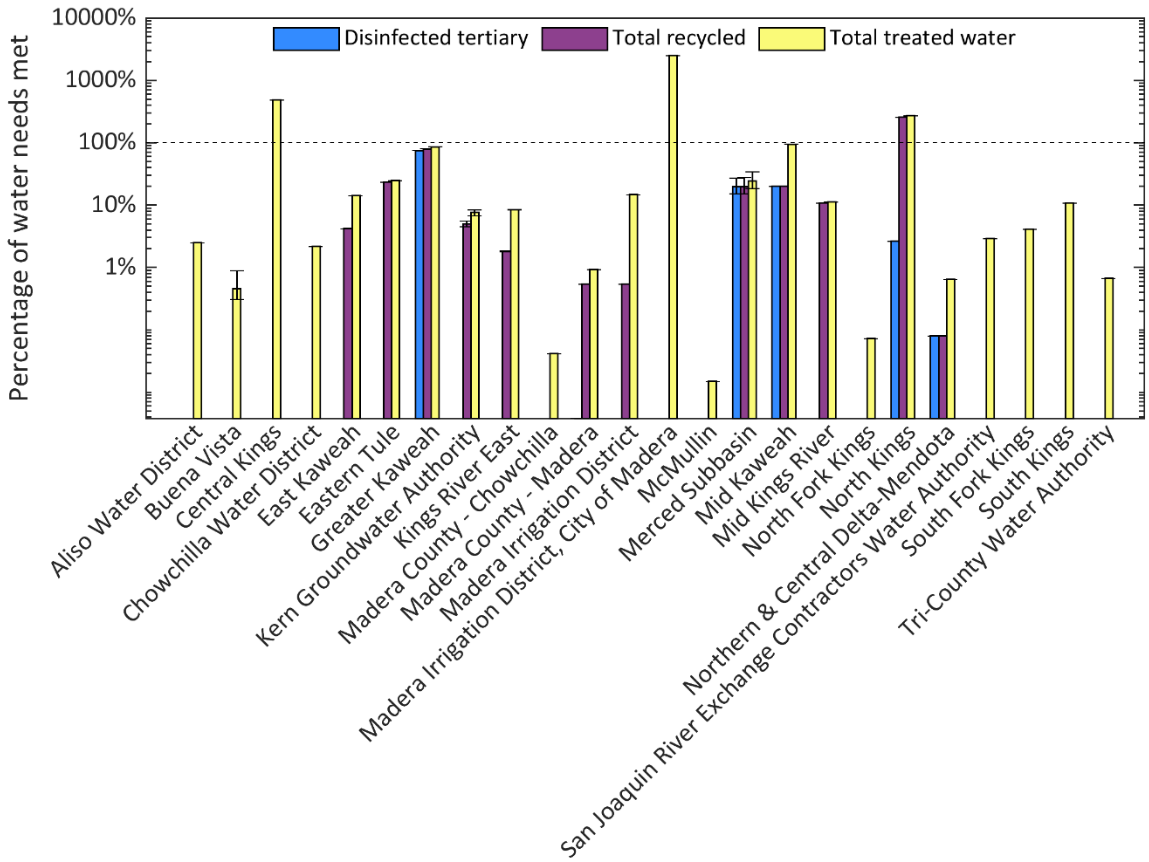


Figure A 22: Percentage of total water needs met.

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