

# Improving California's Water Resilience:

*Developing a Decision Support Tool to Identify Multi-Benefit Groundwater Recharge Locations in California's Central Valley*

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Photo: Kern Water Bank, Bakersfield CA (credit: Bridget Gibbons)

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# Signature Page

As authors of this Group Project report, we archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

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# Abstract

California has an increasingly scarce and unreliable surface water supply. As the climate changes, droughts are expected to become more frequent and extreme, precipitation is expected to fall as rain rather than snow in shorter, more intense periods, and reliance on Sierra Nevada snowpack for storage will become less tenable (1). Strategic groundwater storage can help make farms, cities, and ecosystems more resilient as future water availability is less predictable (2). The Sustainable Groundwater Management Act of 2014 (SGMA) adds regulatory structure with the goal of protecting and augmenting groundwater supplies by requiring a regionalized approach to groundwater management. Many Groundwater Sustainability Agencies have identified managed aquifer recharge as a tool they will use to meet the goals of SGMA during the 20-year implementation period, beginning in 2020. Currently, many groundwater managers lack the tools and information necessary to identify ideal locations to invest in managed aquifer recharge projects that are able to achieve multiple benefits.

Here we develop and demonstrate the application of a decision support tool that can identify areas within any groundwater basin in the Central Valley that are better suited to implementing groundwater recharge projects to achieve multiple benefits. In this project, we define multiple benefits as: protecting water quality, rehydrating domestic wells that have run dry, and supporting groundwater dependent ecosystems. Our tool makes basin-wide information available to groundwater management entities, allowing Groundwater Sustainability Agencies to meet compliance requirements while realizing other locally relevant benefits. The decision support tool not only considers recharge suitability on the soil surface, but also accounts for subsurface characteristics that can affect groundwater recharge. The tool incorporates publicly available information from research institutions and state agencies, eliminating some costs associated with using a recharge siting tool and ensuring transferability across the Central Valley to basins with a varying degree of local data.

We conclude that the Sustainable Groundwater Management Act presents an opportunity to re-envision California's approach to water management by more comprehensively considering the interconnected benefits associated with groundwater recharge and storage. The information available in this tool will facilitate the realization of a suite of benefits to be gained through the implementation of groundwater recharge projects in California and will help the state move forward in achieving a sustainable and resilient water future.

*Keywords: managed aquifer recharge, groundwater, Sustainable Groundwater Management Act, multiple benefits*

# Table of Contents

Abstract	iv
Table of Contents	v
List of Tables	viii
List of Figures	viii
Glossary of Acronyms	x
Executive Summary	1
1 Background	4
1.1 Groundwater in California	4
1.2 The Sustainable Groundwater Management Act	5
1.3 Groundwater Recharge	7
1.3.1 What is Managed Aquifer Recharge?	7
1.3.2 Managed Aquifer Recharge in California	9
1.3.3 Potential Benefits of Recharge Projects	11
1.3.3.1 Water Quantity	11
1.3.3.2 Water Quality	12
1.3.4 Source Water for Recharge	12
1.4 Project Significance	13
2 Objectives	15
3 Methods	16
3.1 Suitable Recharge Locations	16
3.1.1 Surface and Subsurface Conditions	17
3.1.1.1 Soil Agricultural Groundwater Banking Index (SAGBI)	17
3.1.1.2 Depth to Groundwater	20
3.1.1.3 Percent of Coarse Grained Soils	23
3.1.1.4 Corcoran Clay	26
3.1.1.5 Weighted Sum	29
3.1.2 Nitrogen Contamination Potential	30

3.1.2.1	Nitrogen Balances	31
3.1.2.2	Weighted Sum	33
3.1.3	Recommended Recharge Locations	33
3.2	Additional Considerations	34
3.2.1	Benefits	34
3.2.1.1	Groundwater Dependent Ecosystems	34
3.2.1.2	Domestic Wells That Have Run Dry	36
3.2.2	Feasibility	38
3.2.2.1	Existing Water Conveyance Infrastructure	39
3.2.2.2	Locations of Listed Contamination Clean Up Sites	41
3.3	Multi-Benefit Recharge Locations	43
3.4	Source Water Analysis	44
3.4.1	Historic Water Availability	45
3.4.2	Projected Water Availability	45
4	Results	47
4.1	Suitable Recharge Locations	50
4.1.1	Surface and Subsurface Conditions	50
4.1.2	Nitrate Contamination Potential	51
4.1.3	Recommended Recharge Locations	52
4.2	Additional Considerations	57
4.2.1	Benefits	57
4.2.1.1	Groundwater Dependent Ecosystems	57
4.2.1.2	Domestic Wells That Have Run Dry	58
4.2.2	Feasibility	59
4.2.2.1	Existing Water Conveyance Infrastructure	59
4.2.2.2	Locations of Listed Contamination Clean Up Sites	60
4.3	Multi-Benefit Recharge Locations	61
4.3.1	The Engineer’s Scenario	62
4.3.2	The Community Scenario	63

4.3.3	The Ecologist’s Scenario	65
4.3.4	The Equal Weights Scenario	66
4.4	Source Water Analysis	68
4.4.1	Historic Water Availability	68
4.4.2	Projected Water Availability	69
5	Discussion	71
5.1	Recommended Recharge Locations	71
5.2	Multi-Benefit Recharge Locations	72
5.3	Source Water Analysis	72
5.3.1	Historic Water Availability	73
5.3.2	Projected Water Availability	73
6	Limitations	74
6.1	Data Limitations	74
6.1.1	SAGBI	74
6.1.2	Interpolated Data	74
6.1.3	Nitrogen Balance Data	75
6.1.4	Domestic Wells That Have Run Dry Data	75
6.1.5	National Hydrography Dataset	75
6.1.6	Groundwater Dependent Ecosystems Data	76
6.1.7	California Contamination Cleanup Sites	76
6.1.8	Data Flexibility	76
6.2	Future Work	77
6.2.1	Water Quality	77
6.2.2	Feasibility	78
6.2.3	Additional Benefits	79
6.2.4	Source Water	79
7	Conclusion	80
	References	81

# List of Tables

Table 3.1 Modified Soil Agricultural Groundwater Banking Index (SAGBI) score reclassification based on suitability for groundwater recharge.	20
Table 3.2 Depth to groundwater (ft) reclassification based on suitability for groundwater recharge.	23
Table 3.3 Percent of coarse soil material reclassification based on suitability for groundwater recharge.	26
Table 3.4 Corcoran clay depth (ft) reclassification based on suitability for groundwater recharge.	28
Table 3.5 Corcoran clay thickness (ft) reclassification based on suitability for groundwater recharge.	29
Table 3.6 Weighting scheme for combining surface and subsurface condition components.	30
Table 3.7 Nitrogen balance (kg N/hectare/year) reclassification based on suitability for groundwater recharge.	33
Table 3.8 Weighting scheme for combining nitrogen balances (kg N/hectare/year) for 1990, 2005, and 2020.	33
Table 3.9 Ranked distances away from potential groundwater dependent ecosystems (GDEs).	36
Table 3.10 Ranked distances away from reported domestic wells that have run dry.	38
Table 3.11 Ranked distances away from existing conveyance infrastructure.	41
Table 3.12 Ranked distances away from listed contamination clean-up sites.	43
Table 6.1 Risk of geogenic contaminant mobility with differing groundwater conditions.	78

# List of Figures

Figure 1.1 Critically overdrafted groundwater basins in California.	6
Figure 1.2 Schematic of managed aquifer recharge methods.	8
Figure 3.1 Workflow used for data analysis in the decision support tool.	16
Figure 3.2 Soil Agricultural Groundwater Banking Index values for the Madera Subbasin.	18
Figure 3.3 Modified Soil Agricultural Groundwater Banking Index values for the Madera Subbasin.	19
Figure 3.4 Location of wells included in the California Department of Water Resources depth to groundwater dataset for the Madera Subbasin.	21
Figure 3.5 Interpolated depth to groundwater values for the Madera Subbasin.	22
Figure 3.6 Locations of well logs used in the Central Valley Hydrologic Model texture model.	24
Figure 3.7 Interpolated percent of coarse soil material layers for the Madera Subbasin.	25
Figure 3.8 Depth of the Corcoran clay underlying the Madera Subbasin.	27
Figure 3.9 Thickness of the Corcoran Clay underlying the Madera Subbasin.	27
Figure 3.9 Surficial nitrogen balances for the Madera Subbasin.	32
Figure 3.10 Locations of potential groundwater dependent ecosystems in the Madera Subbasin.	35
Figure 3.11 Locations of domestic drinking water wells that have run dry in the Madera Subbasin.	37
Figure 3.12 Location of existing water conveyance infrastructure in the Madera Subbasin.	40
Figure 3.13 Location of GeoTracker points in the Madera Subbasin.	42
Figure 3.14 Conceptual diagram of the tool functionality that allows a user to set managed recharge project priorities.	44
Figure 4.1 Map of decision support tool suitable recharge locations across the Central Valley.	48
Figure 4.2 Decision support tool schematic showing the integration of components.	49
Figure 4.3 Physical surface and subsurface conditions in the Madera Subbasin ranked by suitability for groundwater recharge.	51
Figure 4.4 Surficial nitrogen balances ranked by suitability for groundwater recharge in the Madera Subbasin.	52
Figure 4.5 Recommended recharge locations ranked by suitability for groundwater recharge in Madera Subbasin.	53



Figure 4.6 Distribution of Sustainable Agricultural Groundwater Banking Index (SAGBI) scores within recommended recharge locations in the Madera Subbasin.	54
Figure 4.7 Distribution of depth to water scores within recommended recharge locations in the Madera Subbasin.	54
Figure 4.8 Distribution of percent of coarse grained soil material scores at five depths within recommended recharge locations in the Madera Subbasin.	55
Figure 4.9 Distribution of Corcoran clay thickness and depth scores within recommended recharge locations in the Madera Subbasin.	56
Figure 4.10 Distribution of surficial nitrogen balance scores for recommended recharge locations in the Madera Subbasin.	57
Figure 4.11 Distance from groundwater dependent ecosystems in the Madera Subbasin.	58
Figure 4.12 Distance to wells that have run dry in the Madera Subbasin.	59
Figure 4.13 Distance to existing conveyance infrastructure in the Madera Subbasin.	60
Figure 4.14 Distance from contamination sites in the Madera Subbasin.	61
Figure 4.15 Suggested recharge locations in the Madera Subbasin, prioritizing areas closer to conveyance infrastructure and farther from contamination clean-up sites.	63
Figure 4.16 Suggested recharge locations in the Madera Subbasin, prioritizing areas closer to domestic drinking wells, farther from contamination sites, and closer to conveyance infrastructure.	64
Figure 4.17 Suggested recharge locations in the Madera Subbasin, prioritizing areas closer to groundwater dependent ecosystems and existing infrastructure and farther from contamination sites.	65
Figure 4.18 Suggested recharge locations in the Madera Subbasin with equal prioritization for all additional considerations.	67
Figure 4.19 Days when criteria for releasing water from Millerton Reservoir for Managed Aquifer Recharge (MAR) were met (1995 - 2019).	68
Figure 4.20 Historical (1995-2019) and projected average monthly streamflow into Millerton Reservoir.	69

# Glossary of Acronyms

BGS - below ground surface

CFS - cubic feet per second

CVHM - Central Valley Hydrologic Model (United States Geological Survey)

CWS - Center for Watershed Sciences (University of California, Davis)

DWR/CA DWR - Department of Water Resources (State of California)

GDE - Groundwater Dependent Ecosystem

GRAT - Groundwater Recharge Assessment Tool (Sustainable Conservation)

GSA - Groundwater Sustainability Agency

GSP - Groundwater Sustainability Plan

IDW - Inverse Distance Weighting

LUST - Leaking Underground Storage Tank

MAF - million acre feet

MAR - Managed Aquifer Recharge

NHD+ - National Hydrography Dataset Plus (United States Geological Survey)

NLCD - National Landcover Database (United States Geological Survey)

NRCS - Natural Resources Conservation Service (United States Department of Agriculture)

SAGBI - Soil Agricultural Groundwater Banking Index

(California Soil Resources Lab, UC Davis & UC Division of Agriculture and Natural Resources)

SGMA - Sustainable Groundwater Management Act (State of California)

SWRCB - State Water Resources Control Board (California)

USDA NRCS - United States Department of Agriculture Natural Resources Conservation Service

USGS - United States Geological Survey

UST - Underground Storage Tank

# Executive Summary

California is heavily reliant on groundwater to support agriculture, industry and municipalities. This is particularly true in drought years, when up to 70% of water used for irrigation derives from groundwater (3). Prolonged unsustainable groundwater extraction has resulted in the deterioration of groundwater aquifers throughout the state. In the 21 groundwater basins deemed critically overdrafted by California's Department of Water Resources, a sustained condition of outflows that are greater than inflows has induced groundwater level declines (4).

The Sustainable Groundwater Management Act (SGMA), passed by the California Legislature in 2014, requires that groundwater basins with historical patterns of unsustainable extraction design and implement plans to reach sustainability by 2040 (5–7). Within these plans, Groundwater Sustainability Agencies are encouraged to identify projects and management actions that will be implemented to augment groundwater supply or reduce groundwater demand within their basin in order to balance pumping and recharge (8).

Managed aquifer recharge is one method that many Groundwater Sustainability Agencies plan to use to balance inflows and outflows. Currently, some groundwater managers lack the tools and information necessary to identify recharge locations within their basins that consider more than conditions at the surface or near-surface. The most commonly used assessment tool for planning and siting groundwater recharge is the Soil Agricultural Groundwater Banking Index (SAGBI) that focuses on recharge suitability within the top 6 feet of the soil subsurface (9). There is no publicly available, widely applicable tool to help inform the placement of groundwater recharge projects that considers benefits other than those directly related to water infiltration in the ground surface.

We created a decision support tool that can be used by Groundwater Sustainability Agencies (GSAs) to strategically site groundwater recharge projects that best achieve multiple benefits, defined in this project as: protecting water quality, rehydrating domestic wells that have run dry, and supporting groundwater dependent ecosystems. The tool considers recharge suitability at the ground surface through the inclusion of the Soil Agricultural Groundwater Banking Index (SAGBI), developed by researchers at the University of California, Davis (9). We add to this work through the inclusion of subsurface characteristics that could impact the efficacy of recharge projects, including the depth to groundwater, percent of coarse soil materials to a depth of 250 feet below the ground surface, and the depth and thickness of the Corcoran clay, a low permeability layer found throughout much of the Central Valley that can inhibit recharge (10–

13). We also include a consideration of water quality in the tool, by accounting for surficial nitrogen balances that pose a risk of leaching nitrate into groundwater. By prioritizing locations with less nitrogen accumulation in the soils, a managed aquifer recharge project is less likely to introduce new contamination into groundwater (14).

In addition to a consideration of surface and subsurface conditions and water quality, we designed the decision support tool to allow a user to consider additional benefits that can be achieved through recharge projects, along with feasibility considerations related to initial project construction and cost. The additional benefits in the decision support tool include the ability of groundwater recharge projects to rehydrate wells that have run dry and to support potential groundwater dependent ecosystems. The tool considers the proximity of a potential recharge project location to self-reported dry domestic wells and groundwater dependent ecosystems by giving preference to managed recharge locations near these sites in order to increase the likelihood of creating benefits. We also incorporate the feasibility considerations of proximity of a potential recharge project location to existing water conveyance infrastructure included in the National Hydrography Dataset. Siting groundwater recharge projects closer to existing conveyance allows GSAs an opportunity to reduce costs associated with constructing new infrastructure for transporting water to the managed recharge site. Lastly, the decision support tool considers the proximity of a potential recharge site to a listed contamination cleanup site in the State Water Resources Control Board GeoTracker Database. It is likely preferable to conduct recharge farther from these locations to reduce the risk of introducing new contaminants into the groundwater.

The result of our research is a Central Valley wide, transferable, publicly available decision support tool that can be used to identify areas best suited for achieving multiple benefits from groundwater recharge projects within a specified groundwater basin. The tool prioritizes areas within a basin that have conditions best suited to allow water to infiltrate and percolate into the underlying aquifers while presenting the least risk to adding nitrate contamination to the groundwater. The tool also allows for flexibility in determining the relative importance of the available benefit and feasibility considerations, such that the outputs can be customized to fit the interests and priorities of an individual basin. This functionality allows for the exploration of many scenarios and benefit schemes to assist in the optimal siting of groundwater recharge projects on a basin specific scale.

Implementation of the Sustainable Groundwater Management Act over the next twenty years is likely to include a substantial increase in the size and number of groundwater recharge efforts throughout critically overdrafted groundwater basins in the Central Valley. Our decision support

tool adds depth and breadth to existing knowledge regarding the best areas to locate groundwater recharge projects in order to capitalize on the opportunity to design projects that benefit communities, ecosystems, and the long-term sustainability of water resources.

# 1 Background

## 1.1 Groundwater in California

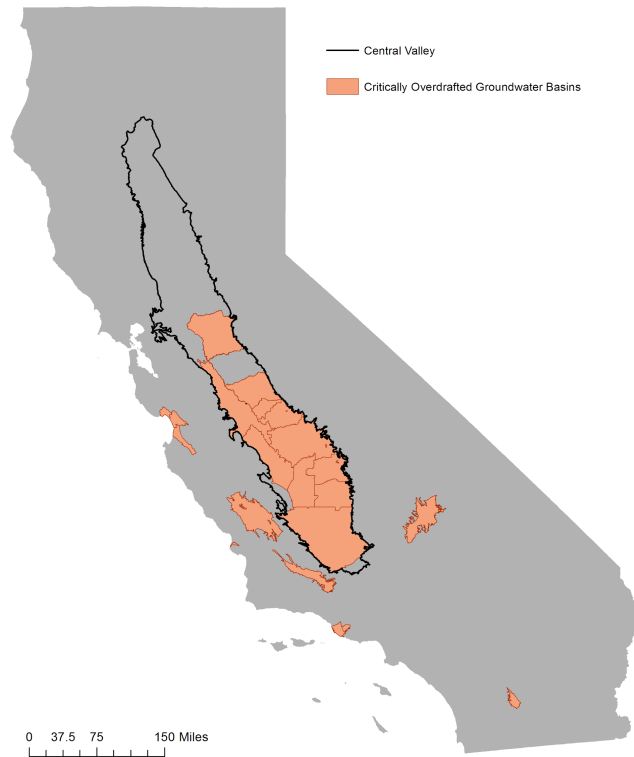
California's groundwater is being depleted at unsustainable rates in many areas, particularly the semi-arid, intensively cultivated Central Valley (15). The Central Valley accounts for one-sixth of irrigated land in the United States and is responsible for one-fifth of the country's groundwater demand (16). Recent extreme drought (2011-2014) combined with the production of water-intensive crops in the Central Valley have exacerbated groundwater depletion (3). Regions with low annual precipitation and large water demand are unable to depend solely on naturally recharged groundwater, and therefore overdraft is most severe in drought years (17). With climate change posing the potential for increased groundwater extraction rates due to higher variability in surface water supply, even areas with high precipitation may not be able to rely only on natural recharge (18). In the semi-arid Central Valley 43% of the water supply comes from groundwater on average, but reliance on groundwater to meet demand can range from about 30% in wet years to up to 70% during extremely dry years (19). This consistent reliance on groundwater to meet water demand has caused widespread overdraft. Overdraft is defined by the CA Department of Water Resources (DWR) as, "the condition of a groundwater basin in which the amount of water withdrawn by pumping exceeds the amount of water that recharges the basin over a period of years, during which the water supply conditions approximate average conditions." (4) Overdraft and low rates of natural recharge during drought years have caused land subsidence and subsequent loss of groundwater storage (20).

Options to abate the negative effects of overdraft in the Central Valley include: 1) substantially reducing pumping or 2) intentionally adding to groundwater storage (17). Because agriculture is an important part of the Central Valley's economy, it is impractical to cease pumping groundwater altogether; agriculture is directly responsible for 15.6% of the total regional economic output and 12.6% of employment in the Central Valley (21). Therefore, capturing water in wet years to store in underground aquifers for later use can be a preferred approach to sustainably managing groundwater, as opposed to demand reduction strategies such as retiring cropland. Groundwater storage has advantages over surface reservoirs because there is a very low rate of evaporation (about 1%) (17) of water stored underground and, in California, the amount of available subterranean storage is six times greater than available surface storage (17). Additionally, subsurface storage and pumping is more cost-effective than desalination or reservoir expansion (18). The demand for groundwater storage is intensifying with the impacts of climate change. Projected impacts of climate change include increased frequency of

droughts and floods, and a decrease in the slow-melting snowpack in the Sierra Nevada Mountains, which has been referred to as California's natural water "safety net" representing the largest surface water storage in the state (18).

## 1.2 The Sustainable Groundwater Management Act

The Sustainable Groundwater Management Act (SGMA) of California, passed in 2014, launched the state on the path towards returning groundwater basins to balance by requiring that outflows are less than inflows (5–7). This legislative package is designed to halt or reverse the numerous undesirable results associated with unsustainable groundwater use, including: lowering of groundwater levels, seawater intrusion, land subsidence, reduction in groundwater storage, surface water depletion, and degraded groundwater quality (22). Groundwater basins designated as critically overdrafted by the Department of Water Resources were required to submit a Groundwater Sustainability Plan (GSP) to the Department of Water Resources by January 31, 2020 (6). Many of these basins are located in the southern half of the Central Valley, or San Joaquin Valley (Figure 1.1). Basins not designated as critically overdrafted must submit GSPs by January 31, 2022 (6). Within each GSP, Groundwater Sustainability Agencies (GSAs) must determine the sustainable yield for the groundwater basin and identify management activities that, when implemented, will result in attainment of the sustainable yield within 20 years of plan submission (23). The sustainable yield of a basin is defined by SGMA as "the maximum quantity - calculated over a base period representative of long-term conditions in the basin and including any temporary surplus - that can be withdrawn annually from a groundwater supply without causing an undesirable result" (5–7). Additionally, GSAs are encouraged to incorporate multiple benefits such as improved water quality and ecosystem health in their sustainability projects (61).



**Figure 1.1 Critically overdrafted groundwater basins in California.** The California Department of Water Resources (DWR) identified groundwater basins within the state that are subject to conditions of critical overdraft. Per the Sustainable Groundwater Management Act of 2014, a basin is subject to critical overdraft conditions when “continuation of present water management practices would probably result in significant adverse overdraft-related environmental, social, or economic impacts” (5–7). Most of the critically overdrafted basins identified by the Department of Water Resources (DWR) are in the southern portion of the Central Valley. Location of critically overdrafted basins sourced from California Department of Water Resources (24).

While there are a suite of management options available for attaining sustainability (22), Managed Aquifer Recharge (MAR) is an attractive option many that GSAs have included in their plans. The Department of Water Resources is supportive of GSAs adopting managed aquifer recharge as a management strategy due to the potential for it to provide multiple benefits in addition to SGMA compliance and avoidance of undesirable results (25). While the Department of Water Resources and SGMA encourage GSAs to include managed groundwater recharge in their portfolio of management strategies, currently many water managers do not have a method to locate the ideal sites to achieve multiple benefits for water quality, ecology and storage.

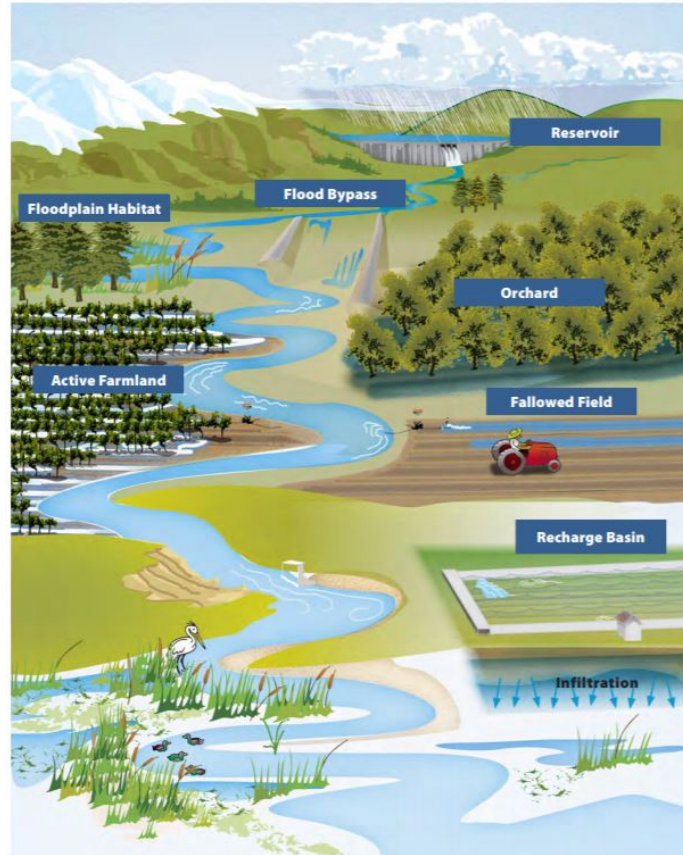


## 1.3 Groundwater Recharge

Groundwater recharge is the “downward flow of water reaching the groundwater table, adding to groundwater storage” (26). Groundwater recharge can occur through a variety of mechanisms, some of which happen naturally and others as part of an intentional management strategy. Natural recharge mechanisms include precipitation falling directly on a permeable surface where it infiltrates into the subsurface and percolates down to the water table, or water in ephemeral or perennial surface-water bodies infiltrating and percolating down to the water table (27). Recharge can also happen incidentally from excess irrigation water (27). However, with projected climate change impacts, groundwater recharged via natural and incidental mechanisms is expected to decrease by an average of 5% by 2100 (27), suggesting an increase in the need for managed aquifer recharge in the future. .

### 1.3.1 What is Managed Aquifer Recharge?

The most common methods of managed aquifer recharge (MAR) include injection wells - where high pressure pumps actively move surface water into an aquifer - and infiltration basins- where constructed basins hold surface water and allow it to infiltrate and percolate down to the water table (28). Directly injecting surface water into the aquifer via an injection well was first used in California to mitigate seawater intrusion coastal groundwater basins by creating a hydraulic barrier (29). Injection wells are less preferable for MAR in inland basins, both because they are more energy intensive and present a greater risk to releasing naturally occurring contaminants in the sub-surface than infiltration basins (30,31). Flooding agricultural land with surface water for the purpose of recharge, often referred to as on-farm recharge, is another mechanism for MAR that is particularly attractive in the Central Valley where agricultural land is abundant and open areas for constructing recharge ponds may be limited (9). Though there is much interest and support for this method (9,18,25), it is relatively new and currently only implemented in limited case studies (32).



**Figure 1.2 Schematic of managed aquifer recharge methods.** This schematic shows the variety of methods by which reservoir release and flood flow surface water can be used to replenish the underlying aquifer. These methods can be implemented concurrently in the same region to improve the resilience of California’s water supplies (25).

In all methods of MAR there are a common set of surface conditions that need to be considered, except in the case of direct injection where near surface conditions are not as influential for recharge. The first consideration is how rapidly water can infiltrate into the underlying soil, measured by a soil’s infiltration capacity, or the maximum rate at which it is able to soak into the soil (33). The topographic slope of the land surface is another important consideration, as steep slopes would cause water to runoff more rapidly than it could infiltrate. Once water is in the subsurface, it is important in all methods of MAR to consider the ability of water to percolate down to the water table. Groundwater movement is a complex process determined by a number of factors that influence both velocity and direction of movement. These include, but are not limited to, the porosity of the substrate the water is moving through, existing pressure heads and gradients, and the presence of any confining substrate layers that may inhibit movement (33). An important consideration specific to active farmland recharge projects (Figure 1.2) is the amount of time water will spend in the root-zone during infiltration, as the prolonged presence of water in this zone of the subsurface can negatively impact perennial crops (9).

### 1.3.2 Managed Aquifer Recharge in California

The ability for an infiltration basin or on-farm managed aquifer recharge (MAR) project to effectively replenish groundwater supplies depends on the surface and subsurface conditions of the project site (31). Geologic conditions affect the movement of water in the subsurface; however, these conditions are heterogeneous and difficult to characterize with enough resolution to accurately represent actual conditions (33). Even complex and widely used models describing regional groundwater flows often involve simplifying subsurface conditions (34,35). Several studies and decision support tools have synthesized data to assess MAR project site suitability in California include approximations of the more complex processes of water infiltration and percolation (9,31,36).

One such study evaluated the potential benefits of managed aquifer recharge in coastal basins dealing with seawater intrusion, with a specific focus on the Pajaro Basin (31). Eleven factors relating to surface and subsurface conditions were weighted and analyzed according to a recharge favorability ranking system established for the study. Weights were assigned to each dataset based on their perceived importance to siting potential MAR projects (31); there is no widely agreed upon standardized weighting system (37).

Researchers at UC Davis developed the Soil Agricultural Groundwater Banking Index (SAGBI) to identify suitable locations for on-farm recharge projects in California, primarily in the Central Valley (9). This index is a weighted combination of five factors related to siting on-farm managed recharge projects, including: deep percolation (to 6 feet), root zone residence time (to consider the risk of crop damage), topography, soil salinity and soil surface condition (a measure of compaction) (10). SAGBI developers identify limitations of their research as not including proximity to existing infrastructure or depth to the water table (10). Managed recharge projects closer to existing water delivery infrastructure will likely result in lower construction and conveyance costs (38,39), and on-farm recharge is more likely to occur on land that has access to existing canals and irrigation ditches (25). Assessments need to be conducted on the regional level to determine whether existing infrastructure can accommodate the high magnitude flows related to managed aquifer recharge projects (40). Depth to the water table is important to consider to ensure that adequate storage capacity exists in the aquifer to accommodate inputs from surface water (38). In addition to the identified limitations, it is important to consider water movement in the deeper subsurface, beyond the six feet considered in SAGBI, in order for managed recharge projects to replenish groundwater supplies (64).

Sustainable Conservation, a California based environmental non-profit organization, developed the Groundwater Recharge Assessment Tool (GRAT) to assist GSAs in identifying the most cost-effective options for groundwater recharge in their basin (36). GRAT models the best locations (considering soil type, crop type and proximity to infrastructure), timing and water quantity

recommended for recharge in a given region (38). GRAT is a proprietary tool and therefore detailed information about its development is not readily available. The tool has only been implemented within the jurisdiction of Madera Irrigation District, Tulare Irrigation District, and Rosedale-Rio Bravo Water Storage District (41). While GRAT takes a multi-faceted approach, it relies on data supplied by the groundwater sustainability agencies (GSAs) to generate results (63).

While implementation of the Sustainable Groundwater Management Act (SGMA) has generated more interest in MAR as a management strategy for sustainably managing groundwater resources, there are many examples of successful groundwater recharge projects that have been operating for years in the Central Valley. Among these are the Kern Water Bank and water storage districts such as the Semitropic Water Storage District. The Kern Water Bank, located in Kern county and in operation since 1985, directs surplus surface water during wet years into the Kern Fan aquifer and recovers stored water for use during dry years (42). In its 25 years of operation, the Kern Water Bank has stored 2.8 Million Acre Feet (MAF) of water, and recovered 1.6 MAF for its customers through pumping (42). In addition to recharging groundwater supplies, the Kern Water Bank has restored 17,000 acres of farmland to upland and intermittent wetland habitat, providing habitat for threatened and endangered species such as the San Joaquin Kit Fox and Tipton Kangaroo Rat (43).

Semitropic Water Storage District, established in 1958 and also located in Kern county, began the Semitropic Groundwater Storage Bank in the early 1990s. This groundwater banking program has recharged approximately 700,000 acre-feet of water in its operational history and is able to deliver 90,000 acre-feet of water per year to banking partners who have supplied water in previous years (44). Other water storage districts, such as Rosedale-Rio Bravo Water Storage District, also have long standing groundwater recharge projects in the Central Valley (45).

The California Department of Water Resources has expressed support for using managed aquifer recharge as a strategy to reach groundwater sustainability (25). In response, the Pixley Irrigation District, Tulare Lake Subbasin, Madera Subbasin, Merced Subbasin and several other Groundwater Sustainability Agencies across the Central Valley have submitted GSPs that include recharge projects for SGMA compliance (46–48).

### 1.3.3 Potential Benefits of Recharge Projects

In addition to being a management strategy for achieving groundwater sustainability, managed aquifer recharge projects can potentially provide many additional public and private benefits including: flood risk reduction, ecosystem enhancement, drought preparedness, climate change adaptation, subsidence mitigation, water quality improvement, and recreation and aesthetics (25). A subsection of these benefits are addressed in more detail in the following sections, broadly divided into benefits associated with increased water quantity and benefits associated with water quality.

#### 1.3.3.1 Water Quantity

Declining groundwater levels can lead to less reliable domestic drinking water supplies for individuals and communities reliant on groundwater. This has been shown to be particularly true for domestic wells in rural areas surrounded by lands with high agricultural productivity, such as the Central Valley (49). In the Western United States, it is estimated that 1-in-30 wells constructed between 1950-2015 were likely dry during a two year study period from 2013-2015 (49), which corresponds with a multi-state drought during the same time period (50). While options exist for improving domestic water reliability, such as drilling deeper wells or trucking in water deliveries to households, these options are costly (49). Often, the cost burden of this groundwater depletion is borne by domestic well owners, and not by the high-volume pumpers of deeper agricultural wells (51). MAR can potentially help improve water supply reliability in these areas (25).

In addition to impacting water supply reliability, declining groundwater levels can also negatively impact ecosystems reliant on groundwater for their function and persistence. These systems, referred to as groundwater dependent ecosystems (GDEs), can be coastal, aquatic, or terrestrial. There are a variety of GDEs, with examples ranging from vegetation communities that primarily access water from subsurface sources to streams that rely on groundwater to maintain base-flows in the dry season (52,53). Wetlands are also classified as GDEs, and while declining groundwater levels have impacted these systems, land use change has led to over 90% loss of natural wetlands in California (54). Under the Sustainable Groundwater Management Act (SGMA), Groundwater Sustainability Agencies (GSAs) must identify potential GDEs in their basins and consider how they will be affected when making management decisions (5–7). Methods for managing groundwater to benefit GDEs and augment habitat previously lost by land use changes have been developed, and adoption of these practices is incentivized by the Sustainable Groundwater Management Act (55). One effective method to address the health and resilience of groundwater dependent ecosystems is to site MAR projects near these ecosystems to increase groundwater levels and potentially preserve habitat (54,56).

### 1.3.3.2 Water Quality

Managed aquifer recharge has the potential to either improve or degrade water quality. The effect of an individual recharge project on groundwater quality depends on contaminant concentrations and the redox conditions of the water being recharged, and the redox conditions of the geologic substrate (30,57). Nitrate contamination of water supplies is of particular concern in highly productive agricultural regions like the Central Valley. Nitrate loads can be removed from percolating water if the subsurface conditions are anoxic, improving the water quality of groundwater supplies (57). However, MAR also has the potential to introduce new nitrate contamination into groundwater by transporting legacy nitrate from the vadose zone into groundwater supplies (58). This potential is largely dependent on the existing abundance of nitrate in the vadose zone, which is higher when high nutrient input crops, such as tomatoes or almonds, have been grown on the land (58). Additionally, MAR is less likely to introduce new nitrate contamination into groundwater supplies when water is recharged consistently in one area and in large volumes (14).

Nitrate is not the only contaminant to consider when recharging groundwater supplies. Naturally occurring elements in soils and sediments, known as geogenic contaminants, such as arsenic or chromium can be released from the sediment into groundwater supplies by recharge activities (30). Notably, even if source water for recharge contains no geogenic contaminants it can introduce new contaminants into groundwater supplies if the redox and pH conditions of the source water and groundwater are sufficiently different (30). Additionally, transport of pesticides into groundwater via MAR is a concern. To reduce risk of introducing pesticide contamination, the California Department of Pesticide Regulation (DPR) prohibits MAR within six months after the application of a pesticide on a specific site, and pesticides used on agricultural land must decay after three weeks of application (59). Commonly used tools for siting managed aquifer recharge projects, such as the Groundwater Recharge Assessment Tool (GRAT) and the Soil Agricultural Groundwater Banking Index (SAGBI), do not account for many important contamination factors that can affect drinking water quality such as nitrates, pesticides, or geogenic contaminants (10,38).

### 1.3.4 Source Water for Recharge

For many groundwater sustainability agencies, complying with the Sustainable Groundwater Management Act (SGMA) will involve implementing groundwater recharge as a management strategy. The question becomes where water will come from for this planned recharge. Climate change will affect water availability in California; the consensus is that wet areas will get wetter, dry areas will get drier, and the temporal variability of precipitation will increase (27,60). The

temporal divergence of wet and dry conditions comes in conjunction with changes in precipitation intensity, resulting in more extreme flood and drought events (27,60). In addition, a higher proportion of annual precipitation will expectedly fall in the form of rain rather than snow, reducing the Sierra Nevada snowpack and changing the timing and intensity of peak streamflows (25). Given these predicted conditions, using high magnitude flows and flood informed reservoir operations to provide the source water for groundwater recharge, a strategy referred to as Flood-Managed Aquifer Recharge (Flood-MAR), is an attractive option. Flood-MAR is supported by the Department of Water Resources largely because of its ability to provide multiple benefits (25). Flood-MAR involves making flood control releases from surface storage reservoirs in anticipation of large storms and then directing these releases, in part, into MAR projects where the water can replenish groundwater supplies (25,40). An analysis of high-magnitude streamflow availability has shown these flows to be most available for Flood-MAR in the northern Central Valley, or Sacramento River Basin, and northern San Joaquin Valley (40).

High-magnitude stream flows are not the only potential source of water for MAR projects. The Orange County Water District is using recycled water as a source for MAR, using injection wells to directly recharge the aquifer (22). The Orange County groundwater basin is primarily urban, supplying water to approximately 2.4 million residents (22). While using recycled water as a source for MAR is a viable option in this setting, where large volumes of wastewater are consistently produced and treated in close proximity to recharge locations, it may not be as effective in less populous areas in the Central Valley. Another water source option for MAR is purchasing surface water imported from elsewhere in the state through the state water market, though this is more expensive than utilizing flood flows (22). Purchasing surface water during wet years when it is cheaper and storing it in a groundwater bank for use during dry years when water is more expensive can be a viable option for water users with sufficient capital (61). Regardless of the source water used for MAR, the feasibility of transporting water to recharge project sites is an important consideration. In many areas, the lack of sufficient conveyance infrastructure is a constraint for MAR projects (25) but is not always an explicit consideration in managed aquifer recharge project siting.

## 1.4 Project Significance

Many Groundwater Sustainability Plans include managed aquifer recharge as a strategy they will implement to achieve sustainable groundwater use in their basins by 2040, but some have not yet identified the locations of these projects. While there is increasing information available for identifying the best sites for groundwater recharge, a reliable method that includes surface and subsurface conditions while addressing multiple priorities such as water quality, ecosystem

health, domestic water access, and water conveyance feasibility is not publicly available. Existing tools for siting recharge projects such as the Groundwater Recharge Assessment Tool and the Soil Agricultural Groundwater Banking Index do not apply a multi-benefit approach, and are primarily concerned with recharge feasibility and groundwater storage. Additionally, obtaining access to sufficient data and computer models to locate potential recharge sites can be costly (22, 55), and some GSAs may find it difficult to allocate funds for this purpose (62). With the anticipation of many groundwater recharge projects being constructed and implemented in the next several years, it is critical to improve access to information for locating potential recharge sites that can best achieve multiple benefits.



## 2 Objectives

The objective of this project is to develop a transferable decision support toolkit that can be used by Groundwater Sustainability Agencies in California's Central Valley to assist in the planning and implementation of groundwater recharge projects by identifying locations that achieve multiple benefits.

In this project, we incorporate publicly available data from government entities and research institutions to locate the optimal sites for aquifer recharge by considering domestic water supply, nitrate contamination risk, water movement in the surface and subsurface, aquifer storage space, groundwater dependent ecosystems, current land use, and existing infrastructure. By using publicly available data, we aim to make our tool accessible to all GSAs, especially those whose access to adequate information to achieve their sustainability objectives is limited by technological or monetary constraints.

## 3 Methods

We built our multiple benefit groundwater recharge decision support tool in ArcMap Model Builder. The tool incorporates spatial data for California’s Central Valley that was publically available through state agencies and research institutions. We repeated the following workflow at multiple points within the tool (Figure 3.1):

1. Added spatial datasets to the tool;
2. Interpolated the data points, if necessary, to create a continuous surface for the Central Valley study area;
3. Ranked and classified values according to relative suitability for recharge projects;
4. Combined classified values in weighted sums to produce an output.



**Figure 3.1 Workflow used for data analysis in the decision support tool.** Data inputs were interpolated to form continuous surfaces for the project study area. Values were then ranked and classified according to relative recharge suitability before being combined through a weighted sum. The workflow was repeated to provide outputs for suitable recharge locations, surficial nitrogen balances, and additional considerations.

We repeated this workflow when considering surface and subsurface conditions, surficial nitrogen balances, and multiple benefits of managed groundwater recharge projects. All data and methods used to develop the tool are discussed in the following sections. Our decision support tool is transferable to any groundwater basin in California’s Central Valley. Here, we demonstrate the methods used to build the tool with outputs for the Madera Basin, located in the southeastern portion of the Central Valley. We chose the Madera Subbasin as our test case after consultation with our clients at the Environmental Defense Fund and our advisors at the California Department of Water Resources.

### 3.1 Suitable Recharge Locations

Suitable recharge locations are identified in the decision support tool as areas of a basin where water can most easily travel from the surface into the underlying aquifer, with limited risk of introducing new nitrate contamination. To assess a location’s suitability, physical and hydrogeological data for surface and subsurface conditions related to groundwater recharge

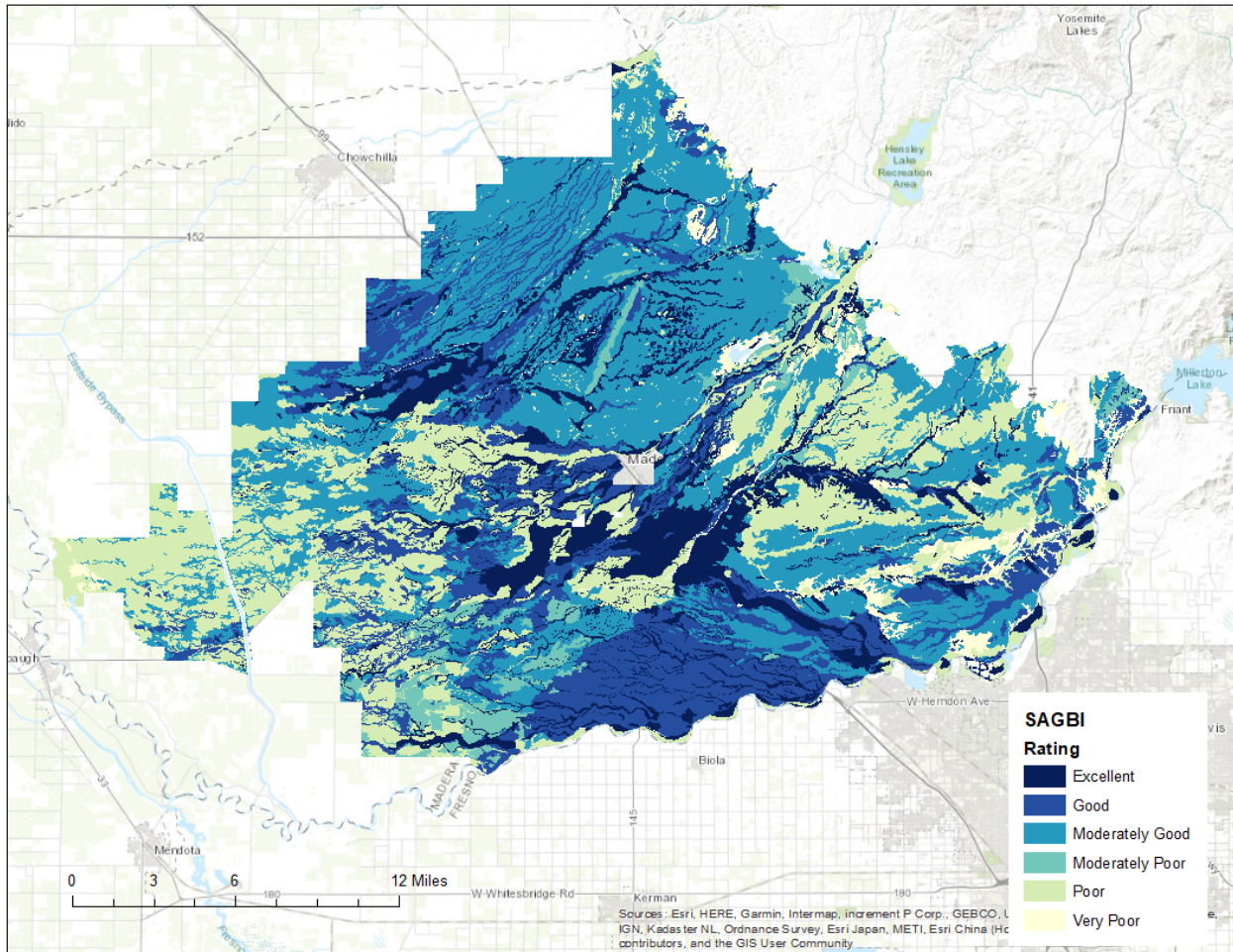
were integrated with water quality considerations. The data selected for analysis, the associated processing methods, and their utilization in the decision support tool are discussed in detail in the following sections.

### 3.1.1 Surface and Subsurface Conditions

The surface and subsurface component of the decision support tool identifies locations within a groundwater basin where water can effectively infiltrate into the subsurface and percolate through deeper substrates to reach the groundwater table. Four geospatial datasets were included in this tool component: the Soil Agricultural Groundwater Banking Index (SAGBI), depth to groundwater, percent of coarse grained soil material, and Corcoran clay depth and thickness.

#### 3.1.1.1 Soil Agricultural Groundwater Banking Index (SAGBI)

The Soil Agricultural Groundwater Banking Index (SAGBI) is a tool designed to identify surface and near surface soil conditions that are suitable for groundwater recharge (9). SAGBI includes five differentially weighted considerations: topographic limitations (20%), surface condition (5%), root zone residence time (27.5%), deep percolation (27.5%), and chemical limitations (20%). SAGBI provides a resulting index score for recharge suitability for a given location, ranging from 0 (Very Poor) to 100 (Excellent) (Figure 3.2) (9).



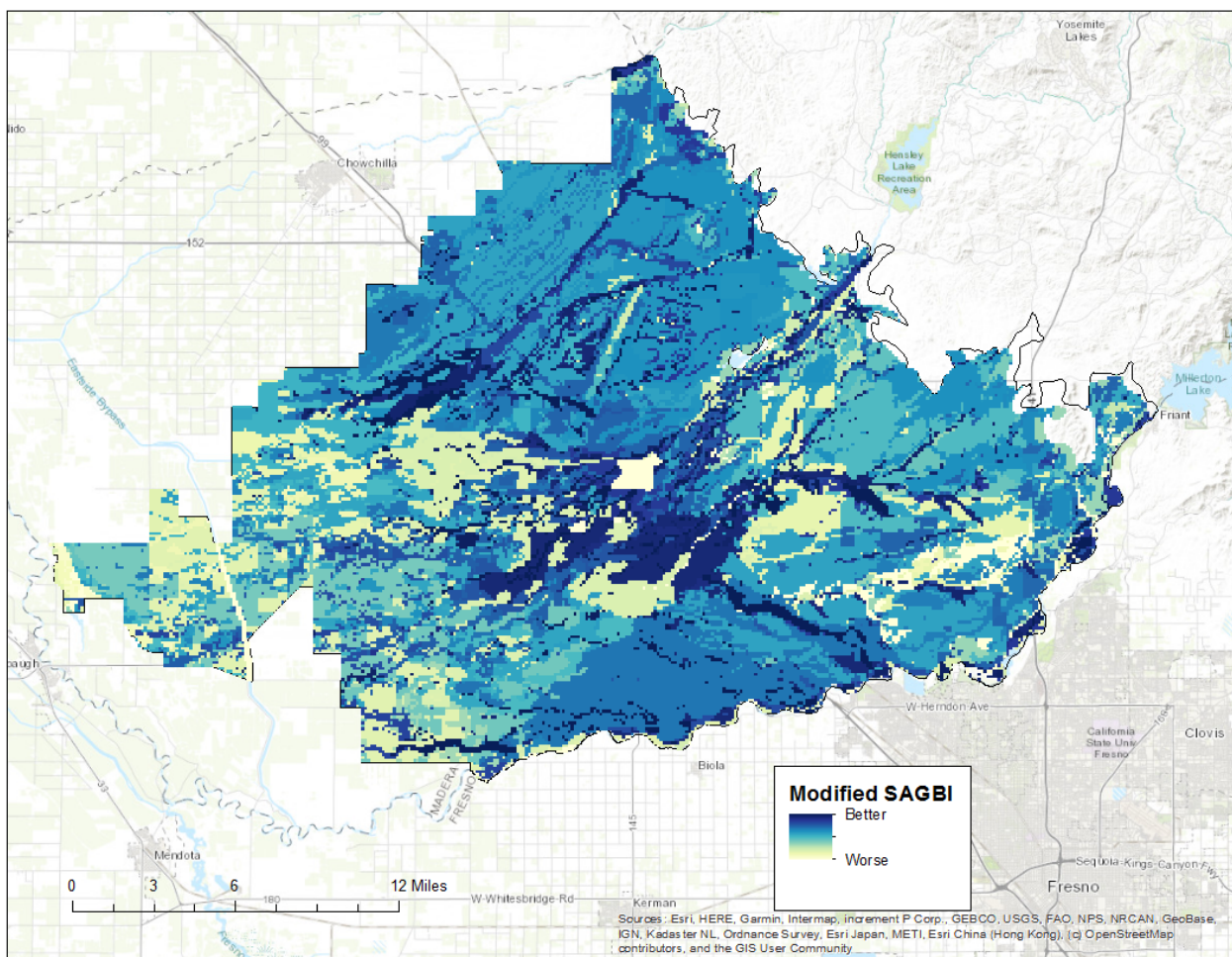
**Figure 3.2 Soil Agricultural Groundwater Banking Index values for the Madera Subbasin.** The index assesses recharge suitability at the surface and near subsurface through the inclusion of topographic limitations, surface condition, root zone residence time, deep percolation, and chemical limitations. Areas rated as excellent for recharge (darkest blue) are located to the south of the city of Madera and in bands in the northern part of the basin. Data from California Soil Resource Lab at UC Davis and US ANR (62).

SAGBI was developed primarily as a tool to consider on-farm managed aquifer recharge projects. The root zone residence time component of SAGBI accounts for the potential of groundwater recharge on agricultural lands to negatively impact crop productivity through periods of prolonged inundation. Our decision support tool considers recharge potential on both agricultural and non-agricultural lands; as such, we modified the SAGBI dataset to remove the consideration of root zone residence time for non-agricultural lands.

We used the 2016 National Land Cover Database (NLCD) to identify active agricultural lands throughout the Central Valley (63). The NLCD provides data on land cover type at a 30m resolution with a 16-class legend based on a modified Anderson Level II classification system (63,64). For locations designated in the NLCD as Cultivated Crops, the original SAGBI rating

was retained. For non-agricultural areas, the root zone residence time score was removed from the SAGBI dataset, and the 27.5% weighting for that component was re-distributed equally across the four remaining SAGBI components, resulting in a final weighting of: topographic limitations (26.9%), surface condition (11.9%), deep percolation (34.4%), and chemical limitations (26.9%).

The two resulting SAGBI subsets were combined to form a continuous layer across all land use types (Figure 3.3). We then divided the index values into 6 score-ranges used by SAGBI developers and ranked them according to recharge suitability from better to worse (Table 3.1) (9).



**Figure 3.3 Modified Soil Agricultural Groundwater Banking Index values for the Madera Subbasin.** The decision support tool considers recharge potential on both agricultural and non-agricultural lands. The Soil Agricultural Groundwater Banking Index includes root zone residence time in its assessment of recharge suitability, which does not apply to non-agricultural lands. Using the National Land Cover Dataset (63), we removed the root zone residence time consideration for non-agricultural lands to avoid underscoring an area’s suitability. Relatively better (dark blue) areas for recharge are located south of Madera in and in bands throughout the northern portion of the basin, with

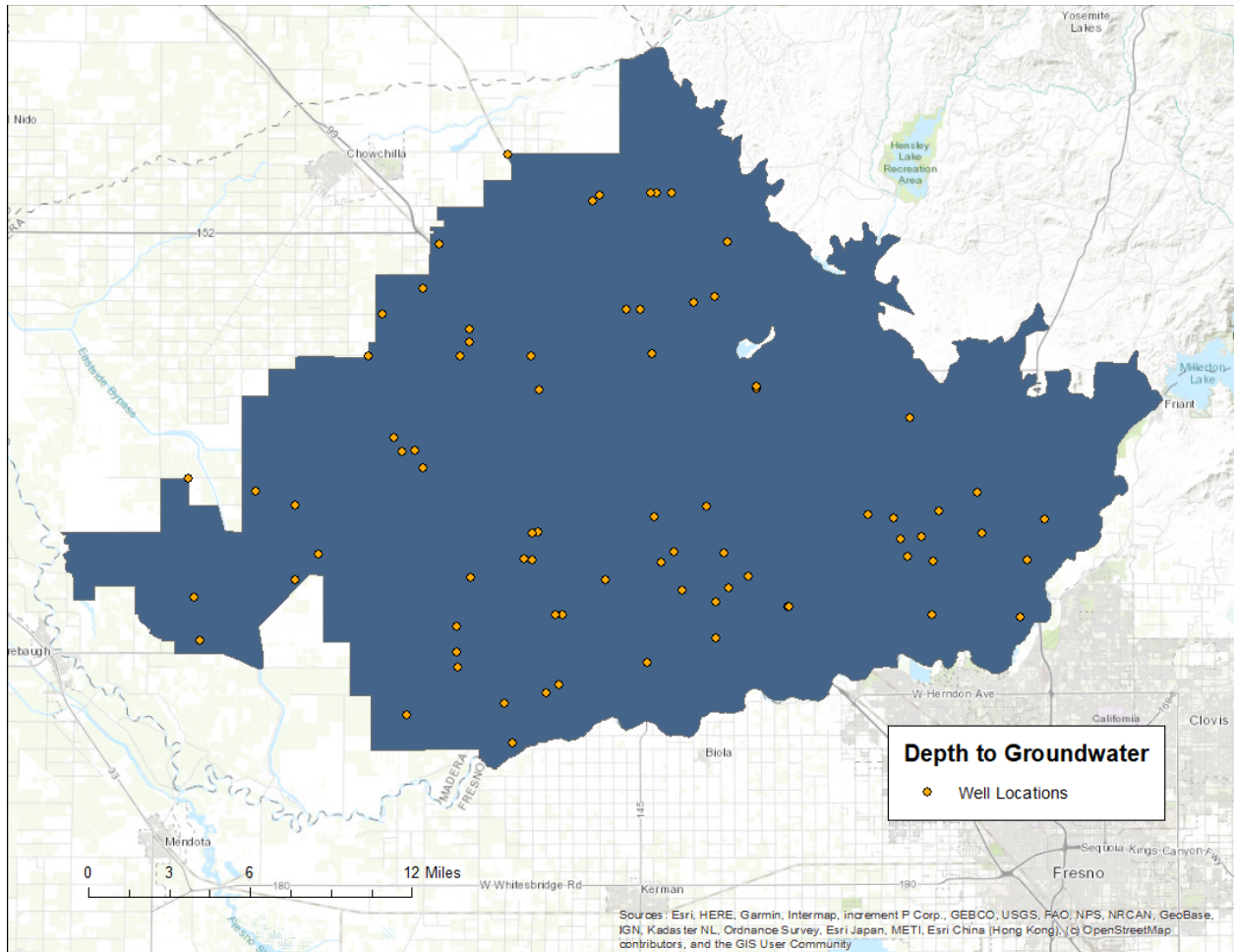
relatively worse areas (yellow) located in the western portion of the basin. Data from California Soil Resource Lab at UC Davis and US ANR (62).

**Table 3.1 Modified Soil Agricultural Groundwater Banking Index (SAGBI) score reclassification based on suitability for groundwater recharge.** Score ranges within each recharge ranking follow the same breakpoint method used by SAGBI developers, which was based on natural jenks in the original dataset. Data source: UC Davis Center for Watershed Sciences (9).

Recharge Ranking	Modified SAGBI Score
1 - Better	85 - 100
2	69 - 85
3	49 - 69
4	29 - 49
5	15 - 29
6 - Worse	0 - 15

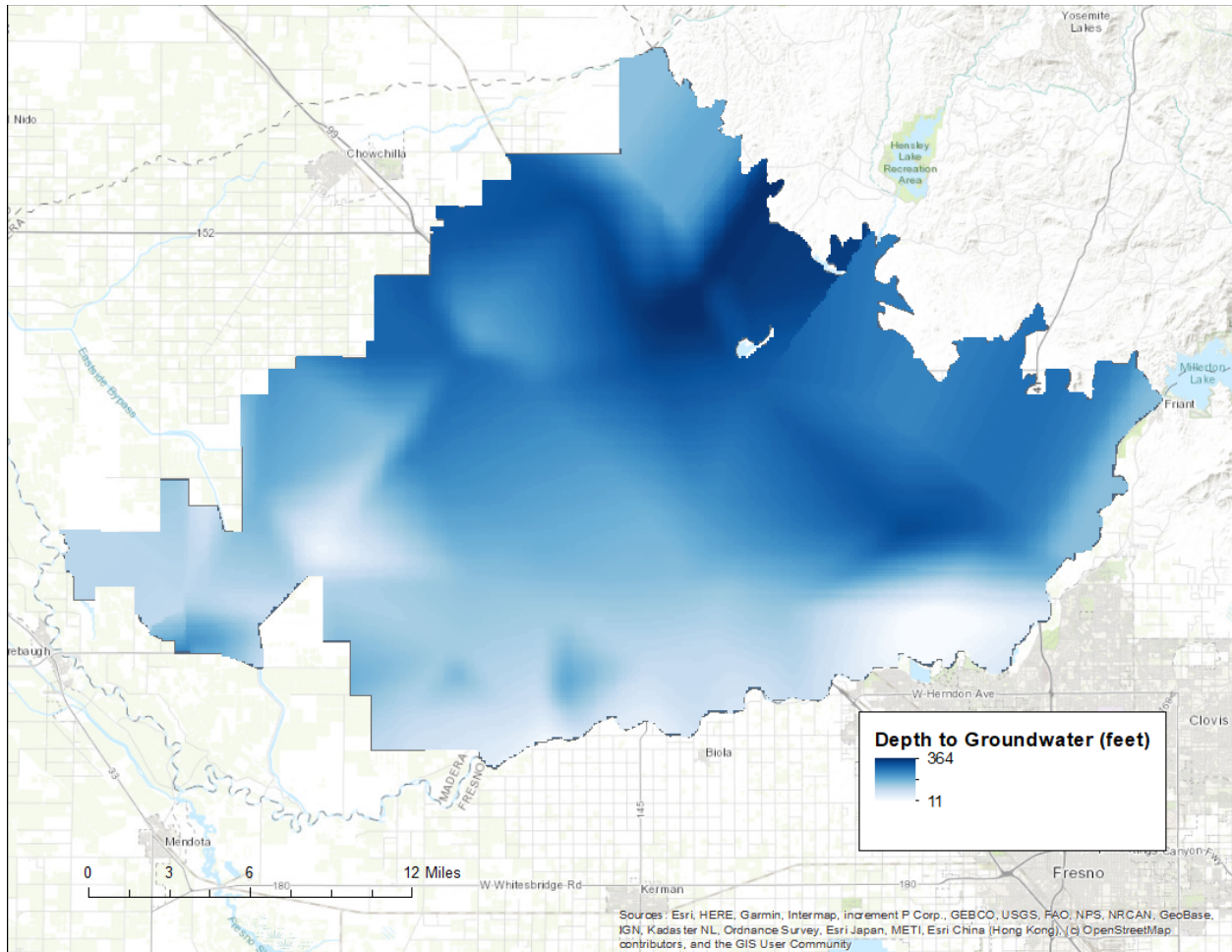
### 3.1.1.2 Depth to Groundwater

Depth to groundwater measures the vertical distance between the ground surface and the groundwater level. We used data from the California Department of Water Resources (CA DWR) which includes point observations collected from wells measured in feet below ground surface (Figure 3.4) (12).



**Figure 3.4** Location of wells included in the California Department of Water Resources depth to groundwater dataset for the Madera Subbasin. Depth to water values are provided as point data measured in feet below the ground surface. Data from CA DWR (12).

We interpolated these data points to create a continuous surface of depth to groundwater measurements (Figure 3.5). After considering alternative methods such as kriging, we selected Inverse Distance Weighting (IDW) as the interpolation method. We did not have information related to spatial correlation or directional bias in the data and therefore considered IDW to be more conservative than alternative methods.



**Figure 3.5 Interpolated depth to groundwater values for the Madera Subbasin.** Point data were interpolated using inverse distance weighting in order to create a continuous layer of depth to groundwater values. Locations with a greater depth to groundwater (dark blue) have more available aquifer space to store recharged water. The water table is deepest in the northeastern portion of the basin. Areas where the water table is close to the ground surface are found along the southern and western basin boundaries. Data from CA Department of Water Resources (12).

The values within the depth to groundwater surface were then reclassified into six bins based on suitability for recharge (Table 3.2). Higher depth to groundwater values, which denote locations where the water table is located farther below the ground surface, have more space for recharged water and are considered more suitable.

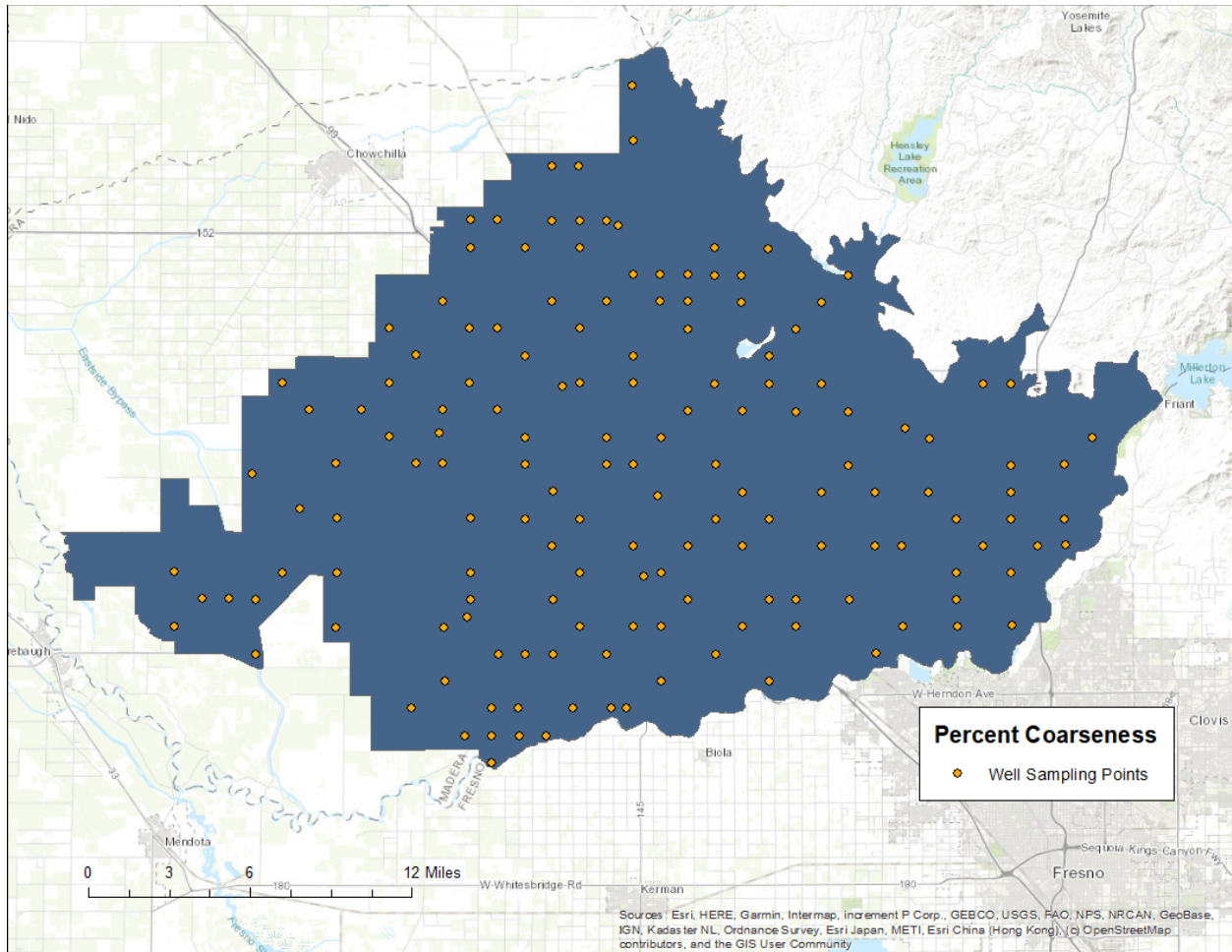


**Table 3.2 Depth to groundwater (ft) reclassification based on suitability for groundwater recharge.** Ranges of depths within each recharge ranking are designed to reflect a deeper groundwater table as more suitable for recharge. Data source: CA Department of Water Resources (12).

<b>Recharge Ranking</b>	<b>Depth to Groundwater in feet (meters)</b>
1 - Better	600 - 700+ (183 - 213+)
2	500 - 600 (152 - 183)
3	100 - 500 (30 - 152)
4	50 - 100 (15 - 30)
5	10 - 50 (3 - 15)
6 - Worse	0 - 10 (0 - 3)

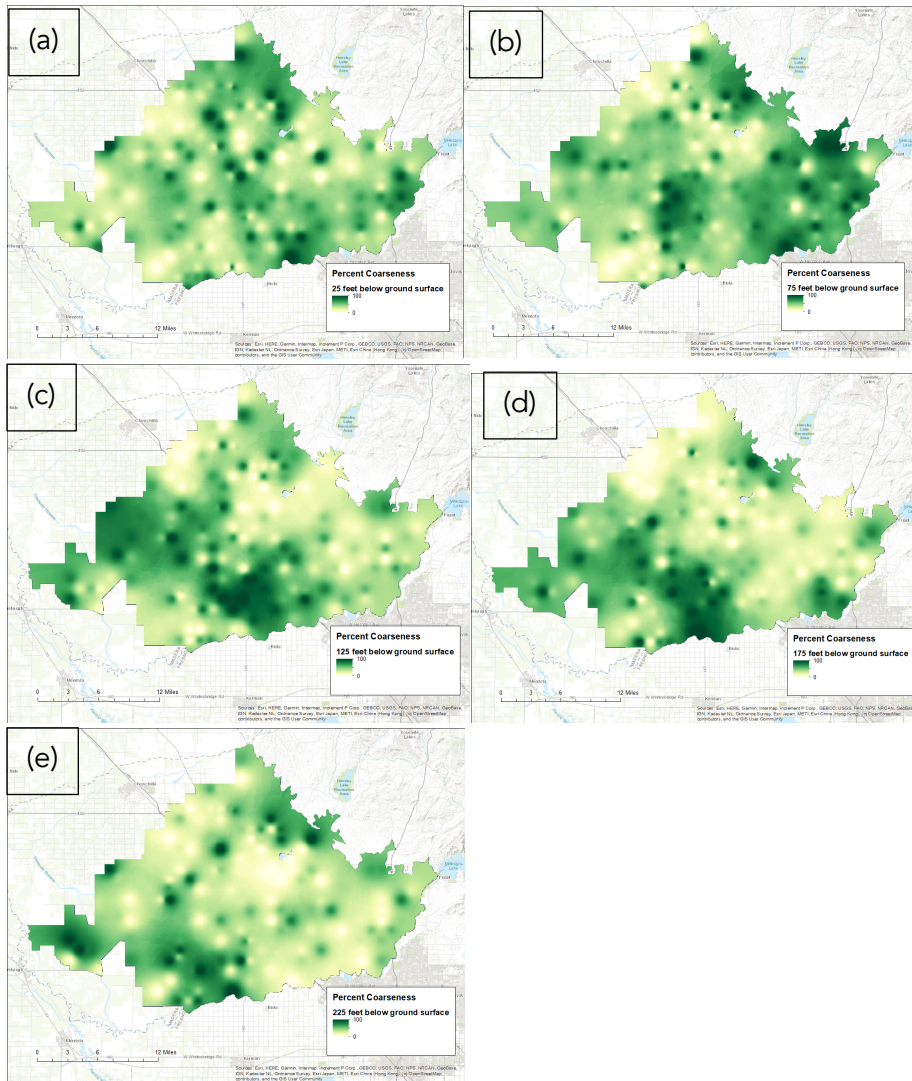
### 3.1.1.3 Percent of Coarse Grained Soils

Percent of coarse grained soils data, which characterizes soil texture, were incorporated into the decision support tool to assess how easily recharged water could percolate through deeper substrates. We used percent of coarse soil material data from the texture model of the Central Valley Hydrologic Model (CVHM) (65). The texture model was created using lithologic data from 8,497 well drilling logs throughout the Central Valley (13). Each interval contained within the well log was divided into a binary texture classification of either “coarse grained” or “fine grained”. Coarse grained soils consist of sand, gravel, pebbles, boulders, cobbles, or conglomerate. Fine grained soils consist of clay, loam, lime, mud, or silt. The binary classifications were organized into stacked vertical bands of 50 ft, beginning at the ground surface down to a depth of 2,300 ft below ground surface. The percent of coarse material was calculated for each layer and assigned to the midpoint of the layer (13).



**Figure 3.6 Locations of well logs used in the Central Valley Hydrologic Model texture model.** Percent of coarse soil material is used in the decision support tool as a proxy for vertical hydraulic conductivity and is a measure of how easily recharged water can infiltrate and percolate through substrates and reach the water table. Percent of coarse soil material is calculated in the texture model through analysis of drilling logs and a binary classification system. Data from Central Valley Hydrologic Model Texture Model (65).

Our decision support tool considers the percent of coarse material from the ground surface to a depth of 250 ft below ground surface. The percent of coarse grained soils data are point observations from each well log included in the analysis (Figure 3.6). We interpolated these data using Inverse Distance Weighting to create a continuous surface of values for each depth layer (Figure 3.7).



**Figure 3.7 Interpolated percent of coarse soil material layers for the Madera Subbasin.** Data layers are included at depths from the ground surface of 25 feet (a), 75 ft (b), 125 feet (c), 175 (d) and 225 feet (e). Higher percentages of coarse soil material (darkest green) will allow recharge water to more easily infiltrate and percolate from the subsurface to the water table. Data from Central Valley Hydrologic Model Texture Model (65).

We then reclassified the values into six bins based on suitability for recharge (Table 3.3). We used the United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS) Saturated Hydraulic Conductivity in Relation to Soil Texture to determine the recharge suitability for each binned range of percent of coarse material values (66,67). Percent coarseness values with the highest associated hydraulic conductivity were ranked better for recharge while percent coarseness values with lower associated hydraulic conductivity were ranked worse.

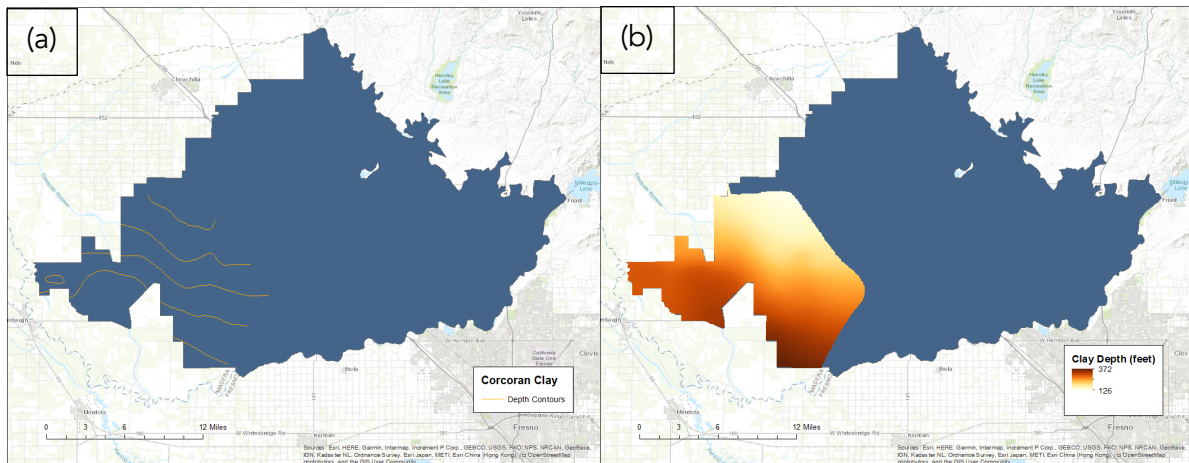
**Table 3.3 Percent of coarse soil material reclassification based on suitability for groundwater recharge.** Ranges of percent coarseness within each recharge ranking are designed to reflect coarser soil material as more suitable for recharge. Data source: Central Valley Hydrologic Model (13).

Recharge Ranking	Percent of Coarse Soil Material
1 - Better	90 - 100%
2	70 - 90%
3	50 - 70%
4	20 - 50%
5	10 - 20%
6 - Worse	0 - 10%

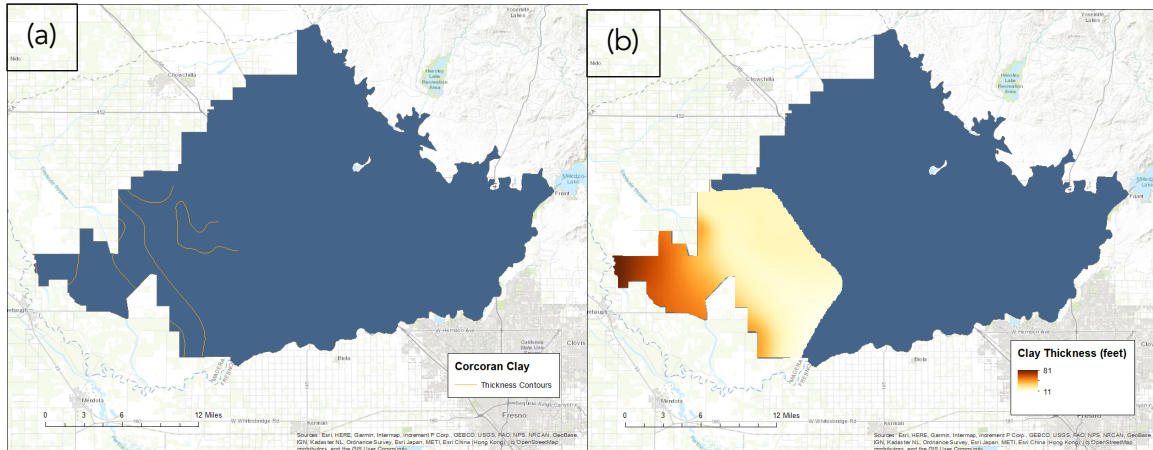
### 3.1.1.4 Corcoran Clay

Corcoran clay is a low permeability soil layer that underlies much of the western portion of the San Joaquin Valley and has the potential to inhibit vertical water movement in the subsurface (35). We consider both the depth of the Corcoran clay layer and its thickness, with the data provided by the United States Geological Survey (USGS) (10,11).

The data layers for both Corcoran clay depth and thickness were downloaded as contour lines and required interpolation to create continuous surfaces (Figures 3.8 and 3.9). The interpolated layers for depth and thickness were constrained by a data layer for the Corcoran clay extent, as the clay does not underlie the entirety of the Central Valley. Locations at which the clay is not present were given null values to finish creating the continuous surface for depth and thickness.



**Figure 3.8 Depth of the Corcoran clay underlying the Madera Subbasin.** Values for Corcoran clay depth were provided as contour lines (a), which were then interpolated to create a continuous layer of values for the clay extent (b). Corcoran clay is a low permeability layer that can inhibit water movement in the subsurface (35). In locations where the clay is farther from the surface (dark orange), the Corcoran clay is less likely to act as a confining layer. Data from the United States Geological Survey (10,11).



**Figure 3.9 Thickness of the Corcoran Clay underlying the Madera Subbasin.** Values for Corcoran clay thickness were provided as contour lines (a), which were then interpolated to create a continuous layer of values for the clay extent (b). Corcoran clay is a low permeability layer that can inhibit water movement in the subsurface (35). In locations where the clay is thicker (dark orange), we believe the Corcoran clay is more likely to inhibit percolation of recharged water to the water table. Data from the United States Geological Survey (10,11).

Values within both the Corcoran clay depth and thickness layers were reclassified into six bins based on suitability for recharge. Throughout the Central Valley, the Corcoran clay depth ranges from approximately 50 ft below ground surface to more than 500 ft below ground surface. Locations where the clay is not present are more suitable for recharge. Where clay is present, greater values for depth are preferable as shallow Corcoran clay can act as an upper confining layer that limits recharged water reaching the aquifer (Table 3.4).

**Table 3.4 Corcoran clay depth (ft) reclassification based on suitability for groundwater recharge.** Ranges of depths within each recharge ranking are designed to reflect a deeper Corcoran clay layer as more suitable for recharge. Data source: USGS (11).

<b>Recharge Ranking</b>	<b>Corcoran Clay Depth in feet (<i>meters</i>)</b>
1 - Better	Not present (Null)
2	500+ (152+)
3	300 - 500 (91 - 152)
4	200 - 300 (60 - 91)
5	100 - 200 (30 - 60)
6 - Worse	50 - 100 (15 - 30)

We conducted a literature review in an effort to determine a relationship between Corcoran clay thickness and groundwater recharge suitability. The results of this analysis were inconclusive; given this, we used equal intervals to bin the values for Corcoran clay thickness, which range from 10 ft to more than 50 ft (Table 3.5). If Corcoran clay is present, it is preferable for the clay to be thinner as it represents a less substantial barrier to vertical water movement.

**Table 3.5 Corcoran clay thickness (ft) reclassification based on suitability for groundwater recharge.** Ranges of depths within each recharge ranking are designed to reflect a thinner Corcoran clay layer as more suitable for recharge. Data source: USGS (10).

Recharge Ranking	Corcoran Clay Thickness (ft)
1 - Better	Not present (Null)
2	10 - 20 (3 - 6)
3	20 - 30 (6 - 9)
4	30 - 40 (9 - 12)
5	40 - 50 (12 - 15)
6 - Worse	50+ (15+)

### 3.1.1.5 Weighted Sum

The individual components of surface and subsurface conditions outlined above were combined using a weighted sum, producing a continuous surface of values representing suitability for groundwater recharge projects (Table 3.6). In determining the appropriate weighting for each component, we considered the relative importance of each data layer to groundwater recharge projects.

The Soil Agricultural Groundwater Banking Index (SAGBI) is itself an index value for recharge suitability at the surface and shallow subsurface that contains five data layers. We weighted SAGBI most heavily in the decision support tool to account for the substantial information contained in the index; additionally, if conditions at the near surface would significantly limit a recharge project's ability to transfer water into the ground, the suitability or unsuitability of the subsurface is of lesser consequence.

We assigned Depth to Groundwater the second highest relative weighting in the decision support tool. In order to most effectively provide a benefit to the groundwater basin, recharge projects should be sited in areas that have a water table that is low enough to provide adequate storage space to hold the recharged water.

We assigned percent of coarse material the next highest relative weight in the decision support tool to account for recharged water’s ability to percolate through deeper substrates. Each vertically stacked layer of the percent coarseness surface was weighted individually within the overall component weight; the upper layer was given the highest weighting, and subsequent layer weightings declined with increasing depth below the ground surface.

The Corcoran clay component of surface and subsurface conditions was given the smallest weighting because the clay is not present throughout the whole Central Valley, and is therefore only a consideration of groundwater recharge in certain areas. Where present, the clay layer may confine recharge of deeper aquifer strata, but does not necessarily preclude recharge activities that would benefit shallower, perched aquifers. The Clay depth layer was given a higher weighting, as it is the layer’s depth that is more closely tied to its function as a confining layer, rather than the clay thickness.

**Table 3.6 Weighting scheme for combining surface and subsurface condition components.** Weights are assigned based on the relative importance of each component for groundwater recharge.

<b>Tool Component</b>	<b>Relative Weighting</b>	<b>Sub-Layer Weighting (Percent of Overall Component’s Relative Weighting)</b>
SAGBI	2.5x	NA
Depth to Groundwater	1.5x	NA
Percent Coarseness	1.0x	25 ft: 40% 75 ft: 30% 125 ft: 15% 175 ft: 10% 225 ft: 5%
Corcoran Clay	0.5x	Thickness: 80% Depth: 20%

### 3.1.2 Nitrogen Contamination Potential

The water quality component of the decision support tool identifies locations within a groundwater basin where recharge projects are least likely to introduce new nitrate contamination into the groundwater. To assess a location’s risk for introducing nitrate



contamination, we calculated nitrogen balances for the ground surface for years 1990, 2005, and 2020. The data selected for analysis, associated processing methods, and their utilization in the decision support tool are discussed in detail in the following sections.

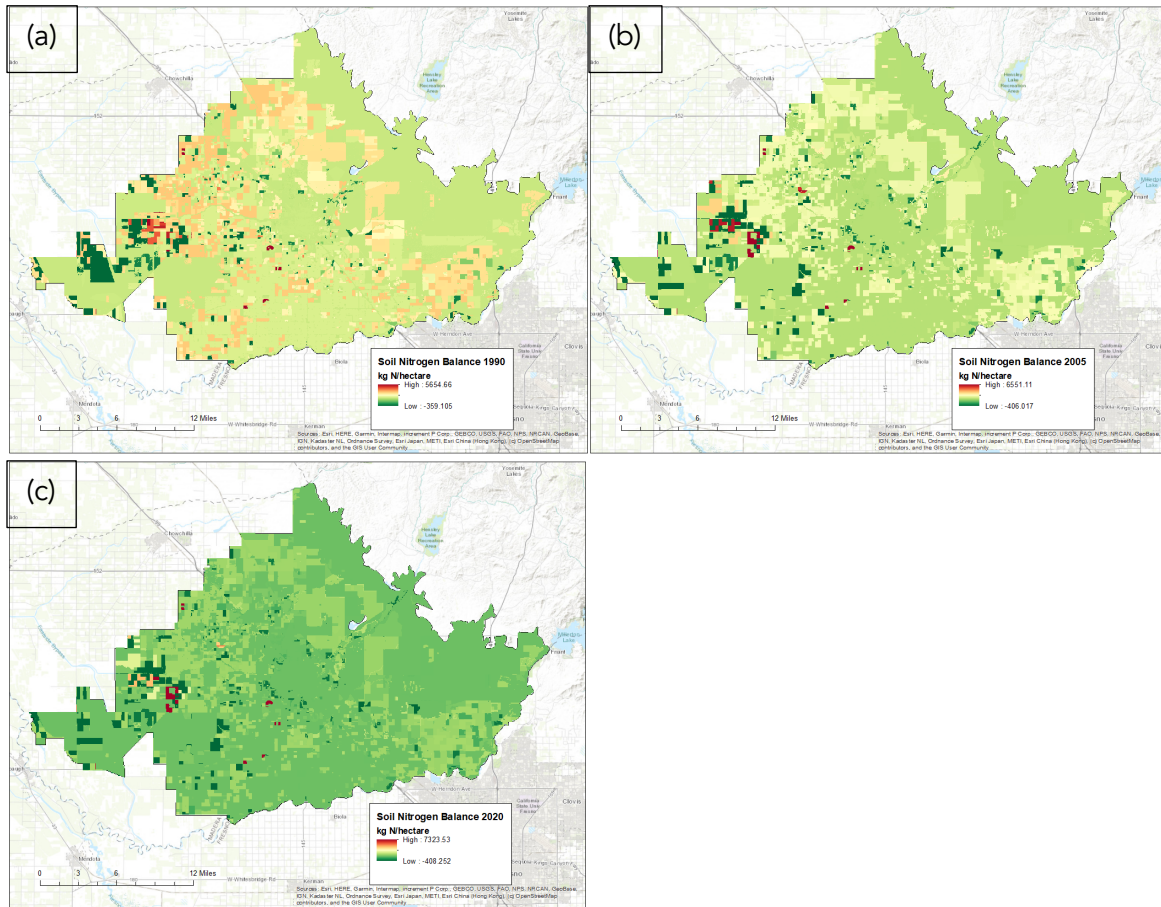
### 3.1.2.1 Nitrogen Balances

We used surficial nitrogen data layers from the UC Davis Center for Watershed Sciences (CWS) (68) to calculate a nitrogen balance. Nitrogen inputs considered in the analysis include: atmospheric nitrogen deposition, synthetic fertilizer application, and applied nitrogen as manure or treated effluent. The geospatial data layers were provided in continuous surfaces for the Central Valley and were summed, resulting in a value for total nitrogen inputs in kg N/hectare/year for any given location within the data extent. Nitrogen losses considered in the analysis include: atmospheric nitrogen losses, estimated nitrogen taken up by crops and harvested, and nitrogen in runoff. We summed the continuous data layers, resulting in a value for total nitrogen losses for any given location within the data extent. The total sum of nitrogen losses was subtracted from the total sum of nitrogen inputs, resulting in a nitrogen balance for the ground surface. The nitrogen balance value, in kg N/hectare/year, is an estimate of the amount of nitrogen that likely remains in surficial soils and poses a risk to groundwater quality.

*Yearly Nitrogen Balance =*

$$\begin{aligned} & \text{(Atmospheric Deposition + Nitrogen Fertilizer Application + Applied Nitrogen)} - \\ & \text{(Atmospheric Losses + Nitrogen Uptake by Crops + Nitrogen Runoff)} \end{aligned}$$

The decision support tool includes nitrogen balances for three years: 1990, 2005, and 2020 (Figure 3.9). Data for 1990 and 2005 are observed values, while the 2020 data is projected. We included the 1990 and 2005 nitrogen balances to represent historical inputs to the surface that could still pose a risk of groundwater contamination. The 30 year study period was deemed sufficient, as previous studies have documented that after three decades, only 12-15% of applied nitrogen remained in surficial soils (69). The year 2020 is the first year of implementation under the Sustainable Groundwater Management Act (SGMA) for critically overdrafted basins (23), at which time many groundwater sustainability agencies will begin the process of siting groundwater recharge projects for their basin. The projected 2020 data addresses the nitrogen balance at the surface during the construction and implementation period.



**Figure 3.9 Surficial nitrogen balances for the Madera Subbasin.** Nitrogen balances were calculated for 1990 (a), 2005 (b), and 2020 (c). Nitrogen balances were calculated by subtracting the sum of nitrogen losses from the sum of nitrogen inputs. Areas with lower nitrogen balances (darkest green) are less likely to introduce additional nitrate contamination into groundwater through recharge projects. Data from (68).

The values for the nitrogen balance for each year were classified into six bins based on the likely risk posed to groundwater during potential recharge projects (Table 3.7). A negative nitrogen balance value, which signifies that more nitrogen was lost from surficial soils than was added in a given year, is better for groundwater recharge. Groundwater recharge on lands with less intensive nitrogen application at the ground surface has demonstrated potential to dilute and reduce contamination in groundwater, particularly in shallower wells (14).

**Table 3.7 Nitrogen balance (kg N/hectare/year) reclassification based on suitability for groundwater recharge.** Ranges of nitrogen balances within each recharge ranking are designed to reflect a smaller nitrogen balance as more suitable for recharge. Data source: UC Davis Center for Watershed Sciences (68).

Recharge Ranking	Surficial Nitrogen Balance (kg N/hectare/year)
1 - Better	< 0
2	0 - 50
3	50 - 100
4	100 - 300
5	300 - 500
6 - Worse	500+

### 3.1.2.2 Weighted Sum

To produce a single continuous surface of the surficial nitrogen balance, we combined the reclassified layers for 1990, 2005, and 2020 into a single layer using a weighted sum (Table 3.8). The 2020 nitrogen balance includes data for what will be the most recent nitrogen inputs into surficial soils prior to beginning a groundwater recharge project, and is therefore weighted most heavily. Nitrogen present at the surface in 2005 and 1990 will have had more time to degrade, reducing associated risk to groundwater, and are therefore weighted less heavily.

**Table 3.8 Weighting scheme for combining nitrogen balances (kg N/hectare/year) for 1990, 2005, and 2020.** The assigned weight for each balance decreases as the year decreases to reflect the reduced associated risk to groundwater supplies.

Surficial Nitrogen Balance Year	Weight
2020	0.5
2005	0.3
1990	0.2

### 3.1.3 Recommended Recharge Locations

We combined the output for the surface and subsurface conditions component with the output for the water quality component of the tool in order to produce a resulting layer identifying locations that can most easily allow for clean water to infiltrate and percolate to the water table.

The values contained in each of the two surfaces for recharge suitability ranged from 1 (better) to 6 (worse). For each grid cell, the worst of the two values was retained as that location's suitability score. For instance, if a location scored a 2 for surface and subsurface conditions, and a 5 for the surficial nitrogen balance, the location would retain an overall score of 5. We combined the two surface layers in this way in an effort to be conservative in assessing locations for groundwater recharge projects; the limiting factor for a recharge project was the value retained for the final ranking.

We then incorporated a consideration of land use types that are best suited for groundwater recharge projects, considering both on-farm flood managed aquifer recharge and constructed basins for managed aquifer recharge. We filtered the surface of suitable recharge locations to retain only land areas with appropriate land use as classified in the National Land Cover Database (NLCD), which included: Cultivated Crops, Pasture/Hay, Grassland/Herbaceous, Shrub/Scrub, and Barren Land (63). Land use types excluded from the suitable recharge locations surface were: Developed, Medium Intensity; Developed, High Intensity; and Forest.

In an effort to provide users of the tool with an appropriate amount of recommended recharge locations for further consideration, we retained only the top 10% of suitable recharge locations within a given basin.

## 3.2 Additional Considerations

### 3.2.1 Benefits

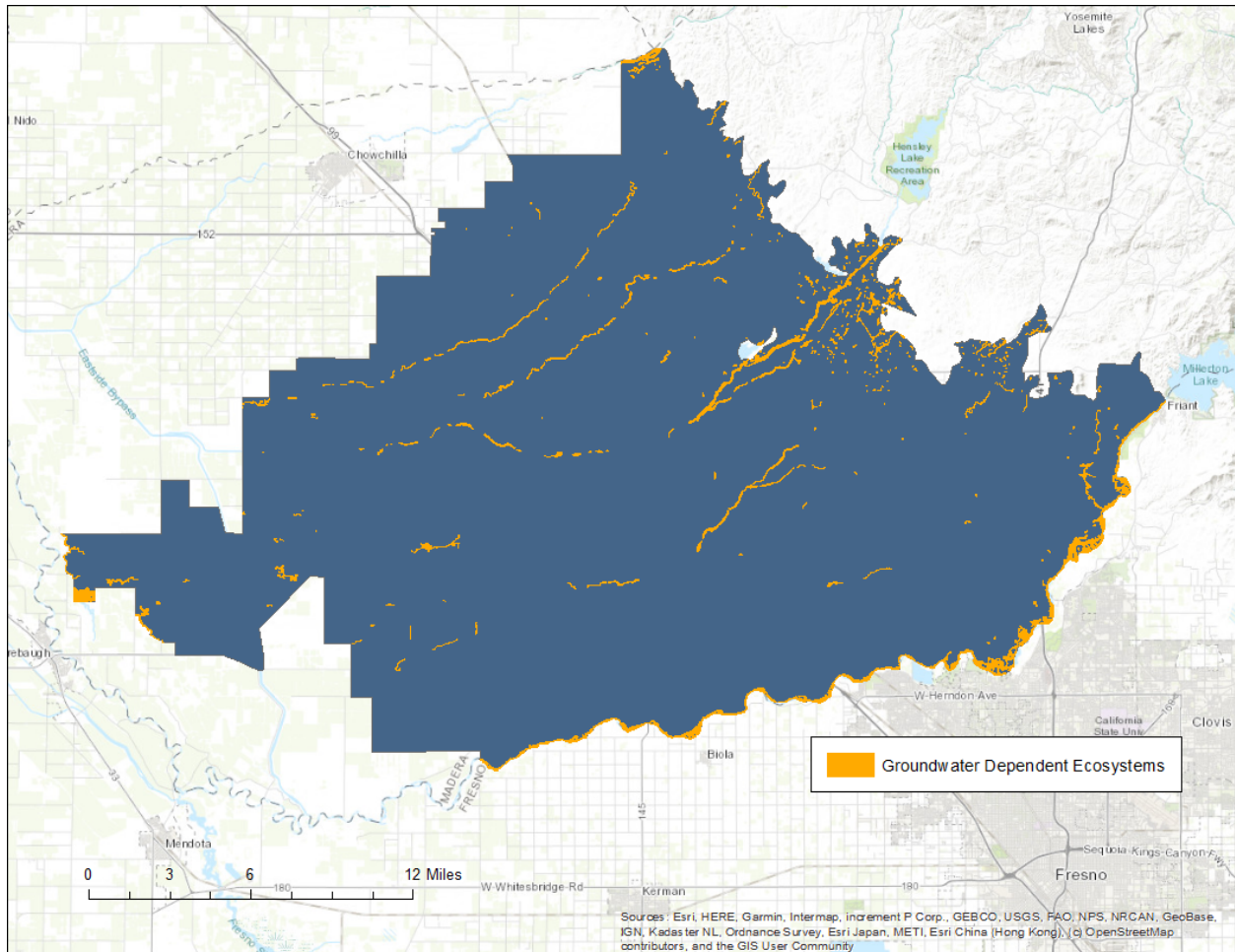
The recommended recharge locations output, which results from the data and methods outlined above, identifies locations where groundwater recharge projects can most effectively move water from the surface down into the aquifer without degrading groundwater quality. We also included additional considerations in the decision support tool related to associated benefits of groundwater recharge, namely the ability of a recharge project to support groundwater dependent ecosystems and a project's ability to increase water supplies for domestic drinking water wells that have run dry.

#### 3.2.1.1 Groundwater Dependent Ecosystems

Declining groundwater levels have impacted groundwater dependent ecosystems (GDEs) by lowering the water table below the reach of vegetation roots and reducing the quantity and quality of instream water supplies during critical summer months (70). Under SGMA, GSAs must identify GDEs in their basins and consider how they will be affected when determining

management decisions (5–7). Research has shown that near-stream groundwater recharge can have demonstrated benefits to ecosystems by reconnecting surface and groundwater (71).

We incorporated the National Communities Commonly Associated with Groundwater Dataset, which identifies potential locations of groundwater dependent wetlands and vegetation (Figure 3.10) (72). The dataset was created by The Nature Conservancy, the California Department of Water Resources, and the California Department of Fish and Wildlife.



**Figure 3.10** Locations of potential groundwater dependent ecosystems in the Madera Subbasin. Potential groundwater dependent ecosystems include vegetation types and wetlands that are likely to be supported by groundwater. Data from The Nature Conservancy, CA Department of Water Resources, CA Department of Fish and Wildlife (72).

To determine a recharge project’s ability to benefit a potential GDE for a given location, we first calculated the linear distance from every location in the basin to the nearest GDE. These distances were then reclassified into four bins with associated rankings for benefit likelihood (Table 3.9).

While it may be intuitive that GDEs are negatively impacted by declining groundwater levels and recharge projects can help mitigate these impacts, to our knowledge there have been no studies on how the magnitude of positive effects from recharge projects changes with distance from a GDE. However, prioritizing recharge projects based on the additional habitat benefits that can be achieved at each site is one of the priority action items identified in the Flood-MAR Research and Data Development Plan (73). The buffer sizes and corresponding rankings in our decision support tool were chosen to be conservative with the acknowledgement that groundwater can move very slowly in the sub-surface, while also still providing managers with recommended options that provided sufficient land area for consideration.

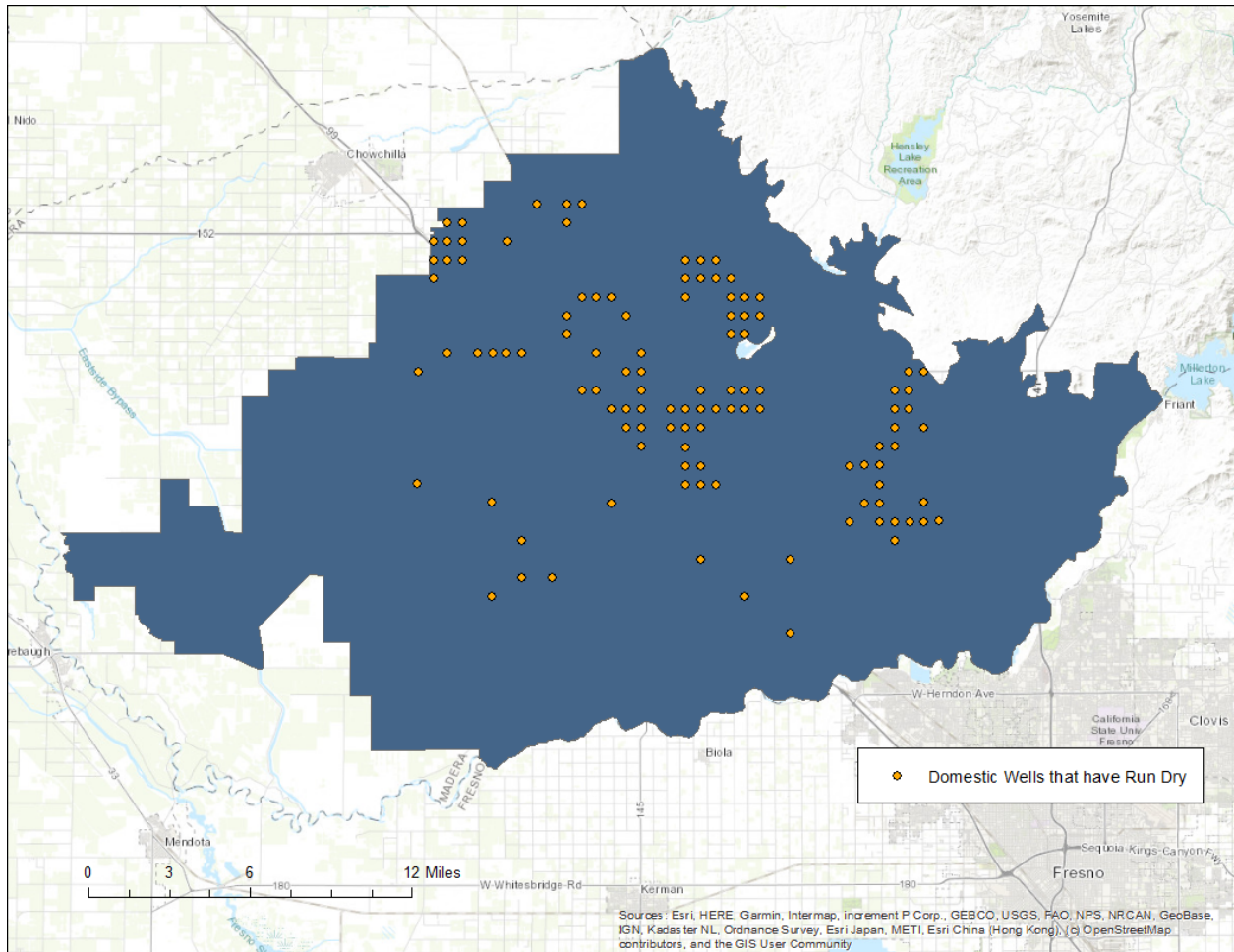
**Table 3.9 Ranked distances away from potential groundwater dependent ecosystems (GDEs).** Recharge projects located closer to potential GDEs are more likely to positively impact the health of these ecosystems, and thus are more preferred. Data source: The Nature Conservancy, CA Department of Water Resources, CA Department of Fish and Wildlife (72).

<b>Rank</b>	<b>Linear distance from any basin location to the nearest groundwater dependent ecosystem in feet (<i>meters</i>)</b>
1 - Most Preferred	0 - 500 (0 - 152)
2	500 - 1,000 (152 - 305)
3	1,000 - 1,500 (305 - 457)
4 - Least Preferred	> 1,500 (> 457)

### 3.2.1.2 Domestic Wells That Have Run Dry

Declining groundwater levels lead to less reliable domestic drinking water supplies from wells, particularly in rural areas surrounded by a high concentration of agricultural lands, such as the Central Valley. Wells used to provide domestic water are more vulnerable to running dry during periods of drought than agricultural wells since they tend to be shallower (49). Raising the groundwater table through groundwater recharge near domestic wells can increase the reliability of domestic water access, particularly in rural areas without municipal water services.

To identify the location of domestic wells that have run dry within the Central Valley, we used data collected from the Household Water Supply Shortage Reporting System, managed by the California Department of Water Resources (Figure 3.11) (74). This is a self-reporting system for individuals not served by a public water system experiencing problems with their water supply, and the reports can be made by those individuals or through an agency representative. Due to the nature of self-reporting, this dataset likely under-represents the number of domestic wells that have run dry in the Central Valley.



**Figure 3.11** Locations of domestic drinking water wells that have run dry in the Madera Subbasin. Well locations collected from the Household Water Supply Shortage Reporting System, managed by the California Department of Water Resources. Reports are made by individuals not served by a public supply system that are experiencing problems with their well supply. Reports can be made directly by individuals or by agencies contacted by individual well owners. Data from CA Department of Water Resources (74).

To determine a recharge project’s ability to benefit a domestic drinking water well that has run dry, we first calculated the linear distance in feet from every location to the nearest location of such a well. The result was a continuous surface of distances to a domestic well that has run dry

from each location; these distances were then reclassified into four bins with associated rankings for benefit likelihood (Table 3.10).

As with the buffers for potential GDEs, the buffer sizes around domestic wells that have run dry and corresponding rankings were chosen to be conservative, while also still providing managers with recommended options. However, the buffer sizes around the well locations are larger than around potential GDEs because of the difference in the range of depths at which groundwater recharge can provide each benefit. Groundwater can only benefit an ecosystem near the surface, in the root-zone or at the elevation of a stream bed. In contrast, groundwater can enter a well at any depth within the well screen, meaning water can travel farther horizontally and vertically and still rehydrate a given well.

**Table 3.10 Ranked distances away from reported domestic wells that have run dry.** Recharge projects located closer to these wells are more likely to increase the reliability of these water sources, and thus are more preferred. Data source: CA Department of Water Resources (74).

<b>Rank</b>	<b>Linear distance from any basin location to the nearest well that has run dry in feet (<i>meters</i>)</b>
1 - Most Preferred	0 - 1,000 (0 - 305)
2	1,000 - 1,500 (305 - 457)
3	1,500 - 3,000 (457 - 914)
4 - Least Preferred	> 3,000 (> 914)

### 3.2.2 Feasibility

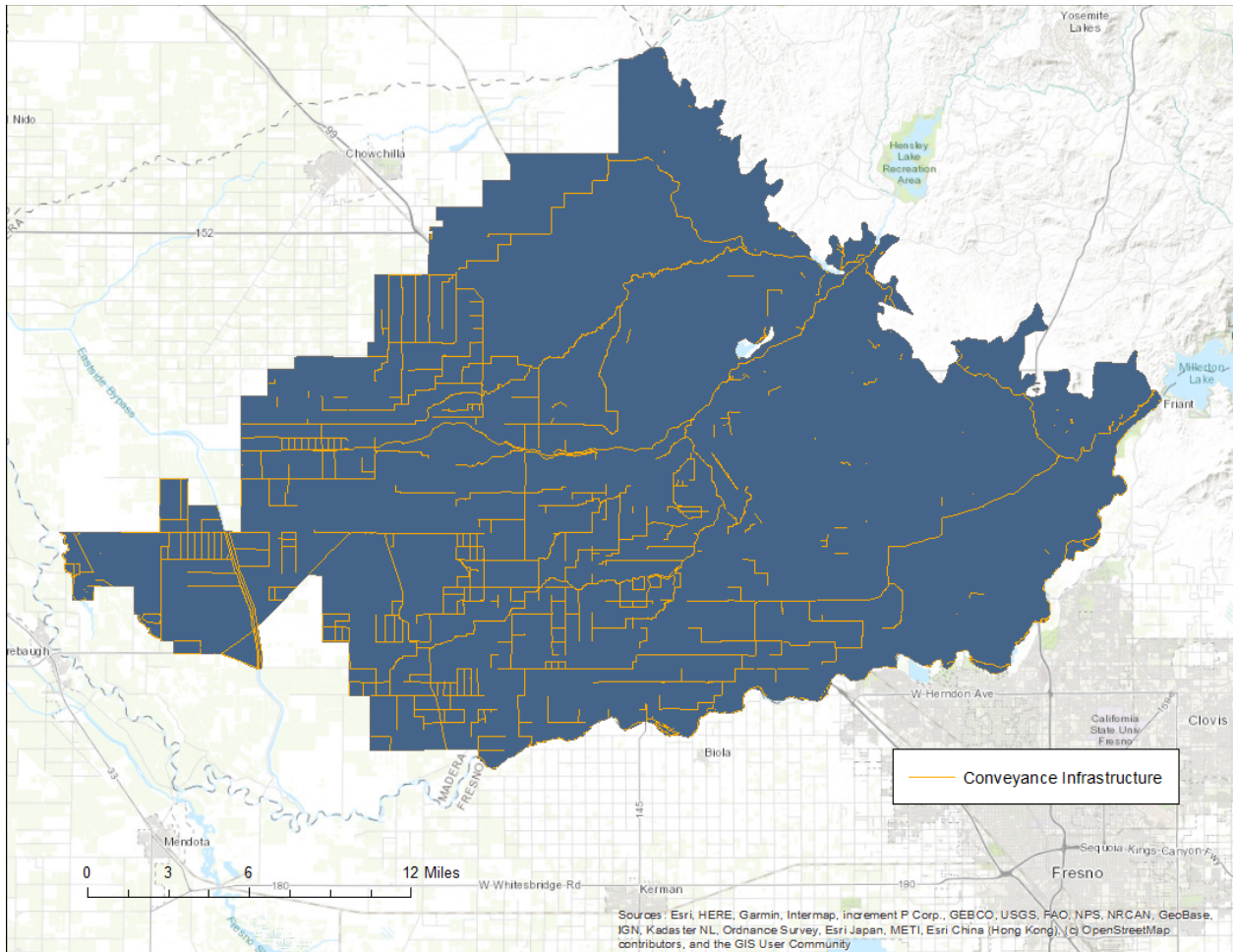
We also included a consideration of recharge project feasibility in the decision support tool, namely the proximity to existing water conveyance infrastructure and distance from a listed contamination clean up site. These components of the decision support tool provide a user the opportunity to limit initial construction costs that may be associated with initiating a groundwater recharge project.



### 3.2.2.1 Existing Water Conveyance Infrastructure

A key consideration in constructing and operating a managed aquifer recharge project is the feasibility of transporting source water to the project. Considerable capital investments will likely occur at the project outset for recharge basin construction costs, which can be further compounded if there is also a need to build new water conveyance to reach the spreading basin. Depending on the financial resources of the Groundwater Sustainability Agency, it may be preferable to limit the costs incurred in establishing a recharge project as much as possible.

To identify the location of existing water conveyance infrastructure, we used the National Hydrography Dataset Plus (NHD+) (Figure 3.12) (75). We selected types of conveyance that could most plausibly be used for transporting water to a recharge project, namely: canals, aqueducts, pipelines, and perennial streams. We removed intermittent and ephemeral streams from consideration, due to the higher potential for water losses during conveyance. Though it is the most comprehensive dataset for water infrastructure that is Central Valley Wide, it is likely that the NHD+ under represents existing conveyance infrastructure and localized data sources could be more comprehensive. The NHD+ does not contain any volumetric information, which is another limitation of the dataset when considering conveyance for MAR projects. However, we reasoned that in some cases it may be less expensive to increase the capacity of existing conveyance rather than begin construction in an area with no existing conveyance.



**Figure 3.12 Location of existing water conveyance infrastructure in the Madera Subbasin.** Types of conveyance infrastructure considered in the decision support tool include: canals, pipelines, aqueducts, and perennial streams. Data from the National Hydrography Dataset Plus (75).

In order to rank a location for feasibility related to water conveyance, we first calculated the linear distance in feet from every location to the nearest location of a canal, pipeline, or perennial stream. The result was a continuous surface of distances to existing water conveyance; these distances were then reclassified into four bins with associated rankings for feasibility (Table 3.11). These bins sizes and corresponding rankings were chosen in order to highlight areas of the basin that could feasibly be connected to existing conveyance, while still providing enough land area in the resulting output for managers to consider when making a final location selection.

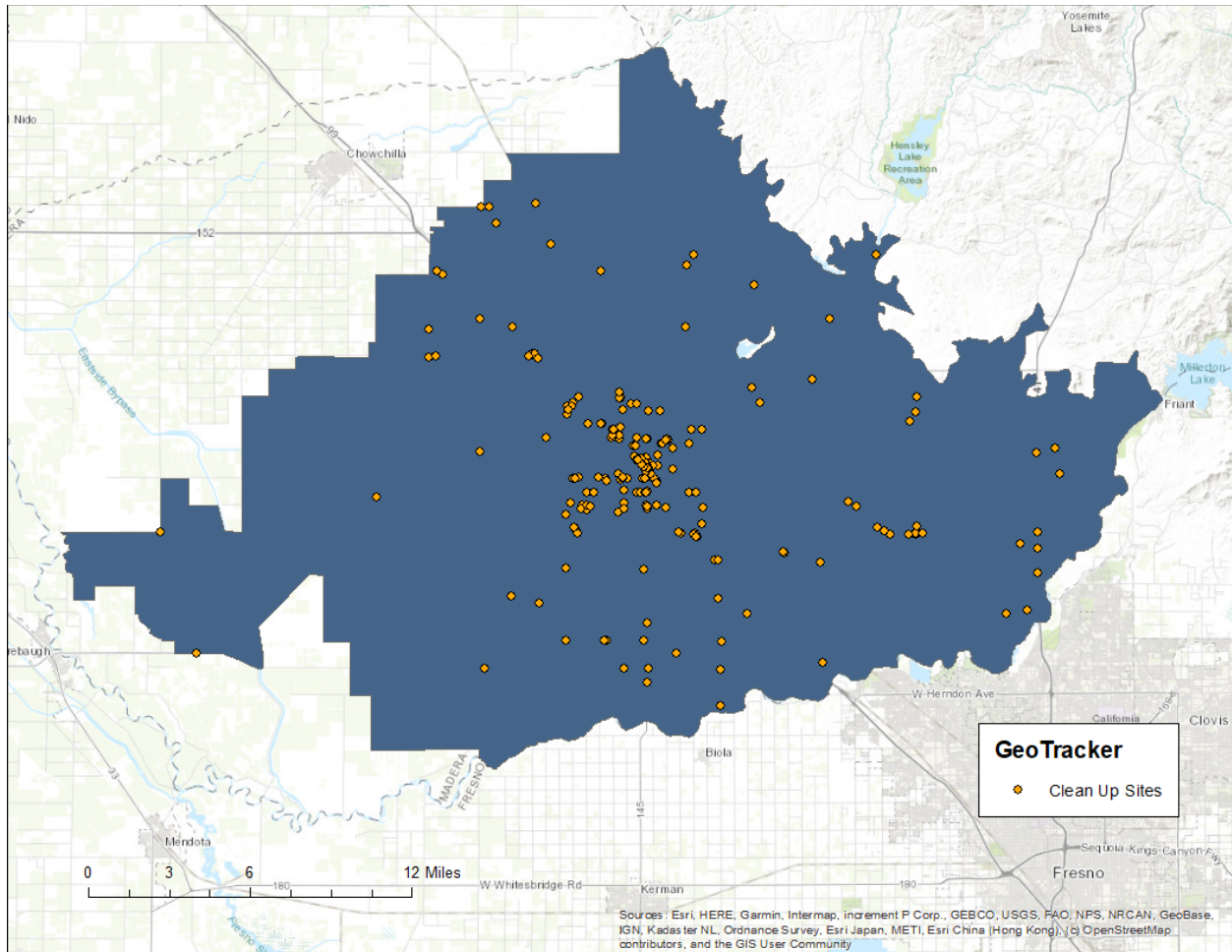
**Table 3.11 Ranked distances away from existing conveyance infrastructure.** Recharge projects located closer to existing conveyance infrastructure will have lower associated cost of construction, and thus are more preferred. Data source: National Hydrography Dataset (75).

<b>Rank</b>	<b>Linear distance from any basin location to the nearest canal, aqueduct, pipeline, or perennial stream in feet (meters)</b>
1 - Most Preferred	0 - 1,500 (0 - 457)
2	1,500 - 3,000 (457 - 914)
3	3,000 - 5,000 (914 - 1523)
4 - Least Preferred	> 5,000 (> 1523)

### 3.2.2.2 Locations of Listed Contamination Clean Up Sites

A second feasibility consideration that can alter initial project construction sites is the presence or absence of existing anthropogenic contamination at the surface or in the shallow subsurface. Sites that have previous impacts and need remediation, or have been only partially remediated, risk introducing additional contaminants into groundwater if a managed aquifer recharge project were to be built in close proximity. The tool provides an analytical method for identifying the proximity of potential groundwater recharge project locations to listed state clean-up sites and prioritizing recharge locations that are further away from contamination risks.

To identify the location of existing contamination sites, we used the California State Water Resources Control Board GeoTracker Database (Figure 3.13) (76). The database includes the location of the following site types: Leaking Underground Storage Tank (LUST), Underground Storage Tank (UST), Military Sites, Land Disposal Sites, Composting Operations, Waste Discharges, Confined Animal/Concentrated Animal Feedlots, and Oil and Gas Monitoring sites. In order to be conservative, we included all GeoTracker points in the tool and did not remove sites with a case status of closed or remediated.



**Figure 3.13 Location of GeoTracker points in the Madera Subbasin.** GeoTracker is a database maintained by the California State Water Resources Control Board that includes contamination cleanup sites that may pose a risk to groundwater. Data from California State Water Resources Control Board (76).

Unlike previous tool components, it is preferable for recharge projects to be located farther away from contamination cleanup sites, rather than in close proximity. In order to rank a location for feasibility related to water conveyance, we first calculated the linear distance in feet from every location to the nearest GeoTracker data point. The result was a continuous surface of distances to a listed contamination cleanup site; these distances were then reclassified into four bins with associated rankings for feasibility (Table 3.12).

These bins sizes and corresponding rankings were chosen by considering the type of data points likely represented in the GeoTracker database, and the depth to which resulting contamination may be present. The farther away from a site, the less likely that a GSA will have to conduct additional remediation to avoid risking groundwater quality. As much of the contamination is likely limited to the depths of previous facility impacts, most commonly located in the shallow

subsurface, an innermost buffer of 500 feet was considered the least preferable for groundwater recharge projects.

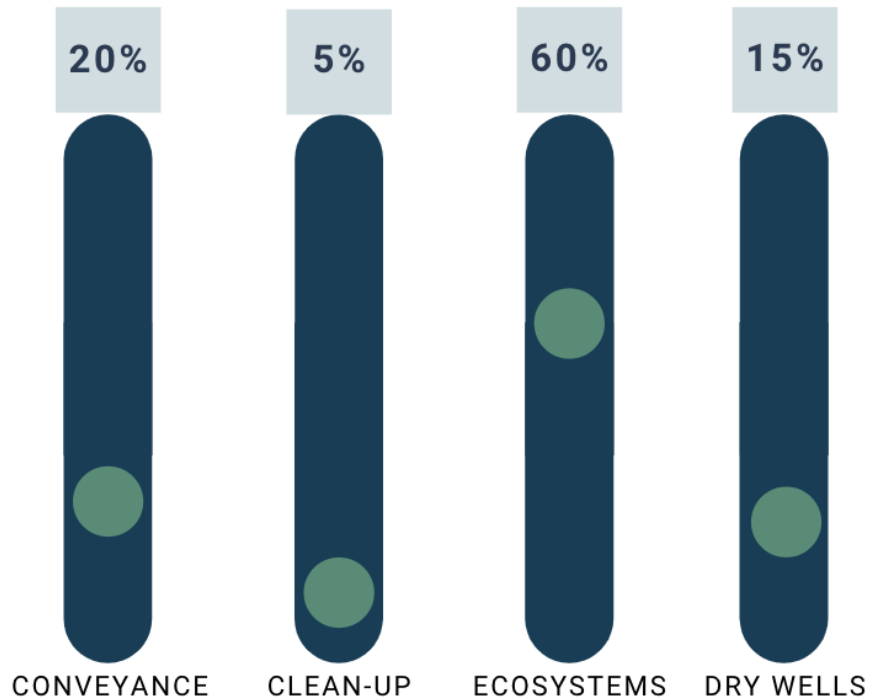
**Table 3.12 Ranked distances away from listed contamination clean-up sites.** Recharge projects located farther away from these sites are associated with lower cost of implementation by avoiding the need for remediation, and thus are more preferred. Data source: California State Water Resources Control Board (76).

<b>Rank</b>	<b>Linear distance from any basin location to the nearest GeoTracker Clean-Up Site in feet (meters)</b>
1 - Most Preferred	> 1,500 (> 457)
2	1,000 - 1,500 (304 - 457)
3	500 - 1,000 (152 - 304)
4 - Least Preferred	0 - 500 (0 - 152)

### 3.3 Multi-Benefit Recharge Locations

We included functionality in the decision support tool that enables groundwater managers to select and specify to what degree the additional benefits and feasibility considerations are considered in their recommended recharge locations output. As mentioned in the previous section, the four components that allow for customized weighting include: the locations of potential groundwater dependent ecosystems, the locations of self-reported domestic drinking water wells that have run dry, proximity to existing water conveyance, and the location of listed contamination cleanup sites.

The four components are combined in a weighted sum; a Groundwater Sustainability Agency (GSA), the intended user of our tool, can assign unique weights to each component, provided that the sum of the weights equals 100% (Figure 3.14).



**Figure 3.14 Conceptual diagram of the tool functionality that allows a user to set managed recharge project priorities.** A user has a total of 100% to allocate between four tool components: a project’s proximity to existing conveyance infrastructure, distance from a GeoTracker contamination clean-up site, proximity to groundwater dependent ecosystems, and proximity to domestic wells that have run dry. The priority settings combine the four components in a weighted sum that is then applied to the top 10% of suitable recharge locations in a basin to identify more or less preferred areas based on the stated priorities.

Results of the weighted sum of additional benefits and feasibility considerations are only retained for the top 10% of recommended recharge locations. The result ensures that the multi-benefit recommendations for recharge locations are still the best places in the groundwater basin for getting clean water into the ground, but further refined based on the user’s chosen priorities.

### 3.4 Source Water Analysis

While this project works to identify areas that would be best suited to achieve multiple benefits through groundwater recharge in basins throughout the Central Valley, we acknowledge there are other important considerations involved in planning and implementing groundwater recharge projects. One of these is the source of water supplies to be directed towards managed groundwater recharge. In an effort to demonstrate one possible approach to identifying available source water to be directed toward recharge, we have conducted a source water analysis specific to the Madera Subbasin.

In order to understand the availability of source water for recharge projects in Madera, we examined the range of surface water supplies that serve the Madera Subbasin. Madera receives surface water from two reservoirs directly to the east of the groundwater Subbasin: Millerton Reservoir on the San Joaquin River and Hensley Lake on the Fresno River. Extensive and detailed historical data is available for Millerton Reservoir and is not available to the same level of detail for Hensley Lake. Due to these data availability constraints, our analysis focused on Millerton Reservoir. Our aim in analyzing potential available source water for recharge projects in the Madera groundwater basin was to answer the question: based on historic data and climate projections, could some amount of water be pre-released from Millerton Reservoir in anticipation of high flow events and directed in part towards recharge locations for underground storage?

### 3.4.1 Historic Water Availability

Data for daily inflows, outflows, releases and storage at Millerton Reservoir was gathered from the California Department of Water Resources (CA DWR) Data Exchange Center (77). These data are collected by automatic sensors operated by the U.S. Bureau of Reclamation and transmitted electronically to the Data Exchange Center portal operated by CA DWR. The period of record for continuous daily data for all four required data variables (inflows, outflows, releases and storage) is 1995 - 2019.

In order to understand whether some amount of water could have been released from Millerton Reservoir and directed to groundwater recharge during the historic period, we tested 10 scenarios with varying criteria to understand the frequency and timing of water availability. The final scenario criteria used for analysis of the historic data were: reservoir storage must be equal to or greater than 90% of the reservoir's active capacity, and inflows must be greater than outflows. The resulting output was a binary classification of each day in the historic record, in which either the criteria was met and some amount of water could have been made available to be directed towards recharge, or the criteria was not met.

### 3.4.2 Projected Water Availability

To understand how historic water availability could inform projected future water availability we compared the results of the analysis described above to projected inflows on the San Joaquin River at Millerton Reservoir, accessed through Cal-Adapt (78). We used the daily inflow data for the historic period to calculate a monthly average inflow into Millerton Reservoir for every year

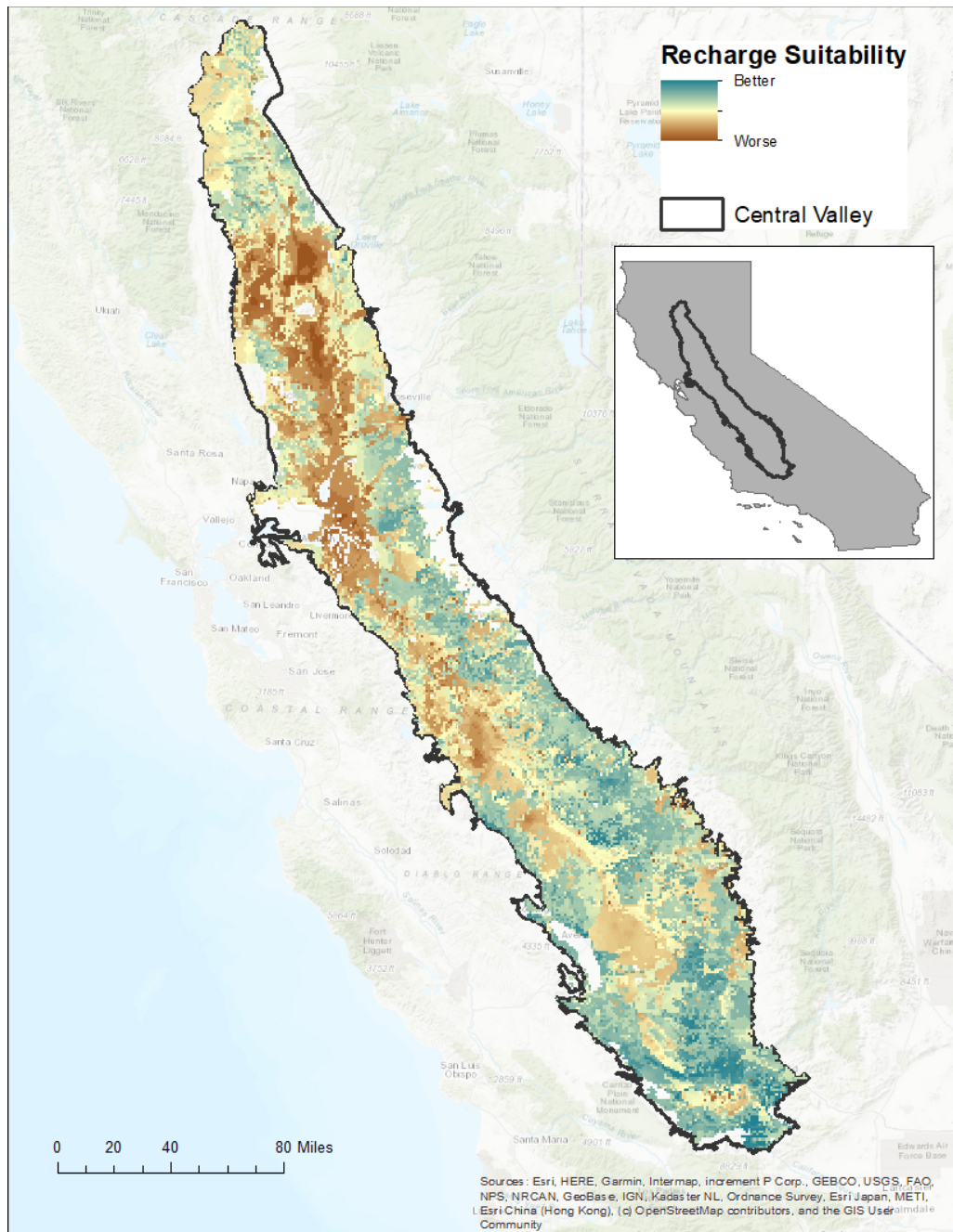
from 1995 - 2019 (77). We then calculated the historic average monthly inflow as the mean monthly inflow of all years in the historic period.

The Cal-Adapt scenarios used in this analysis include: RCP 4.5, which represents a projection in which emissions peak in the year 2040 and then decline, and RCP 8.5, which represents a projection in which emissions continue to rise through 2050 and plateau in 2100. For each of the two projection scenarios, four modeled outcomes were included to represent a range of possible variability in streamflow. These modeled outcomes include: warm/dry, cool/wet, average, and complement (78). These eight streamflow projections were graphed against the calculated historic monthly average inflow to understand how historic conditions compare to projected future conditions of water availability at Millerton Reservoir.



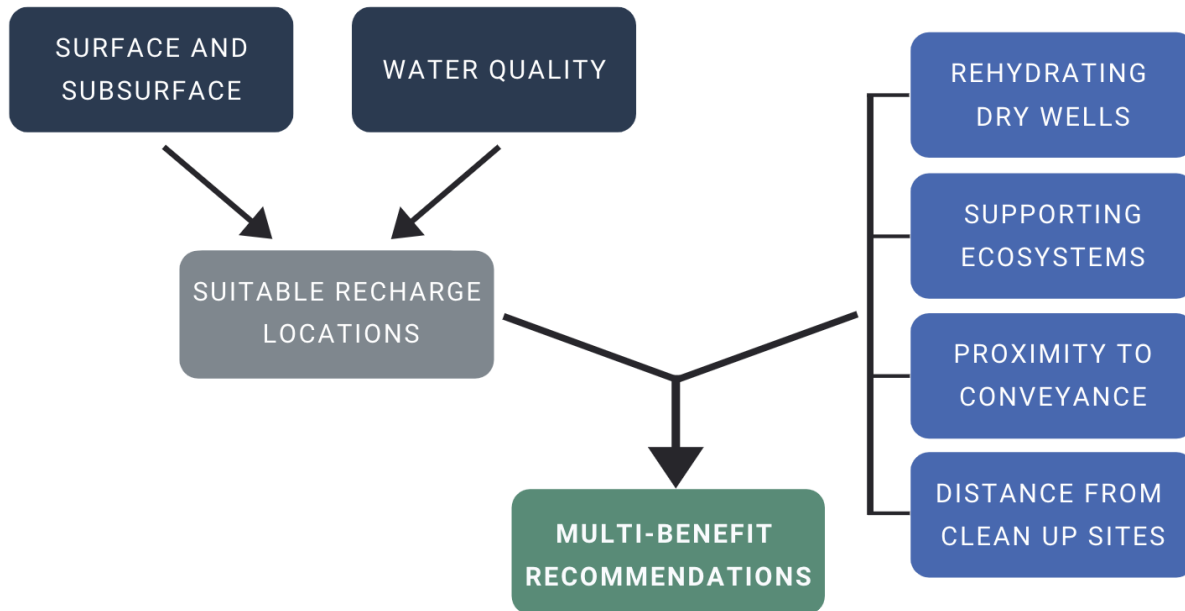
## 4 Results

The result of our analysis is an ArcMap Model Builder workflow designed to visually display a relative ranking of locations well suited to perform groundwater recharge. Suitable recharge locations are those that generally have preferable surface conditions, as determined by the Soil Agricultural Groundwater Banking Index (SAGBI), a lower depth to water, indicating sufficient storage space in the aquifer, a relatively high proportion of coarse grained soil materials, used as a proxy for vertical hydraulic conductivity, where vertical groundwater movement would be least impacted by the presence of the Corcoran clay, and where the surficial nitrogen balance is low (Figure 4.1).



**Figure 4.1 Map of decision support tool suitable recharge locations across the Central Valley.** Results of the analysis show the combination of surface and subsurface conditions and water quality considerations that are better (blue) or worse (brown) for groundwater recharge in the Central Valley. Better conditions for groundwater recharge are primarily located in the south and east regions of the Central Valley, while conditions for groundwater recharge are relatively worse in the northwestern region of the Central Valley. Areas with a better rank for recharge tend to have the following characteristics: suitable ground surface conditions, such as high soil infiltration capacity, a deep groundwater table, a high percentage of coarse soil material in the subsurface, no presence of the low permeability Corcoran clay layer, and a low surficial nitrogen balance. This map compiles and analyzes the following datasets: Soil Agricultural Groundwater Banking Index (62), percent coarseness (65), depth to water (12), Corcoran clay characteristics (10,11), and nitrogen balance (68).

The workflow can be further refined to present a ranking of suitable recharge locations based on local priorities for capturing benefits and accounting for feasibility considerations for recharge implementation. The workflow is a combination of surface and subsurface conditions, water quality, benefits and feasibility resulting in a multi-benefit recommendation for recharge locations within a groundwater basin (Figure 4.2).



**Figure 4.2 Decision support tool schematic showing the integration of components.** Our framework provides a transferable workflow that incorporates physical surface and subsurface conditions with a soil nitrogen balance to determine locations most suitable for adding clean water to the underlying aquifer. Benefit and feasibility consideration rankings are overlaid on the suitable recharge locations to obtain a multi-benefit recommendation of the areas within a groundwater basin that are most likely to achieve multiple benefits of groundwater recharge.

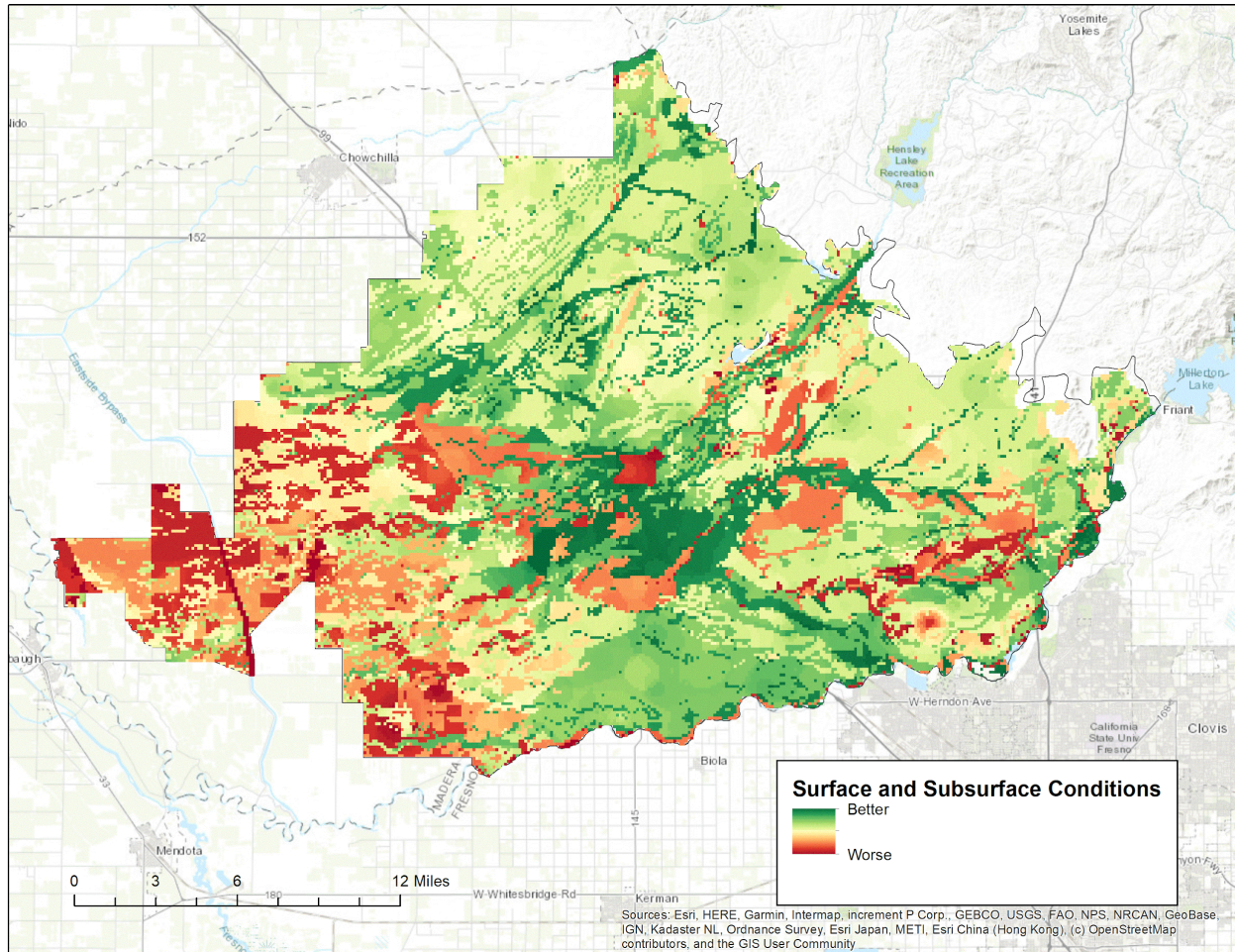
Here we demonstrate the functionality of our decision support tool and the types of outputs available through the use of the tool for the Madera Subbasin, located in the southeastern portion of the Central Valley (i.e., a test case to demonstrate our tool’s functionality and outputs). The Madera Subbasin was chosen after consultation with our clients at the Environmental Defense Fund and our advisors at the California Department of Water Resources. While the results presented here are specific to the Madera Subbasin, the tool is capable of producing comparable results for any subbasin located within California’s Central Valley.

## 4.1 Suitable Recharge Locations

The identification of suitable recharge locations within a groundwater basin provides managers with the information necessary to understand where water can most easily be added to the underlying aquifers without risking the addition of new nitrate contamination. This output is a fixed component of the tool designed to support the identification of the best places within a basin for recharge projects in the context of reaching sustainability as required by the Sustainable Groundwater Management Act (SGMA).

### 4.1.1 Surface and Subsurface Conditions

We ranked the suitability of surface and subsurface conditions for water infiltration and percolation into the underlying aquifer throughout the Madera Subbasin (Figure 4.3). Areas with the most suitable surface and subsurface conditions are located primarily in the central and southern portion of the Madera Subbasin. The worst areas in the Subbasin are the City of Madera, located in the center of the Subbasin, and the southwestern portion of Subbasin where the low permeability Corcoran clay layer is present and likely to inhibit water reaching the lower aquifer. In addition, areas in the southeast of the Subbasin are also not suitable for recharge due to the water table being relatively close to the ground surface, which corresponds to limited aquifer storage space (Figure 4.3).

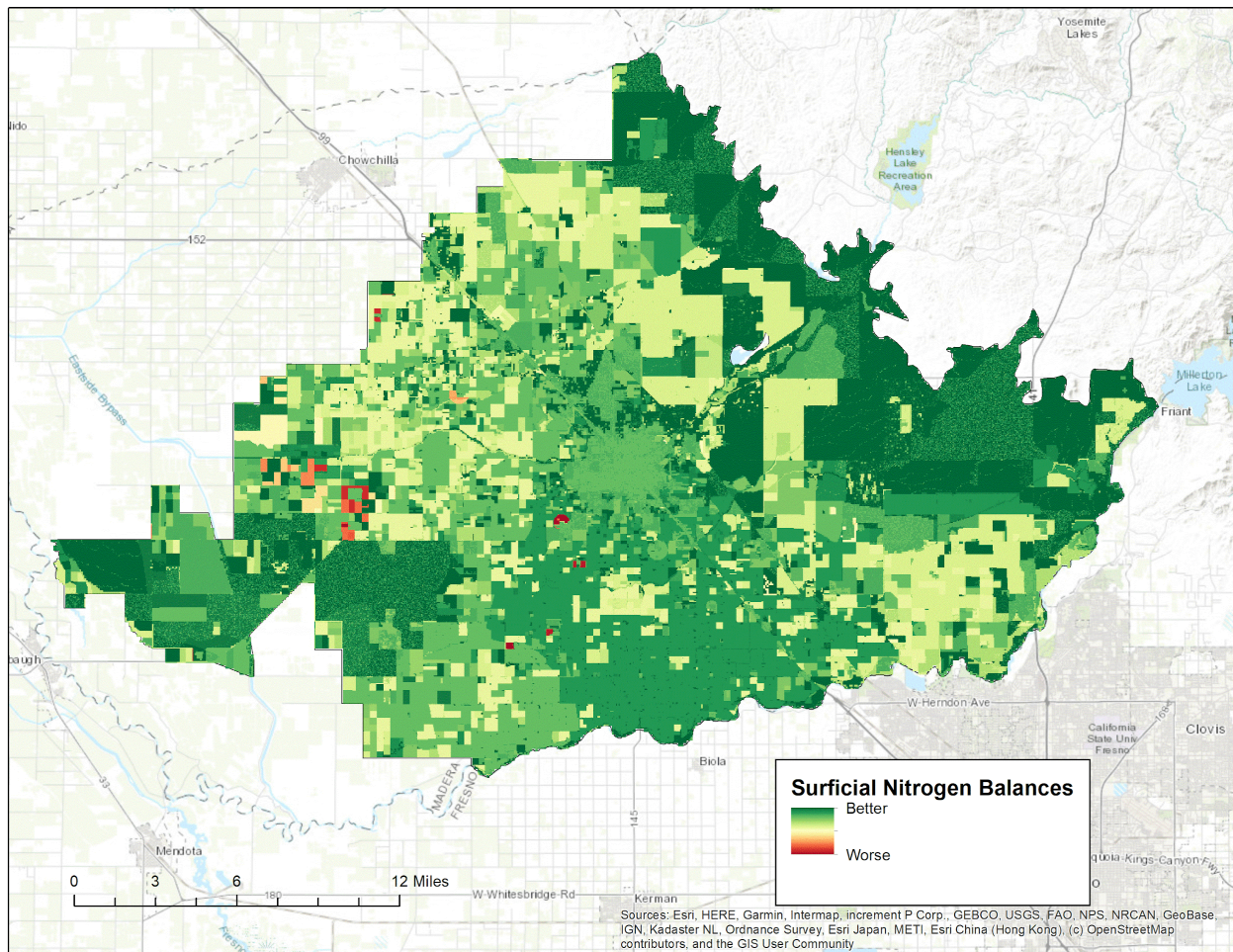


**Figure 4.3 Physical surface and subsurface conditions in the Madera Subbasin ranked by suitability for groundwater recharge.** Results for the Madera Subbasin of the weighted sum which combines all surface and subsurface conditions considered in the decision support tool, ranked from better (green) to worse (red) suitability for recharge. In the southwest, we tend to see relatively worse surface and subsurface conditions for recharge, while the northeast and central portions of the Subbasin have relatively better surface and subsurface conditions for recharge. Areas with better a rank for recharge (darker green) tend to have the following characteristics: suitable ground surface conditions, such as high soil infiltration capacity, a deep groundwater table, a high percentage of coarse soil material in the subsurface, and no presence of the low permeability Corcoran clay layer. This map compiles and analyzes the following datasets: Soil Agricultural Groundwater Banking Index (62), percent of coarse soil material (65), depth to water (12), and Corcoran clay characteristics (10,11).

#### 4.1.2 Nitrate Contamination Potential

The results of the nitrogen balance demonstrate areas within the Subbasin that are more or less likely to introduce new nitrate contamination through the application of water on the ground surface (Figure 4.4). Risk of nitrogen contamination due to recharge is low in most of the Madera Subbasin, with the exception of small discrete areas in the western portion of the Subbasin.

Through the use of satellite imagery, we confirmed that areas with high nitrogen contamination risk are locations of livestock operations that have high inputs and accumulation of nitrate.

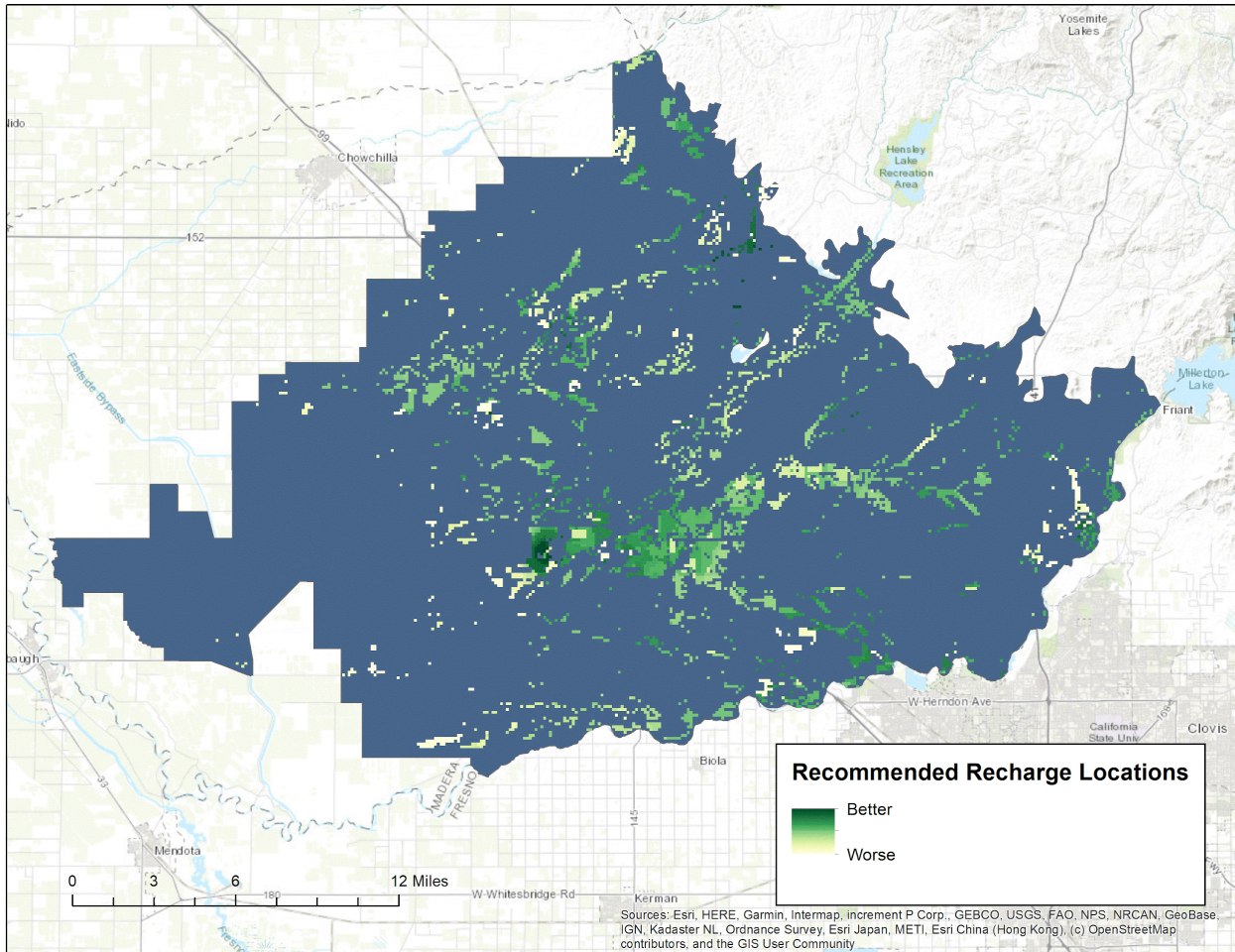


**Figure 4.4 Surficial nitrogen balances ranked by suitability for groundwater recharge in the Madera Subbasin.** Results for the Madera Subbasin of the weighted sum combining surficial nitrogen balances for 1990, 2005, and 2020, ranked from better (green) to worse (red) suitability for recharge. Most locations in the Madera Subbasin have relatively suitable surficial nitrogen balances for recharge, with the best (darkest green) of these areas concentrated along the Northeastern edge of the basin. The relatively better surficial nitrogen balances in this basin (darkest green) have a balance of <math>< 50 \text{ kg/N/hectare}</math> for all three years. Many of the relatively worst nitrogen balances in the basin (red) are dairies (confirmed with satellite imagery). Data used to calculate nitrogen balances sourced from UC Davis Center for Watershed Sciences (68).

#### 4.1.3 Recommended Recharge Locations

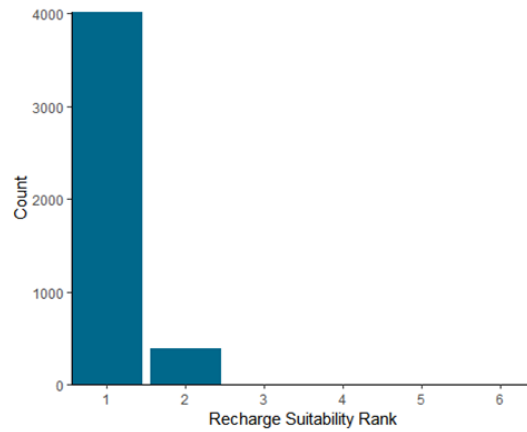
The suitable recharge locations (Figure 4.5) represent the best 10% of land area within the Madera Subbasin to perform recharge. Approximately 28,000 acres of land are ranked within the top 10% of possible scores after combining surface and subsurface conditions with the nitrogen balance and removing areas with unsuitable land use types. The best areas for recharge

within the suitable recharge locations output are located in the central region of the Subbasin, just southwest of the City of Madera, with the largest contiguous areas of suitable recharge locations in the south central part of the basin.



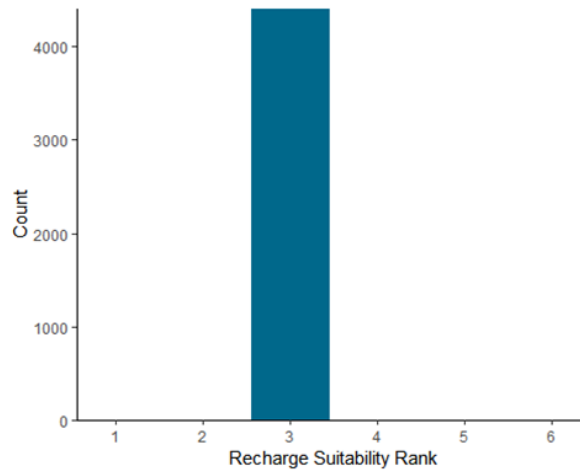
**Figure 4.5 Recommended recharge locations ranked by suitability for groundwater recharge in Madera Subbasin.** Results for the Madera Subbasin of the top 10% suitable recharge locations (recommended recharge locations), ranked from good (yellow) to better (dark green). Suitable recharge locations indicate where water can most easily reach the groundwater table at the lowest risk of introducing new contamination in the basin. Recommended recharge locations are fairly widely distributed throughout the basin, with the largest concentration just south of the basin center and a notable lack of recommended locations in the Southwestern corner of the basin. This map compiles and analyzes the following datasets: Soil Agricultural Groundwater Banking Index (62), percent coarseness (65), depth to water (12), Corcoran clay characteristics (10,11), calculated soil nitrogen balance (68), and land use data (63).

The distribution of SAGBI scores within the recommended recharge locations (Figure 4.6) show that most (80%) of the locations have a SAGBI score of 1, meaning they are among the most suitable surface conditions for recharge.



**Figure 4.6 Distribution of Sustainable Agricultural Groundwater Banking Index (SAGBI) scores within recommended recharge locations in the Madera Subbasin.** All areas included in the top 10% of suitable recharge locations have a SAGBI score rank of either 1 (SAGBI score of 85-100) or 2 (SAGBI score of 69-85), with areas scoring 1 accounting for 80% of the total. On this ranking scale, 1 is most suitable for recharge and 6 is least suitable. SAGBI data sourced from UC Davis Center for Watershed Sciences (62).

The distribution of scores for the depth to water component of the recommended recharge locations (Figure 4.7) shows that all areas within the recommended recharge locations have a depth to water between 100 - 500 feet below ground surface (a rank of 3, described in Methods - Depth to Groundwater section).

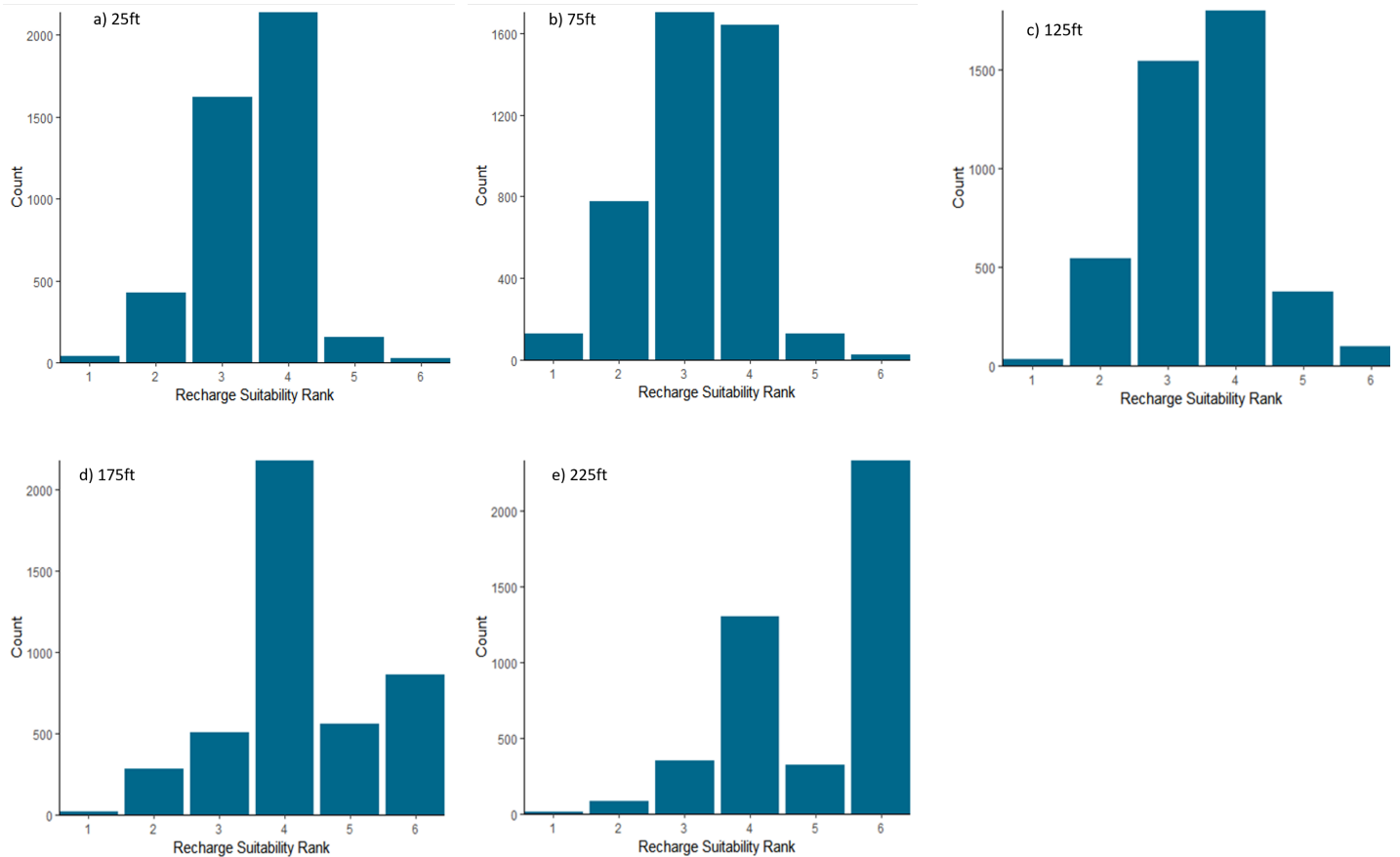


**Figure 4.7 Distribution of depth to water scores within recommended recharge locations in the Madera Subbasin.** All areas included in the top 10% of suitable recharge locations have a depth to water score of 3, corresponding to a water depth of 100-500 ft below ground surface. On this ranking scale, 1 is most suitable for recharge and 6 is least suitable. Data for depth to water sourced from CA Department of Water Resources (12).

The distribution of percent of coarse grained materials at depth (Figure 4.8) show that between 0 - 200 feet below the ground surface, most (85% at 25 feet, 76% at 75 feet, 76% at 125 feet, and 61% at 175 feet) of the soil material scored either a 3 or a 4 indicating a percent of coarse

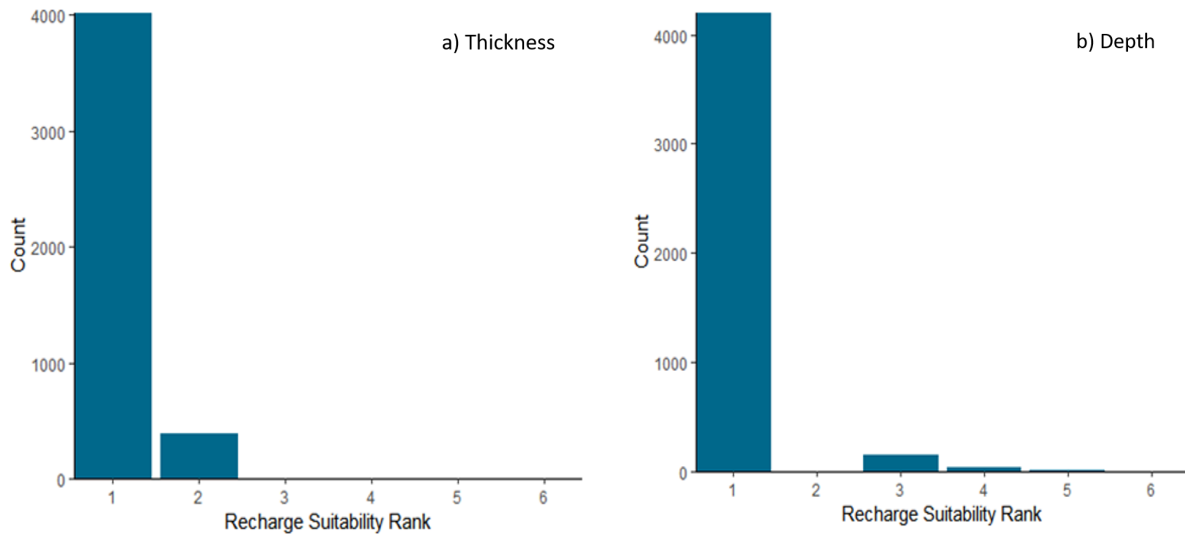


grained soil material between 20 - 70% and an associated estimation of vertical hydraulic conductivity between ~5 - 45  $\mu\text{m}/\text{sec}$ . At deeper depths (beyond 200 ft below ground surface), percent of coarse grained materials decreases to mostly values between 0 - 20%.



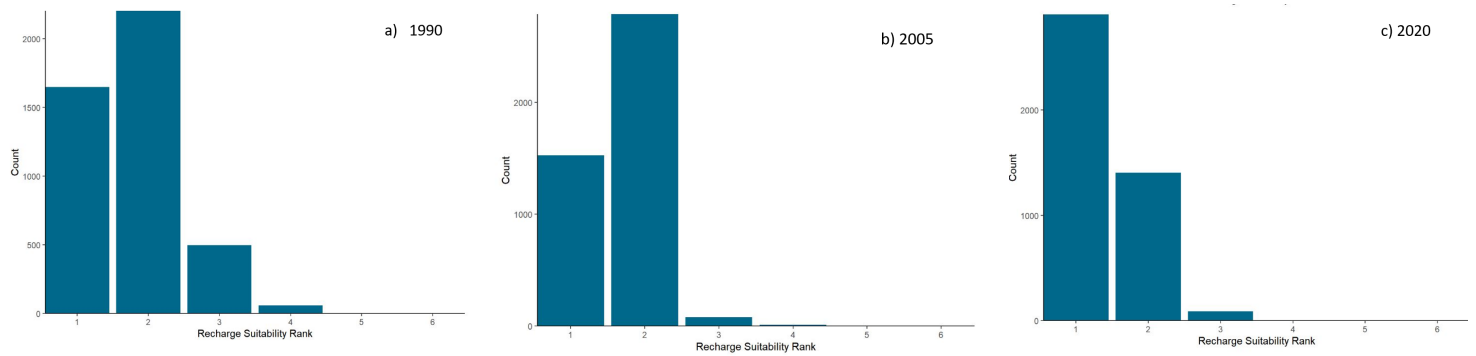
**Figure 4.8 Distribution of percent of coarse grained soil material scores at five depths within recommended recharge locations in the Madera Subbasin.** Areas in the top 10% of suitable recharge locations include soil material scores ranging from 1 to 6 for every soil depth: 25ft (a), 75ft (b), 125ft (c), 175ft (d), 225ft (e). On this ranking scale, 1 is most suitable for recharge (percent coarse soil material 90-100%) and 6 is least suitable (percent coarse soil material 0-10%). Soil material score distributions tend to skew towards a score of 6 as soil depth (ft) increases (25-225ft, a-e). Percent coarse grained soil material data sourced from the texture model in the Central Valley Hydrologic Model (65).

The recommended recharge locations within the Madera Subbasin are located mostly in areas where the Corcoran clay is not present, as shown in the distributions for scores of both clay depth and clay thickness (Figure 4.9), with 95% of observations ranking 1.



**Figure 4.9 Distribution of Corcoran clay thickness and depth scores within recommended recharge locations in the Madera Subbasin.** Areas in the top 10% of suitable recharge locations include scores of 1 and 2 for Corcoran clay thickness (ft) (a), corresponding to clay thickness ranging from Null (no clay) - 20ft. The top 10% of suitable recharge locations include scores of 1,3,4, and 5 for Corcoran clay depth (ft) (b), corresponding to clay depth ranging from Null (no clay) - 100ft. For both thickness and depth, scores of 1 account for the majority of all scores. On this ranking scale, 1 is most suitable for recharge (No clay present for both thickness and depth) and 6 is least suitable (50 - 100ft depth and >50ft thickness). Corcoran clay depth and thickness data sourced from US Geological Survey (10,11).

The range of nitrogen balance scores within the recommended recharge locations in the Madera Subbasin show that surficial nitrogen balances are generally low throughout the recommended recharge locations (Figure 4.10). The large majority of recommended recharge locations have a nitrogen balance less than 100 kg N/hectare/year (scores of either 1 or 2) for each of the years analyzed. In the 1990 nitrogen balance, 87% of recommended recharge location areas had less than 100 kg N/hectare/year, and in the 2005 and 2020 nitrogen balances, 98% of recommended recharge location areas had less than 100 kg N/hectare/year.



**Figure 4.10 Distribution of surficial nitrogen balance scores for recommended recharge locations in the Madera Subbasin.** Nitrogen balances were calculated for years 1990 (a), 2005 (b), and 2020 (c). Areas in the top 10% of suitable recharge locations include scores ranging from 1-4 (<0 - 300 kg N/hectare/year) for nitrogen balances in 1990 and 2005, and from 1-3 (<0 - 100 kg N/hectare/year) in 2020. On this ranking scale, 1 is more suitable for recharge (<0 kg N/hectare/year) and 6 is less suitable (>500 kg N/hectare/year). Nitrogen balance score distributions tend to skew toward 1 in more recent years. Nitrogen balance data sourced from UC Davis Center for Watershed Sciences (68).

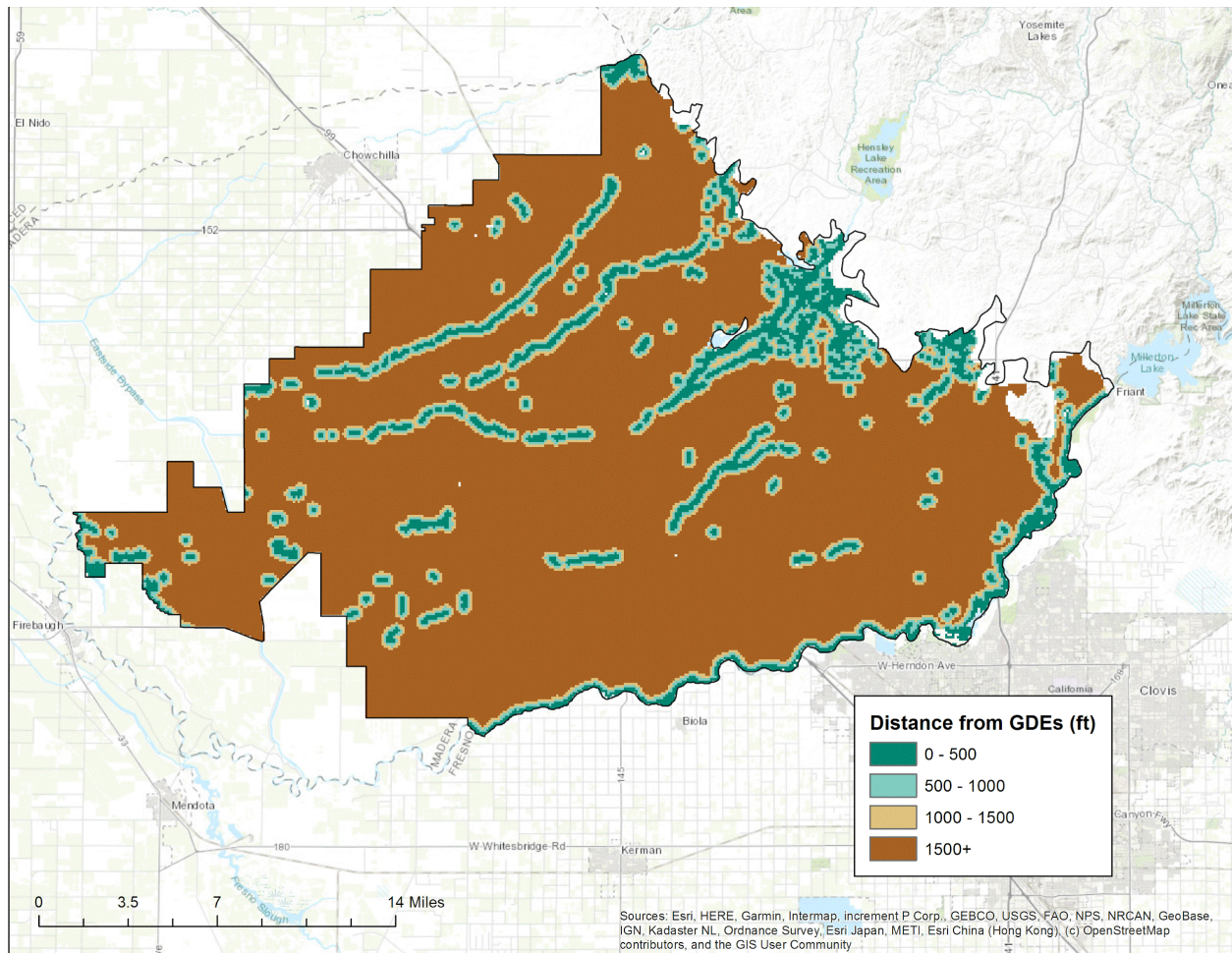
## 4.2 Additional Considerations

The incorporation of additional considerations allows for groundwater managers to preferentially weight potential benefits and feasibility constraints in order to access a customized multi-benefit recommendation that aligns with local priorities.

### 4.2.1 Benefits

#### 4.2.1.1 Groundwater Dependent Ecosystems

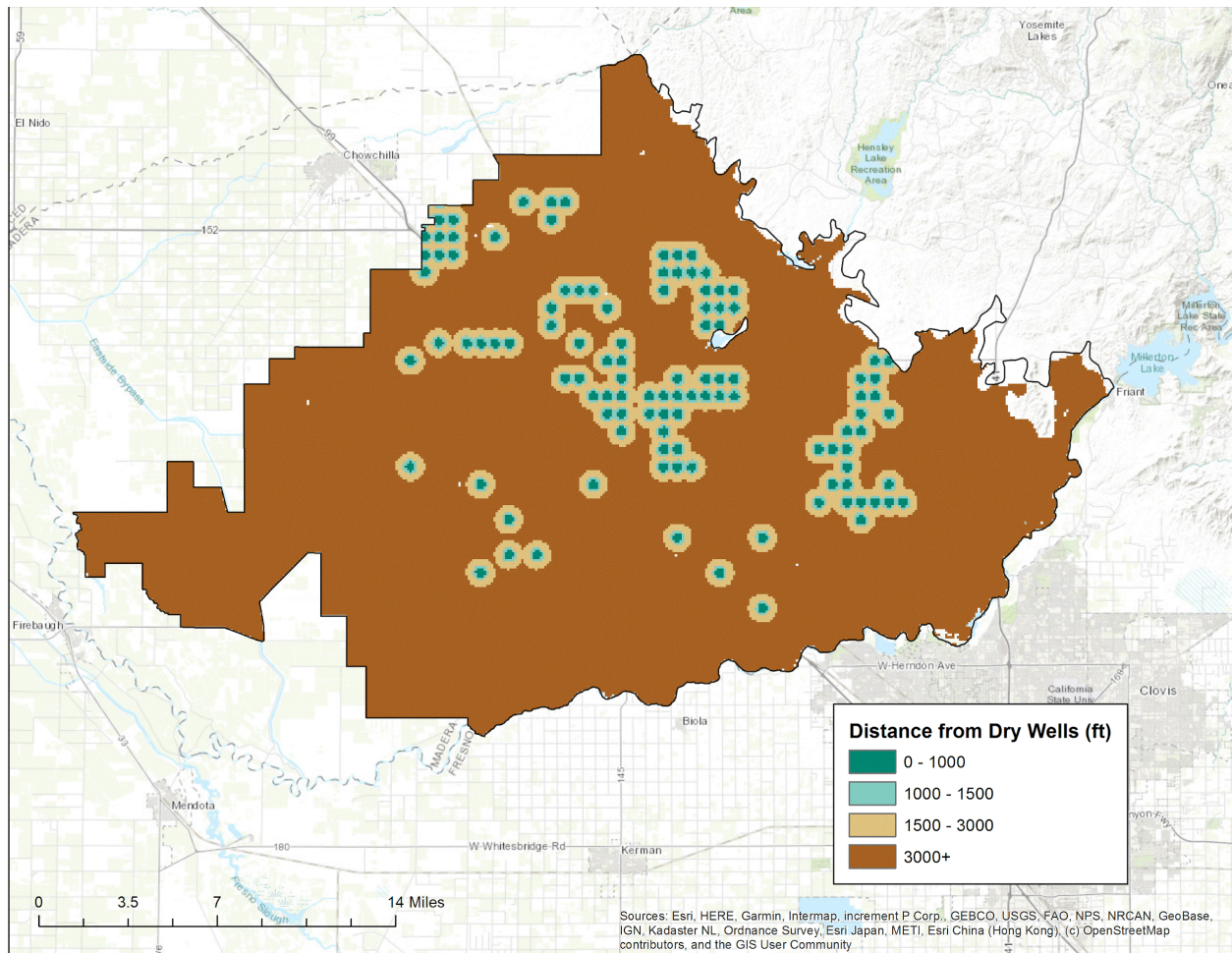
In the Madera Subbasin, the largest concentration of potential GDEs occurs in the north-eastern portion of the Subbasin where surface water bodies originating in the Sierra Nevada foothills enter the Subbasin. Land area within the Madera Subbasin that is within 500ft of a potential groundwater dependent ecosystem is estimated to be over 25,000 acres and describes locations where a recharge project will most be able to support the health of nearby potential GDEs (Figure 4.11).



**Figure 4.11 Distance from groundwater dependent ecosystems in the Madera Subbasin.** This map shows buffer zones around potential groundwater dependent ecosystems in the form of wetlands and vegetation. A range of buffer zones are represented here from a distance of 0-500 ft (dark green), to a distance of 1500 feet or more (brown). Most of the GDEs appear in the northern portion of the Subbasin. Water managers that aim to improve ecosystem health may consider new recharge projects closer to potential GDEs. This map was created from the Natural Communities Dataset compiled by the California Department of Water Resources and The Nature Conservancy (72).

#### 4.2.1.2 Domestic Wells That Have Run Dry

The majority of self-reported domestic wells that have run dry are located in the north-eastern half of the Madera Subbasin. Nearly 8,000 acres of land within the Madera Subbasin is within 1,000 feet of a reported dry domestic well (Figure 4.12). These locations represent areas where a recharge project will be most likely to rehydrate domestic wells that have run dry with the assumption that sustained recharge in these locations could raise the groundwater table enough to rehydrate some of these wells.

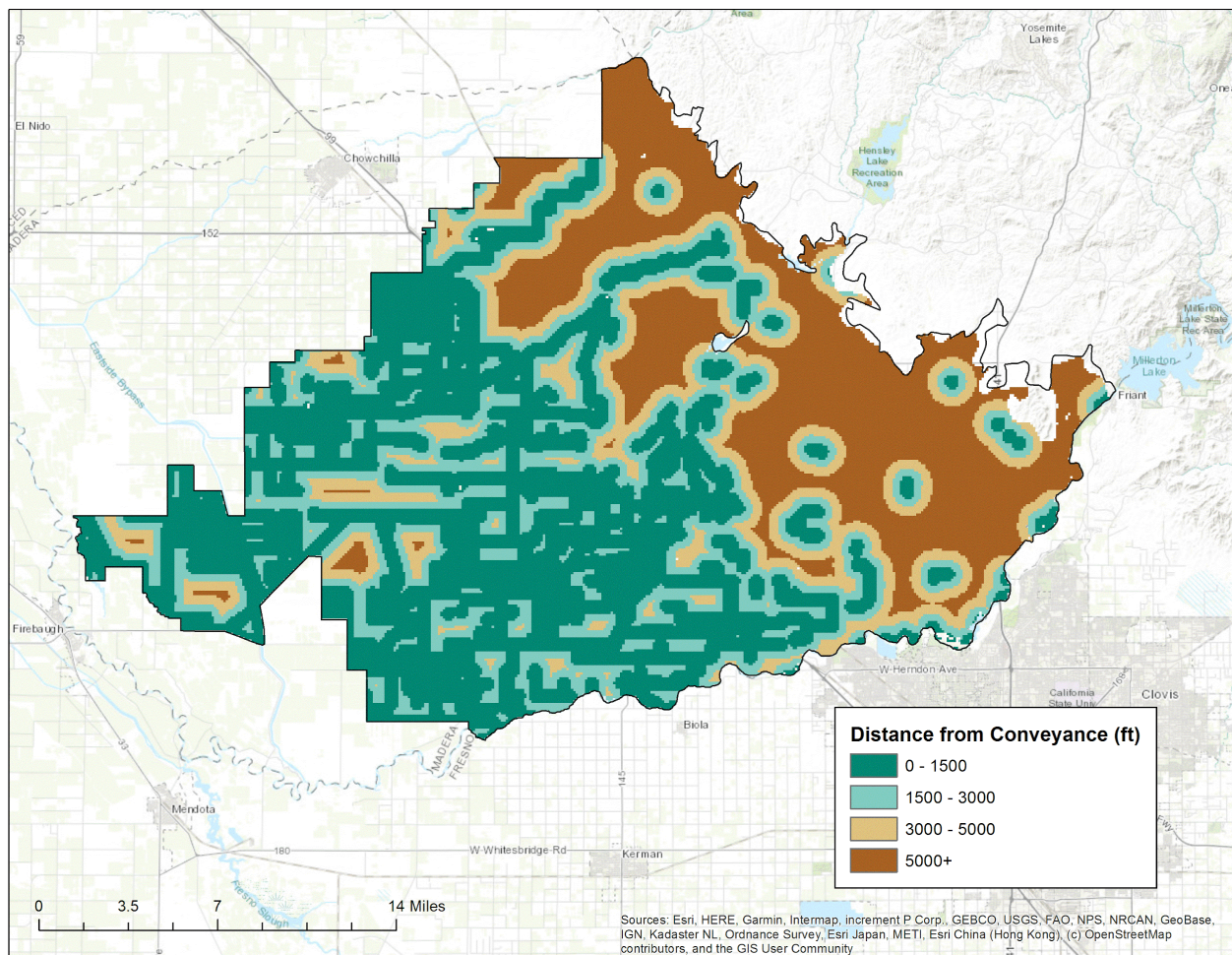


**Figure 4.12 Distance to wells that have run dry in the Madera Subbasin.** This map shows buffer zones around domestic wells where the water table is not high enough to supply sufficient drinking water. The closest zones are within a distance of 0-1000 feet (dark green) from wells and the farthest zones are 3,000 feet away or more (brown) from dry wells. These wells are concentrated in the northern and eastern portions of the Subbasin. Water managers may target recharge projects to benefit residents whose domestic water supply has diminished. This map was created from the Household Water Supply Shortage Reporting System Database, which was compiled by the California Department of Water Resources (74). Data was collected on a voluntary basis, and therefore may not capture the full extent of wells that have run dry in the Madera Subbasin.

## 4.2.2 Feasibility

### 4.2.2.1 Existing Water Conveyance Infrastructure

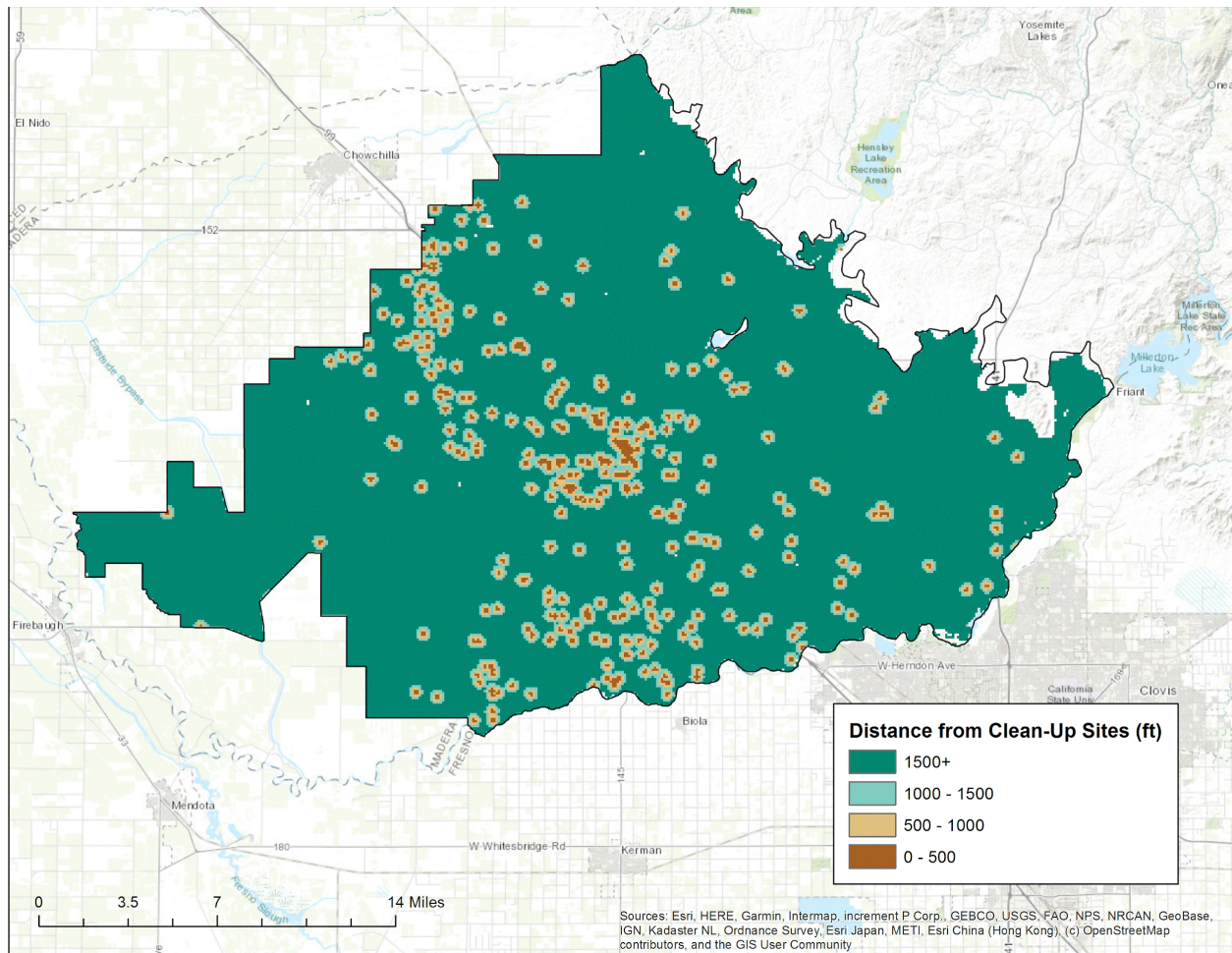
The spatial coverage of conveyance infrastructure in the Madera Subbasin increases in density in the southwestern portion of the Subbasin. There are 142,000 acres of land within the Subbasin that are within 1,500 feet of an existing canal, aqueduct, pipeline, or perennial stream. These land areas require less additional conveyance infrastructure construction to facilitate water deliveries when implementing groundwater recharge projects (Figure 4.13).



**Figure 4.13 Distance to existing conveyance infrastructure in the Madera Subbasin.** This map shows buffer zones around canals, aqueducts, pipelines, and perennial streams. Buffer zones are between a distance of 0-1500 feet (dark green) and 5,000 feet or more (brown) from existing infrastructure. Intermittent and ephemeral streams are not included. Existing conveyance infrastructure is concentrated in the southern and western portion of the Subbasin. Water managers may prefer to build recharge projects closer to existing infrastructure in order to reduce costs for building new conveyance. Data from the National Hydrography Dataset Plus (NHD+), compiled by the United States Geological Survey (75).

#### 4.2.2.2 Locations of Listed Contamination Clean Up Sites

Within the Madera Subbasin, listed contamination cleanup sites are largely concentrated in the central region, with a high density of cleanup sites within the greater City of Madera area. A smaller number of contamination clean up sites are located on the eastern and western edges of the Subbasin. Approximately 300,000 acres of land area within the Madera Subbasin are at least 1,500 feet away from any listed contamination cleanup site (Figure 4.14).



**Figure 4.14 Distance from contamination sites in the Madera Subbasin.** This map shows regions that are 1,500 feet or more (dark green) from sites that present a potential threat to groundwater quality and regions that are 0-500 feet from these sites (brown). Potential contaminant sources included in this dataset are: leaking and non-leaking underground storage tanks for petroleum (LUSTs/USTs), state-designated contamination cleanup sites, military cleanup sites, government-permitted pollution discharge sites, and landfills. Contamination sites appear to be concentrated in the center of the Subbasin, with some clustering in the northwest and the south. Water managers may prefer to locate recharge projects further away from these sites to avoid potential contamination of the water supply. This map was created using the GeoTracker Database, which was compiled by the California State Water Resources Control Board (76)

### 4.3 Multi-Benefit Recharge Locations

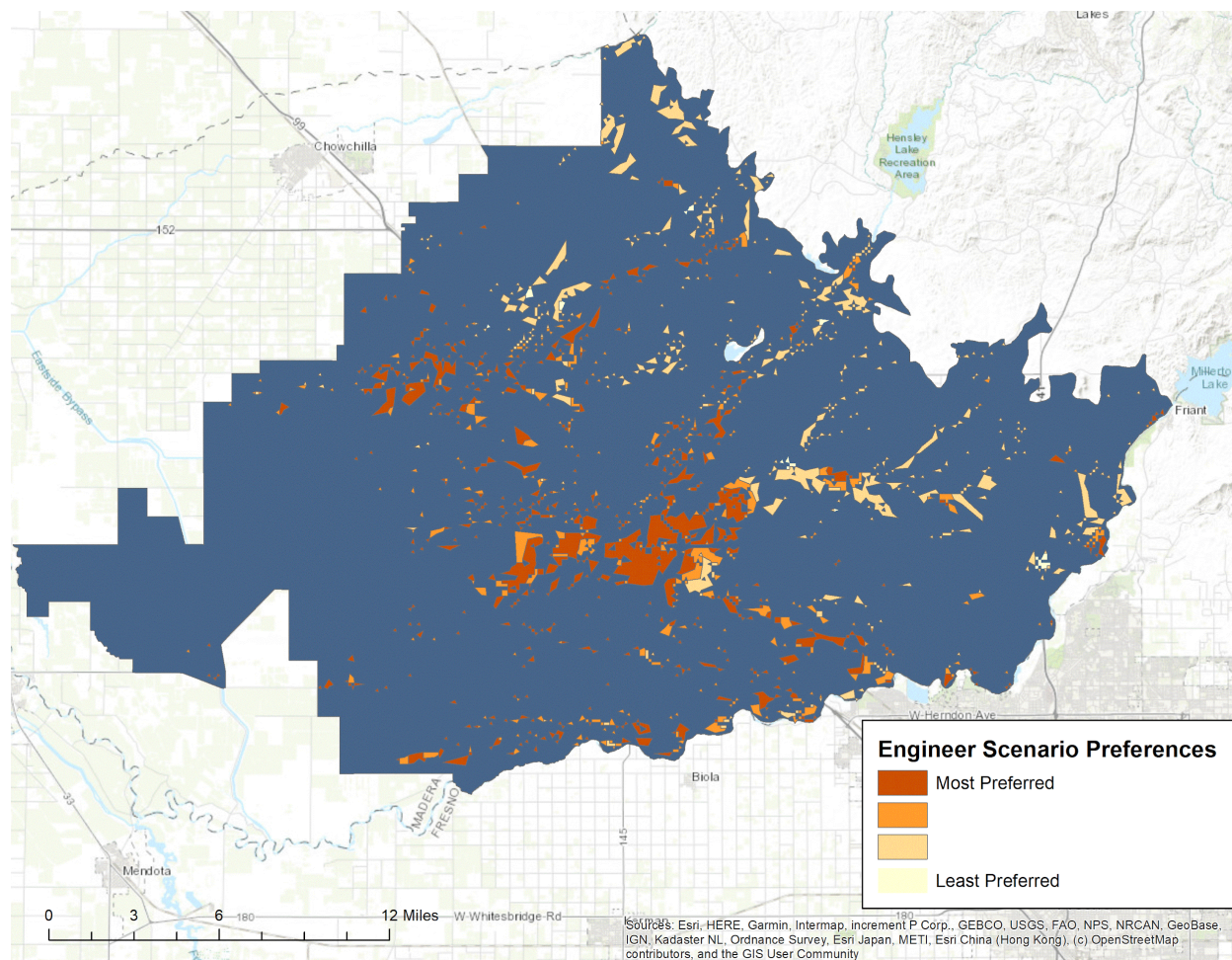
In order to explore the functionality of the outputs created by this tool, we tested four hypothetical scenarios in the Madera groundwater basin. Each hypothetical scenario represents a distinct weighting scheme for additional considerations, and is meant to demonstrate how basin specific preferences can be incorporated into a multi-benefit recommendation output. Each scenario applies a ranked score to the recommended recharge locations. The rank of these

areas displays locations in the Subbasin that are more or less likely to achieve the specified additional benefits.

#### 4.3.1 The Engineer's Scenario

The first of our example scenarios preferentially weights the importance of recharge locations that are proximal to existing water conveyance infrastructure. In this scenario, 80% of the available weighting was applied to prioritizing locations that are close to existing conveyance infrastructure, and the remaining 20% to locations further away from listed contamination cleanup sites. Of the approximately 28,000 acres of recommended recharge locations, nearly 13,000 ranked most preferred in this scenario (Figure 4.15). This result demonstrates that within the Madera Subbasin, nearly half of suitable recharge locations are also within 1,500 feet of existing conveyance infrastructure.



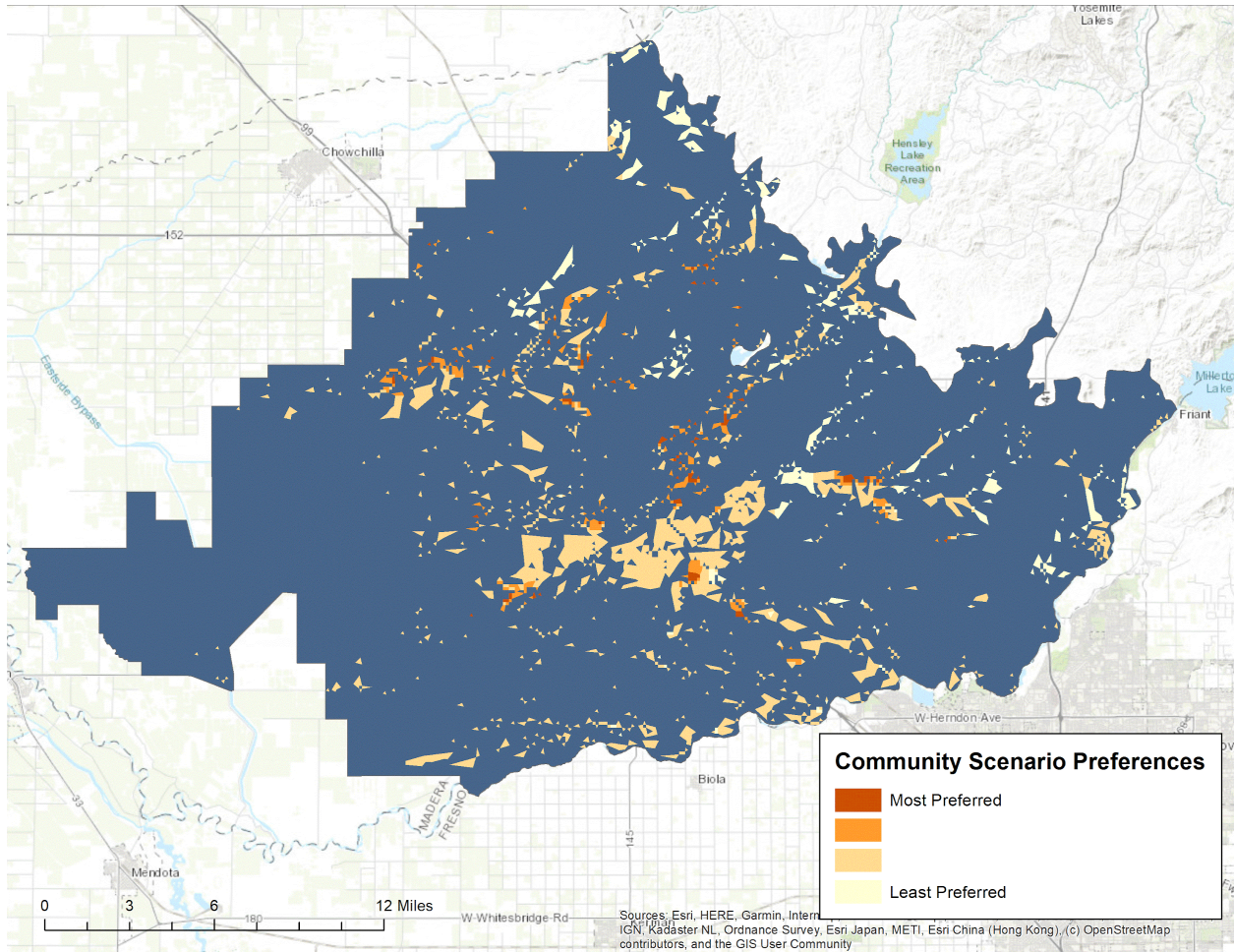


**Figure 4.15 Suggested recharge locations in the Madera Subbasin, prioritizing areas closer to conveyance infrastructure and farther from contamination clean-up sites.** Results of this scenario show ranked preferences within the top 10% of suggested recharge locations. In this scenario, the distance to existing infrastructure is weighted at 80%, and distance from contamination sites weighted at 20%. The most preferred regions for recharge projects (red) appear across much of the suggested land area and the least preferred regions (yellow) are scattered in the north and east of the Subbasin. This map compiles and analyzes the following data: Soil Agricultural Groundwater Banking Index (62), percent of coarse soil material from the USGS Central Valley Hydrologic Model (65), depth to water from the Groundwater Information Center of the Department of Water Resources (12), Corcoran clay considerations from the USGS Central Valley Hydrologic Model (10,11), nitrogen additions and losses from the UC Davis Center for Watershed Sciences (68), land use data (63), infrastructure from the National Hydrography Dataset Plus from the USGS (75) and contamination sites from the GeoTracker Database from the California State Water Resources Control Board (76).

### 4.3.2 The Community Scenario

In the second example scenario, priority was applied to recharge locations that are near to domestic wells that have run dry. In this scenario, 70% of the available weighting was applied to locations near domestic wells that have run dry, 20% applied to areas further from contamination cleanup sites and the remaining 10% applied to locations close to existing conveyance

infrastructure. Within the identified recommended recharge locations, approximately 650 acres of land within the Madera Subbasin ranked most preferred to achieve the additional benefits and feasibility considerations applied in this weighting scheme (Figure 4.16). Because many of the domestic wells that have run dry are located in the northeast portion of the Subbasin, while the recommended recharge locations are concentrated more in the central and southern portions of the basin, only a small portion of the suitable recharge locations are also within 1,000 feet of domestic wells that have run dry.

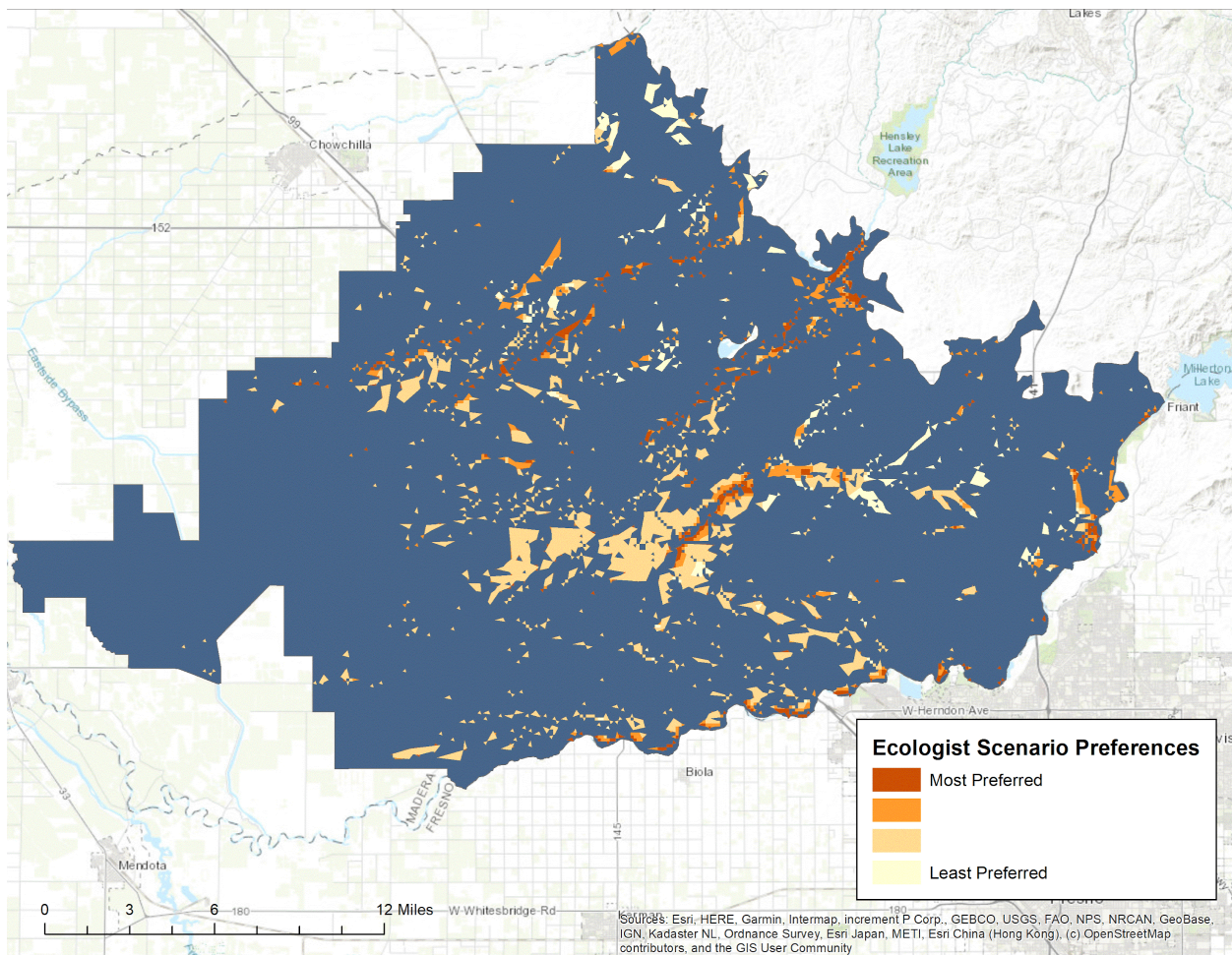


**Figure 4.16 Suggested recharge locations in the Madera Subbasin, prioritizing areas closer to domestic drinking wells, farther from contamination sites, and closer to conveyance infrastructure.** Results of this scenario show ranked preferences within the top 10% of suggested recharge locations. Priority is given to the location of domestic wells that have run dry, with a weight of 70%, distance away from contamination sites with a weight of 20%, and closeness to existing infrastructure with a weight of 10%. Based on this scenario, there are very few regions that are most preferred (red), while the moderately preferred (gold) and least preferred regions (light yellow) are more abundant across the Subbasin. This map compiles and analyzes the following data: recharge suitability at the near-surface from the Soil Agricultural Groundwater Banking Index (62), percent of coarse soil material from the USGS Central Valley Hydrologic Model (65), depth to water from the Groundwater Information Center of the Department of Water Resources (12), Corcoran clay considerations from the USGS Central Valley Hydrologic Model (10,11),

nitrogen additions and losses from the UC Davis Center for Watershed Sciences (68), land use data (63), dry wells from the Household Water Supply Shortage Reporting System Database of the Department of Water Resources (74), infrastructure from the National Hydrography Dataset Plus from the USGS (75), contamination sites from the GeoTracker Database compiled by the California State Water Resources Control Board (76).

### 4.3.3 The Ecologist's Scenario

Another scenario applied priority to recharge locations that could benefit potential groundwater dependent ecosystems within the Subbasin. In this scenario, 70% of the available weight was applied to locations near to potential groundwater dependent ecosystems, 20% applied to locations close to existing conveyance infrastructure, and the remaining 10% applied to locations further away from contamination clean up sites. Of the 28,000 acres that are most suitable for groundwater recharge, 2,400 acres were also ranked most preferred for achieving additional benefits based on the weighting scheme applied in this scenario (Figure 4.17).

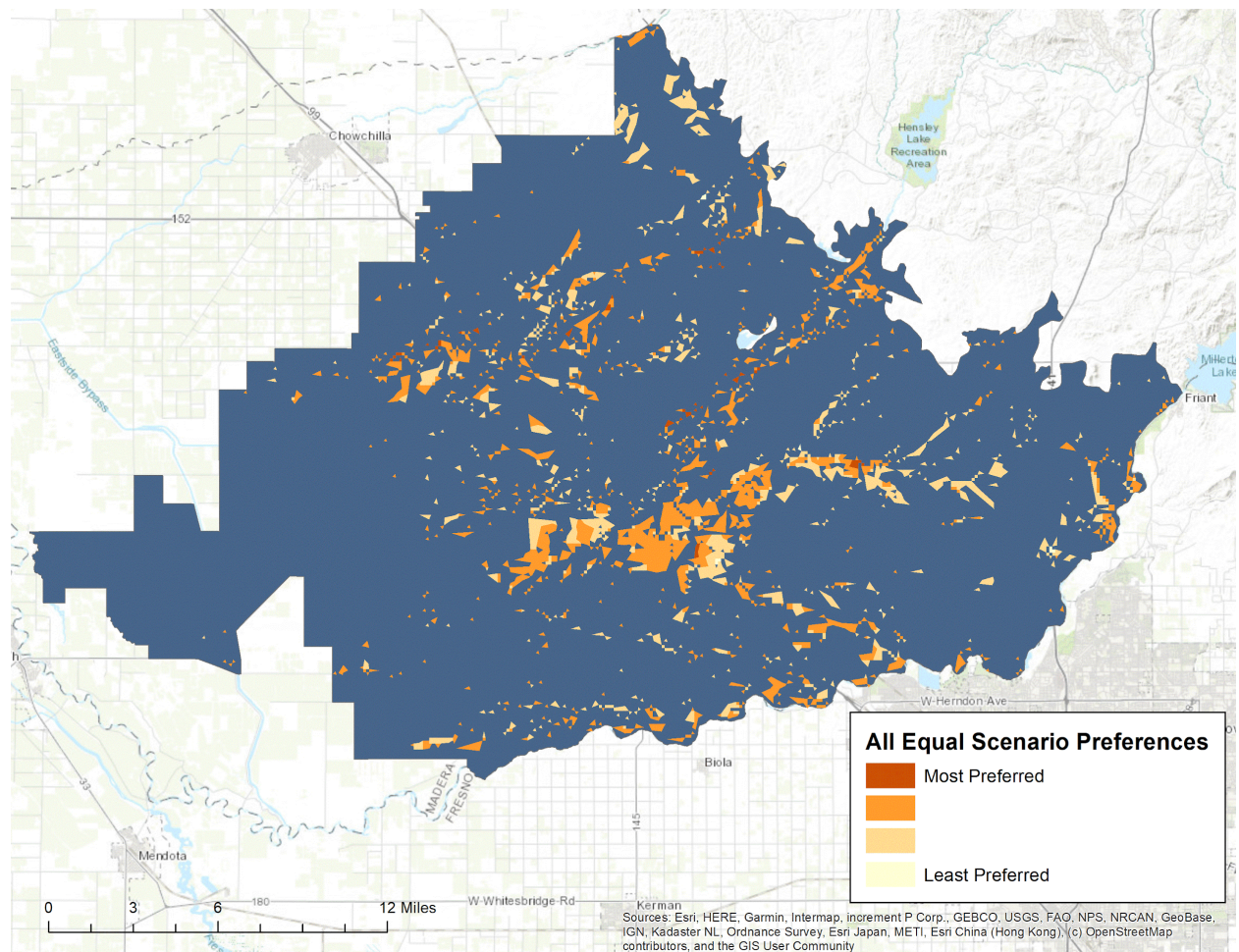


**Figure 4.17 Suggested recharge locations in the Madera Subbasin, prioritizing areas closer to groundwater dependent ecosystems and existing infrastructure and farther from contamination sites. Results of this scenario show ranked preferences within the top 10% of suggested recharge locations. Priority is given to the distance to**

groundwater dependent ecosystems with a weight of 70%, closeness to infrastructure with a weight of 20%, and distance away from contamination sites with a weight of 10%. The most preferred regions (red) appear across the Subbasin and reflect the location of GDEs, while the least preferred regions (yellow) are scattered in the northern and eastern portions of the Subbasin. This map compiles and analyzes the following data: recharge suitability at the near-surface from the Soil Agricultural Groundwater Banking Index (62), percent of coarse soil material from the USGS Central Valley Hydrologic Model (65), depth to water from the Groundwater Information Center of the Department of Water Resources (12), Corcoran clay considerations from the USGS Central Valley Hydrologic Model (10,11), nitrogen additions and losses from the UC Davis Center for Watershed Sciences (68), land use data (63), infrastructure from the National Hydrography Dataset Plus from the USGS (75), contamination sites from the GeoTracker Database compiled by the California State Water Resources Control Board (76) and Groundwater Dependent Ecosystems from the Natural Communities Dataset compiled by the California Department of Water Resources and The Nature Conservancy (72).

#### 4.3.4 The Equal Weights Scenario

Lastly, a weighting scenario was applied in which all four additional considerations were weighted equally, 25% each. In this scenario, approximately 450 acres of recommended recharge locations were ranked most preferred to meet all of the additional benefit criteria (Figure 4.18). This result demonstrates that within the Madera Subbasin, a relatively small portion of the land area (~0.1%) would be well suited to groundwater recharge and also located near to domestic wells that have run dry, potential groundwater dependent ecosystems, and conveyance infrastructure while being a safe distance from listed contamination cleanup sites.



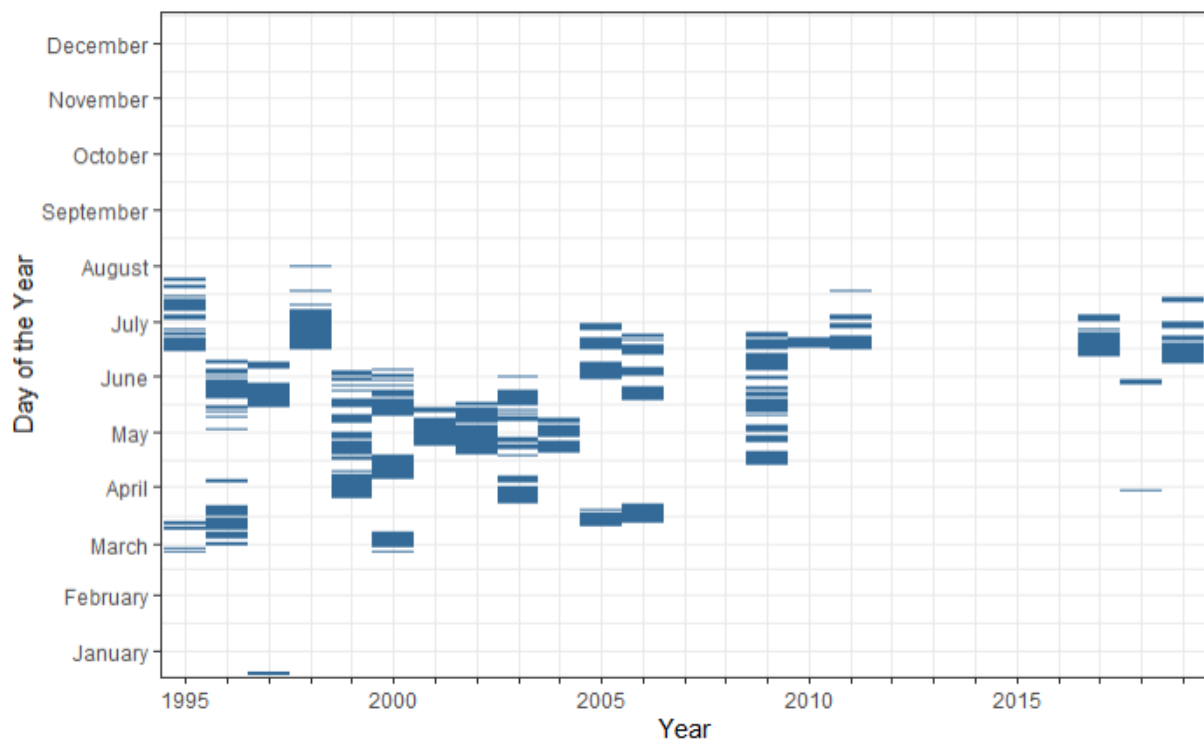
**Figure 4.18 Suggested recharge locations in the Madera Subbasin with equal prioritization for all additional considerations.** Results of this scenario show ranked preferences within the top 10% of suggested recharge locations. All four of the additional considerations for recharge project suitability (closer to groundwater dependent ecosystems, domestic wells that have run dry, and conveyance infrastructure, and farther away from contamination cleanup sites) are weighted equally. The most preferred regions (red) appear sparsely across the north and central portion of the Subbasin while the least preferred regions (light yellow) are sparsely distributed across the central and eastern portion of the Subbasin. Most of the areas appear to be moderately preferred (orange and gold). This map compiles and analyzes the following data: recharge suitability at the near-surface from the Soil Agricultural Groundwater Banking Index (62), percent of coarse soil material from the USGS Central Valley Hydrologic Model (65), depth to water from the Groundwater Information Center of the Department of Water Resources (12), Corcoran clay considerations from the USGS Central Valley Hydrologic Model (10,11), nitrogen additions and losses from the UC Davis Center for Watershed Sciences (68), land use data (63), infrastructure from the National Hydrography Dataset Plus from the USGS (75), contamination sites from the GeoTracker Database compiled by the California State Water Resources Control Board (76), groundwater dependent ecosystems from the Natural Communities Dataset compiled by the California Department of Water Resources and The Nature Conservancy (72) and dry wells from the Household Water Supply Shortage Reporting System Database of the Department of Water Resources (74).

## 4.4 Source Water Analysis

Following the identification of recommended areas to implement groundwater recharge projects to achieve multiple benefits, Groundwater Sustainability Agencies will need to assess the source of water used for recharge. In the Madera Subbasin, we propose that some amount of water could be released from Millerton Reservoir in anticipation of high-flow events on the San Joaquin River in order to capture a larger total quantity of water through a conjunctive water storage approach.

### 4.4.1 Historic Water Availability

The historic data for daily inflows, outflows, and storage at Millerton Reservoir demonstrates that over the past 24 years (1995 - 2019), 472 days met the criteria we established to conservatively identify opportunities for reservoir releases. The criteria considered are: that reservoir storage was at least 90% of the active capacity and that inflows were greater than outflows for that day (Figure 4.19). Of the days that met the criteria, 363 (77%) fell within the months of May, June and July.

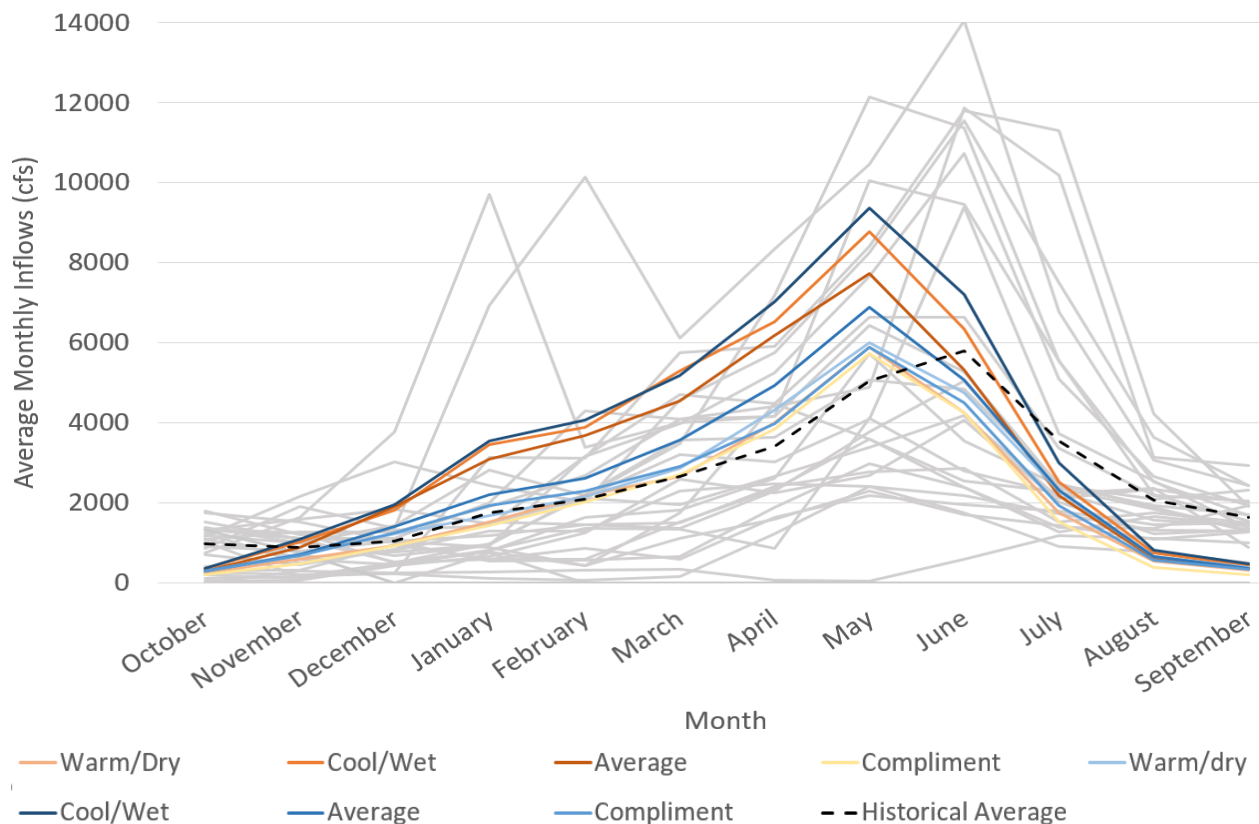


**Figure 4.19 Days when criteria for releasing water from Millerton Reservoir for Managed Aquifer Recharge (MAR) were met (1995 - 2019).** Each blue line represents 1 day in which Millerton Reservoir was at or above 90% capacity and inflows exceeded outflows. On these days it would have been possible to release water from the

reservoir and direct these flows to MAR projects. The majority of these days in the past 24 years fell between May - July. Reservoir flow and storage data sourced from CA Department of Water Resources (77).

#### 4.4.2 Projected Water Availability

The result of our comparative analysis between historic and predicted future inflows show that projected average annual inflows at Millerton Reservoir fall within the range of historic variability. During the historic period analyzed, peak monthly average inflow occurs during the month of June in 11 out of 25 years (44%) and during the month of May in 10 out of 25 years (40%). Considering the calculated 25 year historical average of monthly inflows, flow in the San Joaquin river peaks in the month of June. An important finding of this analysis is that all 8 climate projection scenarios and modeled outcomes indicate that peak average monthly inflows at Millerton Reservoir are likely to shift approximately one month earlier in the year as compared to the historic average. While the historic data indicates an average peak inflow in June, the projected inflows under the analyzed climate scenarios show an average peak inflow in May (Figure 4.20).



**Figure 4.20 Historical (1995-2019) and projected average monthly streamflow into Millerton Reservoir.** Includes monthly average streamflow (cfs) into Millerton Reservoir for each year from 1995-2019 (gray lines) and an average of monthly average streamflow (cfs) for all 24 years (black dashed line). Overlaid are two projected climate scenarios rcp 4.5 (blue tones lines) and 8.5 (red/orange tones lines) and four modeled outcomes: warm/dry, cool/wet, average, and complement. Projected streamflow into Millerton Reservoir is within the historical range, though peak flow is

shifted one month earlier (May) from the historical average (June). Historical streamflow data sourced from CA Department of Water Resources (77) and projected streamflow data sourced from Cal-Adapt (78).



# 5 Discussion

## 5.1 Recommended Recharge Locations

As a product of the combination of surface and subsurface conditions and water quality considerations, the recommended recharge locations (Figure 4.5) identify areas where managers can most easily replenish groundwater supplies at the lowest risk of introducing new contamination into those supplies. Unlike the multi-benefit recharge locations, this result of the tool is not customizable by the user. We consider these two considerations to be integral to effective and responsible recharge activities, and have used the best available science to calculate recommended location rankings. However, it is possible for groundwater managers to update the data inputs into this portion of the tool to incorporate the most accurate available data sources.

The 28,000 acres of land ranked within the top 10% of suitable recharge locations in the Madera Subbasin had the following characteristics:

- 80% of locations have a SAGBI score of "excellent"
- 100% of locations have a depth to water between 100-500 feet below ground surface
- 85% of locations have soils within the first 50 feet of the substrate that are between 20-70% coarse grained material
- 76% of locations have soils between 50-100 feet below ground surface that are between 20-70% coarse grained material
- 76% of locations have soils between 100-150 feet below ground surface that are between 20-70% coarse grained material
- 61% of locations have soils between 150-200 feet below ground surface that are between 20-70% coarse grained material
- 95% of locations have no presence of the Corcoran clay
- 87% of locations have a nitrogen balance less than 100 kg N/hectare/year in 1990
- 98% of locations have a nitrogen balance less than 100 kg N/hectare/year in 2005
- 98% of locations have a nitrogen balance less than 100 kg N/hectare/year in 2020

In other basins, the top 10% of suitable recharge locations may have different suitability rankings, and individual components within these recommended areas may be better or worse for recharge implementation. However, the top 10% of suitable recharge locations represents the relative best areas within a basin to perform recharge.

## 5.2 Multi-Benefit Recharge Locations

The results of the multi-benefit scenarios demonstrate the types of information that local groundwater management agencies are able to access through the use of the decision support tool. While we have built this tool with the intention of increasing available information and understanding in order to inform the placement of groundwater recharge projects that can achieve multiple benefits, we recognize that local knowledge may be appropriate to use in conjunction with the results of our tool.

The customizable tool component was designed to increase flexibility for Groundwater Sustainability Agencies (GSAs), with an understanding that different groundwater basins have varied financial and data resources, diverse community members, and may often need to balance competing interests and priorities. For that reason, we did not want our tool to be prescriptive in assigning value judgements to priorities for additional benefits and feasibility considerations of groundwater recharge; rather, we recognize that GSAs are best suited to identify the needs of their local basins in using this decision support tool.

Where appropriate the tool allows for the addition of more accurate or higher resolution data in order to refine the specificity of outputs. The implementation of the Sustainable Groundwater Management Act presents a substantial opportunity to plan and execute groundwater recharge projects that will not only play a role in basins reaching sustainability during the prescribed implementation period, but that are also capable of achieving additional benefits and augmenting overall water resilience at a regional level.

## 5.3 Source Water Analysis

The demonstrated source water availability analysis represents one methodology that Groundwater Sustainability Agencies (GSAs) could apply to determine possible sources of water to be directed towards recharge projects. By accounting for streamflow predictions and altering reservoir operations to make more space in surface storage in anticipation of high-flow events, local water management agencies may have an opportunity to capture a larger portion of peak streamflow through a combined storage approach. Other sources of water for recharge may be more appropriate and applicable to other subbasins, including recycled water and purchased imported water.

### 5.3.1 Historic Water Availability

We cannot make claims about a specific amount of water that might be available for recharge in the historic record we analyzed due to the complexity and politics around allocation structures. However, this analysis demonstrates the viability of directing some amount of water from Millerton Reservoir to groundwater recharge projects in anticipation of high flow events. Given the established criteria - reservoir storage at or above 90% of its active capacity and inflows exceeding outflows - there were many occasions in which reservoir operations might have been adjusted to direct some water towards underground storage earlier in the calendar year in order to maintain more operational space in the reservoir for capture of high flow events. We recognize that there are many competing interests involved in water allocations, and do not downplay the importance of maintaining base flows, meeting downstream demands, and maintaining operability of reservoirs. With that, we do not suggest that 100% of water beyond that which is required to meet the criteria outlined above would be directed towards recharge, but that a small fraction of that total water over many years would amount to a significant increase in the amount of water stored underground.

### 5.3.2 Projected Water Availability

The demonstrated shift in projected peak streamflow to approximately one month earlier in the calendar year, from June to May, presents an important management implication. Peak streamflow, and consequently peak water supply availability, occurring earlier in the year increases the temporal mismatch between water supply and water demand. In the case that a larger quantity of water is available earlier in the year, storing some water in underground aquifers presents an opportunity to substantially augment total water storage.

While we acknowledge a qualitative importance to shifting water availability, a review of the literature did not indicate an appropriate methodology to quantify the significance of this finding. Similar research on the temporal shift of peak flows reports only a generalized estimation of the magnitude of the expected shift, and does not test statistical significance (79).

## 6 Limitations

### 6.1 Data Limitations

The decision support tool developed during our research is built using all open access, publicly available datasets developed and distributed by academic research institutions and government agencies. While this was a deliberate choice in order to ensure that our tool was transferable and widely applicable, we recognize that the data contained in the analysis include inherent uncertainties and may be unrepresentative of local conditions. As such, the outputs of our tool include the same uncertainties present in the data analyzed.

#### 6.1.1 SAGBI

The use of the Soil Agricultural Groundwater Banking Index (SAGBI) within our tool incorporates any uncertainties in the original researchers' findings into our own findings. The limitations of SAGBI are identified as: lack of consideration for distance to conveyance infrastructure and sources of water, little consideration of the vadose zone including potential contaminant accumulation and depth to groundwater and a lack of accounting for hydraulically restrictive layers in deep sediments (9). Many of the limitations identified by the researchers who developed SAGBI have become components of consideration in our own analysis.

#### 6.1.2 Interpolated Data

The datasets used to characterize conditions in the subsurface - depth to groundwater, percent of coarse grained soil materials, and depth and thickness of the Corcoran clay layer - all imperfectly characterize the actual heterogeneity of these conditions. As such, the data used to represent subsurface conditions is not fully representative. Furthermore, our tool uses point data for depth to groundwater, percent of coarse grained soil materials, and contour lines representing Corcoran clay depth and thickness, and interpolates these data in order to achieve spatially continuous data layers. There is a margin of error present in any interpolation and the output of our tool is not fully representative of the conditions present in the subsurface. We have intentionally designed our tool to accommodate this uncertainty by providing a relative ranking of recharge locations within a basin rather than a specific volume of recharge capacity at any single point. We feel confident that interpolation of these data is an appropriate means of ranking the subsurface conditions at any location that are relatively more or less suitable to performing groundwater recharge.

### 6.1.3 Nitrogen Balance Data

The nitrogen balance developed for our analysis uses surficial nitrogen accumulation data for three years to represent likely conditions over the past thirty years. This component of the analysis was limited by the available data, with information on nitrogen inputs and losses only available for discrete years and not representative of continuous conditions. The years 1990, 2005 and 2020 were the three available datasets of most recency and relevance and were used to estimate general trends in nitrogen accumulation over the past three decades. Similar to the data used to analyze surface and subsurface conditions, the nitrogen balances rank areas as relatively better or worse for recharge given groundwater contamination risk. Areas that have high surficial nitrogen balances in all three of the years included in the analysis are more likely to present risks to groundwater contamination than areas that have had consistently low surficial nitrogen balances.

### 6.1.4 Domestic Wells That Have Run Dry Data

The dataset used to identify the approximate locations of domestic groundwater wells that have run dry contains the information collected through a voluntary reporting system managed by the California Department of Water Resources. Voluntary reporting may not fully capture the scale of the issue for a number of reasons, some among them being a perceived risk of reporting to a government agency, linguistic barriers, or a lack of awareness of the program and the reporting process. Despite these limitations, we determined that the use of the dataset was able to provide adequate indication of the locations most likely to be experiencing domestic water access issues. Our analysis relies on the assumption that these three discrete years of nitrogen balances will provide an indication of the trend of nitrate accumulation on the land surface in order to add to our relative ranking of “better” to “worse” areas to perform recharge. The data used to calculate nitrogen balances does not represent an accurate characterization of actual nitrate accumulations on the soil surface, and the sum of nitrogen balances is not an accurate measure of the presence of nitrogen in the soil. Because our analysis relies on relative rankings rather than specific quantities in order to determine better areas for recharge, the actual concentration of nitrogen in the soil is less important than identifying a trend of increasing or decreasing concentrations.

### 6.1.5 National Hydrography Dataset

Additionally, the National Hydrography Dataset, used to identify the locations of existing water conveyance infrastructure, may not include all of the small and informal conveyance present in a given groundwater basin. For example, some unlined ditches and connections to larger infrastructure may not be captured in the existing dataset. In addition, the National

Hydrography Dataset does not include information on the volumetric capacity of the conveyance infrastructure. Despite these limitations, this was the most representative and spatially complete data that was publicly available at the time of the research. Again in this case, we have determined that the data is sufficient in indicating the locations of most of the existing conveyance infrastructure within a basin.

### 6.1.6 Groundwater Dependent Ecosystems Data

The Natural Communities Commonly Associated With Groundwater data, used to identify potential groundwater dependent ecosystems, includes limitations as well. The dataset is a compilation of vegetation and species types that are known to use groundwater, however it does not represent a spatially accurate identification of ecosystems that are currently reliant on groundwater. This dataset has the potential to overstate the presence of ecosystems that are solely dependent on groundwater for their persistence.

### 6.1.7 California Contamination Cleanup Sites

Lastly, the contamination cleanup sites included in our analysis from the California GeoTracker Database may over-predict the location of sites that are a threat to groundwater quality. The dataset includes sites in multiple stages of remediation, and may not present an accurate representation of the current conditions. There may be locations included in this dataset that have been fully remediated and no longer pose a threat to groundwater quality. In addition, there is no information included in the dataset regarding the type of contaminant that caused the location to be listed, the size or depth of the contaminant plume, or the potential mobility of the contaminant. Additionally, it is unclear based on our review of the literature if the buffer distances we applied to this dataset are sufficient to protect groundwater quality near contamination cleanup sites listed in the GeoTracker Database. This dataset is used in its entirety with the assumption that local knowledge can supplement the results of the decision support tool, and that users are able to make decisions about remediation needs based in part on the tool outputs.

### 6.1.8 Data Flexibility

In an effort to allow for increased flexibility and locally informative outputs, our tool has been developed to allow for the input of higher resolution datasets should a user have access to those. In the case that a groundwater basin using our tool has been collecting highly representative and complete spatial datasets for any of the input variables included, users would be able to designate their chosen datasets as input information. In this way, we have established a baseline for information accessibility in regards to the best locations to site groundwater

recharge projects, while also allowing for improvements to the specificity of the information in the tool outputs where possible and appropriate.

## 6.2 Future Work

We believe that our decision support tool can serve as a helpful resource to Groundwater Sustainability Agencies by providing a thorough analysis of site suitability for multi-benefit groundwater recharge projects. We also recognize that there are considerations for recharge projects that are not included into the tool that are related to: groundwater quality, feasibility, additional benefits, and source water types.

### 6.2.1 Water Quality

We incorporated a consideration of groundwater quality in the decision support tool through the inclusion of surficial nitrogen balances. Areas with lower nitrogen balances are less likely to present a risk to groundwater quality, and are ranked as more suitable for groundwater recharge projects. Though not included in the tool, we recognize that geogenic contaminants also present a risk to groundwater quality and are important to consider before beginning a groundwater recharge project.

Geogenic contaminants, such as arsenic and chromium, are naturally present in soils and sediments and can be released into groundwater under certain geochemical conditions (29). As recharged water infiltrates into the subsurface and percolates downward to the water table, even clean source water can alter conditions and mobilize geogenic contaminants to enter the groundwater (29). Careful consideration of existing groundwater quality, the water chemistry of the groundwater and source water for recharge, as well as geochemical factors of the soils and sediments is necessary to understand and mitigate potential risk from geogenic contaminants. Geogenic contaminants each have a unique set of conditions that lead to higher risks for groundwater contamination, which can be thought of as aquifer conditions to avoid through the introduction of recharged water (Table 6.1) (29).

**Table 6.1 Risk of geogenic contaminant mobility with differing groundwater conditions.** As water is recharged into an aquifer, changed redox potential and pH can lead to new geogenic contamination entering the groundwater from sediment. The varied aquifer conditions to avoid increase the risk of co-occurring contaminants, in which managing the risk factors for one contaminant lead to the creation of risk factors for another contaminant. Figure retrieved from the Environmental Defense Fund (29).

Contaminant	Contaminant Mobility Due to Aquifer Conditions				Aquifer conditions to avoid
	Oxygen-abundant	Oxygen-limited	High pH	Low pH	
Iron (Fe)	↓	↑	↓	↑	Oxygen-limited, low pH
Manganese (Mn)	↓	↑	↓	↑	Oxygen-limited, low pH
Arsenic (As)	↓	↑	↑	↓	Oxygen-limited, high pH, high phosphate, compaction of clay layers from overpumping
Chromium (Cr)	↑	↓	↑	↓	Oxygen-abundant, high pH, fluctuating water table
Uranium (U)	↑	↓	↑	↓	Oxygen-abundant, high pH, high bicarbonate, high nitrate
Vanadium (V)	↑	↓	↑	↓	Oxygen-abundant, high pH
Selenium (Se)	↑	↓	↑	↓	Oxygen-abundant, high pH

When developing our decision support tool, we were unable to identify a comprehensive dataset for the Central Valley that characterized geochemical conditions of the subsurface down to the water table. Additionally, source water for recharge projects, which will have varied water chemistry, will be determined locally by water managers. As such, we were unable to include a consideration of geogenic contaminants in the decision support tool. When considering a potential recharge project, a water manager should consider locally specific hydrogeologic data and the likely water chemistry of the project’s source water to mitigate the risk posed by geogenic contaminants to groundwater quality.

### 6.2.2 Feasibility

We designed the decision support tool to provide information on relative suitability for multi-benefit recharge projects to groundwater managers. Tool users can then use locally specific data and basin information to further refine the outputs before making a final selection for a recharge project site. Our tool does not consider specific crop types within agricultural lands that may be better suited to on-farm recharge projects, as crop type at the field scale can vary significantly from year to year. The decision support tool also does not consider land ownership or what areas may be readily available for conducting recharge projects. Our tool is intended to provide suitability information to water managers who can then assess project feasibility with basin specific information and in partnership with community members and landowners.



### 6.2.3 Additional Benefits

Our decision support tool considers the potential benefits of rehydrating domestic drinking water wells that have run dry and supporting groundwater dependent ecosystems. These benefits were selected after consultation with our client for the project, the Environmental Defense Fund, and after a review of datasets available for the Central Valley. A limitation of our tool is that the multi-benefit recommended locations do not consider other potential benefits of groundwater recharge projects, such as the creation of waterfowl habitat or flood risk mitigation.

We explored flood risk mitigation as a tool component following discussions with our project client and external advisors; managing flood risk in areas of the Central Valley may serve as a priority benefit and driver of managed aquifer recharge projects in some basins. We were unable to find an appropriate geospatial dataset for the study area that delineated flood risk levels in a manner that would allow for inclusion in the tool. Our project instead considers the potential for the Madera Subbasin, our test case during tool development, to use reservoir releases during high flow events as managed recharge source water. If water can be pre-released from reservoirs nearing capacity during high flow events and directed to managed recharge projects, reservoir capacity to receive flood flows will increase.

### 6.2.4 Source Water

For this project, we analyzed the potential for reservoir releases in anticipation of high flow events to serve as source water for recharge projects in the Madera Basin. Our methodology is transferable only to other groundwater basins in the Central Valley that receive surface water from a reservoir with unallocated flood flows. We did not analyze the potential availability of other types of source water for groundwater recharge projects which can include recycled and reclaimed water or imported surface water.

## 7 Conclusion

The Sustainable Groundwater Management Act presents an opportunity to rethink the way that groundwater is managed in California. As Groundwater Sustainability Agencies develop plans and begin implementation of projects designed to reach sustainability in their basins, it is important to strategically include a consideration of benefits to communities and ecosystems. Managed aquifer recharge is one strategy that is recommended by the California Department of Water Resources for its ability to provide multiple project benefits, and many Groundwater Sustainability Agencies plan to implement managed recharge projects.

We developed a decision support tool to provide information to Groundwater Sustainability Agencies for selecting sites for managed recharge projects. Our tool considers the primary goal of replenishing the aquifer by incorporating information related to surface and subsurface conditions that affect recharge rates. The tool also considers multiple benefits of managed recharge projects: protecting water quality, rehydrating domestic wells that have run dry, and supporting groundwater dependent ecosystems. Groundwater managers can use the tool to assign unique priorities to each additional benefit consideration based on their local basin's needs.

We also illustrated one methodology that can be used to identify source water for recharge projects in basins served by a reservoir with unallocated flood flows. By thinking of surface water and groundwater as connected components of California's water storage infrastructure, both natural and constructed, it may be possible to strategically move some water from surface storage to groundwater storage in anticipation of high flow events. Shifting some water storage underground has the potential to reduce flood risk, increase overall water storage, and mitigate negative impacts of overdraft.

Our decision support tool gives water managers the information that they need to consider how to best achieve multiple benefits of managed groundwater recharge projects. As groundwater basins throughout California's Central Valley begin to implement projects to meet the goals of the Sustainable Groundwater Management Act, our analysis will help water managers plan for a more resilient water future.

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