Flood Forward

May 2021

Understanding Multiple Benefits of Floodplain Restoration from Flood-Managed Aquifer Recharge in Madera County, California

Image Source: Maven's Notebook (2019)

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A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management for the Bren School of Environmental Science & Management, University of California, Santa Barbara.

Signature Page

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The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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DWR Statement of Client Role

The Division of Planning at the Department of Water Resources (DWR) appreciates the opportunity to advise the Flood Forward team, graduate students at UC Santa Barbara's Bren School, on their academic project; and would like to recognize the team for their dedicated work during this challenging pandemic. DWR supported the team by identifying data sources, facilitating connections with other professionals and organizations, and identifying opportunities for multiple benefits, including flood risk reduction and ecosystem restoration. The Flood Forward team developed a practical decision support tool for water managers to identify opportunities for multiple benefit recharge projects using flood flows. The tool can be replicated for other locations statewide using best available data. DWR recognizes that as an academic project, this work was completed with limited involvement of local agencies, readily available statewide data sources, and reduced timeline as compared to local agency flood and groundwater plans and projects, including Groundwater Sustainability Plans currently under review per the Sustainable Groundwater Management Act.

Abstract

Groundwater is a critical component of California's water supply portfolio. However, due to pumping, many groundwater basins have been depleted, causing undesirable results. The passage of the Sustainable Groundwater Management Act (SGMA) in 2014 requires Groundwater Sustainability Agencies to implement strategies to bring groundwater use to sustainable levels within the next 20 years. This requires the balancing of groundwater withdrawals with recharge, which is the process of replenishing aquifers through the infiltration of surface water. The California Department of Water Resources has emphasized Flood-Managed Aquifer Recharge (Flood-MAR) as a management strategy with the potential to provide multiple benefits in addition to groundwater recharge. However, the capacity of Flood-MAR to achieve multiple benefits is spatially dependent and remains largely unknown. This project provides an analytical framework for determining priority areas for achieving flood risk reduction benefits, ecosystem enhancement benefits, or both, while simultaneously replenishing groundwater through recharge. The results from this framework produce a spatial distribution of priority locations for multiple-benefit recharge projects within the two groundwater subbasins in Madera County. This project conducts a tradeoff analysis between the co-benefits of flood risk reduction and ecosystem enhancement to demonstrate its ability to make recommendations to stakeholders with various management preferences. These results can help to inform managers within the Madera and Chowchilla subbasins when planning the implementation of multiple-benefit groundwater recharge projects. Together with other recharge, flood mitigation, and restoration efforts, this project provides an additional tool to help strengthen the management toolkit available for stakeholders seeking to bring their groundwater basins to sustainable levels under SGMA.

Key Words: Sustainable Groundwater Management Act, groundwater recharge, multiple benefits, flood managed aquifer recharge, water resources, flood risk reduction, ecosystem enhancement

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Executive Summary

Groundwater provides critical storage for much of California's water supply. On average, it supplies up to 40% of California's water, a number that increases significantly during drought years (Chappelle & Hanak, 2017). Groundwater use, particularly for agriculture in California's Central Valley, has resulted in the depletion of groundwater supplies, lowering of water tables, reductions in aquifer storage, degradation of water quality, land subsidence, wells running dry, and depletions of connected surface waters. To address these issues, the state passed the Sustainable Groundwater Management Act (SGMA) in 2014 requiring local agencies to develop plans for bringing their basin's groundwater use to sustainable levels by 2040 (SGMA, 2014). These Groundwater Sustainability Agencies must seek ways to balance groundwater withdrawals with recharge to ensure that depletions do not continue to have adverse impacts. An important strategy that many agencies are choosing to implement is the augmentation of groundwater supply through the expansion of recharge projects.

Flood-Managed Aquifer Recharge (Flood-MAR) is an integrated water resource management strategy "that uses flood water resulting from, or in anticipation of, rainfall or snow melt for managed aquifer recharge on agricultural lands and working landscapes, including but not limited to refuges, floodplains, and flood bypasses" (DWR, 2018). In 2019, the California Department of Water Resources released a *Flood-MAR Recharge Research and Data Development Plan* outlining priority action items necessary to support and expand the implementation of Flood-MAR projects in California. Among these items was the mapping of floodplain habitats and their potential for groundwater recharge through Flood-MAR.

Flood-MAR can be achieved by diverting flood flows offstream onto agricultural or working lands, but current infrastructure capacity is constrained in its ability to fully capture the highest-magnitude flood flows (Escriva-Bou & Hanak, 2018). Utilizing floodplains as additional natural conveyance infrastructure for flood flows provides a less resource-intensive strategy for achieving recharge. The expansion of floodplains and riparian corridors provides an opportunity for improving groundwater recharge by allowing more water to percolate into underlying aquifers during precipitation or high flow events. This project focuses specifically on floodplain habitats and their capacity to achieve groundwater recharge with multiple benefits.

Flood-MAR projects are unique opportunities to combat groundwater overdraft while simultaneously providing multiple benefits. These benefits include flood risk reduction, drought resilience, ecosystem enhancement, aquifer replenishment, subsidence mitigation, water quality improvement, and climate change adaptation (DWR, 2018). SGMA emphasizes the use of multiple-benefit strategies like Flood-MAR in groundwater sustainability planning.

The Flood Forward project analyzes the multiple benefits of implementing Flood-MAR in the historical floodplains of river systems in the Madera and Chowchilla groundwater subbasins, located in the San Joaquin Valley of Central California. Priority benefits of analysis for this project, as determined by Flood Forward and its clients, the Environmental Defense Fund and California Department of Water Resources, are: 1) flood risk reduction, 2) floodplain ecosystem enhancement, and 3) groundwater recharge. Using geospatial models, this project provides an analytical framework for determining priority areas in Madera and Chowchilla Subbasins for locating groundwater recharge projects for the achievement of the co-benefits of flood risk reduction and ecosystem enhancement. This project uses an output of recharge suitability produced by a previous Bren School Group Project, called Recharge for Resilience, so that it can be assumed that all sites in this analysis at least provide some recharge benefit. To build upon Recharge for Resilience's findings, this project conducts a flood risk reduction priority analysis, ecosystem enhancement priority analysis, site suitability analysis, sensitivity analysis, and multiple-benefit tradeoff analysis. Due to lack of adequate data, our approach cannot resolve all local stakeholder preferences in all locations.

The results from the analyses provide information for water managers and other stakeholders in Madera and Chowchilla Subbasins who plan on implementing multiple-benefit groundwater recharge projects. The sensitivity analysis results can be used to improve recharge project site prioritization by demonstrating which locations consistently receive high priority scores when the relative weight assigned to each input parameter is experimentally adjusted. The tradeoff analysis develops an understanding of how priority site locations may change depending on different potential management preferences between the co-benefits of flood risk reduction and ecosystem enhancement. Ultimately, being better informed when prioritizing locations for multiple-benefit Flood-MAR in floodplain habitats will allow managers and stakeholders to implement such projects in their efforts to achieve SGMA compliance.

Successful compliance with SGMA will likely include the implementation of integrated water management strategies and expansion of groundwater recharge projects. Implementing Flood-MAR projects in floodplain and riparian habitats will be supplemental to a larger portfolio of integrated water resource management strategies for California's future.

1. Background

Water resources management strategies in California must adapt to highly variable weather events intensified by climate change. Droughts and more extreme precipitation events are projected to occur (**Figure 1.1**) (Mount & Swain, 2020). Precipitation is expected to fall more as rain instead of snow, reducing the reliance on the Sierra snowpack as a reliable source of water storage (Hanak et al., 2011). The California Water Resilience Portfolio draft, released in early 2020, prioritizes integrated, multiple benefit management approaches to ensure the resilience of the state's water system (CNRA, CalEPA & CDFA, 2020). Increasing effort has been focused on enhancing the reliability of groundwater to improve California's water supply.

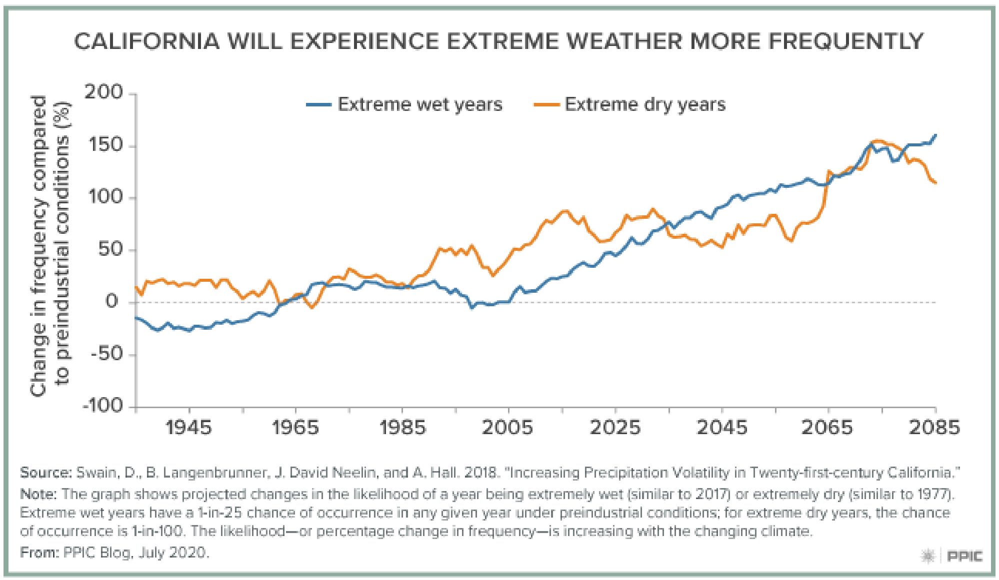


Figure 1.1 Anticipated extreme weather for California. This graph represents the likelihood of occurrence for extreme precipitation or extreme drought. The frequency of extreme weather conditions in California is expected to increase through the 21st century. Source: (Mount & Swain, 2020)

1.1 Groundwater

Groundwater is crucial to support California's agriculture, industry, and municipalities. The California Central Valley depends on groundwater for 43% of their average water supply (Faunt et al., 2016). In years of drought, such as the exceptional dry period observed from 2012 to 2016, Central Valley farmers and residents rely on groundwater for as much as 70% of water supply (Faunt et al., 2016). Extreme drought coupled with the demand for irrigating crops has led to unsustainable groundwater extraction causing depletion of aquifers. This often leads to further problems, such as wells running dry, disconnecting surface water and groundwater, land subsidence, and accelerated groundwater storage loss that makes accessing this critical freshwater resource even more challenging (DWR, 2021).

1.2 The Sustainable Groundwater Management Act

The passage of the Sustainable Groundwater Management Act (SGMA) in 2014 requires local groundwater sustainability agencies to halt overdraft of groundwater resources, and bring high and medium priority groundwater basins into balanced levels of pumping and recharge by 2040 (SGMA, 2014). This requires inflows of groundwater to be equal to outflows. SGMA aims to reduce the negative impacts from unsustainable groundwater use, such as groundwater level reduction, degraded groundwater quality, saltwater intrusion, land subsidence, and loss of groundwater storage supply (SGMA, 2014). Critically overdrafted subbasins, such as Madera and Chowchilla groundwater subbasins, submitted groundwater sustainability plans in January of 2020, and experts have acknowledged a heavy reliance on supply side management options, including managed aquifer recharge (Ayres, 2020). Madera subbasin proposed 96 thousand acre-feet per year of groundwater recharge supply expansion, while Chowchilla subbasin has proposed 75 thousand acre-feet per year (Ayres, 2020). One of these recharge options is flood-managed aquifer recharge (Flood-MAR), the strategy of using flood water from, or in anticipation of, precipitation events for managed aquifer recharge. Flood-MAR provides an opportunity to simultaneously reduce flood risk during storm events and recharge underlying aquifers to increase the state's drought-resilient water supply, while enhancing natural ecosystems (DWR, 2018).

1.3 Flood-Managed Aquifer Recharge

Flood-MAR can be utilized to modernize California's natural and built infrastructure to recharge groundwater throughout the basin landscape (**Figure 1.2**). Managed aquifer recharge can be used by groundwater sustainability agencies to comply with SGMA and provide multiple benefits. These benefits include water supply reliability, flood risk reduction, drought preparedness, water quality enhancement, subsidence mitigation, ecosystem enhancement, and climate change adaptation (DWR, 2018).

Academics and environmental non-governmental organizations have recently explored recharge suitability and location prioritization, leading to the development of existing decision support and analytical tools, including the Soil Agricultural Groundwater Banking Index from UC Davis, Groundwater Recharge Assessment Tool from Sustainable Conservation and The Earth Genome, and most recently, the Recharge for Resilience Decision Support Tool from the Bren School of Environmental Science & Management (O'Green et al., 2015, Sustainable Conservation, 2017, Gibbons et al., 2020). In order to understand the degree to which Flood-MAR may achieve the range of potential benefits laid out in the *Flood-MAR White Paper*, studies moving forward should be pointed at current knowledge gaps beyond general site suitability (DWR, 2018, Scanlon et al., 2016).

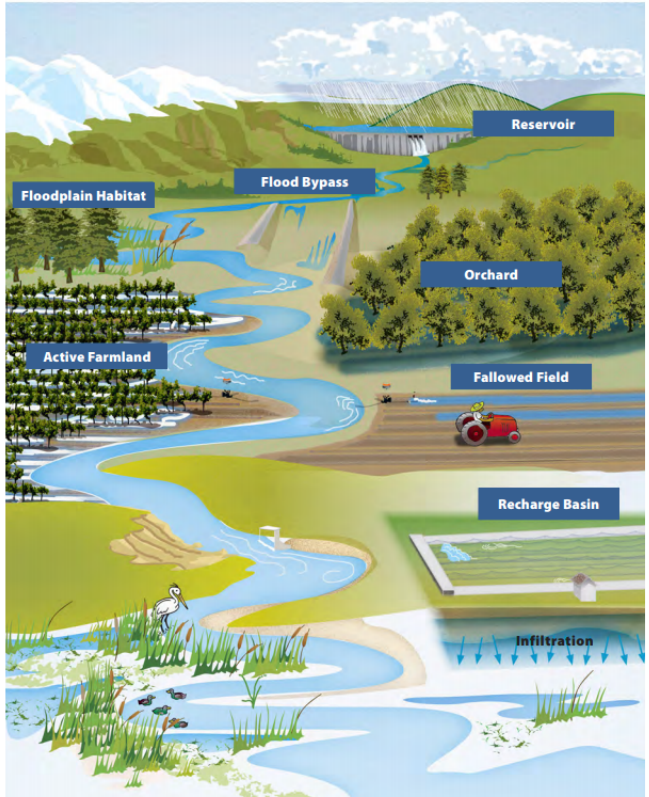


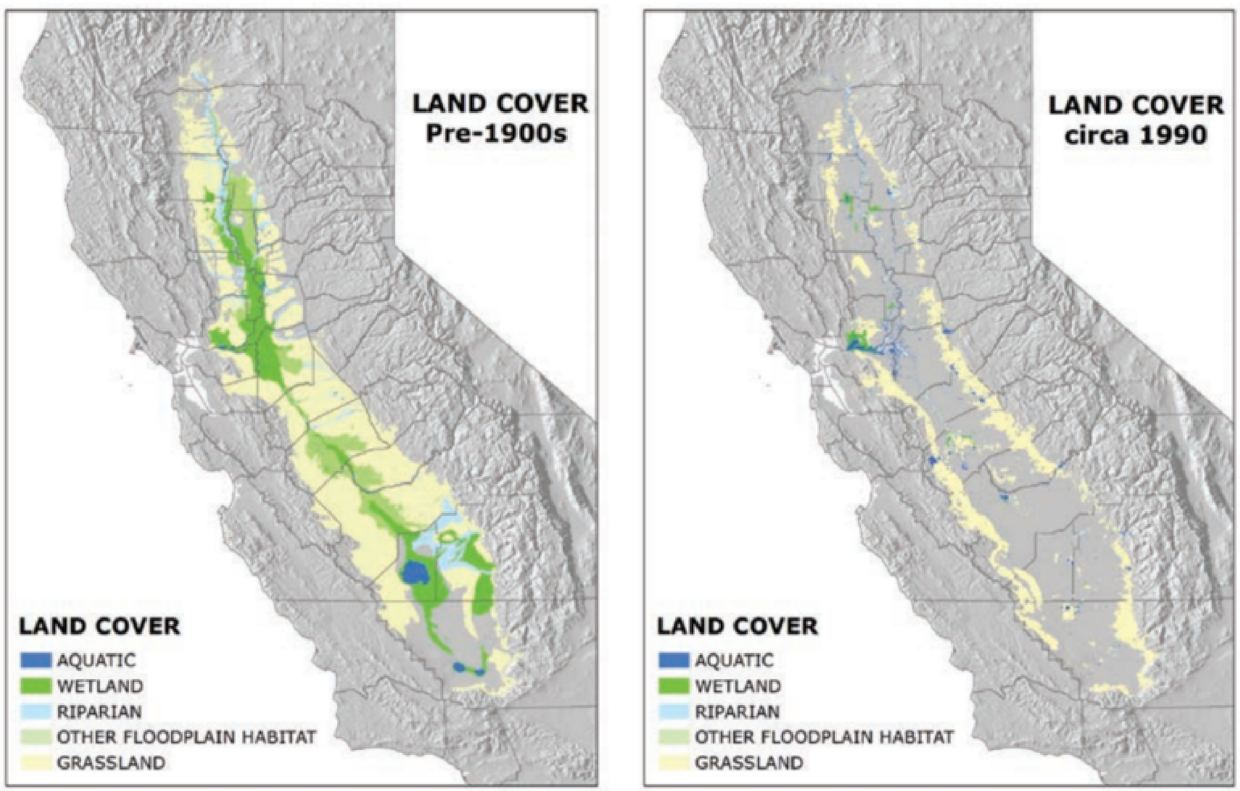
Figure 1.2 Flood-managed aquifer recharge conceptual diagram. This conceptual model describes various Flood-MAR projects including restoring the adjacent floodplain, utilizing recharge basins, recharge on agricultural land, and flood bypasses. Source: (DWR, 2018)

The Bren 2020 Group Project, Recharge for Resilience, began this work by creating a framework for identifying regions of the Central Valley best-suited for multiple benefit managed aquifer recharge. Sites were prioritized based on land, soil, and water quality parameters. Additional considerations were made for conveyance infrastructure, rehydrating dry wells, and supporting groundwater dependent ecosystems. The 'Flood Forward' Group Project contributes to the understanding of the multiple benefits of managed aquifer recharge by expanding upon the findings from Recharge for Resilience work. This project will identify locations where flood risk reduction and ecosystem enhancement benefits can be achieved by applying geospatial analyses to complete a site prioritization for floodplain restoration in Madera County.

1.4 Floodplains

Floodplains are "productivity pumps" and the main driver of productivity in river systems (Junk et al. 1989). Simply, a floodplain is any river-adjacent land of temporary inundation by high river flows (Opperman et al., 2010). Hydrologically connected floodplains are those which are permitted to be inundated periodically from overtopping rivers in high flood stages, either naturally or through land-water management strategies (Eisenstein & Mozingo, 2013).

California wetlands and floodplain habitats have been altered over the last century due to flood control and irrigation measures, including those historically found in the San Joaquin Valley (**Figure 1.3**) (Hanak et al., 2011). Healthy floodplain habitats provide a multitude of ecosystem benefits. These benefits include flood protection, water quality enhancement, aquifer recharge, and habitat improvement for spawning fish, migratory birds, and riparian wildlife (The Nature Conservancy, 2018). The extent to which Flood-MAR can contribute to or enhance those benefits is an emerging field of study. Flood-MAR has been identified by the California Department of Water Resources, Environmental Defense Fund, and American Rivers as a valuable area of research in their ongoing process to understand the benefits and applicability of Flood-MAR in California.



Disappearance of Central Valley wetlands © Central Valley Historic Mapping Project, California State University, Chico, Geographic Information Center, 2003

Figure 1.3 Floodplain habitat loss in the Central Valley and Madera County. Over 90% of floodplains in the Central Valley and Madera County have been altered. The left map shows land cover types in the Central Valley before the 20th century, while the right map shows land cover in the same geography around 1990. The majority of wetlands, riparian areas, and other floodplain habitat disappear in the time period between the two maps. Source: California State University, Chico.

1.5 The Multiple Benefits of Floodplain Restoration

Healthy functioning floodplains provide provisioning, regulating, and supporting ecosystem services that benefit human livelihoods. These services include flood risk mitigation, water flow regulation, water storage, erosion control, water quality enhancement, nutrient cycling, biodiversity production, carbon sequestration, and recreation (Loos & Shader, 2016). Healthy floodplains serve as natural flood protection infrastructure, slowing and spreading otherwise harmful flood waters during high flow events (American Rivers, 2019). Floodplains also support a mosaic of habitats including riparian corridors, side channels, oxbows, wetlands, and other landforms that occur naturally over time. This array of natural habitats and natural movement of water allows for sediment and nutrient transfer. These ecosystems support a vast array of biodiversity, including aquatic species, migratory birds, riparian wildlife, and vegetation.

Inundation of floodplains during high flow events helps replenish underlying groundwater aquifers. Groundwater depletion has resulted in loss of storage, land subsidence, and declining water levels for domestic wells. Land use change to irrigated agriculture and development of water storage and conveyance projects has eliminated most of the Central Valley's natural flood control infrastructure, disrupted riparian and floodplain habitats, and disconnected the link between seasonal flood flows and groundwater supply (Hanak & Lund, 2012, Bay Institute, 1998). Recharge through floodplain inundation can benefit communities that are dependent on groundwater resources. Flood control infrastructure like levees and berms prevent high flows from entering floodplains, reducing their capacity to store flood waters and sustain healthy riparian and wetland habitats (Opperman et al., 2009). Experts predict that climate change is expected to amplify extreme flooding events in California (Huang et al., 2020). Thus, restoration of natural floodplain connections, reformation of channels, and restoration of native plant habitat that act as a storm buffer will provide long term protection, climate resilience, and ecosystem service benefits to humans for generations to come.

1.6 The Central Valley Flood Protection Plan

The Central Valley Flood Protection Plan, which was most recently updated in 2017, provides strategies to promote multiple benefit projects that prioritize flood risk management and the improvement of associated ecosystem functions (DWR.1, 2017). It also provided a Conservation Strategy for integrating ecological restoration with flood risk reduction projects where feasible (DWR.2, 2017). Flood Forward seeks to determine where such projects would be most feasible within the Madera and Chowchilla groundwater subbasins. Although significant progress has been made in flood management in the San Joaquin Valley, a region with one million residents and $80 billion in infrastructure and agriculture, it is still at considerable risk of flooding (Madera Subbasin Coordination Committee, 2020). Investment in sustainable flood management and reduction measures are essential to reduce these risks to valuable property, ecosystem health, and human lives.

1.7 Madera County

The project focuses specifically in Madera County, which includes the Madera subbasin and a large portion of the Chowchilla subbasin (**Figure 1.4**). Groundwater is an essential source of water for agricultural, domestic, municipal, industrial, and environmental sectors of Madera

County, which has a population of over 156,000 people (Madera Subbasin Coordination Committee, 2020). The largest economic sector in Madera is agriculture, which utilizes 500,000 acre feet of groundwater each year (~93% of total groundwater use in the basin), providing commodities to the nation and generating at least $2 billion annually for the county (Madera Subbasin Coordination Committee, 2020). However, the Madera subbasin is identified as critically overdrafted. To comply with SGMA, groundwater sustainability agencies in the Basin were required to develop a groundwater sustainability plan. In total, there are seven groundwater sustainability agencies within the Madera subbasin, four of which collaborated to develop a joint groundwater sustainability plan for the basin. The plan was completed in January 2020 and has recently been approved by the state (Madera Subbasin Coordination Committee, 2020). All GSAs completed a GSP for their area, and all seven GSAs are collaborating to implement the four GSPs.

The groundwater sustainability plan outlines how the groundwater sustainability agencies will define, monitor, and maintain sustainable groundwater management in Madera subbasin over the next 20 years and beyond. The strategy to sustainably manage the groundwater of the basin includes understanding historical trends and the current groundwater conditions, such as groundwater levels, extraction, and water quality. The groundwater sustainability plan prioritizes two types of projects to be used in the basin for implementation of SGMA goals: recharge and conveyance projects (Madera Subbasin Coordination Committee, 2020). Additionally, it recognizes the necessity to analyze future climate scenarios and shift management practices in order to more sustainably manage its groundwater resources into the future. Floodplain restoration and Flood-MAR projects will be essential in achieving the goals described in the Madera subbasin *Joint Groundwater Sustainability Plan.*

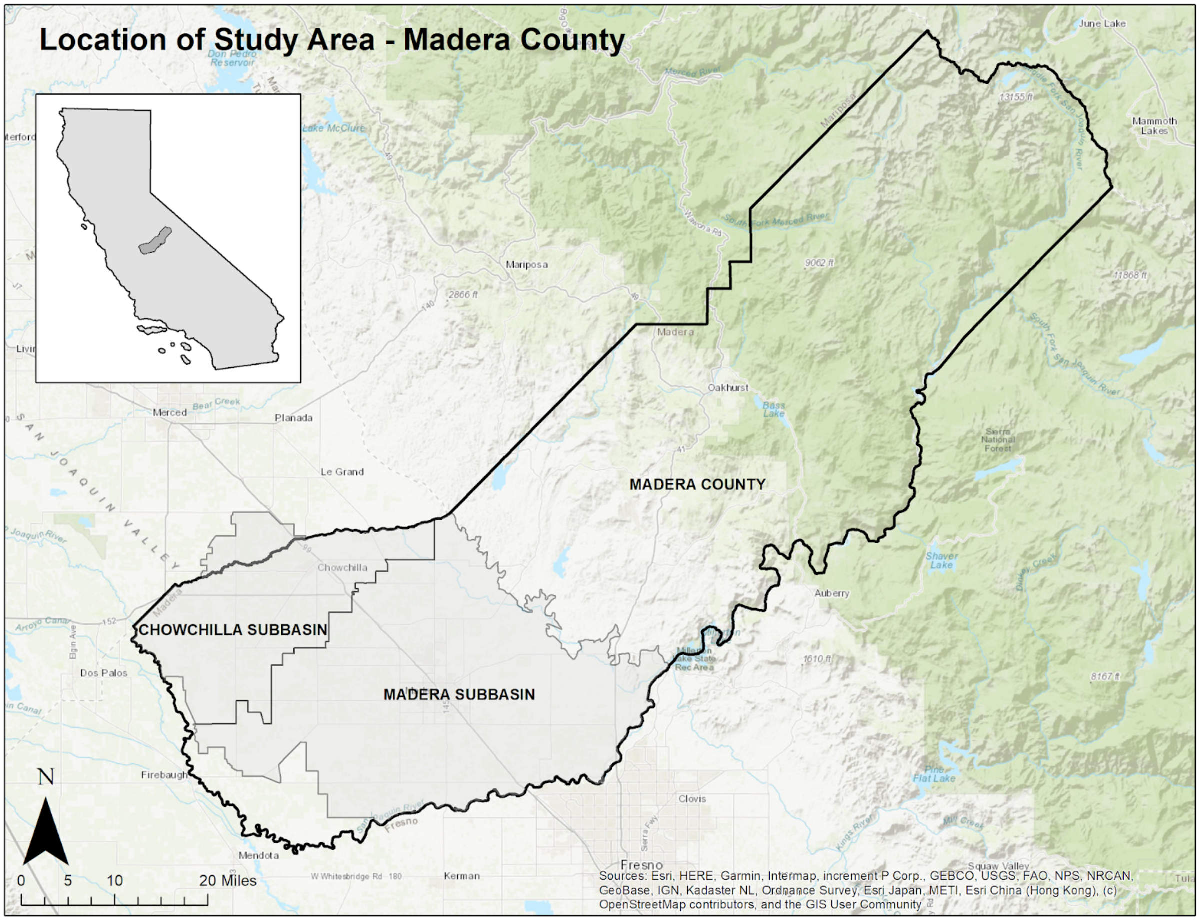


Figure 1.4 Map of Madera County, Madera subbasin, and Chowchilla subbasin. Madera County is located on the northeast portion of the San Joaquin Valley of the larger California Central Valley. The county contains the majority of the Chowchilla subbasin and the entire Madera subbasin in the southwestern portion, and it extends northeast into the Sierra Nevada mountains.

There are several other reasons why Madera County was chosen for this project. First, Madera is vulnerable to flood risk. There have been 6-7 major flooding events from 1978 - 2009 (Hanak et al., 2011). Additionally, climate change is likely to increase the number of flooding disasters in Madera, as precipitation will fall more as rain, and in more intense bursts (Huang et al., 2020). Second, Madera has lost over 90% of its floodplain habitat (Hanak et al., 2011). Restoring this critical resource will help reduce flood risk throughout the county. Third, there is limited funding in Madera for water resource management projects. This project will help prioritize sites to reduce flood risk through restoring the adjacent floodplain and identify where groundwater can be achieved with Flood-MAR. Additionally, there is a knowledge gap between flood risk benefits with Flood-Mar at the local scale. Research has analyzed the connection between Flood-MAR and flood risk reduction throughout the Central Valley, but not in a highly localized area. This work looks to address this knowledge gap by focusing on flood risk potential specifically within Madera County.

2. Objectives

This project has two objectives:

1. The first objective is to ***identify areas within Madera County where floodplains can achieve flood risk reduction benefits from Flood-Managed Aquifer Recharge.***

2. The second objective is to ***identify areas within Madera County where floodplains can achieve ecosystem enhancement benefits from Flood-Managed Aquifer Recharge.***

The subsequent section details the methods used to achieve these two main objectives.

3. Methods

To execute the objectives of identifying areas within Madera County that can achieve flood risk mitigation and ecosystem enhancement benefits from Flood-MAR, a flood risk analysis and an ecosystem analysis were conducted in ArcMap Model Builder using publicly available data. With outputs of priority areas for reducing flood risk and priority areas for enhancing ecosystems, the results were then combined with an analysis of site suitability. Lastly, a tradeoff analysis was performed between the two co-benefits: flood risk reduction and ecosystem enhancement to create the final output of top suitable sites for achieving multiple benefits from flood managed aquifer recharge projects (**Figure 3.0**).

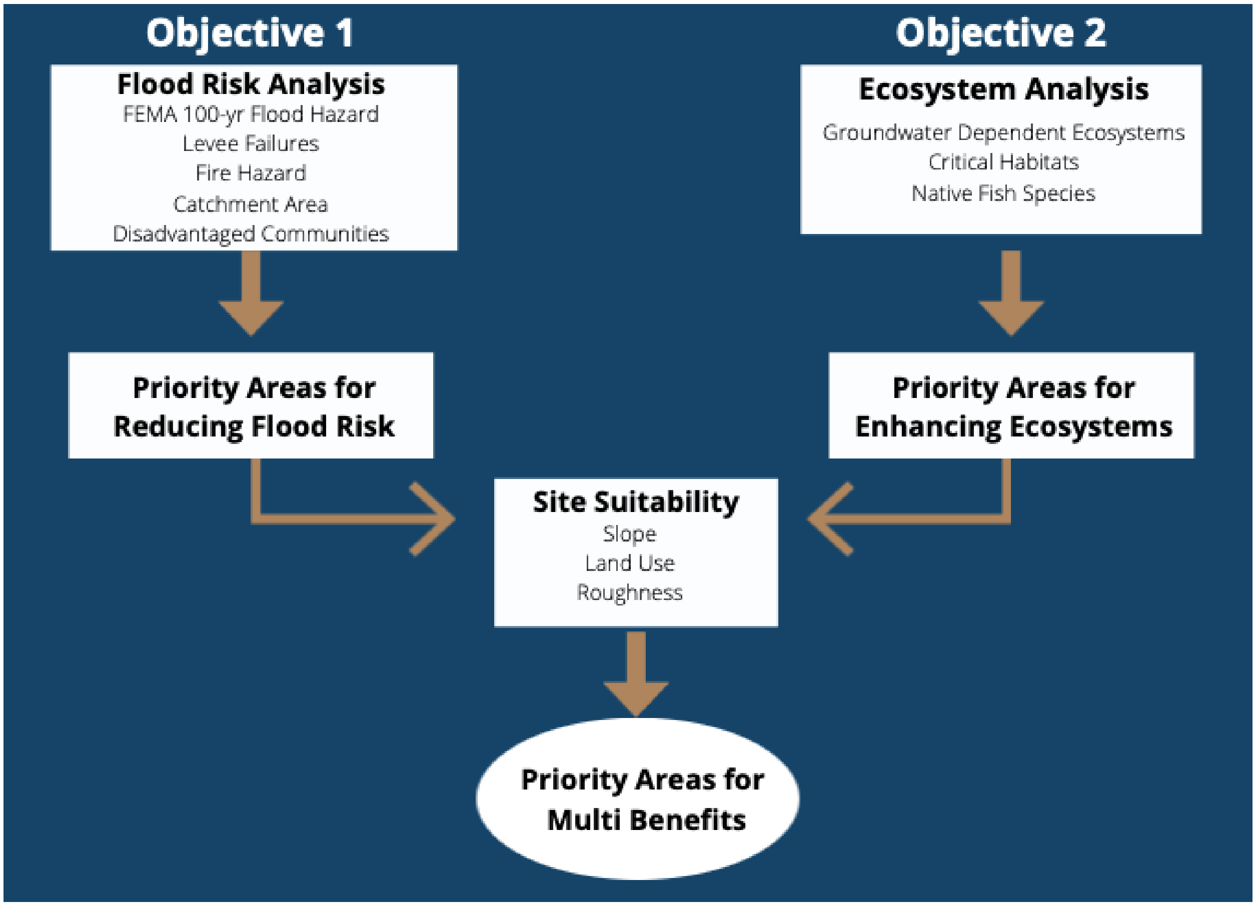


Figure 3.0 Schematic diagram displaying the methodology used to achieve the project's two objectives. Objective 1 (flood risk reduction benefits) is on the left branch of the schematic. Using the five datasets listed, the areas of greatest risk are prioritized for risk reduction. Objective 2 (ecosystem enhancement benefits) is on the right branch of the schematic. Using the three datasets listed, the riparian areas of greatest ecosystem enhancement potential are identified. The two priority outputs (flood risk locations and ecosystem enhancement locations) are then combined with a site suitability layer that analyzes the three datasets (slope, land use, and surface roughness). This final step produces an output of priority areas on which multiple benefit recharge and restoration projects should be implemented.

3.1 Watershed Delineation

The first step in the analysis was to delineate the watersheds to create catchments for the flood risk reduction analysis. A ten meter digital elevation model was used in ArcMap Model Builder to create the catchment boundaries. The 'Hydrology Toolset' was used to delineate the watershed catchment areas. The first step was to define the movement of water with the flow direction tool. The flow accumulation tool then created the river network by assessing how many cells and which cells drain into downsloping cells. The streams were created with the stream network, stream link, and stream order tools that create hierarchical order of the streams in the network. The basin tool utilized flow direction to determine the connected set of cells to create basins. And the watershed boundary took the basin raster to create polygons to form the watershed boundaries. The model produced nine riparian catchment areas: San Joaquin River, Fresno River, Cottonwood Creek, Buttonwillow Slough, Dry Creek, Berenda Creek, Berenda Slough, Ash Creek, and Chowchilla River (**Figure 3.1**).

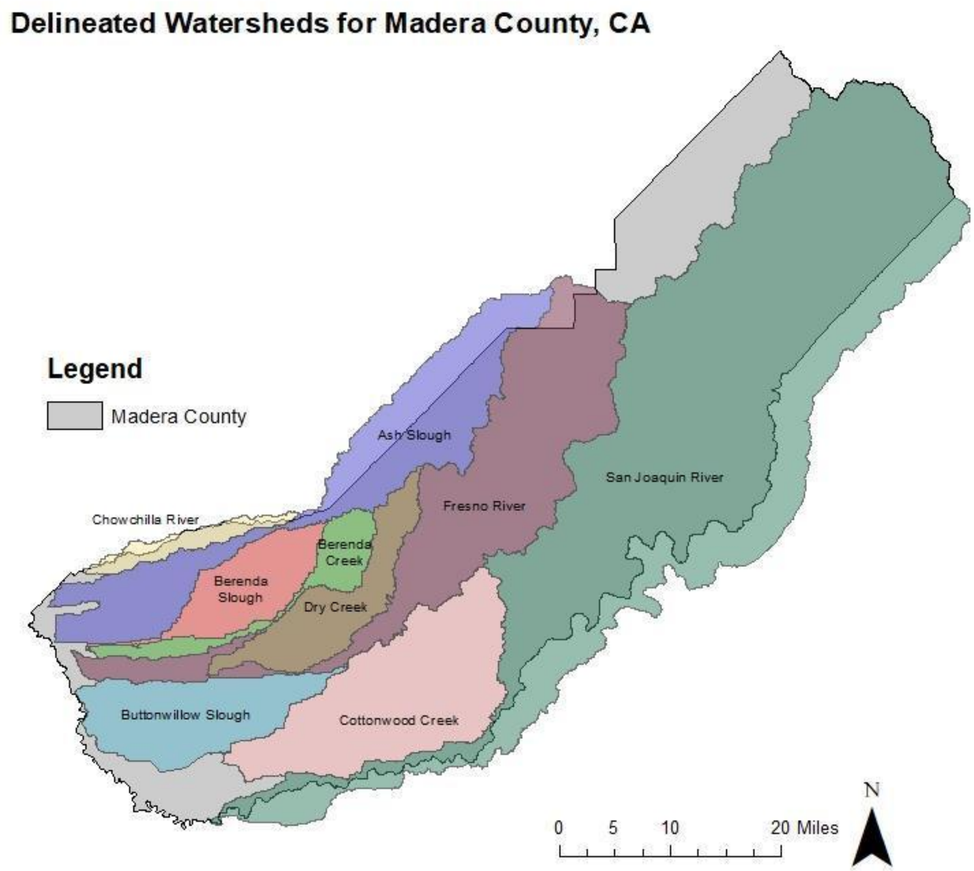


Figure 3.1 Nine delineated Watersheds for Madera County. This was created by the Hydrology Toolset in ArcGIS. Watersheds include: San Joaquin River, Fresno River, Cottonwood Creek, Buttonwillow Slough, Dry Creek, Berenda Creek, Berenda Slough, Ash Creek, and Chowchilla River. The largest watershed by area is the San Joaquin River watershed (shown in green), which extends along the eastern edge of the county and northeast into the Sierra Nevada mountains. Data Source: USGS.3, 2020

3.2 Riparian Delineation

Riparian corridor mapping was executed to identify potential restoration areas for additional site suitability analysis. Riparian areas were mapped using the Riparian Buffer Delineation Model v.5.3 for ArcGIS Desktop (Abood et al., 2012). This model utilizes flood stage data and digital elevation models to delineate riparian corridors that more accurately reflect local hydrology and geomorphology when compared to fixed riparian buffers. The model operates using the 50-year floodplain as the hydrologic indicator of riparian zones, as defined by Ilhardt et al. (2000). Running this model provided key insights as to where floodplains could be restored and utilized for natural recharge infrastructure. The following sections discuss in detail the data required and workflow of the model, and the final delineation of riparian buffers in the area of analysis.

3.2-1 Data Requirements

The Riparian Buffer Delineation Model requires three data inputs. The model processes riparian buffers for any given area of interest and watershed by watershed. For this analysis, 25 Hydrologic Unit Code 12 (HUC12) watersheds that intersect with either Chowchilla or Madera subbasins were selected. The boundary data is from the Watershed Boundary Dataset from the United States Geological Survey (USGS.1, 2020). Additionally, the model requires a network of rivers and streams to delineate riparian areas. Stream polylines were acquired in the National Hydrography Dataset from the United States Geological Survey (USGS.2, 2020). Necessary stream reaches for this model are labeled as ‘Stream/River’ or ‘Artificial Path’ (FType = 460 or 558), and must have an associated stream order as an attribute. Lastly, the model requires a digital elevation model with spatial resolution of at most ten meters. A ten meter digital elevation model was used in this analysis and acquired from the 3D Elevation Program datasets from the United States Geological Survey (USGS.3, 2020).

3.2-2 Fifty Year Flood Stage

To run the model, all rivers represented by the National Hydrography Dataset flowlines, must be assigned a 50-year flood-stage elevation. Hydrologic estimations of flood stage were calculated using the 50-Year Flood Dashboard from *riparian.solutions* based on streamflow data from 60 USGS stream gauges (**Table 3.2-2**) (Riparian Solutions 2020). Calculations are based on the methods developed by Mason (2007).

Table 3.2-2 50-year flood stage by stream order. Flood stage increases with stream order ranging from 0.25 meters to 1.5 meters. The greatest stream order in the area of interest is five (USGS.2 2020).

Stream Order	Flood Stage (m)
1	0.25
2	0.40
3	0.60
4	0.76
5	1.5

3.2-3 Model Output

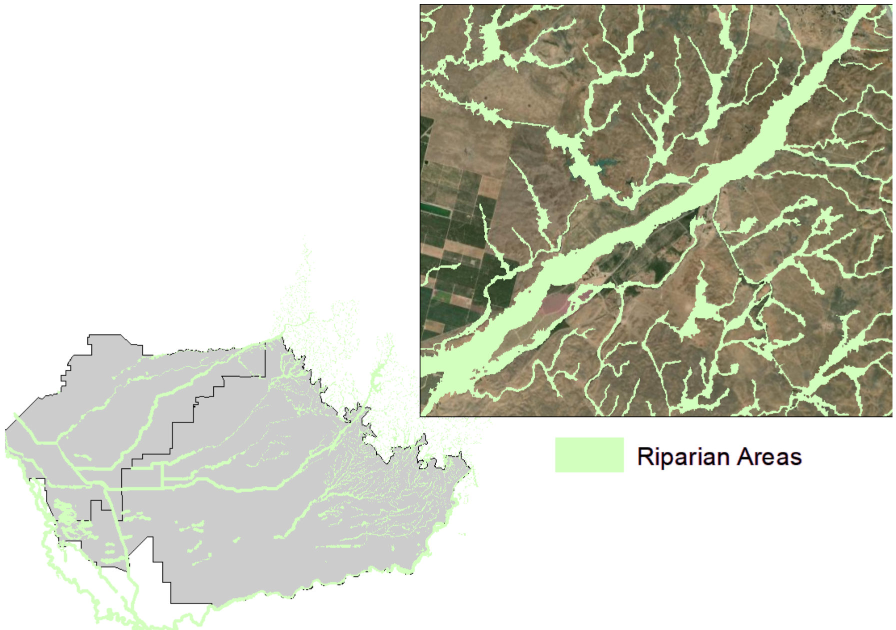


Figure 3.2-3 Riparian delineation output. Areas highlighted in green are potential floodplain areas to be analyzed further for site suitability. The delineated riparian zones follow the stream channel and are a function of the local topography. Riparian zone width varies along the stream network and provides a more accurate representation of areas of inundation than a traditional fixed width riparian buffer. Data source: U.S. Geological Survey.

3.3 Flood Risk Analysis

A critical first step in studying the potential for floodplain restoration to reduce flood risk is to assess overall flood risk for the area of study. Areas determined to be at greater risk of damaging floods are areas where floodplain restoration activities to reduce flood risk should be prioritized. To assess flood risk in the nine delineated watersheds, a flood risk analysis was completed in ArcMap Model Builder. The flood risk analysis consisted of five components: The Federal Emergency Management Agency (FEMA) National Flood Hazard Layer dataset (FEMA, 2021), total delineated catchment area, historic levee failure data from Madera County, the California Department of Forestry and Fire Protection (CALFIRE) Fire Hazard Severity Zone dataset (CALFIRE, 2020), and the Office of Environmental Health Hazard Assessment CalEnviroScreen disadvantaged communities dataset (CalEnviroScreen, 2018). For each of the following components, a greater ranking as determined by the analysis, corresponds with a higher risk of flooding and therefore higher priority for siting flood risk reduction projects.

3.3-1 FEMA Flood Hazard

The flood risk reduction analysis began with an exploration of which areas within Madera County were considered to be in flood hazard zones. The FEMA Flood Insurance Rate Map database is a public repository of flood hazard maps for communities across the United States (FEMA.1, 2021). After a review of the spatial datasets available, it was found that FEMA's National Flood Hazard Layer would be the most useful for this analysis. The National Flood Hazard Layer is a geospatial database that provides current flood hazard data as part of the National Flood Insurance Program (FEMA.2, 2021). It classifies locations of elevated flood risk based on criteria for determining special flood hazard areas. The criteria that proved useful for this analysis was the 100-year flood hazard zones.

Areas within a 100-year flood hazard zone are those which, in any given year, have a 1% chance of having their property inundated by a large flow event (USGS.1, 2018). The FEMA National Flood Hazard Layer dataset classifies 100-year flood hazard zones further into subcategories with different implications towards flood insurance rates for those areas. For the purposes of this project, areas within any of the 100-year flood hazard zones were combined into one spatial layer classified as high-risk within Madera County (**Figure 3.4-1**).

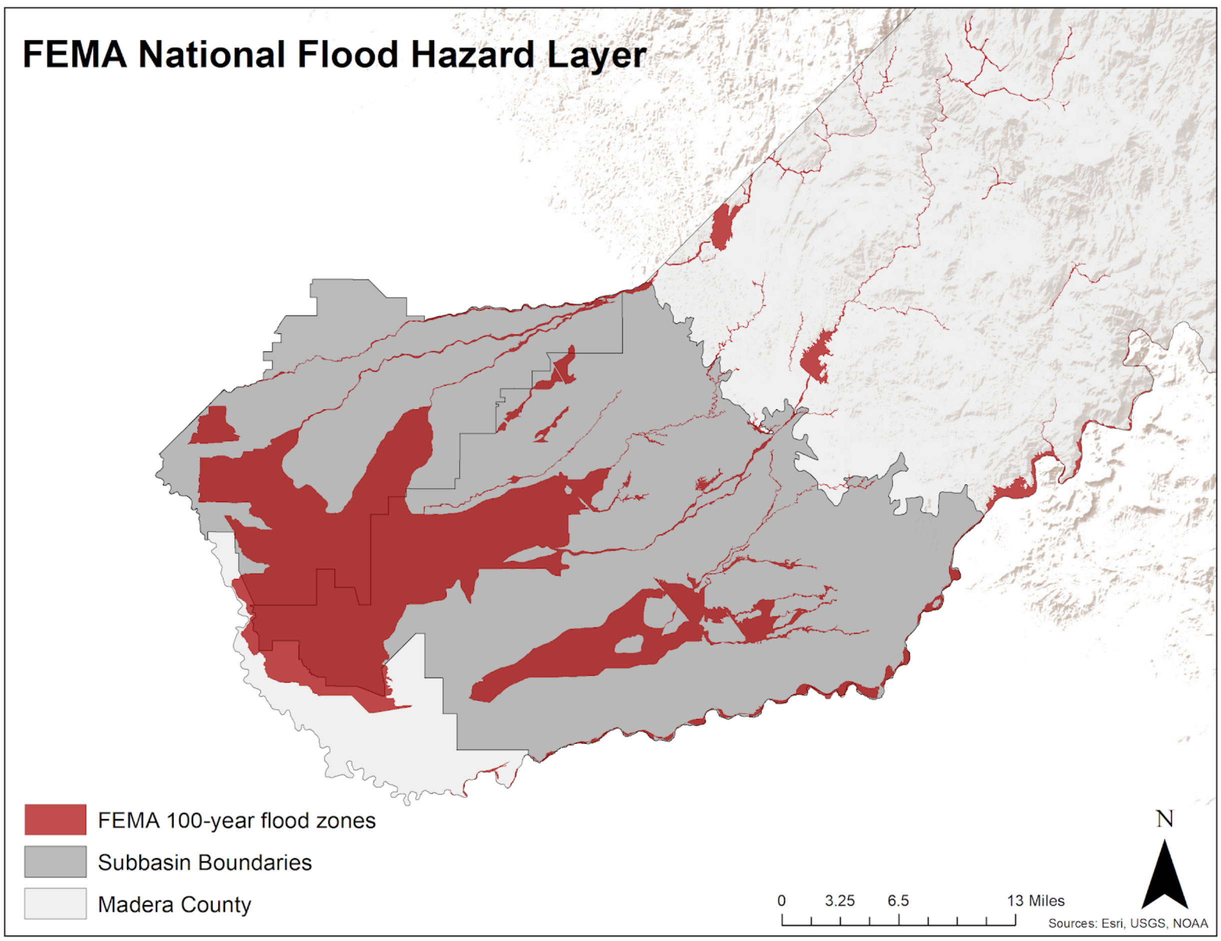


Figure 3.3-1 Locations of 100-year flood hazard zones. Flood zones are classified in red, subbasin boundaries are represented in dark grey, and Madera County is shown in light grey. Most of the flood zones are located in the western portions of Chowchilla and Madera subbasins. Flood zones are also located along the major streams. Source: FEMA National Flood Hazard Layer spatial dataset.

Most of the areas in Madera County that are within these 100-year flood zones are in the western portion of the two groundwater subbasins, Chowchilla and Madera. This is where the topography of the county flattens out onto the San Joaquin Valley floor.

The 100-year flood zone layer was analyzed to determine a ranking of flood risk for each of the watersheds that had been previously delineated. To achieve this, a Zonal Statistics tool was used in ArcMap Model Builder to calculate the total area of the 100-year flood zones that fell within each of the delineated watersheds. The values found for the area of 100-year flood hazard zones were then reclassified into a 1 to 6 ranking for each watershed using Jenks natural breaks (Jenks, 1967). A ranking of 6 indicated the greatest area of flood hazard within a watershed, which relates to the highest flood risk. A ranking of 1 meant a watershed contained the least area of flood hazard and therefore had the lowest flood risk. This ranking, along with the following 4 components, were given weighted sums to determine the final flood risk priority score for each watershed. Since the FEMA Flood Hazard Layer component most closely factors into direct flood risk to communities, it was given a relatively greater weight (0.4) than the following components (0.15 each).

3.3-2 Flood Contribution by Catchment Area

The California Irrigation Management Information System (CIMIS) operates one weather station within Madera County located near the city of Madera. While useful for gathering information on historical precipitation data and seasonality for this station, it only provides accurate precipitation data for this exact location. Since precipitation can vary substantially from one location to another, it is important to obtain data from additional monitoring stations to get an accurate model. Stream flow gauge station data was also limited in Madera County both spatially and temporally. Gauges that recorded stream discharge were found at limited sites and had a limited number of years on record. This analysis uses the watershed catchment area as a proxy for precipitation calculations due to the limited weather station and stream flow stations in Madera County. It is assumed that a greater catchment area equates to a greater potential to capture more precipitation.

3.3-3 Historic Levee Failures

Data on historic levee failures comes from Madera County. The levee dataset breaks down levee failures, and where they have occurred, into three categories: levee erosion, levee breaks, and levee seepage (**Figure 3.3-3**). A levee break or breach describes a situation where a levee fails and water that was once held behind the levee is able to travel through and flood areas once protected. Levee erosion occurs when wind, water, or organisms wear down the levee structure. Levee seepage is the process of water trickling through or under a levee structure. A levee experiencing erosion or seepage runs the risk of becoming a break later on. For the purpose of this analysis, a count of levee failures was calculated for each major stream/river (**Table 3.3-3**).

Table 3.3-3 Total Levee Failures by Stream. Source: Madera County Levee Failure Dataset

Stream	Total Levee Failures
Chowchilla River	1
Dry Creek	6
Ash Slough	3
Berenda Creek	2
Fresno River	6
Cottonwood Creek	0
San Joaquin River	5
Berenda Creek	2

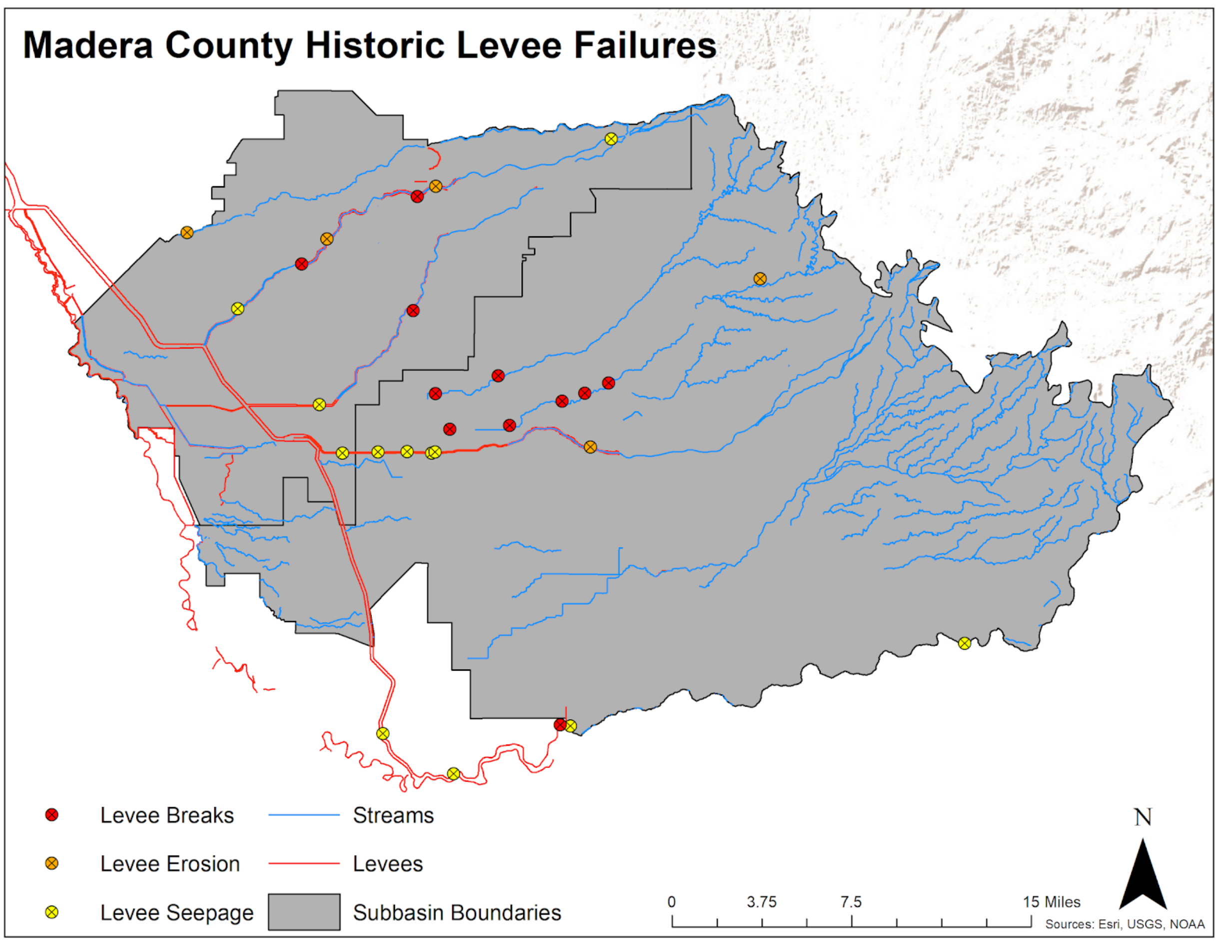


Figure 3.3-3 Location of levee failures in Madera County. Displays rivers and streams in blue and locations of levee failures within the Madera and Chowchilla subbasins. Orange circle indicated levee erosion failure, red circle indicates levee break failure, and yellow circle indicates levee seepage. Dry Creek and Fresno River have the most levee failures (6), followed by San Joaquin River (5), Ash Slough (3). Source: Madera County levee failure dataset.

3.3-4 Disadvantaged Communities

The California Communities Environmental Health Screening Tool (CalEnviroScreen 3.0, 2018) was incorporated into the model to account for disadvantaged communities. The CalEnviroScreen identifies communities that are vulnerable and disproportionately burdened by various sources of pollution. It is based on scores for individual census tracts from environment, health, and socioeconomic factors. Areas within the Madera and Chowchilla subbasins where at least 75% of the population is classified as a disadvantaged community (**Figure 3.3-4).** This analysis is important because a higher priority should be given to locations with more disadvantaged communities to provide resources and protections to these communities. The disadvantaged communities scores were created with 6 ranks of lowest risk to highest risk. The scores were created by calculating the area of land within each catchment where a disadvantaged community is located. The catchment areas with the highest percentage of disadvantaged communities were given a higher risk score.

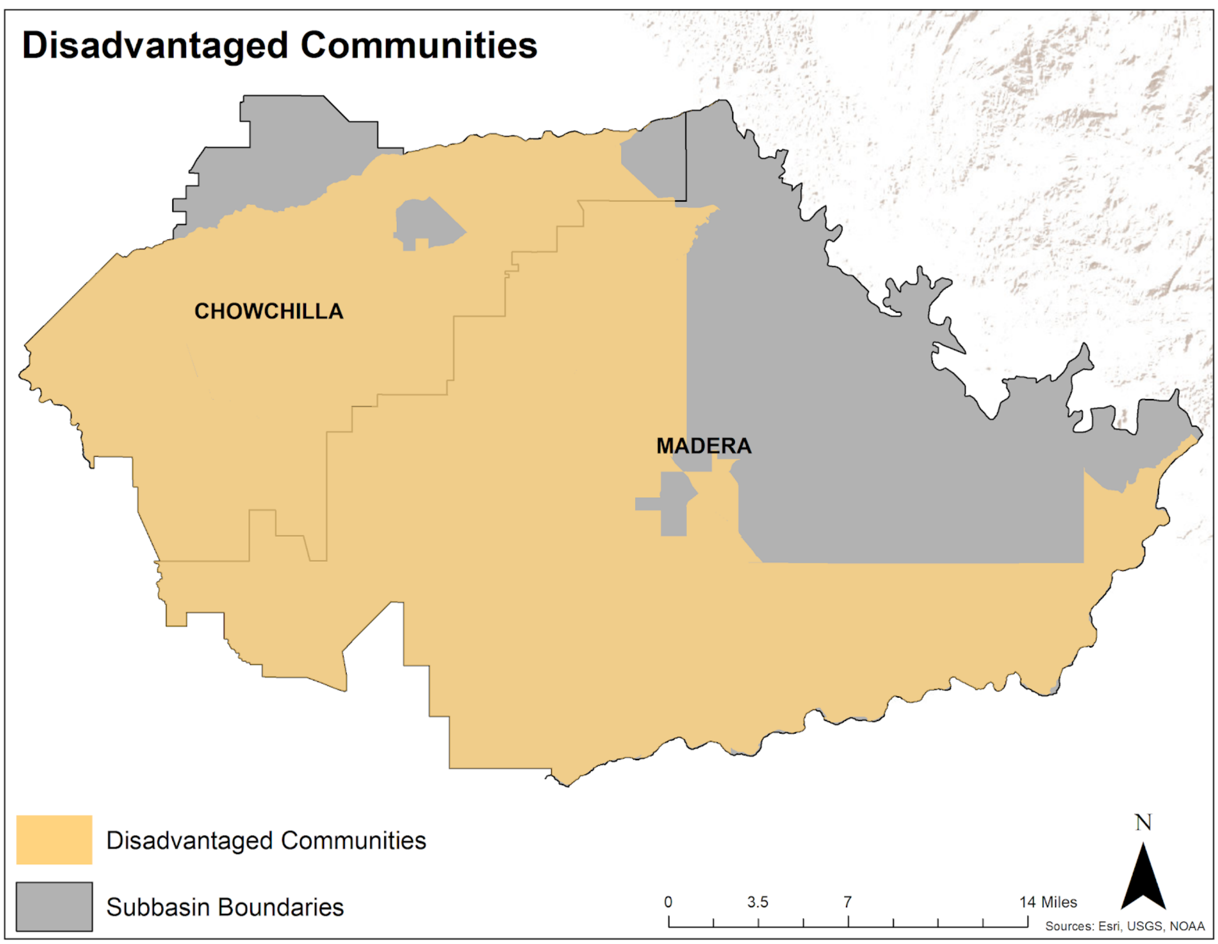


Figure 3.3-4 Locations of disadvantaged communities within the Madera and Chowchilla subbasins. Most of the County contains disadvantaged communities in the top 25% CalEnviroScreen score and is therefore a high priority for flood risk mitigation projects. Source: CalEnviroScreen 3.0.

3.3-5 Fire Hazard

There is a strong correlation between fire burn area and post fire floods and debris flows. Fires expose soil and contribute to loss of vegetation, which can have major consequences during intense precipitation events. According to the California Water Science Center at the United States Geological Survey, increased surface runoff and flooding related to wildfires can occur for several years after an active fire (USGS.2, 2018). The Creek fire, which started on September 04, 2020, lasted for a total of 153 days and spanned Fresno and Madera counties. Due to the salience of the Creek fire and the history of wildfires in Madera County and the greater San Joaquin Valley at large, the CALFIRE Fire Hazard Severity Zone dataset was incorporated into the flood risk analysis. The assumption being that areas in Madera County with a higher fire hazard severity score will also be at risk for flooding due to the connection between wildfires and post fire flood events.

The CALFIRE Fire Hazard Severity Zone dataset assigns a different fire hazard score ranging from 1-3 (1 = moderate hazard, 2 = high hazard, 3 = very high hazard) to different areas based on factors that contribute to wildfires including fuel, slope, and fire weather) (CALFIRE, 2020). The Fire Hazard Severity Zone consists of two datasets, a dataset with Local Responsibility Area Lands and one for State Responsibility Area lands. Both datasets were downloaded from the CA.gov California State Geoportal website and uploaded into ArcMap along with the Madera County shapefile. It was found that no Local Responsibility Area lands data resided within the geographic scope of Madera County, so the analysis only includes the State Responsibility Fire Hazard Severity Zone data. A significant portion of the center of Madera County at the foothills of the Sierras lies within a fire hazard severity zone (**Figure 3.3-5)**. In ArcMap Model builder the total area in acres of each watershed that falls within a fire hazard severity zone was calculated. The decision was made to calculate the area sum instead of the sum of scores within each watershed because all of the scores, 1-3, signify increased fire risk and increased flood risk.

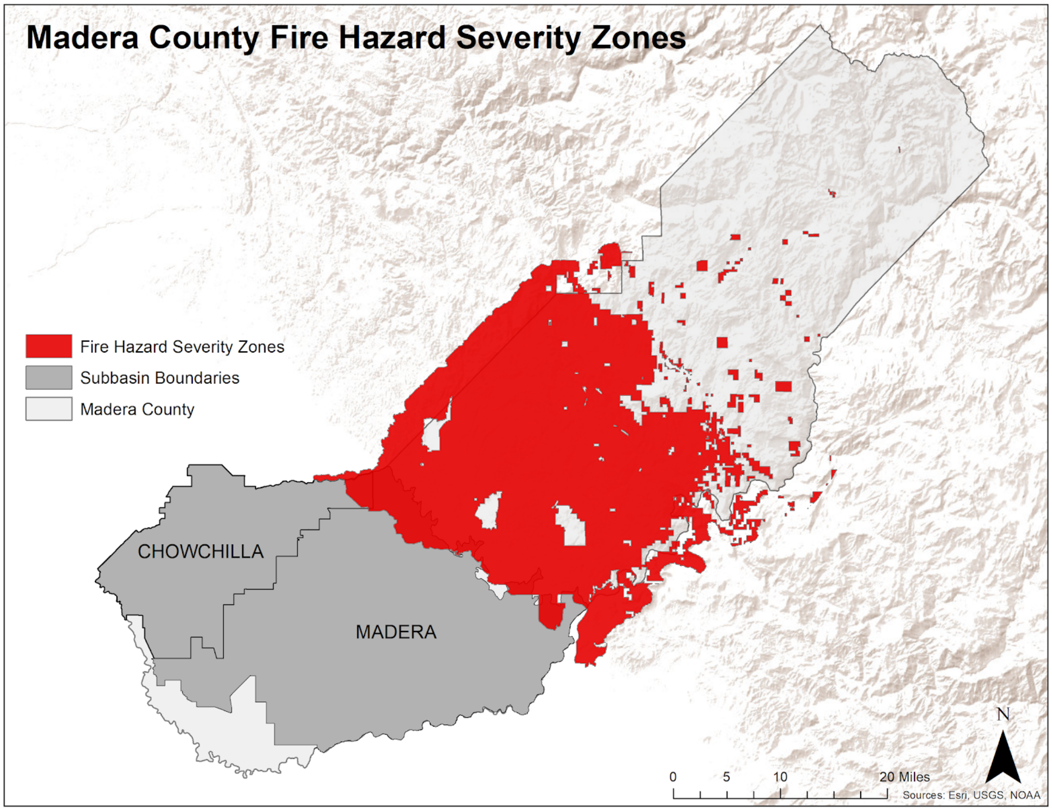


Figure 3.3-5 Location of Madera County Fire Hazard Severity Zones. Areas indicated as having moderate, high, or very high fire hazard within Madera County are shown in red. Most of the fire hazard zones are located in the eastern portions of the county within the sierras. This is likely to impose downstream consequences to the Madera and Chowchilla Subbasins downstream as debris flows and flooding are highly correlated with fire events. Data source: CALFIRE Fire Hazard Severity Zones.

3.3-6 Flood Risk Reduction Score

The final score for the flood risk analysis was determined by calculating a weighted sum of the rankings by watershed for each of the five components that went into the analysis. Each component was reclassified into a 1 to 6 scale, with 1 being the lowest flood risk and 6 being the highest. Scores were normalized consistently using Jenks natural breaks optimization (Jenks, 1967). The flood hazard ranking from the FEMA National Flood Hazard Layer was given a relatively greater weighting than the other components due to it being a more direct assessment of flood risk areas. That component was given a weighting of 0.4, and the remaining four components were each given a weight of 0.15 (**Table 3.3-6**). A sensitivity analysis is conducted, shown in **Section 5**, to check and adjust the distribution of weights appropriately.

Table 3.3-6 - Weighting factors assigned to each component of the flood risk analysis.

Parameter:	Weighting Factor:
FEMA National Flood Hazard Layer	0.4

Catchment Area	0.15
Levee Failures	0.15
Disadvantaged Communities	0.15
Fire Hazard Severity Zones	0.15

3.4 Ecosystem Enhancement

Floodplain restoration and near-channel recharge project locations are prioritized based on their potential to *enhance ecosystems*. For the purposes of this project ecosystem enhancement is defined according to the California Department of Water Resources as "reconnecting and inundating floodplains; creating floodplain habitat (e.g., riparian), marsh, and wetlands; supplementing base flows; and supporting groundwater dependent ecosystems through increased baseflow resulting from higher groundwater levels" (DWR, 2018).

Unlike the flood risk analysis, the ecosystem enhancement analysis was performed specifically on areas within riparian corridors that correspond to the 50-year floodplain surrounding the major streams and tributaries of the study area. Section 3.2 above describes the process for delineating the riparian areas for this analysis.

3.4-1 Groundwater Dependent Ecosystems

The ecosystem enhancement analysis started by assessing where groundwater-dependent ecosystems may exist within the Chowchilla and Madera subbasins. Groundwater-dependent ecosystems are specifically defined under SGMA as "ecological communities or species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface" (Groundwater Resource Hub, 2003). These natural communities, which include wetlands, riparian corridors, estuaries, and springs, provide important habitat for aquatic and terrestrial plant and animal species. Most of these ecosystems have been destroyed in the Central Valley in the last 100 years as a result of agricultural and urban development, making their restoration a priority for many environmental groups and agencies. In fact, SGMA includes a requirement that groundwater sustainability agencies must identify groundwater dependent ecosystems in their sustainability plans and "consider impacts to [groundwater dependent ecosystems] in making groundwater management decisions" (The Nature Conservancy, 2019).

Understanding the location of groundwater-dependent ecosystems is a crucial first step in assessing where opportunities for ecosystem enhancement exist in the study area. When groundwater is replenished through recharge activities, it can directly enhance groundwater-dependent ecosystems. To assess where these ecosystems exist in Madera and Chowchilla subbasins, this analysis utilized the indicators of groundwater-dependent ecosystems dataset from The Nature Conservancy and California Department of Water Resources

(Groundwater Resource Hub, 2021). A more locally-specific groundwater dependent ecosystem dataset was provided to this group by officials from Madera County, but The Nature Conservancy's dataset is more inclusive of areas that could potentially be groundwater dependent ecosystems. For the purposes of this analysis, which sought to consider all potential opportunities for groundwater dependent ecosystem restoration, the The Nature Conservancy's indicators of groundwater dependent ecosystems dataset was chosen so as not to exclude any potential sites (**Figure 3.4-1**).

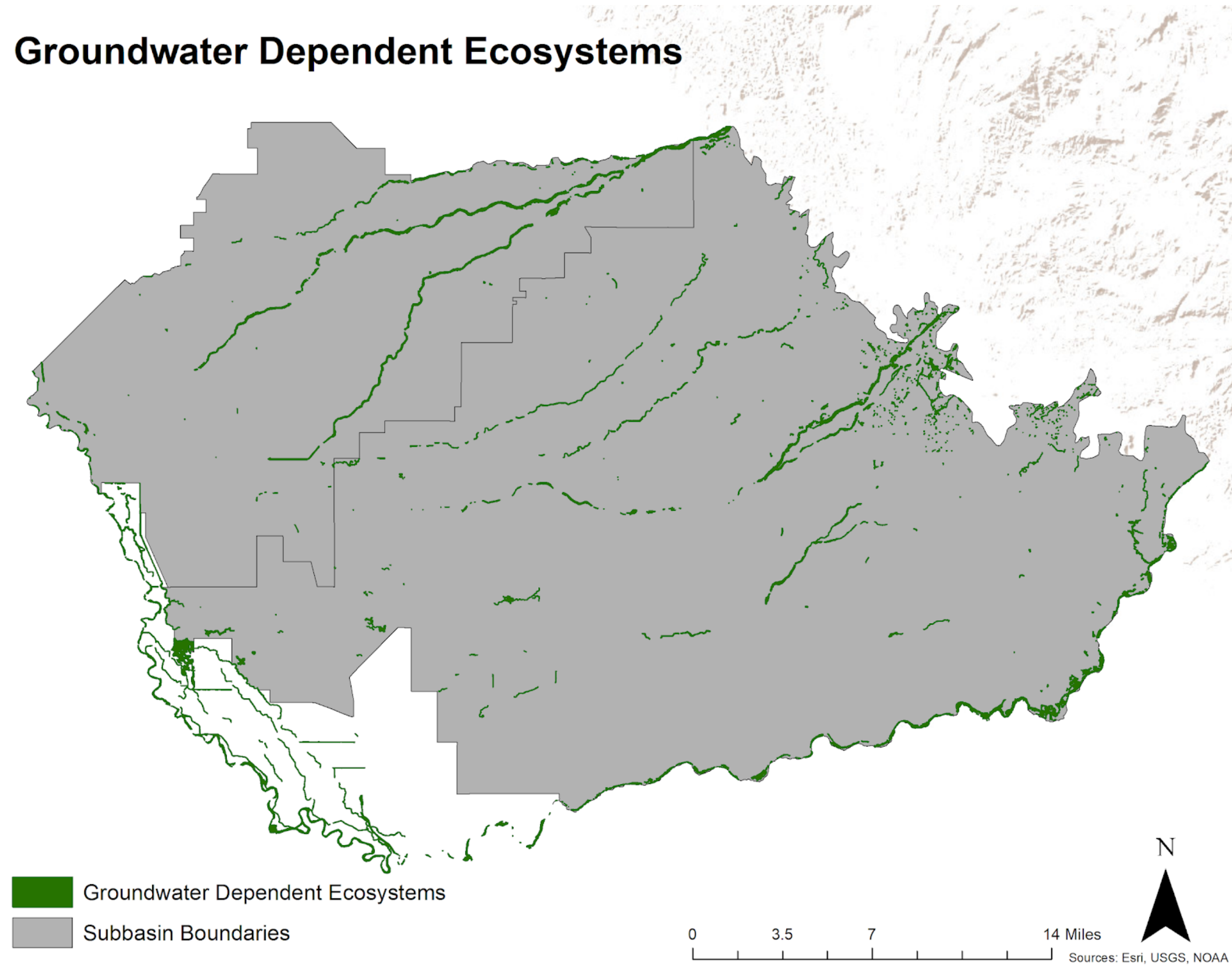


Figure 3.4-1 TNC-defined Groundwater dependent ecosystem locations. Groundwater dependent ecosystems are highlighted in green, while grey represents the Chowchilla and Madera subbasins. The most optimal groundwater dependent ecosystem locations are located along the major streams and riparian corridors. Source: indicators of Groundwater Dependent Ecosystems dataset from The Nature Conservancy and California Department of Water Resources.

The indicators of groundwater dependent ecosystems dataset shows that the highest densities of groundwater dependent ecosystems tend to be located in the riparian and near-stream corridors of major rivers and tributaries of the study area. Since this portion of the analysis looked at specific riparian areas, a proximity analysis was used to rank suitable recharge sites. Areas within the riparian delineation that were closer to groundwater dependent ecosystems were considered to be higher priority for achieving ecosystem enhancement benefits than those further away. The "Near" tool was used in ArcGIS Model Builder to calculate distances from riparian areas to groundwater dependent ecosystems. The distances for each cell within the riparian buffer were reclassified to a 1 to 6 scale using Jenks natural breaks optimization. A ranking of 6 represents the least distance between the riparian recharge site and therefore the highest priority, and a ranking of 1 represents the greatest distance and the lowest priority for ecosystem enhancement.

3.4-2 Critical Habitats

The next parameter for ecosystem enhancement potential was the presence of critical habitat for endangered or threatened species. The approach for the critical habitats parameter was adapted from the Floodplain Restoration Opportunities Analysis report, an appendix to California Department of Water Resources' Central Valley Flood Protection Plan - Conservation Strategy. In the Floodplain Restoration Opportunity Analysis report, prioritization for floodplain restoration was given to areas in or near critical habitat for salmonid species. This project expanded the species of interest to include any endangered or threatened species as listed by the federal and/or state Endangered Species Act.

In Madera County, there are several species listed as endangered or threatened at the state and federal levels. This includes the California Tiger Salamander, San Joaquin Kit Fox, Valley Elderberry, Longhorn Beetle, and bald eagle (MCRMA, 2007). This analysis considered critical habitats for these species to be high priority for locating recharge projects with the ecosystem enhancement benefit. A dataset from the United States Fish and Wildlife Service Environmental Conservation Online System was used to visualize the spatial distribution of critical habitats for endangered species in and around Madera County (USFWS ECOS, 2021). The results from this spatial dataset (**Figure 3.4-2**).

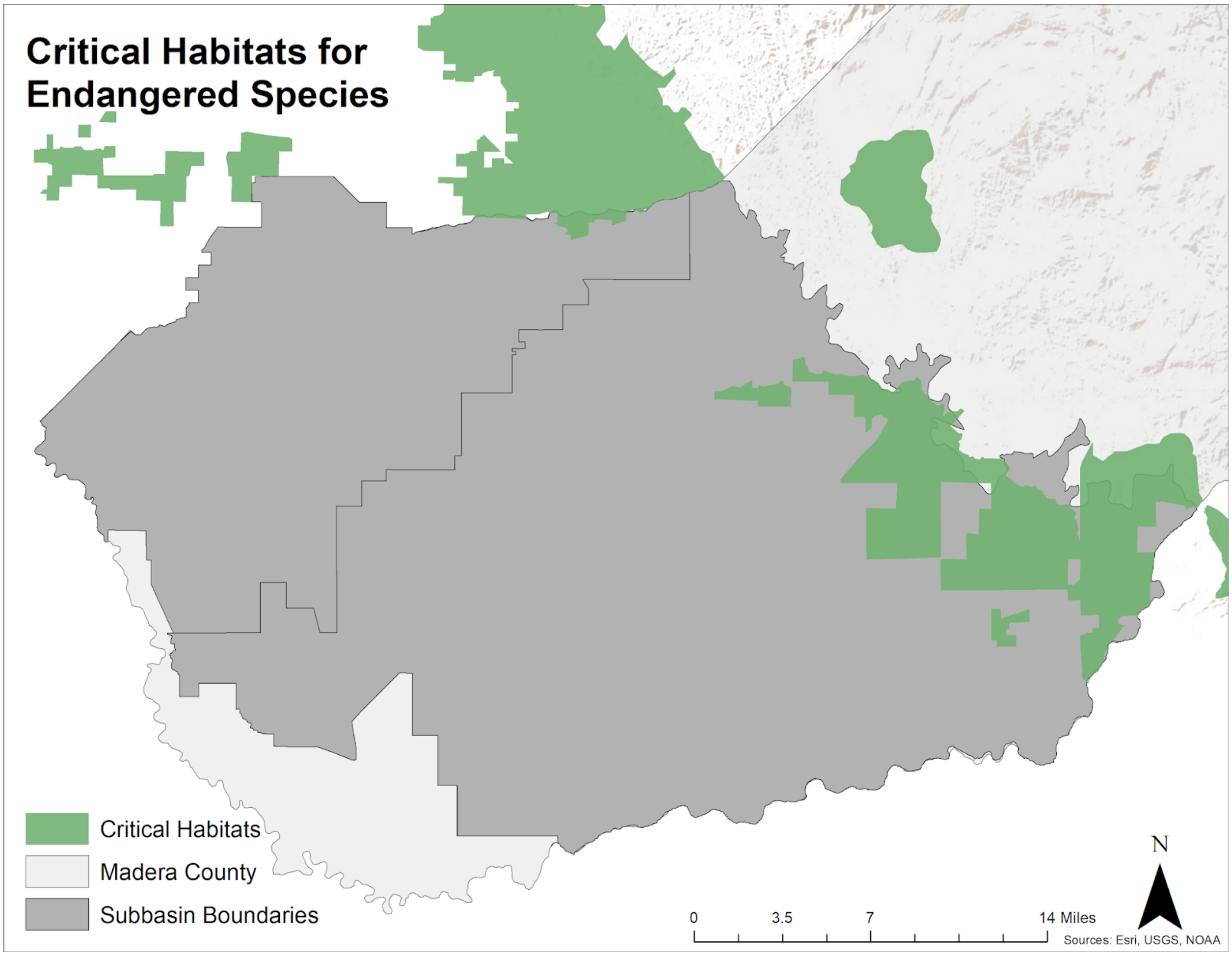


Figure 3.4-2 Locations of critical habitats for federally endangered or threatened species in and around the western portion of Madera County. Most locations for critical habitat are located in the Southeast portion of Madera subbasin and the North East portion of the Chowchilla subbasin. Source: USFWS ECOS.

Similar to the groundwater dependent ecosystems parameter, a proximity analysis was used to rank riparian areas in Madera and Chowchilla subbasins. This approach was used because critical habitats for endangered or threatened species are priority areas for ecosystem enhancement. The riparian areas closer to those habitats have the greatest opportunity to provide ecosystem benefits. Riparian areas were ranked on a 1 to 6 scale by using the Near tool in ArcGIS Model Builder and reclassifying distances from each critical habitat. A rank of 6 represents the least distance from a critical habitat, and therefore highest priority, while a ranking of 1 represents the greatest distance, and lowest priority.

3.4-3 Native Fish Species by Watershed

The rivers and streams in Madera County are home to a variety of native fish species. Floodplain habitats provide important spawning and feeding habitat for these species. Therefore, the richness of native fish species in each watershed provides another metric for determining where opportunity exists for achieving ecosystem enhancement with groundwater recharge projects.

Data on native fish species was acquired from the California Department of Fish and Wildlife's Native Fish Species by Watershed spatial dataset (CDFW, 2021). This dataset provided counts of native fish species by HUC12 watershed (**Figure 3.4-3)**.

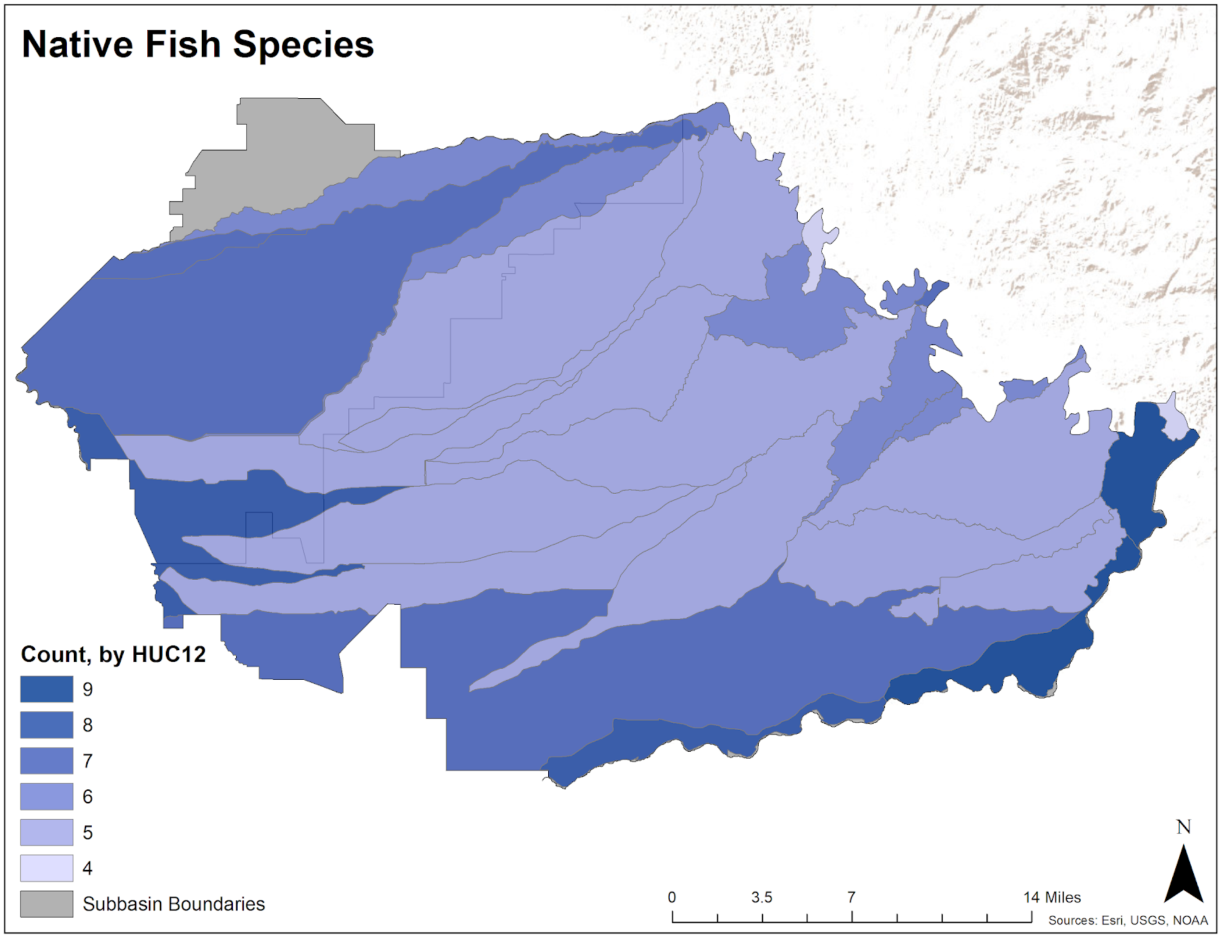


Figure 3.4-3 Locations of Native fish species count for each HUC12 watershed. Larger counts of native fish species are represented in darker purple and indicate more species richness, while lighter purple indicates less species richness. Source: CDFW Native Fish Species by Watershed.

The California Department of Fish and Wildlife dataset provides fish species counts by watershed (**Figure 3.4-3**), but the ecosystem enhancement analysis was only looking at areas suitable for recharge within a 50-year riparian buffer. To convert the native fish counts to the desired spatial resolution, the results were extracted through a mask of the delineated riparian areas of interest. When doing this, the counts for a given HUC12 watershed would be transferred to the riparian areas that reside within that watershed. Then, those riparian areas were assigned ranks based on how many native fish species were present in the watersheds in which those areas are located. Since there were 6 levels of counts in the watershed (each integer from 4 to 9 native fish species), these values were easily reclassified onto the 1 to 6 scale for consistency with the other parameters. A ranking of 6 represented areas with the greatest richness of native fish species and a ranking of 1 had the least.

3.4-4 Ecosystem Enhancement Score

After analyzing each of the three parameters, groundwater-dependent ecosystems, critical habitats, and native fish species, the scores for each were combined to produce a final output of priority riparian areas for achieving ecosystem enhancement benefits with groundwater recharge projects. All of the ecosystem parameters were ranked on a 1 to 6 scale with 6 being the highest priority and 1 being the lowest priority, making combining scores convenient to do. A weighted sum was used to combine the three scores, with equal weighting (0.33) being given to each of the three parameters (**Table 3.4-4**). A sensitivity analysis was performed to determine how changing the weighting for these parameters will affect the outcome of priority locations for achieving ecosystem enhancement.

Table 3.4-4 - Weighting factors assigned to each component of the ecosystems enhancement analysis.

Parameter:	**Weighting Factor:**
Groundwater-dependent Ecosystems	0.33
Critical Habitats	0.33
Native Fish Species Richness	0.33

3.5 Site Suitability

Once outputs had been produced for both the flood risk reduction and ecosystem enhancement benefits, the next step was to determine the suitability of sites for achieving these benefits with groundwater recharge projects. This site suitability analysis was conducted on lands within the 50-year delineated floodplain that were determined to be suitable for recharge by the Recharge for Resilience group project. Land slope, surface roughness, and land use type were combined to produce a final score for site suitability which applies to priority areas for both the flood risk reduction and ecosystem enhancement benefits.

3.5-1 Land Surface Slope

The best indicator of site suitability for achieving groundwater recharge, flood risk reduction, and ecosystem enhancement is the slope of the land surface at that site. When the slope is lower, the terrain is flatter and better suited for slowing down and dispersing flows as they are transported down a watershed by gravity. This allows water more time to settle in place, where it can infiltrate into underlying aquifers, reduce flood risk, and enhance ecosystems. For this reason, sites with lower slopes (shallower) were assigned a greater ranking for suitability than sites with higher (steeper) slopes.

To determine the land slope of riparian areas within the Madera and Chowchilla subbasins, the “Slope” tool in ArcGIS Model Builder was used on a 10-meter digital elevation model which provided the topography of the region. This tool produced a raster containing the values of slope (in percent) for each cell that fell within the delineated 50-year riparian zone. The resulting values of slope were then reclassified using Jenks natural breaks optimization into a 1 to 6 scale. Since lower slopes equate to greater suitability, a score of 6 means those sites have the lowest slope and the greatest suitability score, whereas a score of 1 represents sites with steep slope and low suitability.

3.5-2 Surface Roughness

Similar to land slope, land surface roughness provides another metric of a site's ability to slow down and disperse flows to achieve groundwater recharge, flood risk reduction, and ecosystem enhancement. For surface roughness, however, the primary mechanism at work is friction. The rougher a land surface, the more that friction is capable of slowing down flows as they travel over the land surface adjacent to streams. The abundance and type of vegetation is typically associated with surface roughness on natural landscapes. For this analysis, surface roughness was determined by association with land use type data from the National Land Cover Database (NLCD, 2016). A report on dam breaches in Kansas provided values of the Manning's *n* coefficient of roughness associated with each land use type in the National Land Cover Database (USDA, 2016). From that document, the following Manning's *n* values and land use types were used for this analysis (**Table 3.5-2**).

Table 3.5-2 - National Land Cover Database land use types and associated Manning's *n* coefficients of surface roughness.

NLCD Land Use Value	**Land Use Description**	**Manning's *n***
21	Developed, open space	0.040
31	Barren Land	0.025
41	Deciduous Forest	0.160
42	Evergreen Forest	0.160
43	Mixed Forest	0.160
52	Shrub/scrubland	0.100
71	Grassland/herbaceous	0.035
81	Pasture/Hay	0.030
82	Cultivated Crops	0.035
90	Woody Wetlands	0.120
95	Emergent Herbaceous Wetlands	0.070

For the purposes of this project, several land use types were removed from the analysis reflecting the fact that restoration projects would not be feasible on those lands. These include open water and developed land of low, medium, and high intensity. The NLCD database was filtered through the 50-year delineated riparian zone to only include sites of interest for this project. The land uses in those areas were then reclassified from their National Land Cover Database grid code value into their associated Manning's *n* value. Those values were then reclassified again using Jenks natural breaks optimization to get a 1 to 6 scale of suitability, with 6 again being the most suitable and 1 the least suitable. In this case, a higher surface roughness (i.e. higher Manning's *n* value) meant a greater capacity to slow down and disperse flows and therefore was assigned a greater suitability score.

3.5-3 Land Use Type

The final parameter of site suitability also incorporated land use types from the National Land Use Cover database. Land use types were ranked based on their priority for siting floodplain restoration projects, an approach adapted from the Floodplain Restoration Opportunity Analysis report. In that document, the first priority for restoration projects was given to natural lands, like grasslands or herbaceous land cover types, followed by agricultural land as a second priority. After that, no other land use types were considered for floodplain restoration projects (FROA, 2016). Following that approach, a priority score was assigned to each land use type in Madera County **(Table 3.5-3)**.

Table 3.5-3 - Priority rankings by land use types of the National Land Cover Dataset. Source: National Land Cover Database, 2016; Floodplain Restoration Opportunities Analysis Report, 2016.

NLCD Land Use Value	Land Use Description	Assigned Priority
90	Woody Wetlands	6 (best)
71	Grasslands/herbaceous	5
52	Shrub/scrubland	4
81	Pasture/Hay	3
82	Cultivated Crops	2
31	Barren Land	1
n/a	All others	Not considered

The natural vegetation types were ranked highest (woody wetlands, grasslands/herbaceous, and shrub/scrubland), followed by agricultural lands (pasture/hay and cultivated crops). Barren land was ranked as the least priority. These land use types were ranked on a scale of 1 to 6 where 6 represents the most suitable sites and 1 represents the least suitable.

3.5-4 Site Suitability Score

The results from the three site suitability parameters, slope, roughness, and land use type, were combined to produce a final output of the most suitable sites for achieving groundwater recharge, flood risk reduction and/or ecosystem enhancement. A weighted sum was used to combine each of the individual rankings into a final site suitability score. Since slope is the strongest indicator of a site's ability to slow down and disperse flows, it was given a greater weight than the other two parameters. Slope was assigned a weight of 0.7, and surface roughness was assigned a weight of 0.3. Once those two scores were combined into one, the resulting score was weighted equally with land use type in another weighted sum (**Table 3.5-4**). Once site suitability was determined, the next step was putting that together with flood risk reduction and/or ecosystem enhancement priorities as part of a multiple-benefit tradeoff analysis.

Table 3.5-4 - Weighting factors assigned to each component of the site suitability analysis.

Parameter:	**Weighting Factor 1:**	**Weighting Factor 2:**
Slope	0.7	0.5
Surface Roughness	0.3	
Land Use Type	--	0.5

3.6 Tradeoff Analysis and Final Outputs

To ensure that the model was applicable and useful to stakeholders in Madera County, a tradeoff analysis was conducted to replicate potential management preferences between the flood risk reduction and ecosystem enhancement co-benefits. In this tradeoff analysis, a weighted sum was used to combine the final flood risk priority scores and ecosystem enhancement priority scores. The weights can be set manually depending on a stakeholder's preferences. For example, setting weights of 0.8 for flood risk and 0.2 for ecosystem enhancement would reflect the preferences of a flood control agency and result in a final output that prioritized the flood risk reduction benefit more than the ecosystem enhancement benefit.

This report will describe the results from three example weighting scenarios which reflect different possible stakeholder interests. The three scenarios are as follows:

1) Flood risk reduction only - 100% weighting given to the flood risk reduction benefit and 0% given to the ecosystem enhancement benefit
2) Ecosystem enhancement only - 0% weighting given to the flood risk reduction benefit and 100% given to the ecosystem enhancement benefit

3) Equal weighting - 50% weighting given to the flood risk reduction benefit and 50% given to the ecosystem enhancement benefit

Once the tradeoff analysis was complete. The resulting prioritization scores were combined with the site suitability scores using an equally-weighted sum to produce a final output of the best locations where groundwater recharge projects can achieve any combination of the two co-benefits.

4. Results

The following section will display the results from each of the analyses performed for this project: flood risk reduction, ecosystem enhancement, and site suitability.

4.1 Flood Risk Analysis

The results from each of the five variables within the flood risk reduction analysis indicate which watershed catchments should be prioritized in order to achieve the project's first objective: prioritizing areas within Madera County that can receive flood risk reduction benefits from Flood-MAR activities.

4.1-1 FEMA Flood Hazard Results

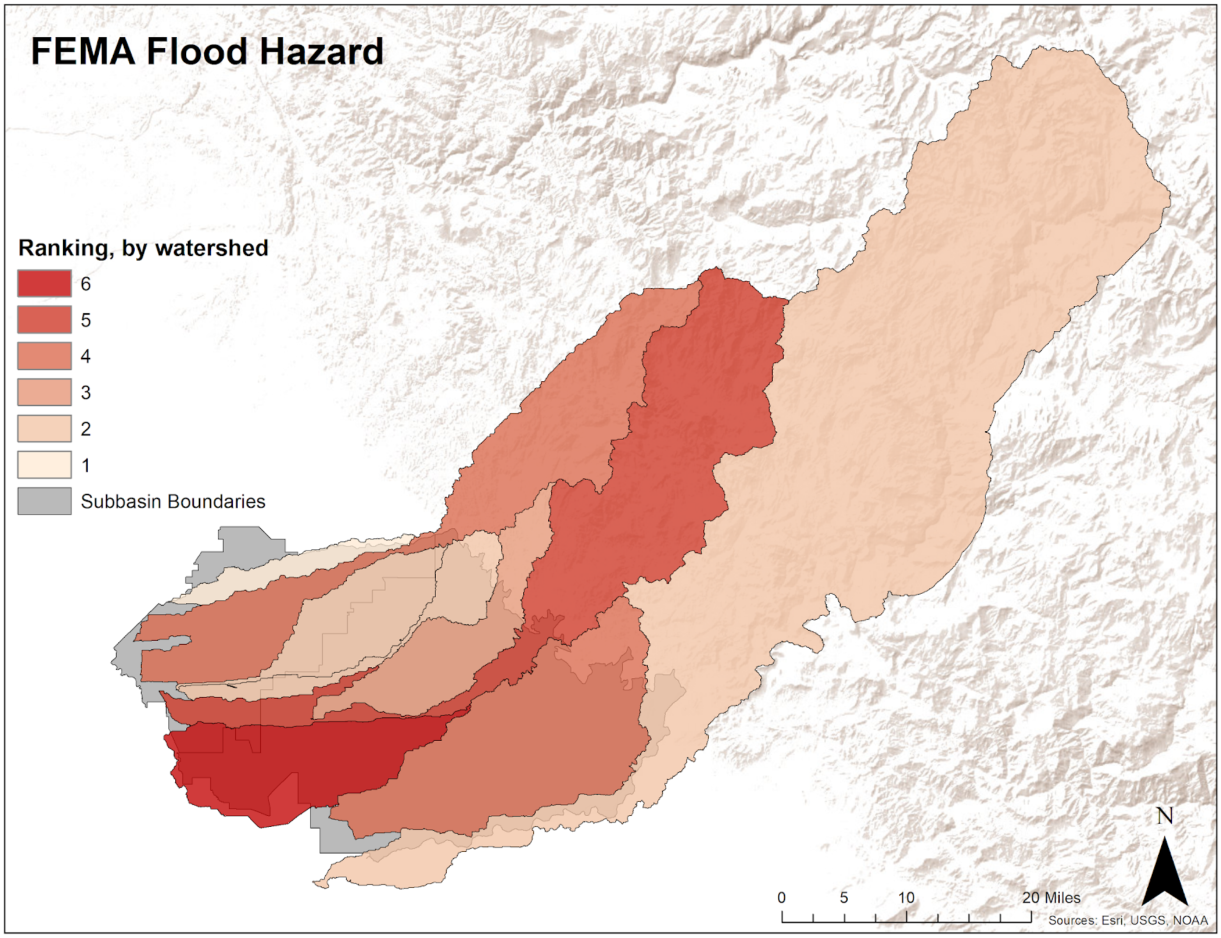


Figure 4.1-1 FEMA flood hazard score results. Source: FEMA National Flood Hazard Layer.

The FEMA Flood Hazard Results demonstrate which watersheds are most at risk of being inundated by a 100-year flood event. The watersheds most at risk, have a score of 6 and the watersheds least at risk of inundation by a 100-year flood event have a score of 1.The watersheds that are most at risk are Buttonwillow Slough, shown in dark red, followed by Fresno River, then Ash Slough and Cottonwood Creek (**Figure 4.1-1)**. These are the watersheds where the FEMA 100-year flood hazard layer covers the most area.

4.1-2 Disadvantaged Communities Flood Exposure Results

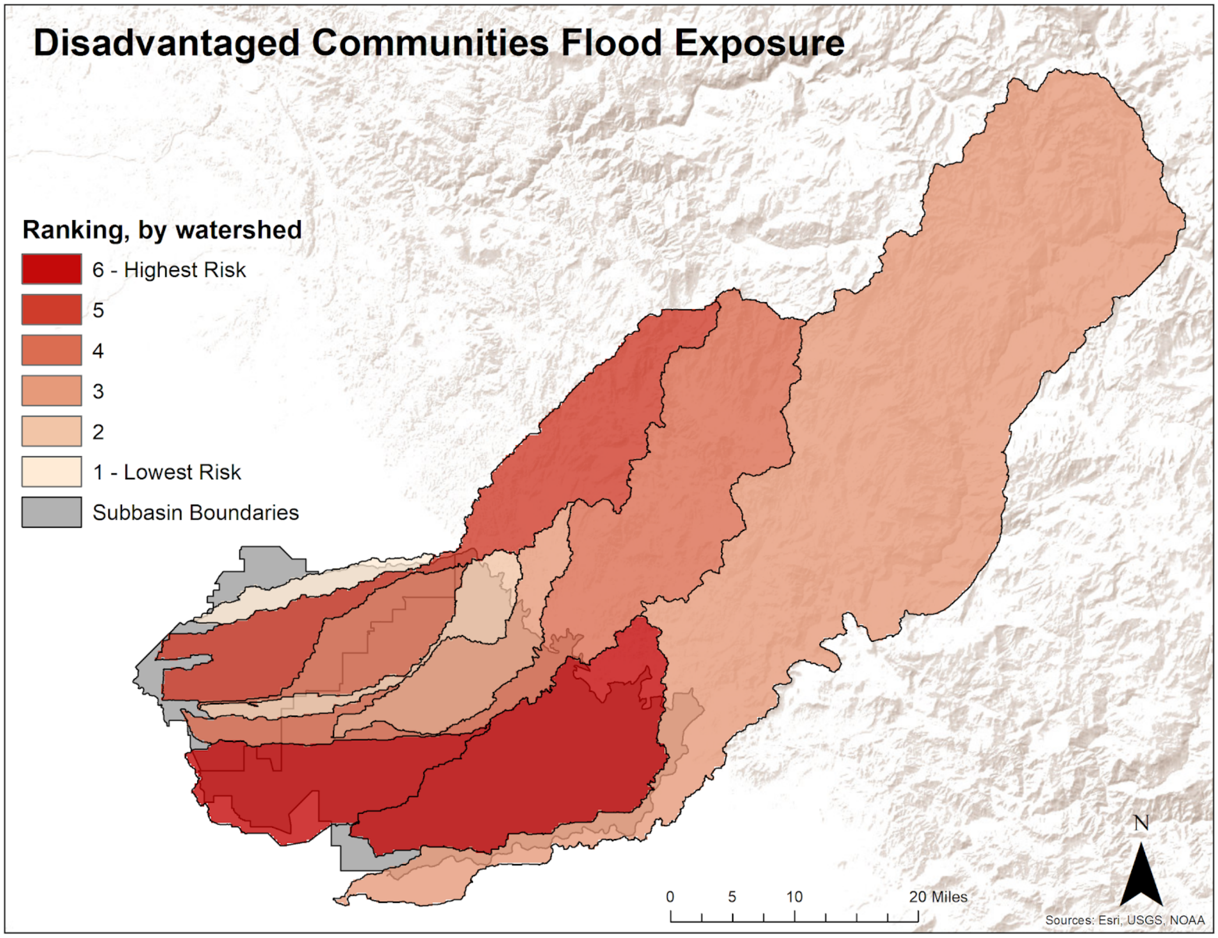


Figure 4.1-2 Disadvantaged communities score results. Source: California Communities Environmental Health Screening Tool (CalEnviroScreen 3.0).

To reduce potential exposure to flooding for disadvantaged communities, the California Communities Environmental Health Screening Tool (CalEnviroScreen 3.0) was used to determine the total area of disadvantaged communities located within each watershed. The watersheds determined to have the highest risk, have a score of 6 and the watersheds at lowest risk have a score of 1. The results of the disadvantaged communities analysis illustrate that flood risk prioritization efforts should focus on the Cottonwood Creek, Buttonwillow Slough, and Ash Slough watersheds (**Figure 4.1-2**). These are the watersheds where the largest areas of disadvantaged communities are located.

4.1-3 Fire Hazard Results

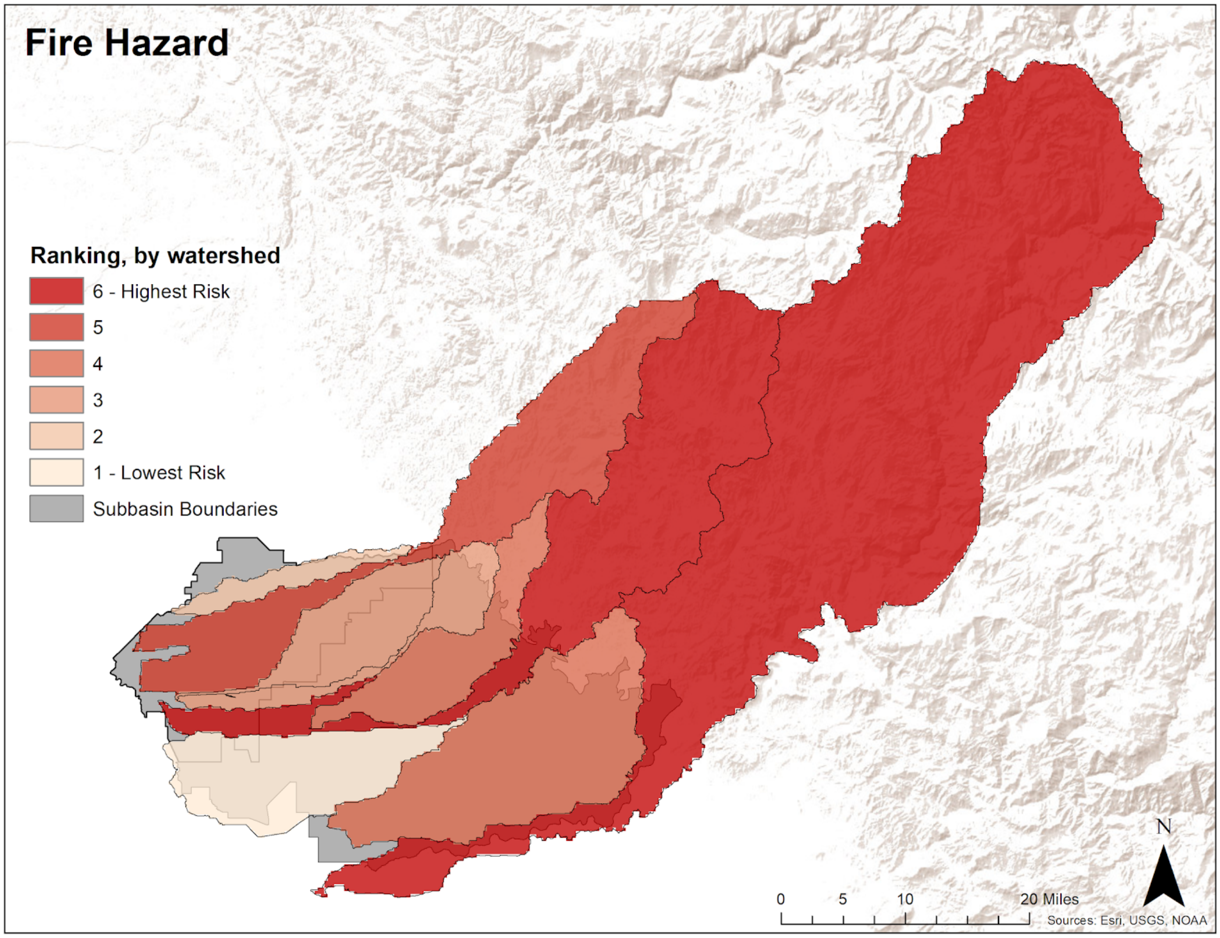


Figure 4.1-3 - Fire hazard score results. Source: Fire Hazard Severity Zone (FHSZ) Dataset (CALFIRE).

The fire hazard result exhibits the potential flood hazard imposed on each watershed as a result of their fire hazard (**Figure 4.1-3)**. Fire hazard data comes from the CALFIRE Fire Hazard Severity Zone Dataset. The watersheds that received a score of 6 were determined to have the highest risk for fire hazard and the watersheds that received a score of 1 have the lowest risk for fire hazard. The watersheds that received a score of 6 are the San Joaquin River and Fresno River watersheds followed by Ash Slough which received a score of 5. These three watersheds extend up into the Sierra Nevada mountains in the eastern portion of Madera County.

4.1-4 Watershed Area Results

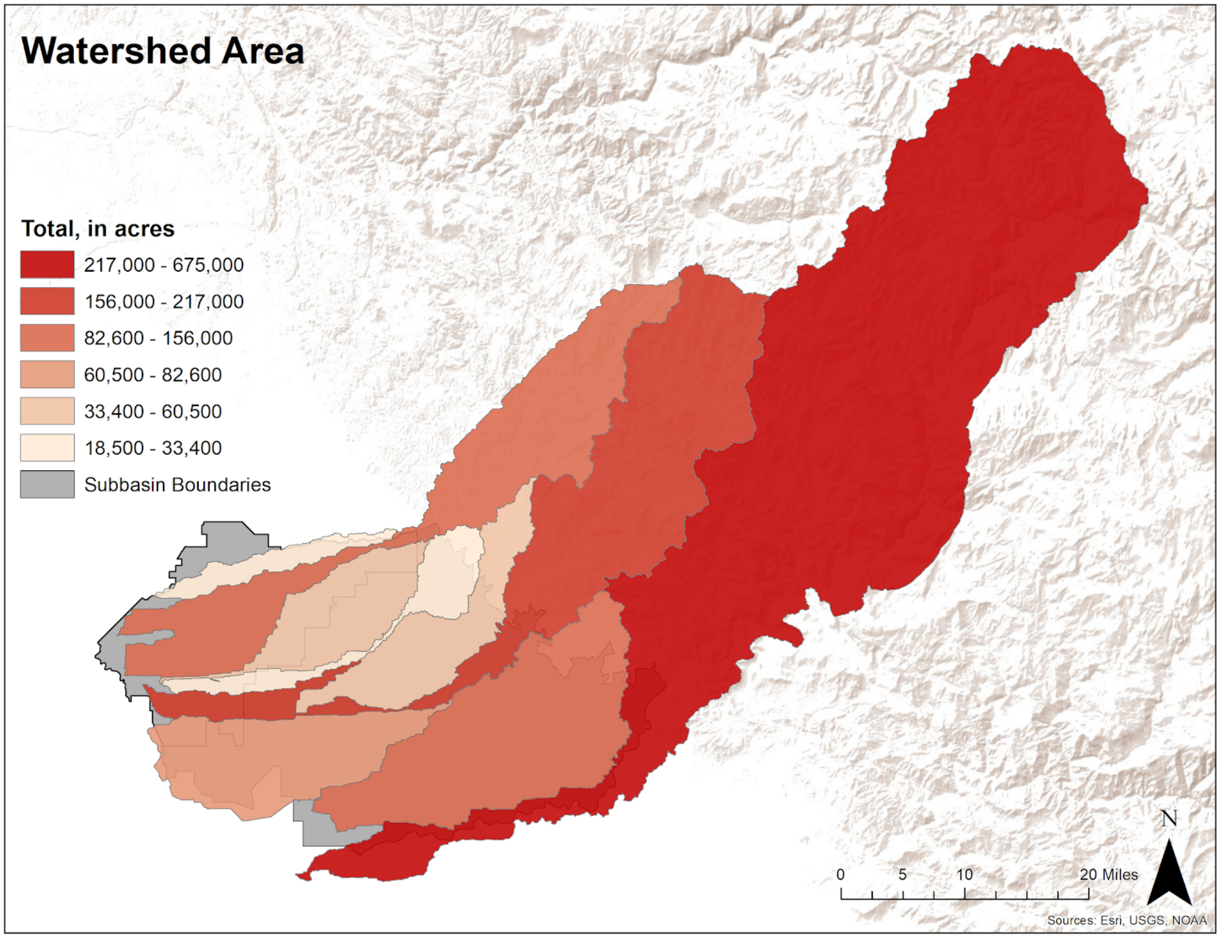


Figure 4.1-4 - Watershed area score results.

Watershed area was used to determine which catchments have the potential to capture the most precipitation and therefore contribute the most to downstream flooding (**Figure 4.1-4**). The watershed with the largest area is the San Joaquin River followed by the Fresno River.

4.1-5 Historic Levee Failures Results

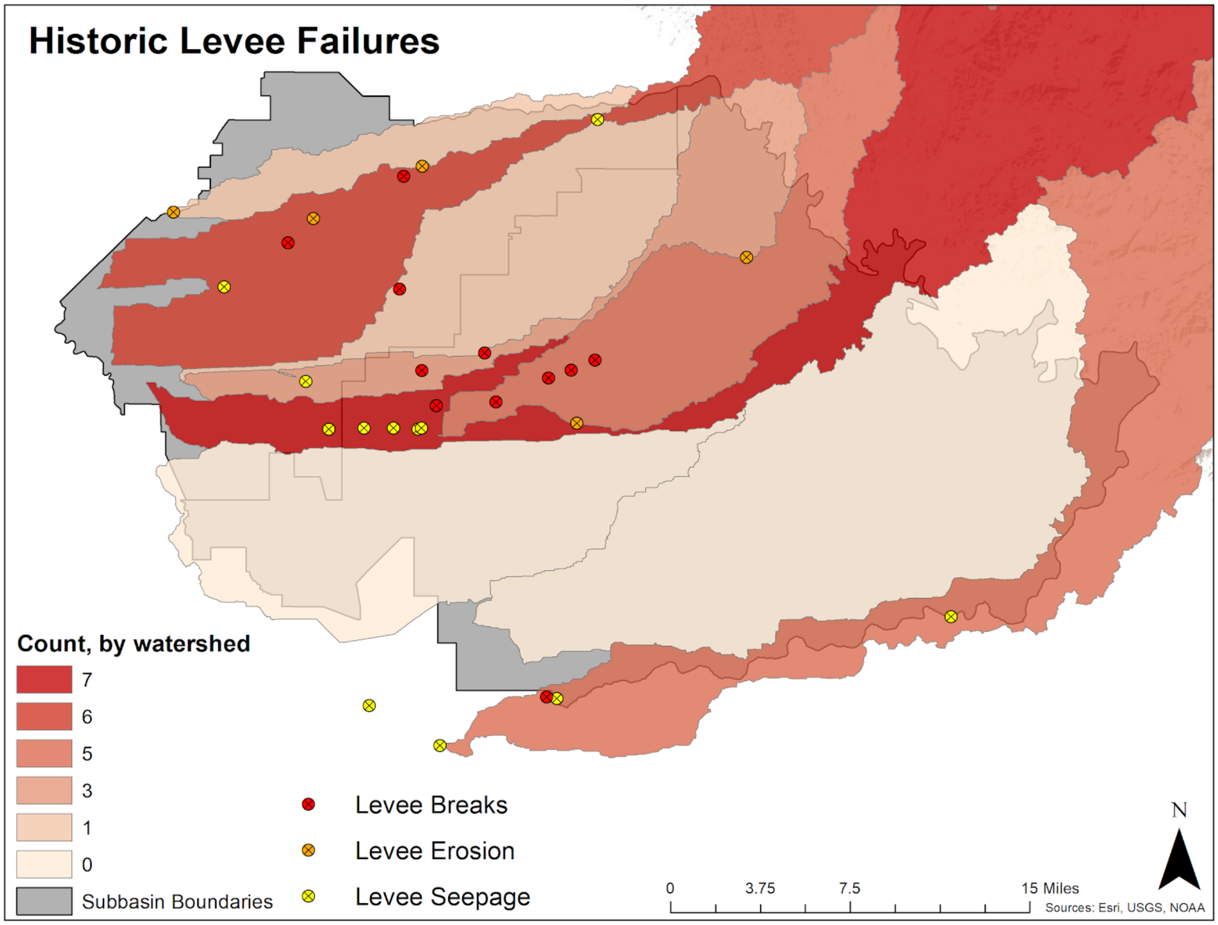


Figure 4.1-5 - Historic levee failures score results. Source: The Madera County Flood Control and Water Conservation Agencies Madera County levee shapefiles, prepared by KSN, Inc.

These results show the watersheds where the greatest number of levee failures have occurred (**Figure 4.1-5**). Areas with a history of levee failures can provide insight into which parts of the county's levee system are more stressed, putting them at greater risk of potential failures in the future. To reduce this stress on the levee system, watersheds where more failures have occurred were given higher flood risk reduction priority. These watersheds are the Fresno River, Ash Slough, and the San Joaquin River watersheds respectively.

4.1-6 Comparison of Flood Risk Analysis Results

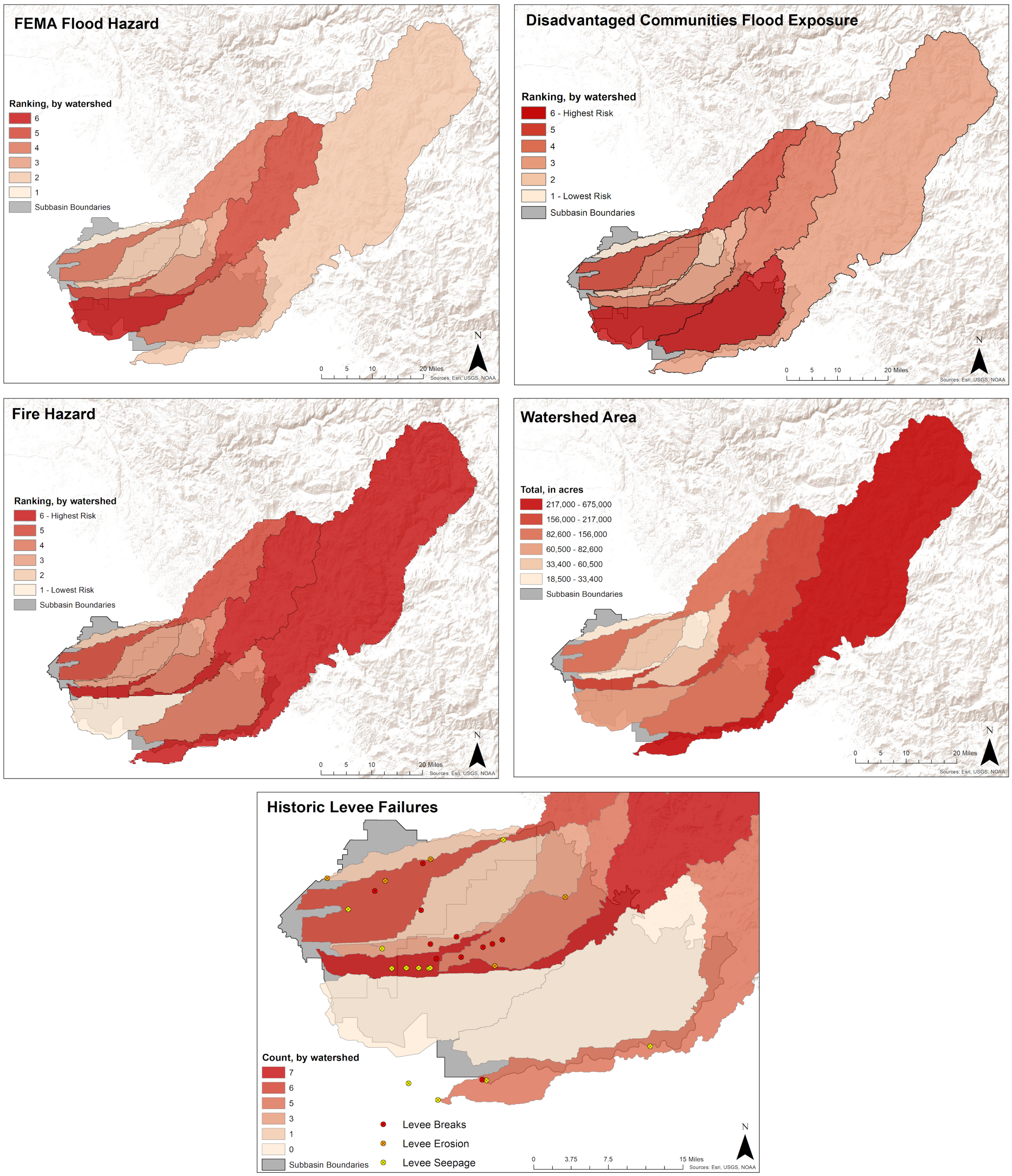


Figure 4.1-6 - Side-by-side comparison of results for each parameter of the flood risk analysis. FEMA flood hazard (top left), disadvantaged communities flood exposure (top right), fire hazard (middle left), catchment area as a proxy for flood contribution (middle right), and historic levee failures (bottom).

4.1-7 Final Flood Risk Prioritization Score

The final result from the flood risk analysis was produced by combining the results of each of the five flood risk parameters (**Figure 4.1-7**). Watersheds of highest priority are indicated in darker red, while watersheds of lower priority are indicated in lighter red to white. The results show that the greatest priority watersheds for achieving flood risk reduction with groundwater recharge projects are the Fresno River and Ash Slough. These watersheds were among the highest priority for each of the 5 parameters. The next highest priority watersheds are Buttonwillow Slough, Cottonwood Creek, and San Joaquin River, which all display similar final flood risk scores. The watersheds listed here should be given the highest priority for achieving flood risk reduction benefits with Flood-MAR projects in Madera County.

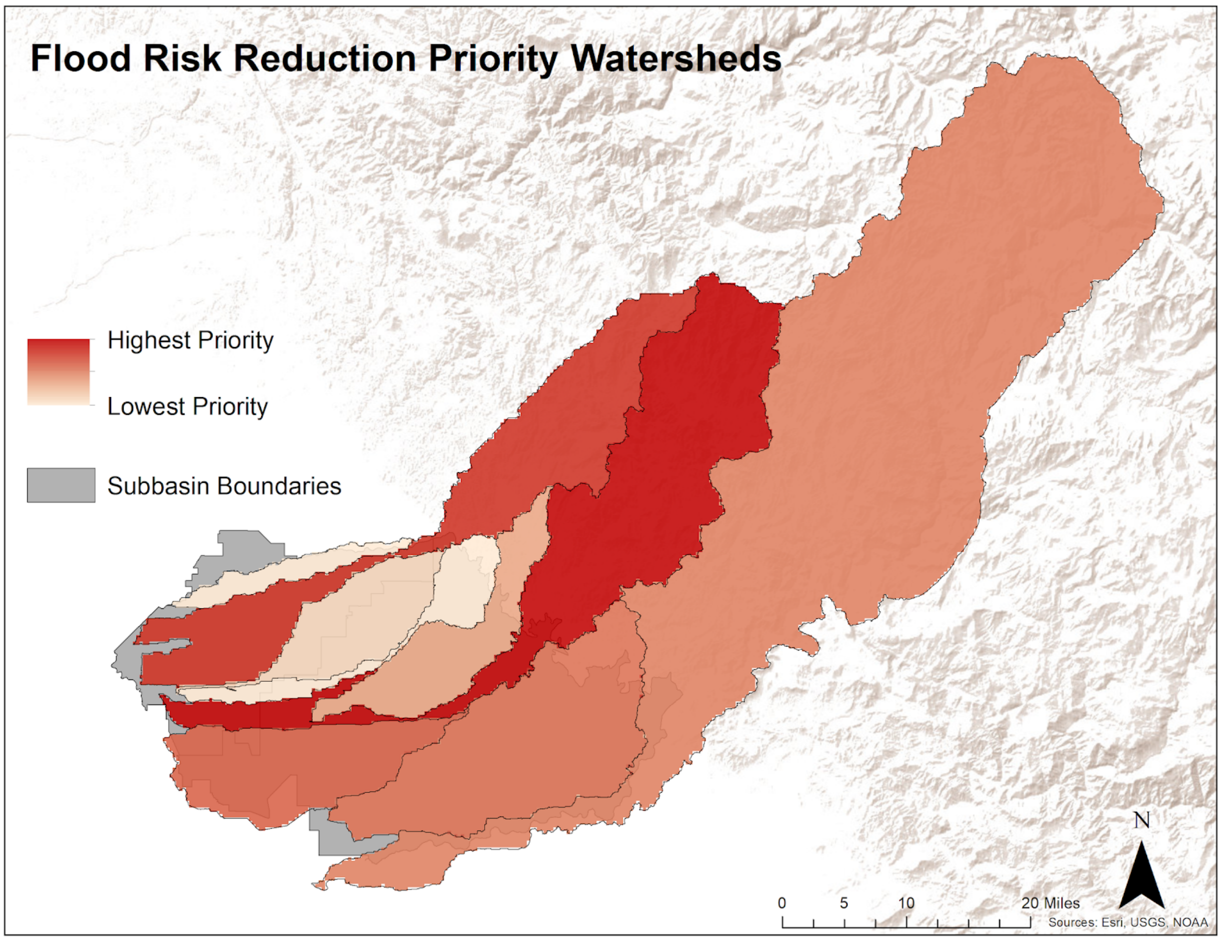


Figure 4.1-7 - The final results of the flood risk analysis by delineated watershed in Madera County. Based on analysis of FEMA flood hazard, watershed area, disadvantaged communities, historic levee failures, and fire hazard zones, it has been determined that the Fresno River watershed is at highest risk for floods. Because of its high risk factor, the Fresno River watershed is given highest priority for implementation of recharge projects aimed at reducing flood risk.

4.2 Ecosystem Enhancement

The ecosystem enhancement results provide insight into which sites within Madera and Chowchilla Sub Basins have significant ecosystems that could be enhanced through floodplain restoration and groundwater recharge projects. Ecosystem enhancement priorities were determined using a combination of three parameters: proximity to groundwater-dependent ecosystems, proximity to critical habitats for endangered or threatened species, and the richness of native fish species in each HUC12 watershed. The results from each of these parameters are described in this section.

4.2-1 Groundwater-Dependent Ecosystems

Groundwater-dependent ecosystems from The Nature Conservancy's indicators of Groundwater Dependent Ecosystems dataset are present along most of the riparian corridors of the major rivers and tributaries in Madera County (**Figure 4.2-1)**. The areas with the closest proximity to groundwater-dependent ecosystems (in green) are along the major ephemeral stream channels that flow from northeast to southwest across the Madera and Chowchilla subbasins. This includes significant portions of (from north to south) Berenda Slough, Berenda Creek, Dry Creek, Fresno River, and Cottonwood Creek. Some of these areas even have distances of 0 meters from potential groundwater-dependent ecosystems, which would make them the highest priority for siting groundwater recharge projects with the ecosystem enhancement benefit.

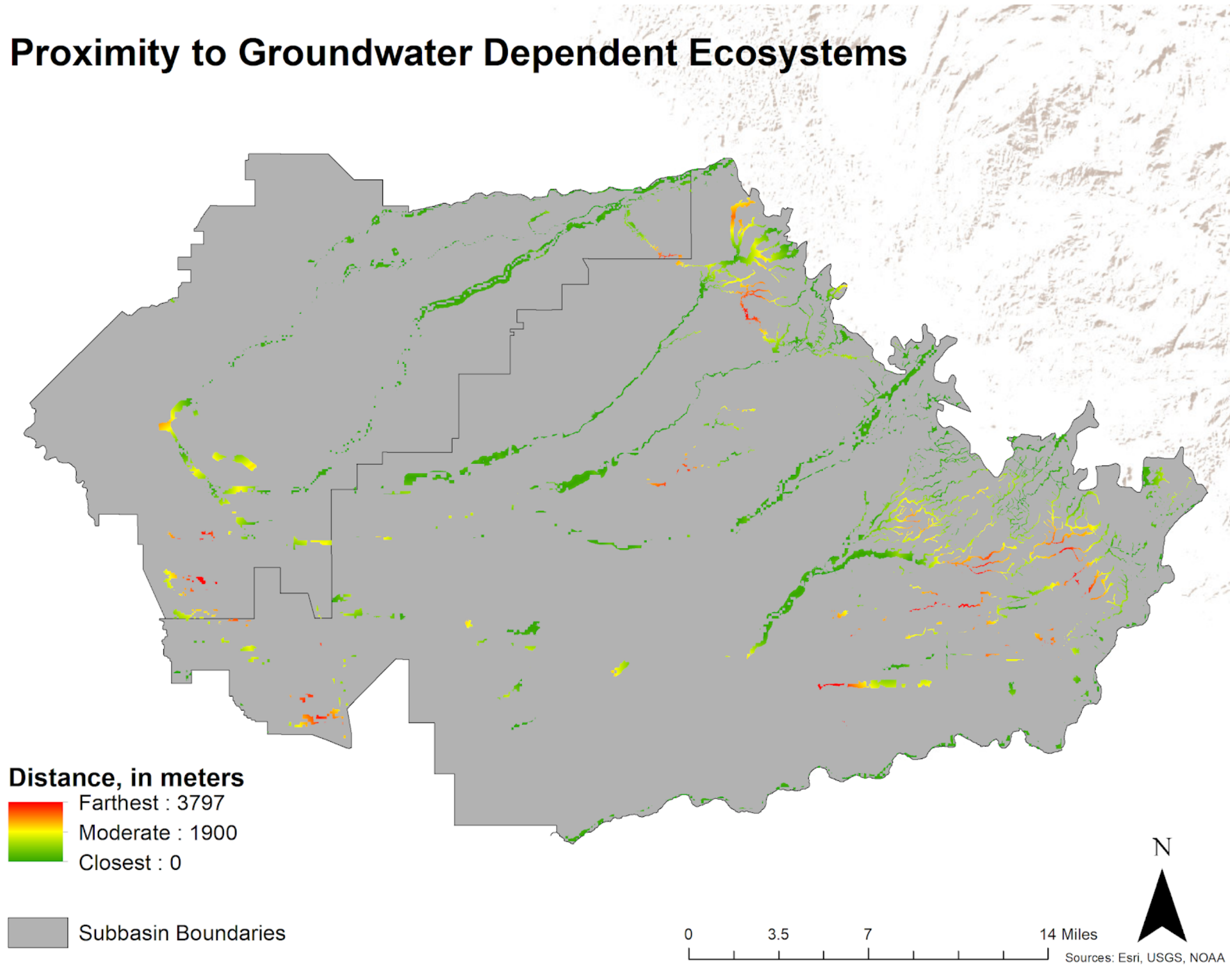


Figure 4.2-1. Distance from riparian sites of interest to TNC-defined groundwater dependent ecosystems. Darker green represents riparian areas closest to a groundwater-dependent ecosystem, yellow represents moderate proximity to a groundwater-dependent ecosystem, and red indicates farthest proximity to a groundwater dependent ecosystem. Most areas closest to groundwater-dependent ecosystems are along the major streams. Source: The Nature Conservancy's iGDE dataset.

4.2-2 Critical Habitats

The second parameter for determining priority ecosystem enhancement locations was proximity to critical habitats. The critical habitats for endangered or threatened species from the United States Fish and Wildlife Service dataset are mostly located along the northern and eastern boundaries of the study area. The results demonstrate that there are smaller distances and therefore areas of higher priority for riparian sites (in green) in the eastern portion of the Madera and Chowchilla subbasins **(Figure 4.2-2).** High priority areas were distributed across each of the major streams in the study area, all of which showed the same pattern of high priority in the east and low priority in the west. The critical habitats score was determined by reclassifying these distances on a 1 to 6 scale, with 6 being the least distance to a critical habitat and 1 being the greatest distance to a critical habitat.

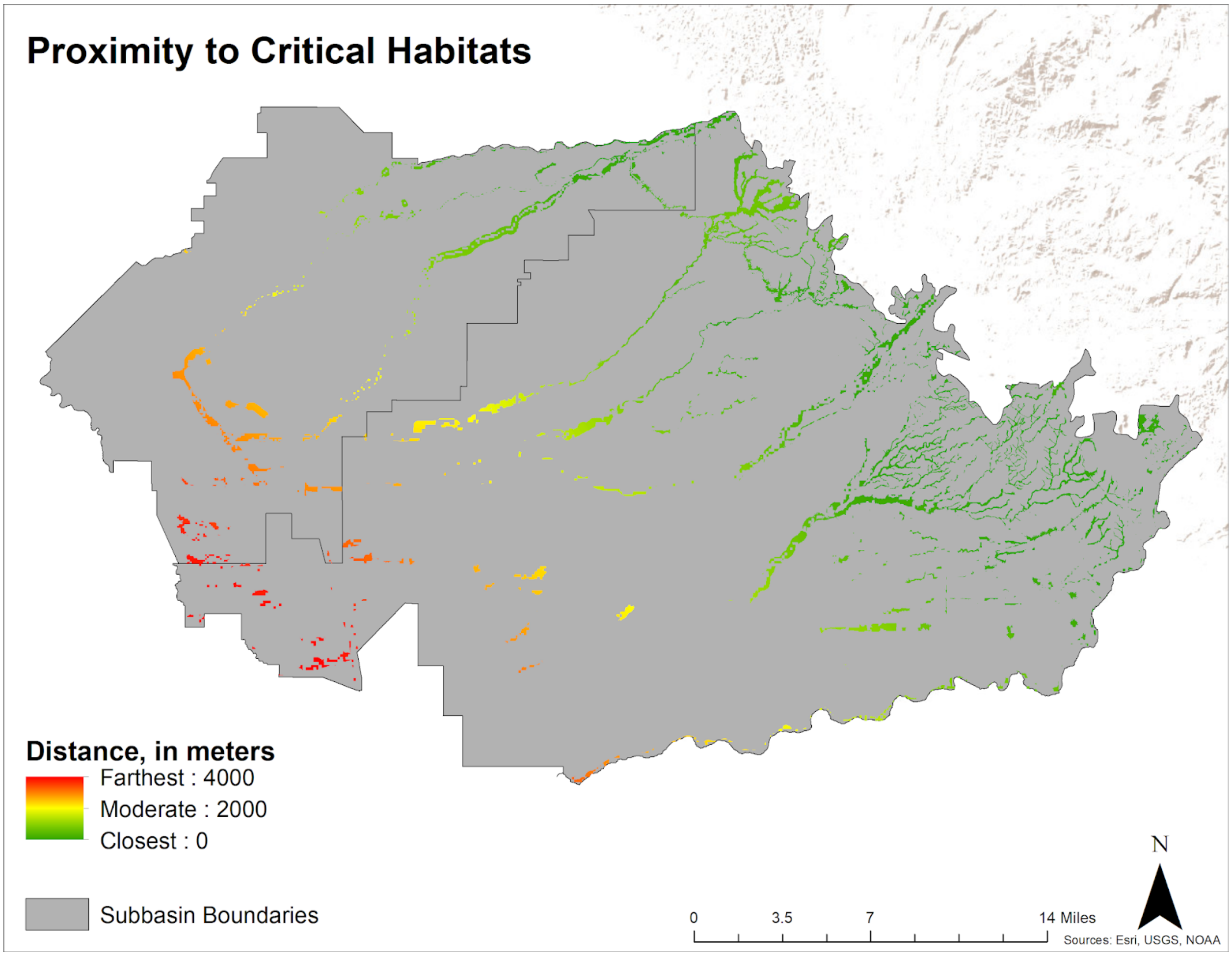


Figure 4.2-2. Distance from riparian sites of interest to critical habitats for endangered or threatened species. Green indicates riparian areas in closest proximity to critical habitats. These are the riparian areas of higher priority. Yellow indicates moderate proximity to critical habitats. Red indicates farthest proximity to critical habitats and areas of lowest priority. Source: United States Fish and Wildlife Services critical habitats for endangered or threatened species dataset.

4.2-3 Native Fish Species

The final parameter of ecosystem enhancement prioritization is the richness of native fish species present in each HUC12 watershed of the study area. The results by watershed (**Figure 3.4-3**) from the California Department of Fish and Wildlife Native Fish Species Counts Database were extracted through a mask of recharge-suitable sites within the delineated riparian buffer. The locations with the most fish species, represented in magenta, are located along the San Joaquin River at the southern boundary of Madera subbasin (**Figure 4.2-3**). The major ephemeral streams in the Chowchilla subbasin (Chowchilla River, Ash Slough, Berenda Slough) all show high species richness of native fish. These areas were given higher priority rankings for the native fish species parameter for ecosystem enhancement.

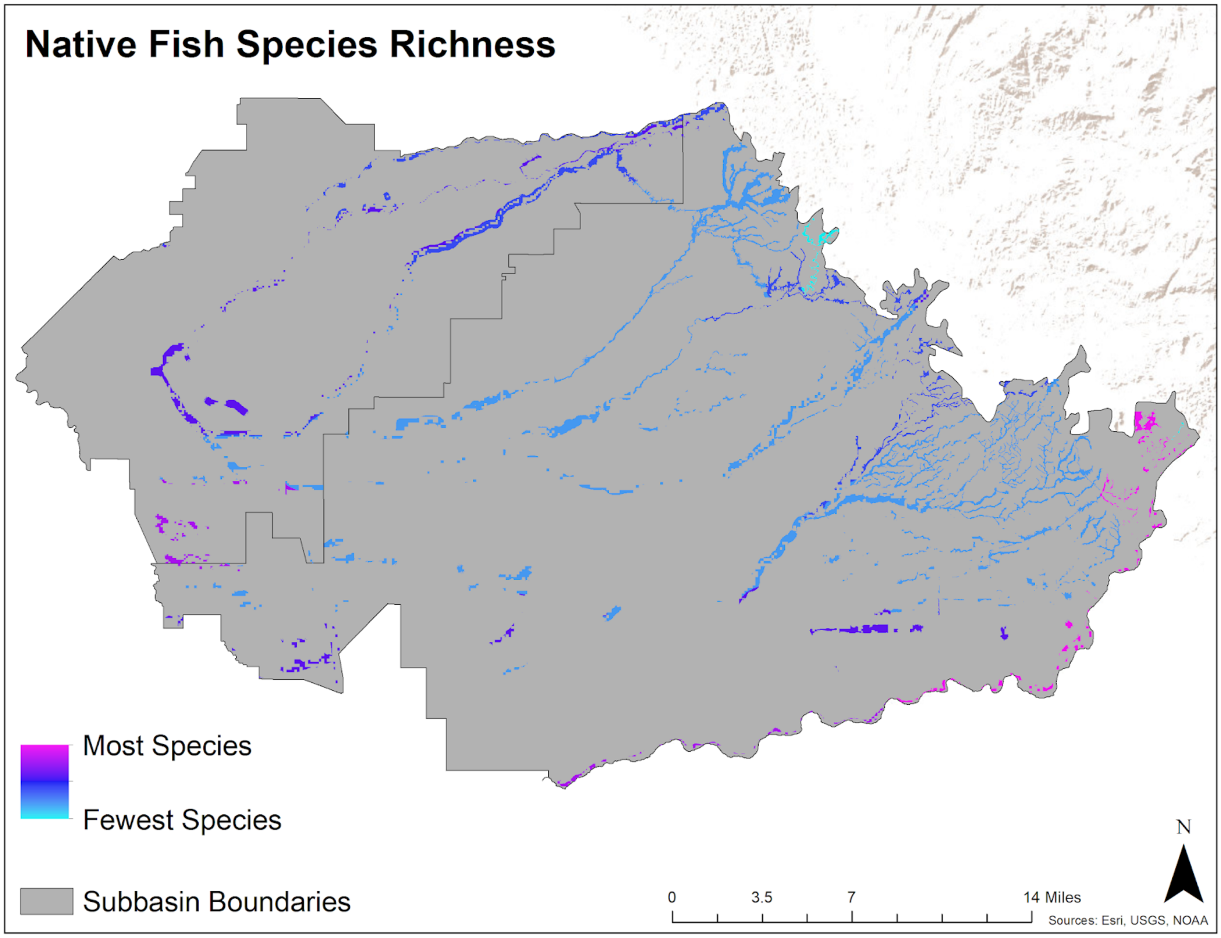


Figure 4.2-3. Results of native fish species richness for riparian areas within HUC12 watersheds. Magenta represents areas that have the most native fish species, while blue represents areas that have fewest native fish species. Areas along the San Joaquin River, and the major streams in the Chowchilla subbasin all show high species richness of native fish. Source: California Department of Fish and Wildlife Native Fish Counts Database.

4.2-4 Final Ecosystem Enhancement Priority Ranking

The three parameters for the ecosystem enhancement analysis, groundwater-dependent ecosystems, critical habitats, and native fish species, were combined with equal weighting to produce an output of priority riparian areas for achieving ecosystem enhancement benefits from groundwater recharge projects (**Figure 4.2-4**). The areas in dark blue are the higher priority and areas in yellow to light green are lower priority, but still good options for siting ecosystem enhancement projects. Much of the higher priority sites are on the northeastern end of the Chowchilla subbasin on Berenda Slough and the northernmost end of the Chowchilla River and Ash Slough. Some areas of high priority can be seen in Madera subbasin as well, on sections of the Fresno River, Cottonwood Creek, and the San Joaquin River. These locations represent the best options for achieving ecosystem enhancement benefits from groundwater recharge projects.

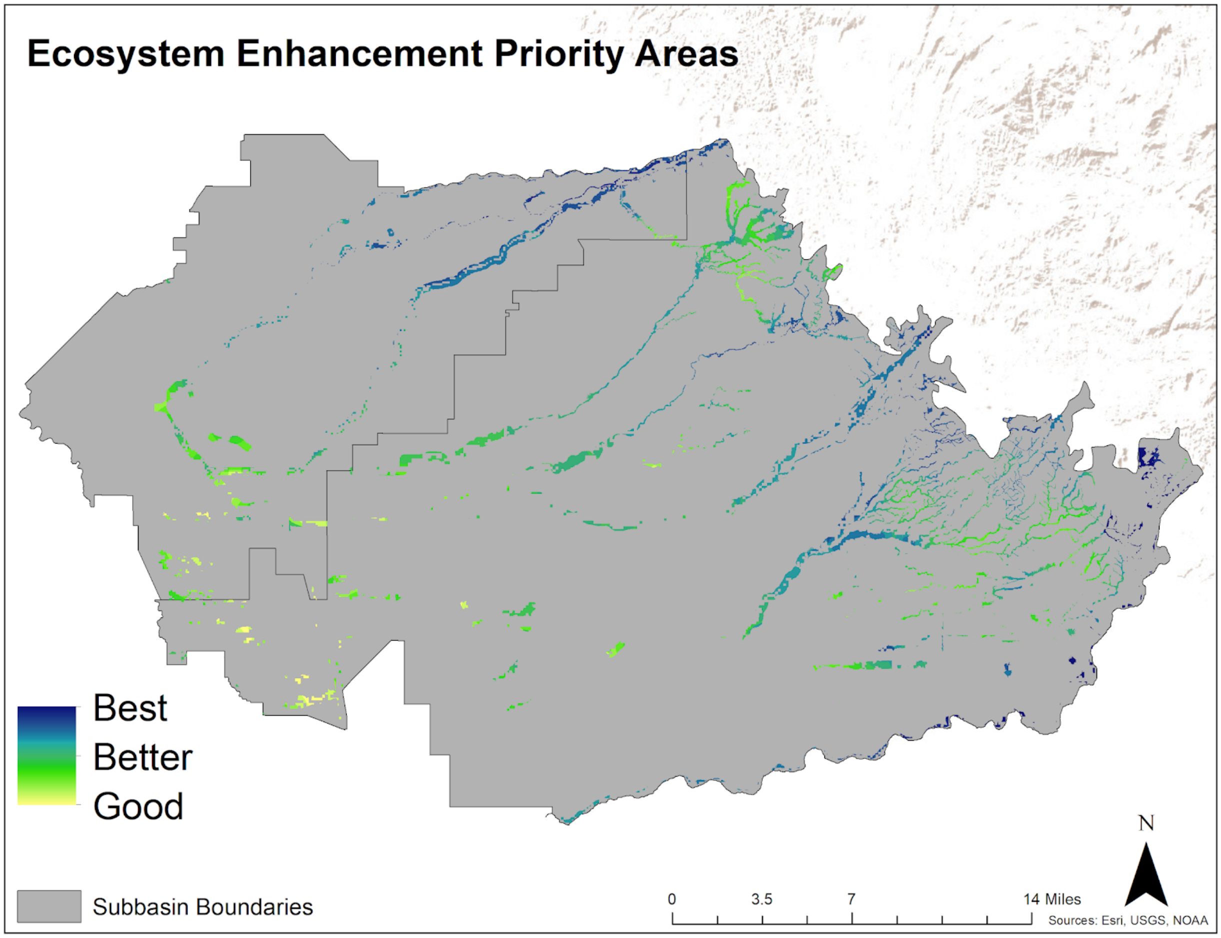


Figure 4.2-4. Final output showing the results from the ecosystem enhancement analysis. Blue represents areas that are best suited for ecosystem enhancement prioritization, green represents areas that are better suited, and yellow indicates areas that are good for ecosystem enhancement.

4.3 Site Suitability

The site suitability analysis determined which locations within the Madera and Chowchilla subbasins would be most suitable for siting groundwater recharge projects with the flood risk reduction benefit, ecosystem enhancement benefit, or both. This analysis began by taking the top 50% of land determined to be suitable for recharge by Recharge for Resilience's tool and filtering out lands that were within the 50-year floodplain riparian zone. For this reason, all sites in this analysis were considered to provide a baseline of at least some groundwater recharge benefit. The parameters of land surface slope, surface roughness, and land use type were used to determine site suitability for achieving either of the multiple benefits of groundwater recharge.

4.3-1 Recharge area

This analysis began by exploring the total amount of area that was suitable for recharge within the delineated riparian buffer of each watershed. This was not included in the final ranking analysis for the site suitability score, but was used to understand roughly which catchments provide the greatest capacity for reducing flood risk or enhancing ecosystems.

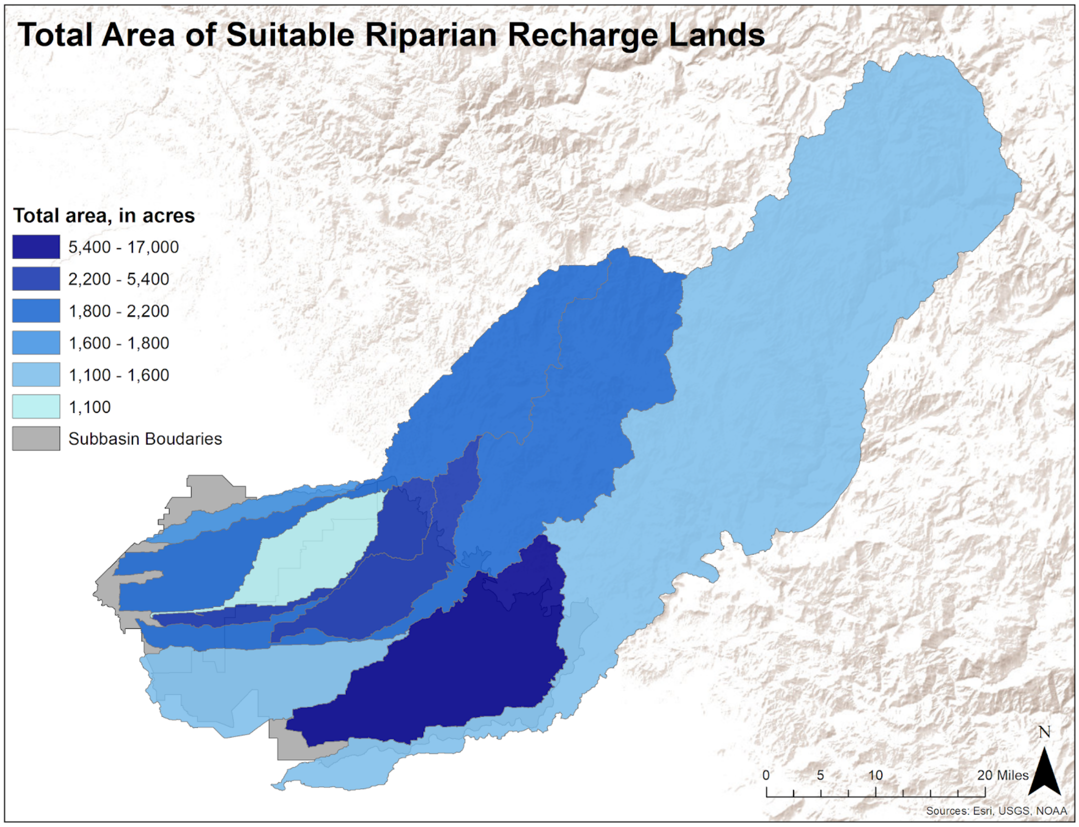


Figure 4.3-1. Total area (in acres) of land that is suitable for recharge within the delineated 50-year floodplain riparian buffer. Darker blue indicates catchment areas that are more suitable for riparian recharge, while lighter blue indicates areas that are less suitable for riparian recharge.

The results from the total area of suitable riparian recharge land (**Figure 4.3-1**) highlight Cottonwood Creek, Berenda Creek, and Dry Creek as the catchments with the most area of land that is suitable for recharge.

4.3-2 Riparian Slope

Riparian slope was calculated utilizing the 10 meter digital elevation model in ArcMAP Model Builder. Lower sloped riparian corridors tend to have more capacity to slow down and disperse flows during precipitation events. Therefore, areas with a lower riparian slope are given a higher ranking, while areas with a higher riparian slope are given a lower ranking. Prioritizing floodplain restoration in areas with lower slopes can reduce flood risk by allowing water to slow down, disperse throughout the floodplain, and infiltrate to recharge groundwater. Since Madera and Chowchilla subbasins are located on the San Joaquin Valley floor, most of its riparian areas have relatively low slope. The slope decreases moving from the east to the west across the subbasins, as the foothills of the Sierra Nevada mountains transition into valley floor (**Figure 4.3-2**). As a result, the outcome for the slope parameter shows areas with lower slope and higher suitability of slowing down flows along the western portion of the region. However, much of the suitable land for recharge has a relatively low slope as seen by the mostly blue and green riparian areas.

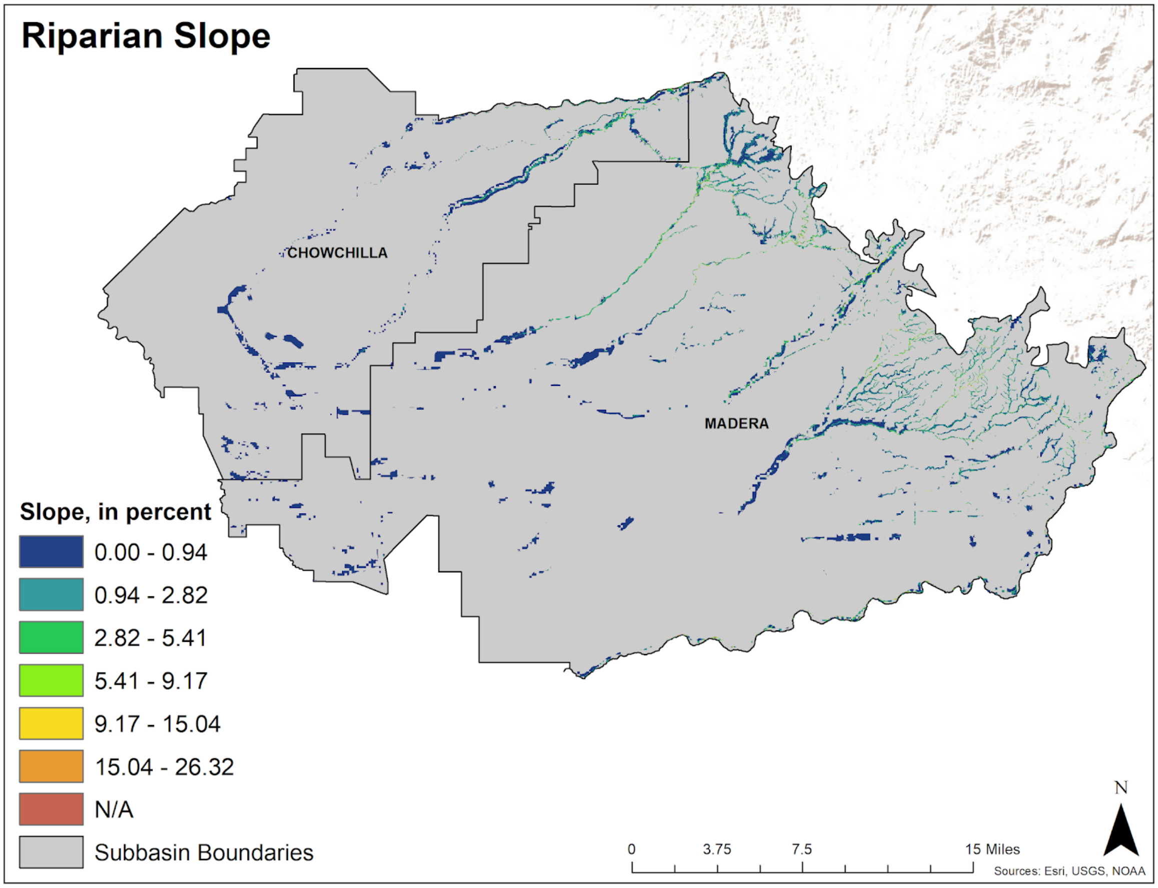


Figure 4.3-2. Values of land surface slope (in percent) for riparian areas within the study area. Less slope indicates areas that are more suitable for recharge and are shown in blue and green, while a steeper riparian slope indicates areas that are less suitable for recharge and are shown in yellow and red. The western portion of the subbasins are most suitable for recharge based on riparian slope. Source: United States Geological Survey 10 meter Digital Elevation Model.

4.3-3 Land Use Surface Roughness

The next step in the site suitability analysis was to assess land surface roughness. Land surface roughness was determined by land use type from the National Land Cover Database **(Figure 4.3-3)** (NLCD, 2016). A higher Manning's n value correlates with a higher land surface roughness and includes areas that are best suited for flood risk reduction.

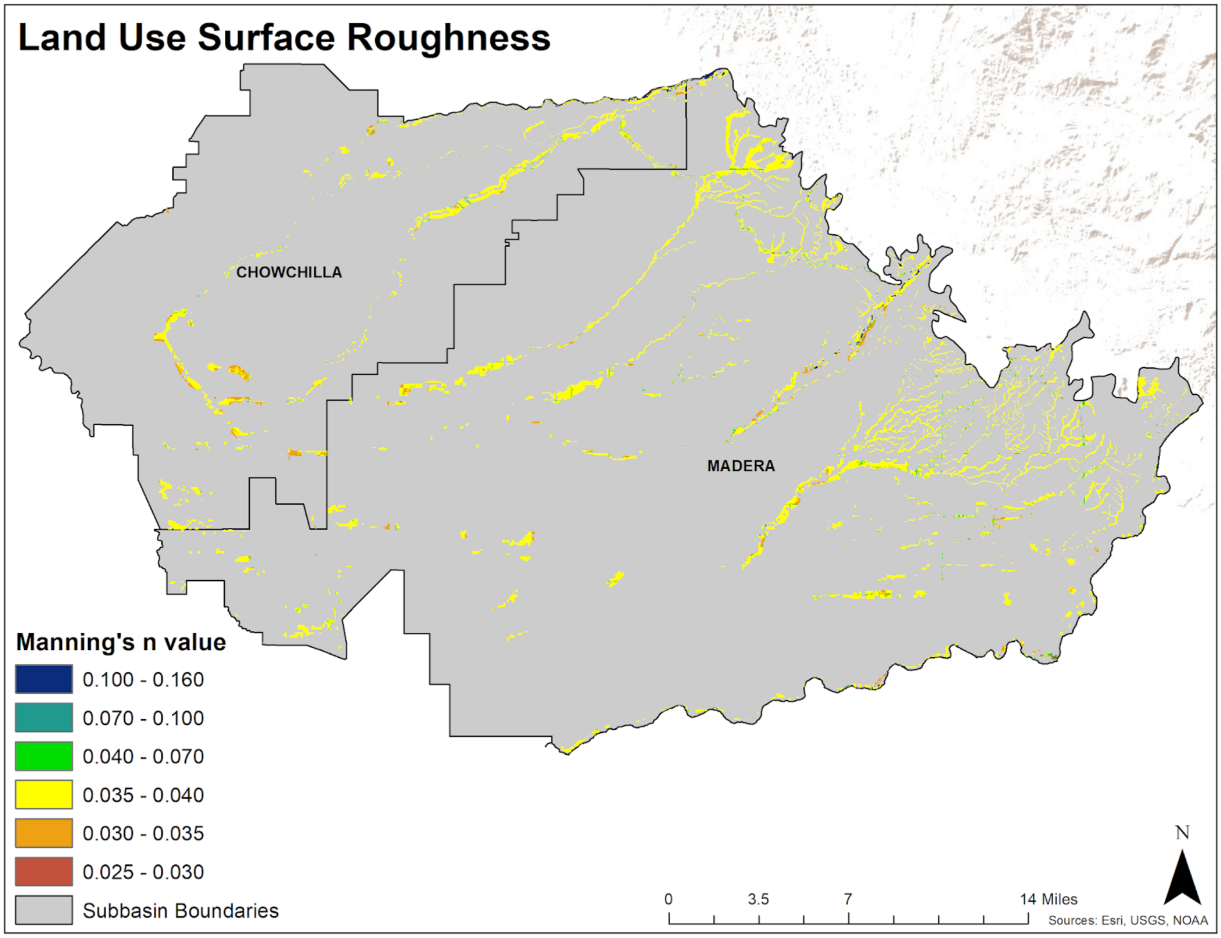


Figure 4.3-3. Manning's n coefficient of surface roughness associated with the National Land Cover Database land use type for riparian areas in the study area. Most of the land surface roughness is classified as yellow (0.035 - 0.040). Land surface roughness ranging from 0.035 - 0.040 are associated with agriculture, grassland/ herbaceous, and open space land types. Source: National Land Cover Database.

The results indicate that most of the areas suitable for recharge have a Manning's n value ranging between 0.035 to 0.040. These Manning n's values are associated with land use types ranging from agriculture (pasture/hay, cultivated crops) to grassland/herbaceous and developed open space. There are some areas with a Manning's n score ranging between a higher range of values between 0.040 to 0.070, and a lower range of values between 0.030 to 0.035.

4.3-4 Land Use Types

The final parameter for site suitability used the National Land Cover Database (NLCD), but this time used it to prioritize land use types based on the approach used in the Floodplain Restoration Opportunities Analysis report. Based on this approach, the highest priority land uses consist of natural vegetation types like grasslands and herbaceous vegetation (in blue) and shrub and scrubland (in green) (**Figure 4.3-4**). These are followed by agricultural land use types, with hay or pastureland (in green) being slightly higher priority than cultivated cropland (in yellow).

Finally, barren land (red) was prioritized the lowest. Barren land tends to be the most prevalent in the eastern, upland portion of the Madera subbasin, but land use transitions to a mix of agricultural and natural vegetation as it moves westward along the riparian zones. The riparian corridors of the major streams generally have favorable land use types, as is seen by the abundance of blues and greens in the center of each subbasin. This result helped to improve the overall suitability score of sites within the delineated riparian buffer.

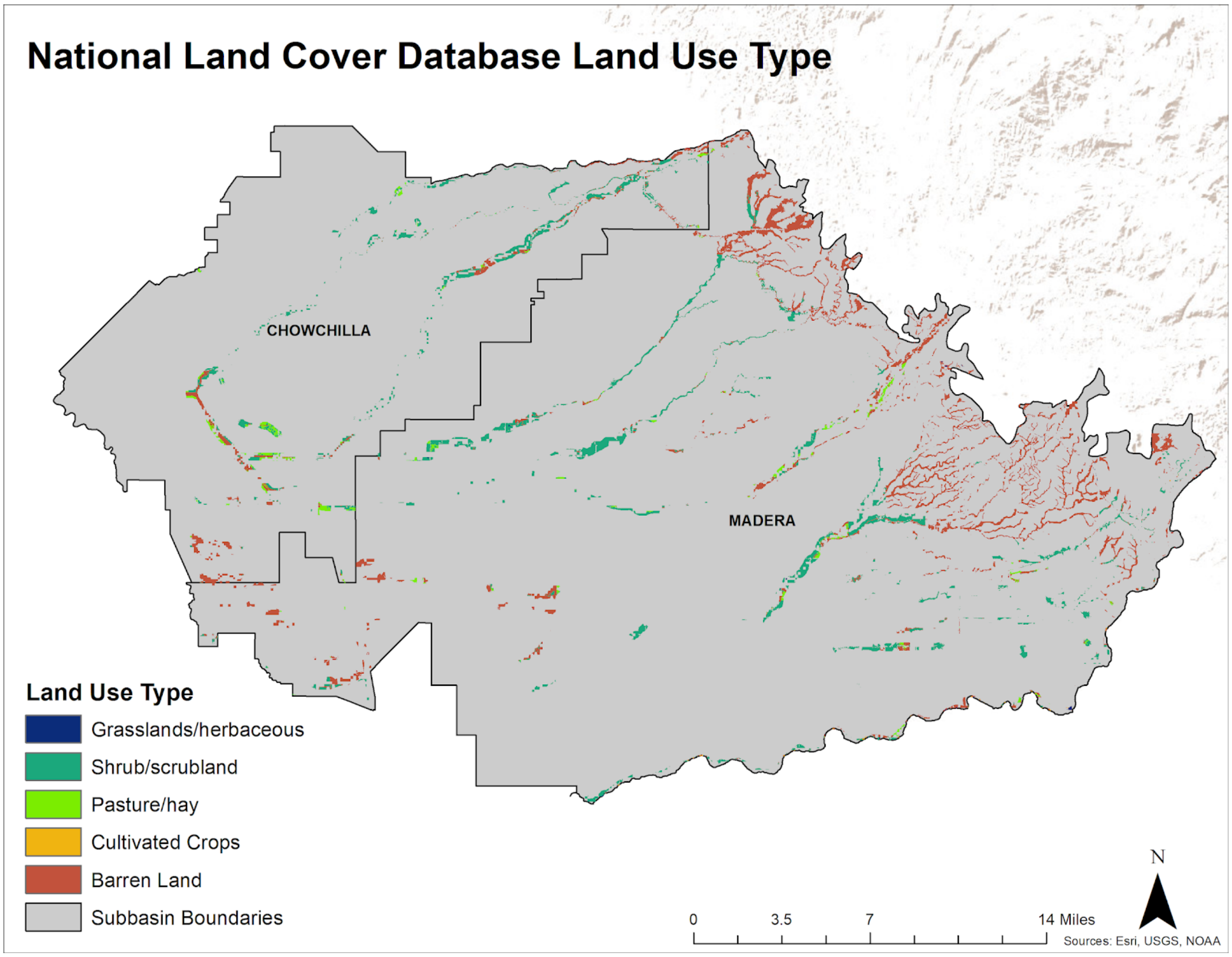


Figure 4.3-4. Spatial distribution of land use types in the study area. Land use types that are more favorable for locating recharge projects with multiple benefits were given higher priorities based on methodology found in the Floodplain Restoration Opportunity Analysis report. Natural vegetation (grasslands/herbaceous in blue and shrub/scrubland in dark green) were given highest priority, followed by agricultural land (pasture/hay in light green, cultivated crops in yellow), then barred land (in red) as lowest priority. Source: National Land Cover Database, 2016.

4.3-5 Final Site Suitability Score

Combining the three parameters of slope, surface roughness, and land use type produced the final output for site suitability (**Figure 4.3-5**). The most suitable sites are in dark blue and the least suitable sites are in light blue. Since slope was given the most weighting when combining scores, a similar trend of increasing priority moving from the east to the west across the basin can be seen in the final site suitability output. This is because the topography flattens even more towards the west end of the basins. The areas of highest priority can be found in the center of each subbasin, where large dark blue portions of the major streams and tributaries are present (**Figure 4.3-5)**. Specifically, portions of Ash Slough, Berenda Creek, Dry Creek, Fresno River, and Cottonwood Creek all provide highly suitable land for locating groundwater recharge projects with either the flood risk reduction or ecosystem enhancement co-benefits.

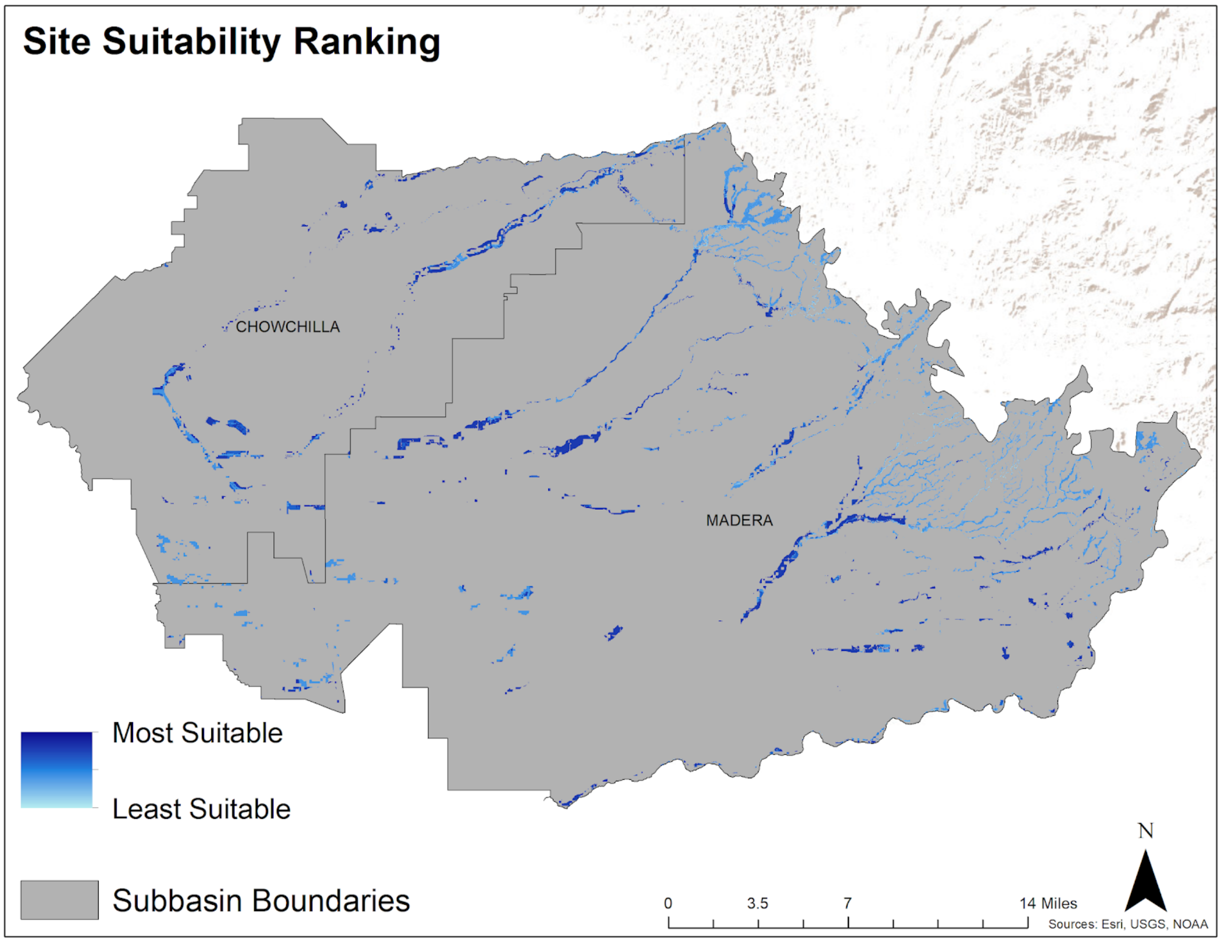


Figure 4.3-5. The final output for site suitability for Madera and Chowchilla subbasins. Results for the site suitability final output were produced by combining the slope, surface roughness, and land use type scores using a weighted sum. The slope score was given a higher weighting than the other parameters due to its relative importance to a site's ability to slow down and capture flows. Sites in darker blue are more suitable for multiple-benefit recharge than those in lighter blue.

4.4 Final Results

The outcomes from analyses of the two co-benefits of groundwater recharge projects - flood risk reduction and ecosystems enhancement - were combined with each other and then with the results from the site suitability analysis. This produced a final output with priority rankings for locating groundwater recharge projects which consider any combination of the two co-benefits.

A sample of one such output, as seen below, is where the tradeoff between flood risk and ecosystems was set to an equal preference for both (e.g. both co-benefits weighted as 0.5 when combining scores) (**Figure 4.4**). In this sample, large sections of the highest priority areas (dark blue) can be along Cottonwood Creek and Fresno River in the central and eastern portions of Madera subbasin. These high priority areas are locations where groundwater recharge projects are best suited to achieve an equal mix of both flood risk reduction and ecosystem enhancement co-benefits. Final outputs look similar to this one, but differ depending on the preferences set for the tradeoff between flood risk reduction and ecosystem enhancement benefits. This project conducted a tradeoff analysis to determine how the final results change based on different potential stakeholder preferences. The results of the tradeoff analysis are discussed in **Section 6** of this report.

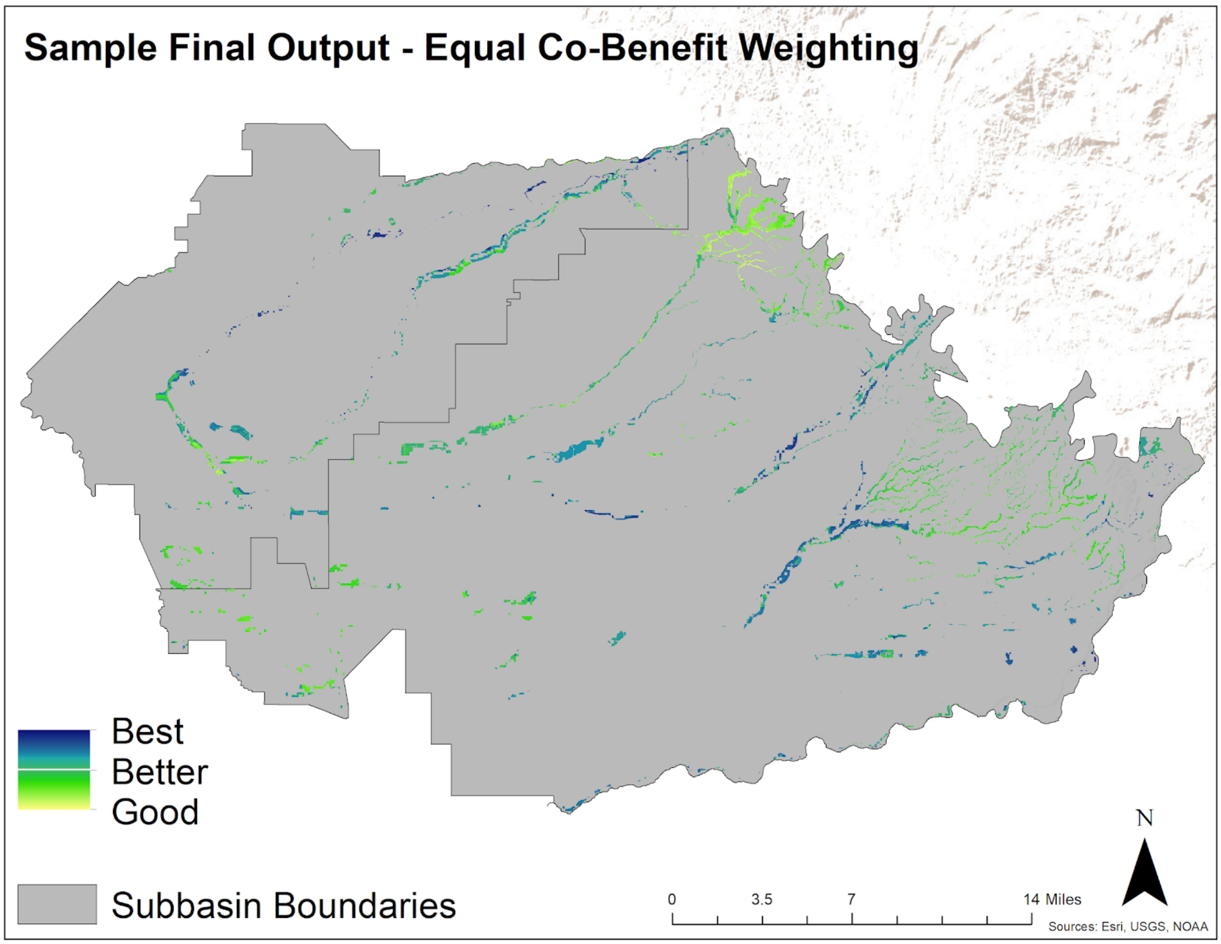


Figure 4.4. **Sample of final priority output under scenario where tradeoff between flood risk reduction and ecosystem enhancement co-benefits are weighted equally.** This output provides a spatial distribution of priority sites for locating groundwater recharge projects that can equally achieve both co-benefits. The weighting between co-benefits can be altered based on user preferences to produce different final outputs with different distributions of priority sites.

5. Sensitivity Analysis

After completing the flood risk reduction, ecosystem enhancement, and site suitability analyses and combining results into a final output, this project sought to test the sensitivity of those results to changes in input parameters. A sensitivity analysis was performed to understand how final priority locations for multiple-benefit recharge projects would change if the input variables for the floods or ecosystems analyses were given different weighting factors.

5.1 Sensitivity Analysis Methods

For the sensitivity analysis, each of the input variables for flood risk and ecosystem enhancement were isolated and assigned different relative weightings to test how the final outputs change. There were a total of eight input parameters between the two analyses: FEMA flood hazard layer, fire hazard, disadvantaged communities, watershed area, levee failures, groundwater-dependent ecosystems, critical habitats, and native fish species richness. For each parameter, an iteration of sensitivity analysis was conducted in which the relative weighting of that parameter was set at either 0.00 or 1.00, and all other parameters of that analysis were adjusted accordingly. For example, the fire hazard parameter weight would be set at 0.00 in one iteration, and the remaining four parameters of flood risk would be adjusted to 0.25 each. In the next iteration, the fire hazard weighting would be set to 1.00 and the rest of the flood risk parameters would be changed to 0. If a flood risk parameter were altered in a given iteration, only the weightings of the other flood risk parameters would be adjusted and all ecosystem parameters would remain their original weighting, and vice versa. With the new weightings assigned for each iteration, the rest of the analysis was conducted as usual, with site suitability and tradeoff analyses held constant across all iterations. The tradeoff analysis was set at 50-50 weighting between flood risk and ecosystems for the sensitivity analysis.

Using this method, 16 iterations of sensitivity analysis were conducted - two (a maximum and minimum weighting) for each of the eight input parameters. This was done to test how the most extreme possible alterations to each parameter would impact final priority results. The final spatial distribution of priority locations produced by each iteration in ArcGIS were downloaded and transferred to RStudio to complete the second half of the sensitivity analysis. In RStudio, the rasters for each iteration were assigned a value for each 20 meter by 20 meter grid cell, based on whether that cell was considered "high priority" in a given iteration. The threshold for determining "high priority" was set at a final priority score of four or higher (out of a possible six). High priority cells were assigned a value of 1 and other grid cells were assigned a 0. The rasters for each of the 16 iterations were then stacked and, for each grid cell, a sum was taken across all iterations. The result was a final value of 0 to 16 for every raster cell which represents the amount of times that cell would result in a "high priority" site across all iterations of the sensitivity analysis. For example, a cell with a value of 14 means that it received a final priority score greater than four in 14 out of 16 iterations. Cells with higher values in the sensitivity analysis results are those that are more resilient to changes in input weighting.

5.2 Sensitivity Analysis Results

The results of the sensitivity analysis provide insight into which sites are consistently prioritized highly for multiple-benefit recharge projects. Locations that resulted in a “high priority” score more often across iterations of the sensitivity analysis are those that are better suited for locating recharge projects with the flood risk or ecosystem enhancement co-benefit. This is because those sites have been demonstrated to remain high priority regardless of changes in input parameter weighting. This alleviates potential discrepancies that may exist between the framework’s assigned weighting factors and the relative importance of each parameter in real life applications of this analysis.

The results of the sensitivity analysis show the spatial distribution of sites in Madera and Chowchilla Subbasins with their value for the number of iterations in which those sites are considered high priority. Those that are frequently high priority are in light or dark green and those that are infrequently high priority are in red or orange (**Figure 5.2a**). Sites with a value at or near 16 should be prioritized first when locating multiple-benefit recharge projects, as they are the most resilient to possible differences in input parameters. Many of these sites can be seen along sections of Cottonwood Creek, Fresno River, Dry Creek, and Berenda Slough. The top 20% of sites based on their sensitivity analysis results can provide a valuable starting point for water managers when making decisions on where to implement multiple benefit recharge (**Figure 5.2b**).

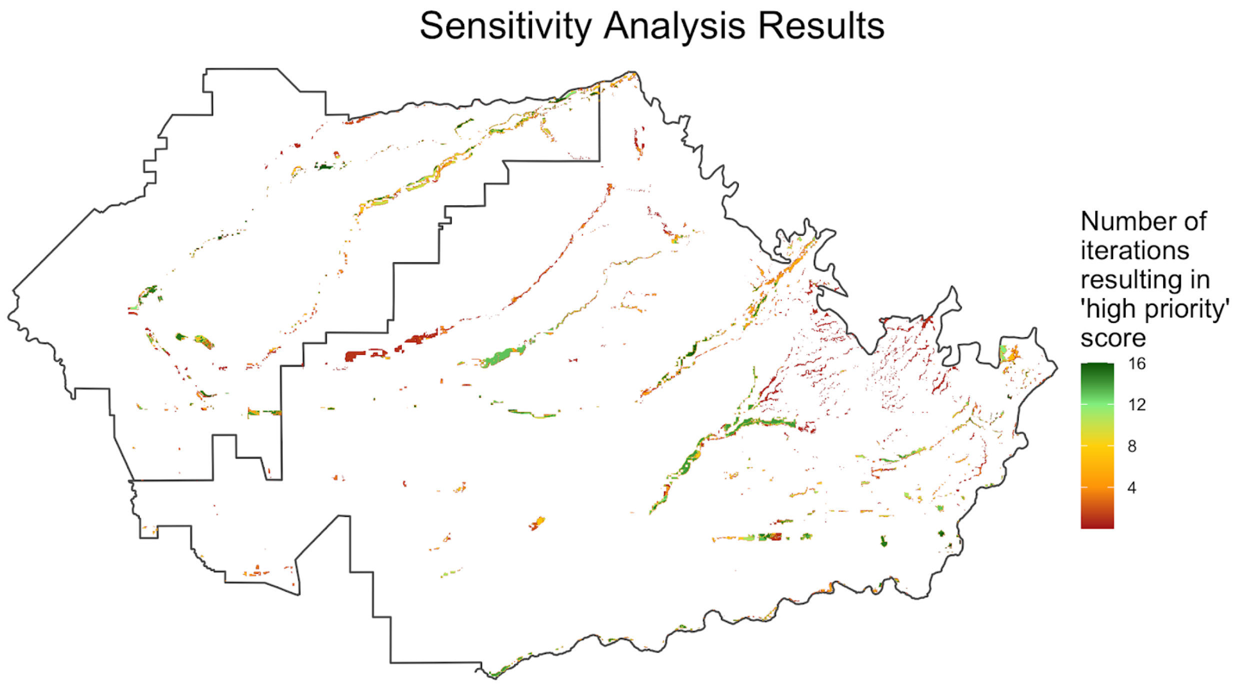


Figure 5.2a - Results showing the count of times each grid cell would appear as a high priority site across the 16 iterations of sensitivity analysis. For every iteration, the weighting of a given input parameter for the flood risk or ecosystems analyses was changed. The sites that consistently showed up as "high priority" no matter how the input parameters were changed are in dark green.

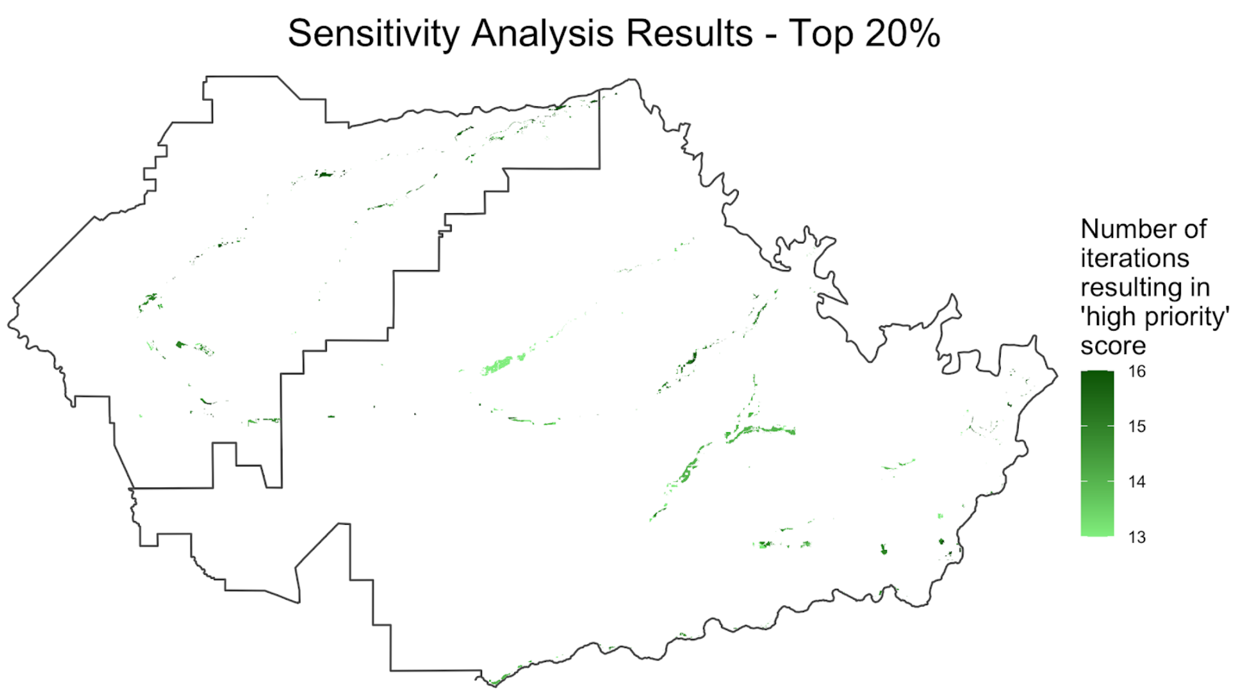


Figure 5.2b - The top 20% of sites from the sensitivity analysis results. The locations that scored in the top 20% for how often they appeared as "high priority" sites in the 16 sensitivity analysis iterations. Changes in the weighting

of input parameters either do not alter or only slightly alter their priority for locating multiple benefit groundwater recharge projects.

The sensitivity analysis serves to strengthen the final results found from combining flood risk, ecosystems, and site suitability analyses. It helps to justify the choices made when assigning weighting factors to each of the eight input parameters for flood risk reduction and ecosystem enhancement. It also helps managers make more-informed decisions regarding where to locate multiple-benefit groundwater recharge projects. Managers may have differing opinions on how they would weigh certain parameters relative to others, and this analysis helps resolve potential conflicts that may arise as a result. The combination of sensitivity analysis and tradeoff analysis (discussed in **Section 6.2**) provide several sets of definitive locations to prioritize first regardless of the perceived real-life importance of input parameters or potential management preferences.

6. Discussion

6.1 Total Suitable Area

The total area of riparian land that is suited for multiple benefit aquifer recharge is roughly 14,939 acres. This amount of land is just above 3% of the total land area comprising both Chowchilla and Madera groundwater subbasins. Given that further investigation into these suitable lands is required, and that floodplain restoration requires capital investment from water managers, it is unlikely that all of this area can be utilized as natural recharge infrastructure. Furthermore, it was calculated from the National Hydrography Dataset that the vast majority of the streams and rivers in the area, 97 percent, are intermittent or ephemeral and only flow seasonally. The remaining 3 percent of waterways are larger, perennial rivers. Understanding when and where water will be available for recharge, whether that is seasonally from precipitation events or planned from reservoir operations, will be critical for managers to narrow down site selection for riparian and floodplain restoration.

6.2 Tradeoff Analysis

The analysis and methods detailed in this report look at three aspects of location prioritization for riparian recharge projects: 1) areas that are most prone to flood events, 2) areas that are of high priority for enhancing riparian ecosystems, and 3) areas located along riparian corridors that are most physically suitable for inundation with the goal of multiple benefit aquifer recharge. It is important to understand and consider how the spatial distribution of priority sites changes based on the different enabling conditions of each co-benefit. The results from synthesizing these inputs are influenced by the weighting factor assigned to each co-benefit: flood risk reduction and ecosystem enhancement. The relative weighting of the two co-benefits reflects the tradeoff that managers may have to consider when making decisions on where to locate groundwater recharge projects. As part of a tradeoff analysis, the two co-benefits of flood risk and ecosystem enhancement results were assigned various weighting factors based on different potential management scenarios, and the results from the site suitability were always given constant weighting. Given the possibility of varying water management goals among stakeholders, three specific scenarios were considered to show how the tradeoff between co-benefits impacted final project location prioritization results. For the following scenarios, the top 10 largest and contiguous areas of high priority riparian recharge lands are highlighted based on variable input weighting. Land ownership and project implementation feasibility are not considered in location prioritization.

6.2-1 Flood Risk Reduction Scenario

The first scenario considers the notion that Madera County is vulnerable to flood risk, and with the threat of more severe storm events due to climate change, stakeholders may want to only look at riparian areas that can reduce flood risk downstream by slowing down flows and reducing strain on existing flood control infrastructure. This scenario assigns 100% of the variable weighting to flood risk reduction score and 0% of the variable weighting to ecosystem enhancement score. The result shows the locations of riparian areas that are high priority for reducing local flood risk with groundwater recharge projects. The largest contiguous areas containing these high priority sites are capable of achieving the greatest flood risk reduction benefit (**Figure 6.2-1a**). The top 3 locations, all of which fall along segments of Cottonwood Creek, are highlighted below (**Figure 6.2-1b**).

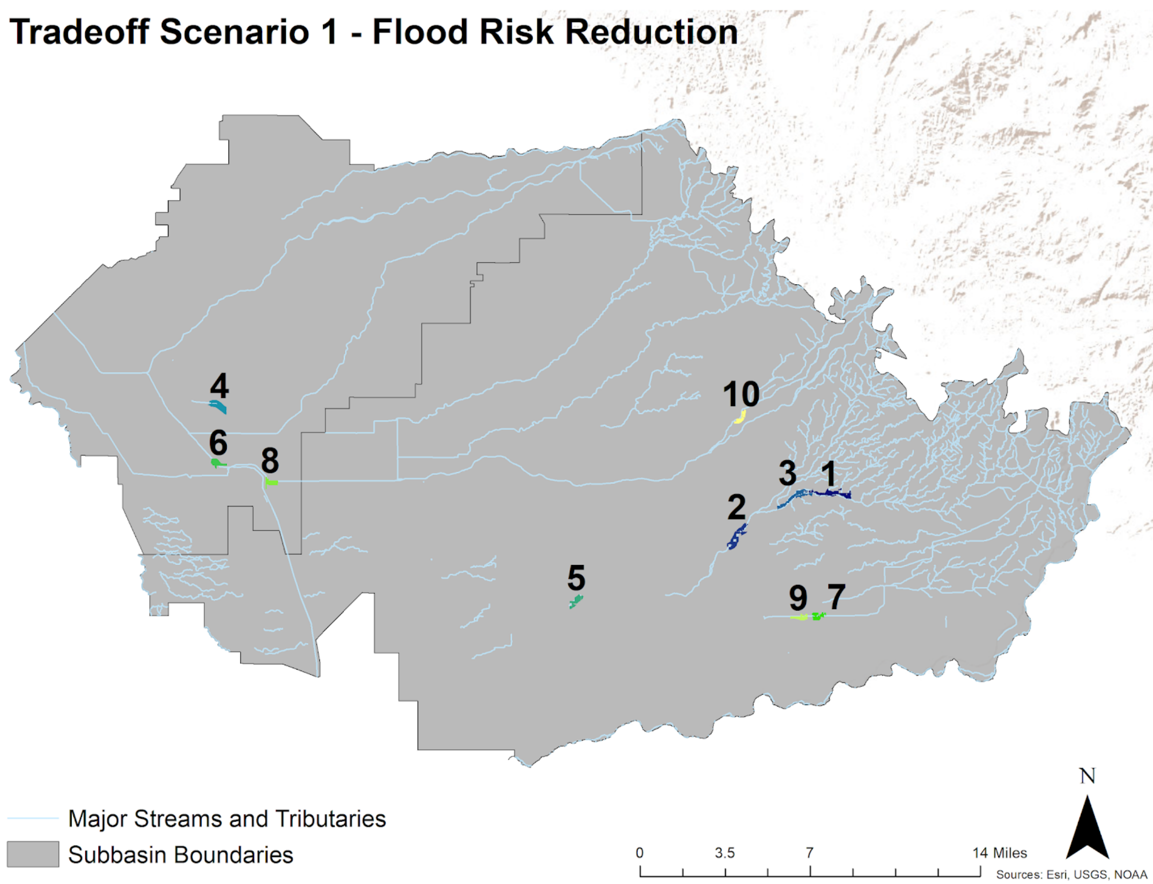


Figure 6.2-1a - Top 10 largest contiguous sites for achieving the co-benefit of flood risk reduction with groundwater recharge projects. To produce these results, the relative weighting of the co-benefits was set to 100% flood risk and 0% ecosystem enhancement. Each of these sites received a final prioritization score greater than 4 (out of 6), which was the threshold for determining a "high priority" site. The sites are ranked by largest contiguous areas of high priority.

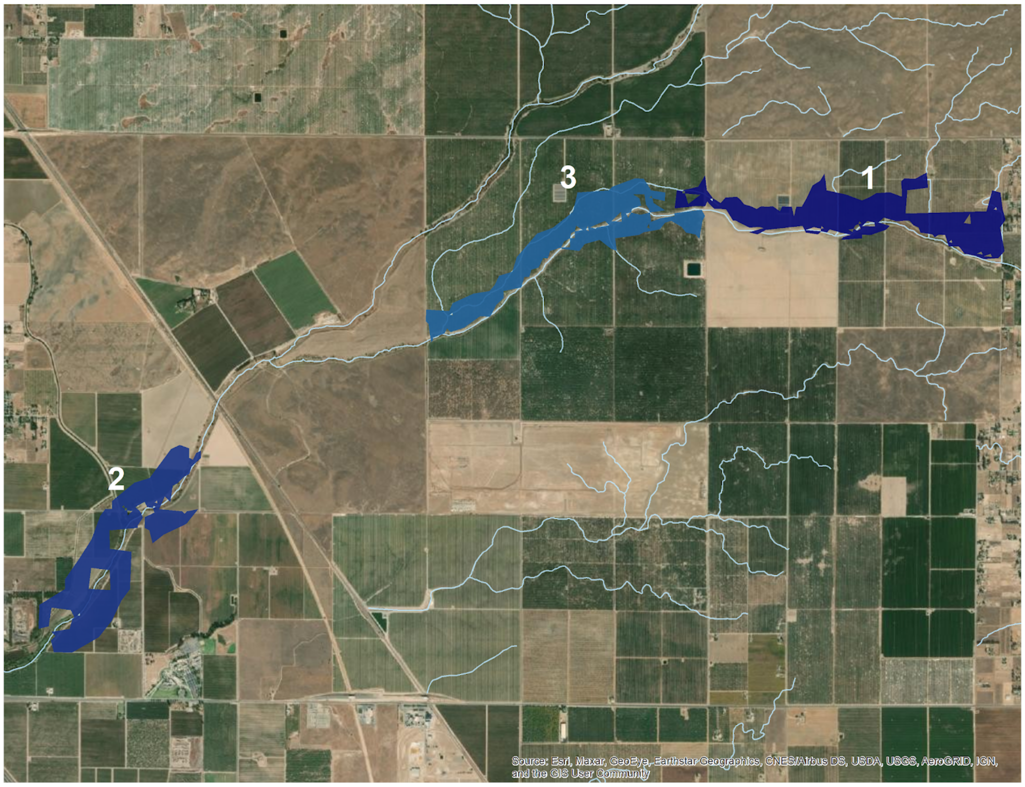


Figure 6.2-1b - Aerial view of the top three largest contiguous sites of high priority for flood risk reduction co-benefit. All of the sites are located along Cottonwood Creek, in what appears to be a highly agricultural part of Madera subbasin. Water managers may want to consider these sites first for their ability to achieve the greatest amount of flood risk reduction with groundwater recharge.

In this scenario, the top 10 locations are areas that water managers should consider if their goal is to implement recharge projects that reduce local flood risk. These areas, which make up a total of 1107 acres of land, should be supplemental to other flood control infrastructure and best management practices.

6.2-2 Ecosystem Enhancement Scenario

The next scenario considers stakeholders who may be interested in the ecological benefits of groundwater recharge through floodplain expansion and riparian restoration projects. This scenario may help environmental nonprofits, land and water trusts, and private landowners identify areas that are highest priority for restoring and enhancing ecosystems. This management scenario assigns 100% of the variable weighting to ecosystem enhancement score and 0% of the weighting to flood risk reduction score. The result shows the locations of riparian areas that are high priority for enhancing riparian and wetland ecosystems with groundwater recharge projects. The largest contiguous areas containing these high priority sites are capable of achieving the greatest ecosystem enhancement benefit (**Figure 6.2-2a**). A cluster of highly suitable areas for ecosystem enhancement exists along the Chowchilla River, Berenda Slough, and Ash Slough (**Figure 6.2-2b**).

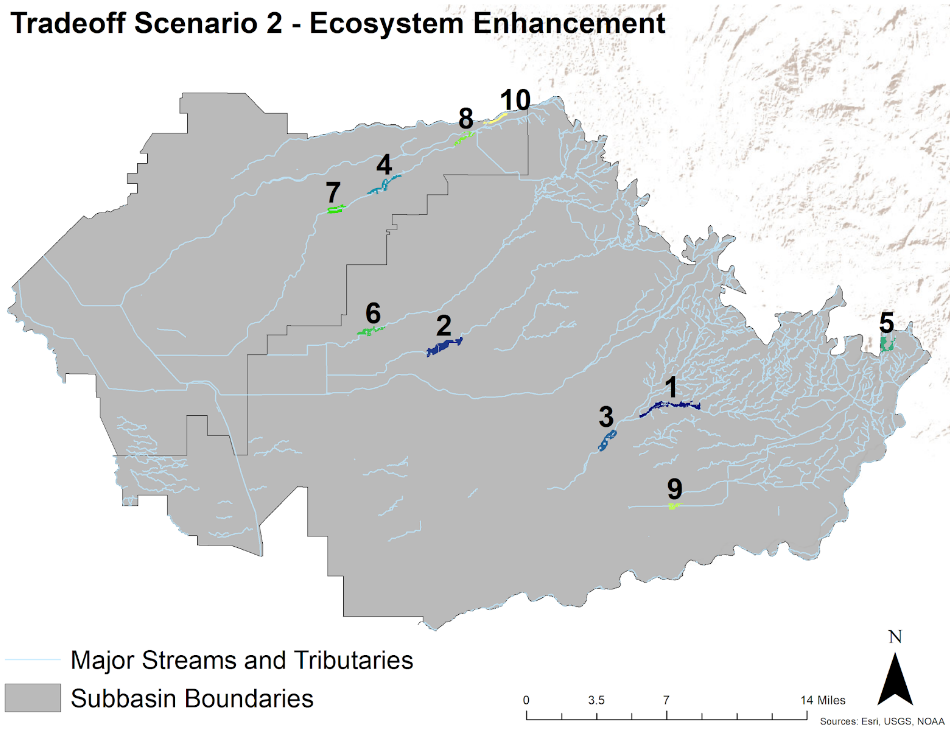


Figure 6.2-2a - The top 10 largest contiguous sites for achieving the co-benefit of ecosystem enhancement with groundwater recharge projects. To produce these results, the relative weighting of the co-benefits was set to 100% ecosystem enhancement and 0% flood risk. Each of these sites received a final prioritization score greater than 4 (out of 6), which was the threshold for determining a "high priority" site. The sites are ranked by largest contiguous areas of high priority.

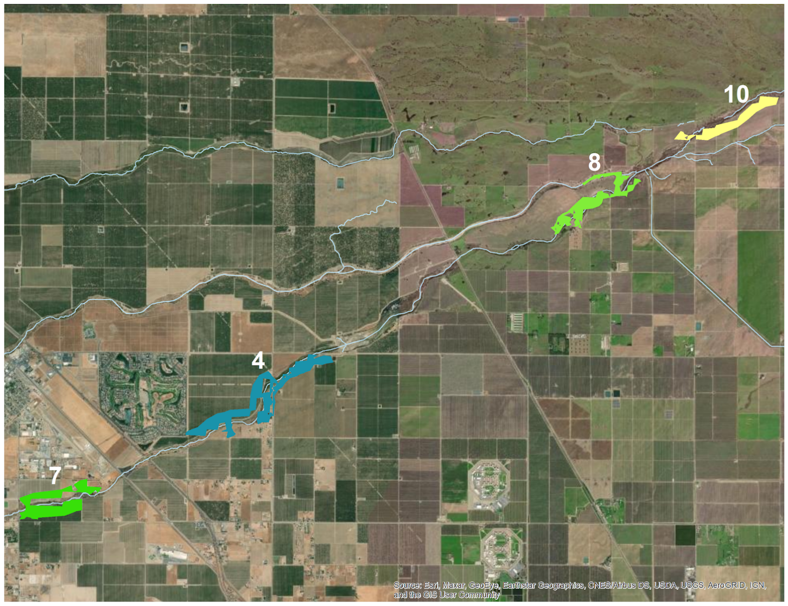


Figure 6.2-2b - Aerial view of the four of the largest contiguous sites of high priority for ecosystem enhancement co-benefit. These sites are located along upstream portions of the Chowchilla River, Berenda Slough and Ash Slough. Water managers may want to consider these sites first for their ability to achieve the greatest amount of ecosystem enhancement with groundwater recharge.

In this scenario, the top 10 locations are the areas that should be investigated first if management goals are to recharge groundwater in conjunction with riparian habitat reconciliation. These areas can provide the greatest ecological enhancement from recharge efforts and natural inundation. It is important to consider that inundation along the Chowchilla River, the Fresno River, and the San Joaquin River will likely be through reservoir operations, in which water is released from upstream dams during or ahead of anticipated precipitation events. The other rivers and streams in the area of study are not below major storage infrastructure and will likely rely on natural flow regimes and precipitation in order to inundate suitable riparian areas.

6.2-3 Multiple Benefit Scenario

The final scenario considers the possibility that water managers may have one goal in mind: implement groundwater recharge projects with as many co-benefits as possible. This scenario assigns equal weighting to both the flood risk reduction score and the ecosystem enhancement score to determine which areas are best suited to achieve both benefits while at the same time recharge groundwater. While this scenario is aimed at achieving both co-benefits, these areas are not the optimal locations for maximizing either flood risk reduction benefits or ecosystem enhancement benefits. The results show the locations of riparian areas that are high priority for achieving both flood risk reduction and ecosystems recharge with groundwater recharge projects. The top 10 largest contiguous areas containing these high priority sites are those that have the greatest capacity for achieving an equal amount of both co-benefits (**Figure 6.2-3a**). A cluster of 7 of the 10 largest contiguous suitable areas are located in the central Madera subbasin along Dry Creek, Fresno River, and Cottonwood Creek (**Figure 6.2-3b**).

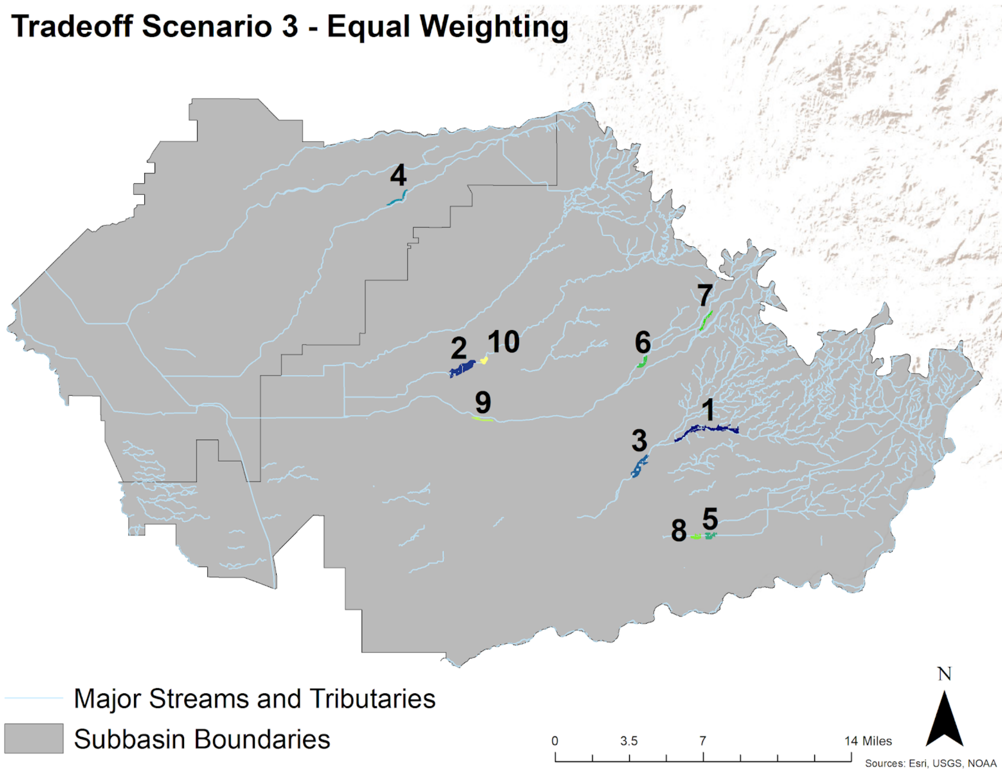


Figure 6.2-3a - The top 10 largest contiguous sites for achieving both flood risk reduction and ecosystem enhancement benefits equally. To produce these results, the relative weighting of the co-benefits was set to 50% ecosystem enhancement and 50% flood risk. Each of these sites received a final prioritization score greater than 4 (out of 6), which was the threshold for determining a "high priority" site. The sites are ranked by largest contiguous areas of high priority.

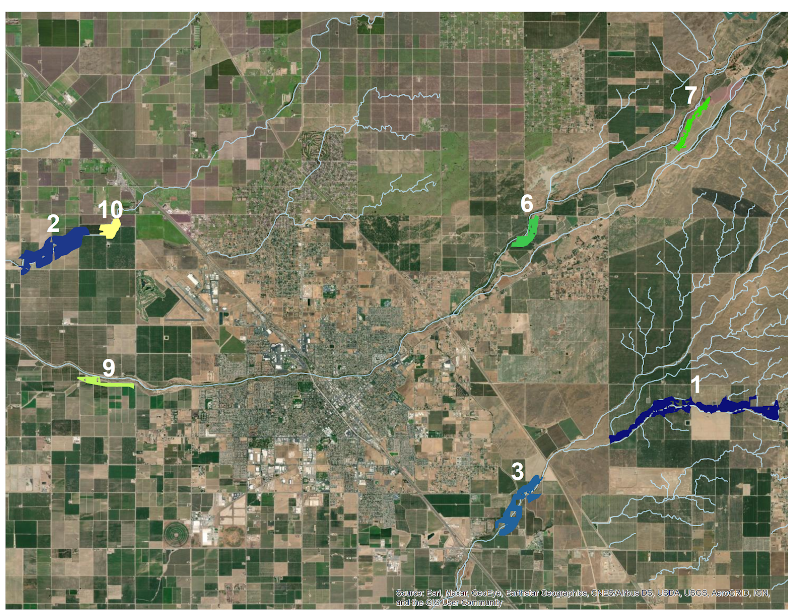


Figure 6.2-3b - Aerial view of several of the largest contiguous sites of high priority for achieving both flood risk and ecosystem enhancement co-benefits equally. These sites are located in central Madera subbasin, along

portions of Dry Creek, Fresno River, and Cottonwood Creek. Water managers may want to consider these sites first for their ability to achieve both co-benefits of groundwater recharge projects.

In this multiple benefit scenario, these are the areas to be explored first as natural riparian infrastructure for groundwater recharge projects. This equal weighting scenario is likely appealing to GSAs and other water managers as it satisfies the potential interests of a variety of stakeholders. With limited funding, water, and land available for floodplain expansion and recharge efforts, optimizing opportunities to include as many auxiliary benefits as possible is a valuable strategy.

7. Limitations

Our analysis utilized publicly available datasets from research institutions and government agencies. Some of the data contained in the analysis has inherent uncertainties. Additionally, there are several limitations within the analysis that led us to make a number of assumptions.

7.1 Data Limitations and Assumptions

7.1.1 2D Hydraulic Modeling

Much of the project's analysis would have been improved with more accurate and detailed 2D hydraulic modeling. However, due to time constraints hydraulic modeling was not incorporated into the analysis. Without 2D hydraulic modeling, it is not possible to accurately incorporate dams and levee influences on water flow, movement, and extent of inundation. Although many rivers in the catchments have dams and levees that impair the natural flow of water, this project assumes unimpaired flows, even flow of water throughout the watershed, and even distribution of precipitation throughout the catchments. Additionally, 2D hydraulic modeling would allow for more accurate analysis of slope, direction, and roughness. The lack of 2D modeling led us to find alternative methods that required making additional assumptions.

7.1.2 Stream Gauge and Precipitation Data

Our flood risk analysis utilizes the watershed catchment area as a proxy for discharge calculations due to the limited weather station and stream flow stations in Madera County. The California Irrigation Management Information Systems (CIMIS) operates only one weather station within Madera County. This only provides accurate precipitation data for the city of Madera. Precipitation is assumed to be distributed equally throughout each watershed. However, precipitation varies substantially from one location to another, especially with changes in land use, topography, and elevation. Without the ability to measure precipitation data in a variety of different locations throughout Madera County, it was not possible to make an accurate analysis regarding the nine catchments abilities to capture, store, and maneuver water.

Stream flow data was also limited in Madera County both spatially and temporally. Gauges that recorded stream discharge were found at limited sites and had a limited number of years on record. Therefore, it was assumed that a larger catchment area equates to a greater potential to capture more precipitation and contributes to more extreme flows that could lead to flooding events. However, if more streamflow data were available, it would have been possible to make a more accurate analysis of the different runoff scenarios within each catchment based on the specific stream discharge rates recorded at gauge stations. Each river has different characteristics that determine precipitation and stream discharge patterns.

7.1.3 Fire Hazard

It is difficult to model and predict with accuracy the timing, location, and severity of a new wildfire, so there are inherent assumptions in this analysis. The fire hazard severity zone dataset used in the flood risk analysis does not predict when or where a fire will occur, but instead identifies where wildfire hazards may be more severe (California State Geoportal, 2020). In areas burned by a wildfire, vegetation loss and soil exposure can lead to increased risk of floods and debris flows (USGS, 2018). For this reason, this project assumed that watersheds with a higher fire hazard severity score are also at an enhanced risk of flooding.

7.1.4 Climate Change

Climate change is expected to cause more severe flooding, drought, and wildfire events throughout California. Climate warming allows air parcels to hold more water, which will cause a roughly 25% increase in average precipitation during future atmospheric rivers. However, it will also cause a much lower proportion of precipitation to fall as snow. The result is an estimated increase in surface runoff of nearly 50% (Huang et al., 2020). In addition, longer, more severe droughts induced by climate change will increase wildfire risk across the state, which also contributes to flood risk in this project's framework. Since there was a lack of available precipitation or streamflow data, this project's analysis was not able to quantify potential future increases in flood risk or fire hazard due to climate change. However, if reliable data were to become available, current average precipitation or streamflow measurements used in this analysis could be increased by 25-50% to reflect expected climate change impacts.

7.2 Feasibility

Our analysis does not incorporate an in-depth study on the political, social, or cultural feasibility of implementing floodplain restoration projects at the suitable sites. Although land use data was incorporated that prioritizes land types that are more suited for floodplain restoration and Flood-MAR projects, there was not an analysis on the feasibility of land owners approving these projects. Based on calculations from a public lands dataset, the land in Madera County is 98.6 percent privately owned, while only 1.4 percent is publicly owned. It is unclear if private landowners would be willing to implement Flood-MAR projects on their property. However, the purpose of this project was not to instruct local stakeholders on how to manage their land and water resources, but rather to provide information to assist managers when deciding on the implementation of multiple benefit groundwater recharge projects.

As a result of local-specific data used in this project, its analysis is not easily transferable to other locations. Most datasets used had state-wide coverage, but others, like the historic levee failures dataset, were specifically provided by the County of Madera. This limits the ability of managers from other basins to perform the same analysis. However, the framework from this analysis could be applied in other basins throughout California if similar local data were available in those basins.

8. Future Work

The various limitations of the analysis offer opportunities for future work. 2D hydraulic modeling would provide a higher-resolution analysis on which sites to prioritize for multiple benefit recharge. The flood risk analysis could be improved if more precipitation and stream gauges were added throughout Madera County. Expanding coverage of precipitation stations and stream gauges would help fill these data gaps. Climate change modeling should also be incorporated into the analysis to best estimate how drought, flooding events, snowpack, fire behavior, and weather will change and affect flood risk, ecosystem enhancement, and groundwater replenishment. In addition, steps could be taken to make the analyses performed in this project more reproducible for other subbasins or regions, depending on the availability of similar data. The Flood Forward group has begun, and will continue to work on, developing a Shiny application using RStudio to communicate project results to stakeholders in an interactive, accessible, online format.

9. Conclusion

The objectives of this project were to provide a spatial understanding of priority locations within Madera and Chowchilla subbasins where groundwater recharge projects using floodplains as natural infrastructure could achieve the co-benefits of flood risk reduction and ecosystem enhancement. The results found from this analysis should provide Madera County, its GSAs, and other stakeholders the ability to prioritize locations for implementing multiple-benefit recharge projects. Looking specifically at floodplains as natural infrastructure for these projects means that their implementation will be less resource-intensive than it would be if built conveyance infrastructure were constructed to divert flood water off stream and to recharge sites. For this reason, natural infrastructure and the recommendations of this project may be preferable for Madera County, whose flood control agency remains notably underfunded. However, it should be noted that this comprises just one strategy in a larger management portfolio for accomplishing the groundwater recharge goals laid out in the GSPs for these subbasins. In some locations, it may make more sense to divert water off stream using existing or constructed infrastructure to achieve even more groundwater recharge with the same benefits. Between the recommendations of this project and the Recharge for Resilience project, GSAs and stakeholders should have a robust portfolio of managed aquifer recharge project prioritization, both in floodplains and off-stream. Together, this should allow these users to be able to effectively augment their groundwater supply to help achieve long-term groundwater sustainability in a way that provides multiple benefits of flood risk reduction and ecosystem enhancement.

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