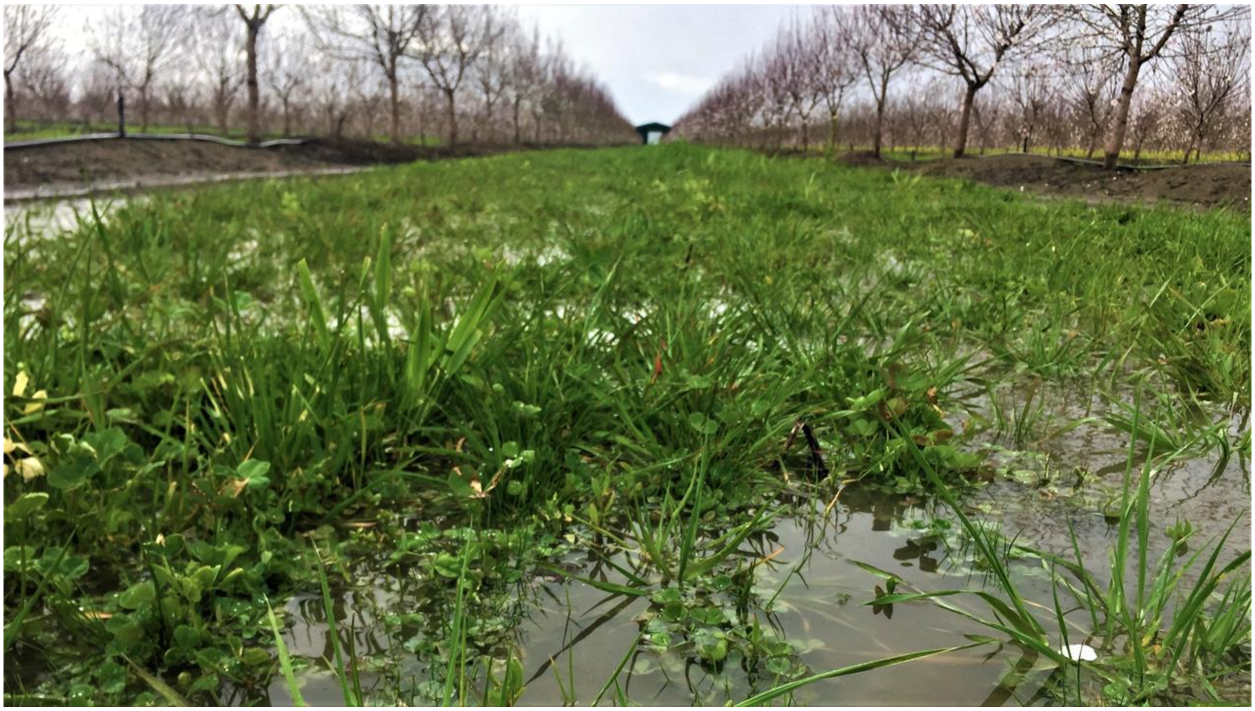
Managed Aquifer Recharge Opportunities in the Solano Subbasin
Technical Memo



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1. INTRODUCTION

1.1. Purpose

The Sustainable Groundwater Management Act (SGMA)[1] requires Groundwater Sustainability Plans (GSPs) to develop Projects and Management Actions (PMAs) to support groundwater sustainability and avoid undesirable results in groundwater basins. This Technical Memorandum (TM) analyzes distributed groundwater recharge practices on agricultural fields in the Solano Subbasin (Figure 1), focusing on agricultural fields where managed aquifer recharge (MAR) has potential to benefit groundwater sustainability and to achieve multiple benefits. This memo is about the methods and analyses conducted to characterize recharge suitability in the Area of Interest in the Solano Subbasin. It discusses scenarios and tools that the Solano Subbasin Groundwater Sustainability Agencies (GSAs) can use to develop and implement PMAs as needed in the Solano Subbasin.

The following introductory sections identifies primary and secondary funding sources for this analysis, its connection to the Solano Subbasin GSP planning process, and briefly summarize physical, hydrologic, economic, and social characteristics of the Solano Subbasin relevant to analyzing groundwater management actions on local farms.

1.2. Grant Funding, Tasks, and Deliverables

Funding for this analysis was provided by a Sustainable Groundwater Planning Grant from the California Department of Water Resources (DWR) [Proposition 68 funding, project titled “Component 2 GSP Development, Category (c): Stormwater Recharge Project Planning.” The analytical methods for the sub-section also included in the Memo, Rain-MAR, were developed using matching funds and California Natural Resources Conservation Service (NRCS) through a Conservation Innovation Grant (CIG Grant # NR209104XXXXG007)].

1.3. Groundwater Sustainability Planning in Solano Subbasin

The Solano Collaborative is a group of GSAs, each having authority for portions of the Solano Subbasin, working through a Collaboration Agreement (Solano Collaborative, 2019) to develop a single GSP for the entire Solano Subbasin. The Solano Collaborative is made up of the five GSAs located in the Solano Subbasin: the Solano GSA, the City of Vacaville GSA, the Sacramento County GSA, the Solano Irrigation District GSA, and the Northern Delta GSA (Figure 1).

As noted in the GSP, groundwater in a localized northwestern portion of the Subbasin has declined by approximately 10 feet or more between the period of 1988 and 2018 (LSCE Team, 2021, GSP Figure 3-19). Therefore, the Solano GSP Team recommended the Northwest Focus Area (Figure 1) as an area of focus for multi-benefit recharge projects. Within the Northwest Focus Area, multiple analyses were done in conjunction with the Solano Collaborative technical team to optimize potential PMA actions and locations.

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[1] SGMA is a three-bill legislative package composed of AB 381739 (Dickinson), SB 1168 (Pavley) and SB 1319 (Pavley), which is codified in Section 10720 et seq. of the 39 California Water Code.

1.4. Overview of Agricultural Resources in the Solano Subbasin

This section provides a synopsis of physical, economic, and social characteristics of the Solano Subbasin of relevance to the irrigated agricultural sector, largely drawing on other portions of the Solano Subbasin GSP, with additional data from other local sources as noted. The purpose of this section is to provide context for the development of distributed surface and groundwater conservation practices on farm fields.

1.4.1. Physical and Hydrological Landscape

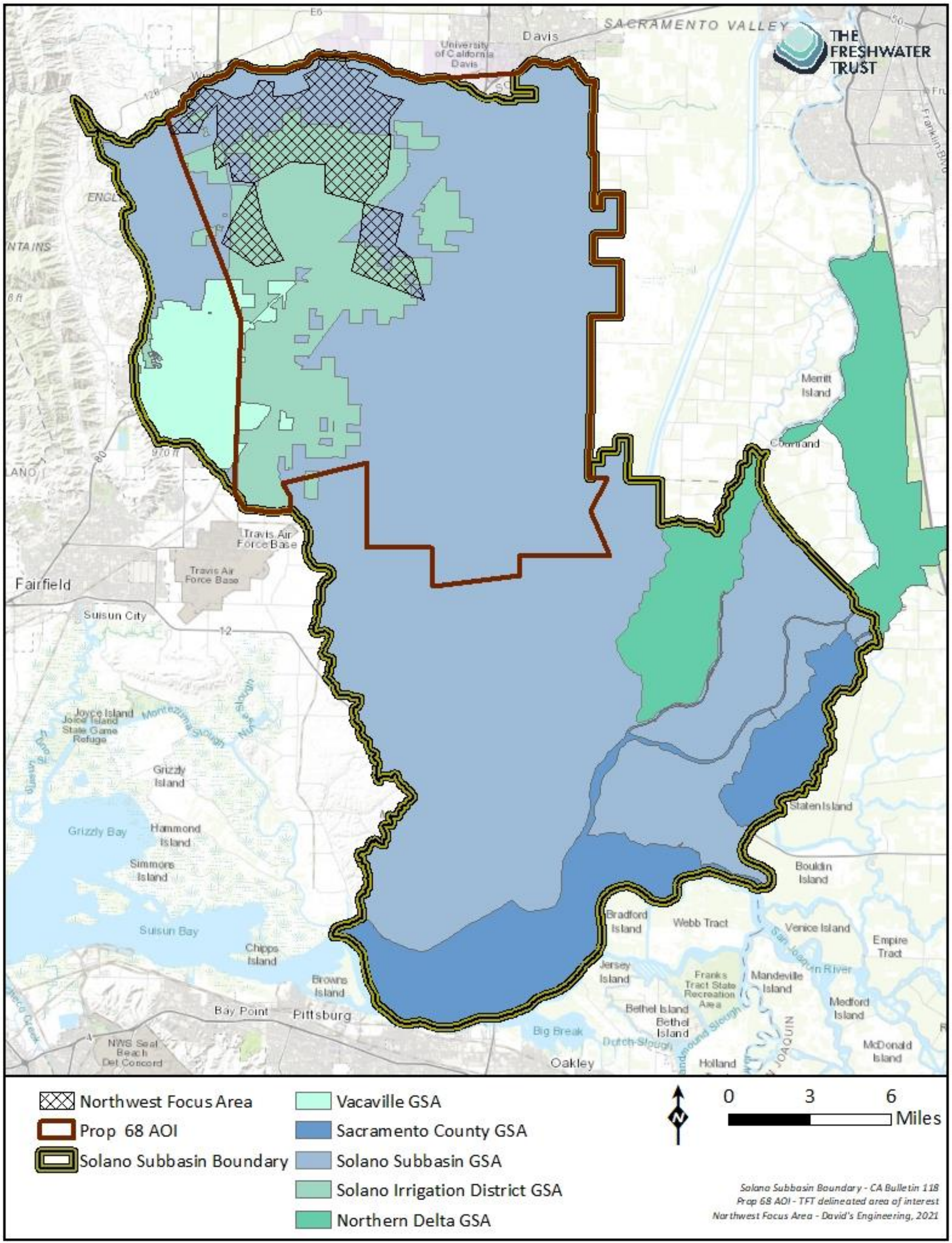
Study Area. The study area for this project comprises the cultivated agricultural areas of the Solano Subbasin (*Figure 1. Areas of Study*). The Solano Subbasin includes the southernmost portion of the Sacramento Valley Groundwater Basin and extends into the northern portion of the Delta. Subbasin boundaries are defined by Putah Creek on the north, the Yolo County line on the east, the North Mokelumne River on the southeast (from Walnut Grove to the San Joaquin River), and the San Joaquin River on the south (from the North Mokelumne River to the Sacramento River). The western Subbasin boundary, which extends through a portion of Vacaville, is partly defined by the boundary between the San Francisco Bay and Sacramento River Hydrologic Regions as described by Department of Water Resources (DWR, 2020).

Topography and Hydrology. Most of the Solano Subbasin topography is relatively flat, with elevations within the Subbasin ranging from 700 feet above sea level in the more northern to central and western areas of the Subbasin abutting the Coast Range to 20 feet below sea level within the Delta. Historically, groundwater use within the region has been more concentrated in the northern part of the Subbasin. There are higher densities of groundwater wells in this area that serve both urban and agricultural needs. The southern portion of the Subbasin relies more heavily on surface water. There has been no documented inelastic subsidence within the Subbasin, and long-term groundwater level trends have remained relatively stable with some shorter-term fluctuations such as increases in Wet Years and decreases during drought conditions (LSCE Team, 2021; GSP Chapter 3).

The Solano Subbasin GSP notes that the Subbasin is, "…hydro-geologically complex with influences from a variety of surface water features and tidal influences (e.g., Sacramento-San Joaquin Delta) and encompasses both shallow and deeper groundwater resources. The primary sources of surface water for the subbasin are watersheds in the lower elevation Coast Range Mountains, which lack significant snowpack." Prevailing groundwater flow directions in the Subbasin within the Alluvial Aquifer and Upper Tehama zone tend to be from west/northwest to east/southeast away from the English Hills and Montezuma Hills towards the Sacramento River and Delta. This context is relevant to estimating the benefit of infiltrated water as it pertains to ecosystems and communities (LSCE Team, 2021, GSP Chapter 1).

Groundwater recharge and discharge are key water budget components of the Subbasin. Groundwater recharge within the Solano Subbasin occurs primarily through infiltration and deep percolation of precipitation falling directly on the landscape, applied water (e.g., irrigation), seepage from natural surface waterways, seepage from water conveyance systems such as leaky canals, ditches, and pipes, and deeper subsurface recharge from adjacent and upland recharge source areas outside of the Subbasin (LSCE, 2021, GSP Chapter 3). These are important mechanisms to consider when designing PMAs related to agricultural working lands.

Figure 1. Solano Subbasin and Areas of Interest.



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Surface water. Another level of hydrologic complexity is surface water resources management in the Solano Subbasin, which include the Solano Project on Putah Creek (the Monticello Dam at Lake Berryessa and the Putah Diversion Dam at Lake Solano). Similarly, the State Water Project has licenses to use water originating from the Sacramento River, which was originally stored in Lake Oroville and provided using the North Bay Aqueduct. Lastly, the Delta portion in southern Solano Subbasin includes many direct diversions from local rivers, creeks, and sloughs from pre-1914 riparian rights claimants and pre- and post-1914 appropriative rights claimants. In addition to the conjunctive use of groundwater and surface water resources, Solano Irrigation District and individual agricultural water users recycle tailwater (LSCE Team, 2021, GSP Chapter 2).

Groundwater supplies. As noted in the Basin Setting for the GSP, groundwater well depths vary across the Subbasin. Domestic wells in the Subbasin are generally shallower than other well types with most domestic wells ranging between 100 and 300 feet deep. Agricultural wells in the Subbasin tend to be relatively deep with average depths greater than 300 feet deep across most of the Subbasin. Public water supply wells and industrial wells are typically somewhat deeper with average well depths typically greater than 300 feet. Higher densities of domestic wells occur in the more northern and central parts of the Subbasin, especially in areas north of the City of Vacaville (LSCE, 2021, Chapter 3). Analyses for the Solano GSP has documented declining water levels in the northwestern part of the Subbasin (LSCE Team, 2021).

Groundwater contamination. The GSP identifies potential migration of local groundwater contamination as an important consideration when planning and implementing PMAs. The GeoTracker website (SWRCB, 2021a) identified approximately 260 potential groundwater contamination sites in the Solano Subbasin, including 34 sites associated with former military operations. Nearly 70 percent of all sites were designated as leaking underground tank cleanups and the remainders as cleanup or another program. More than 80 percent of all sites were classified as closed or eligible for closure. Nearly 50 sites remain open with the status of inactive, assessment, remediation, or verification monitoring. While these sites are not included in the Subbasin-wide analyses, future MAR-project site selection may require further analysis of potential contamination risks arising from these sites to avoid mobilizing potential contaminants.

Groundwater Dependent Ecosystems. Groundwater dependent ecosystems (GDEs) are ecological communities that depend on groundwater emerging from aquifers or occurring near the ground surface (The Nature Conservancy, 2019). Many of California's GDEs have adapted to dealing with fluctuating groundwater levels and intermittent periods of water stress; however, if these groundwater conditions are prolonged, adverse impacts to GDEs can result. The Solano Subbasin GSP Technical Memorandum on Surface Water and Groundwater Conditions (LSCE Team, 2021; GSP Chapter 3 Appendix), identifies the likely GDEs in the southern portion of the Subbasin (areas where depth to water has generally been less than 10 feet during the past 20 years). GDEs in the northern subbasin are less frequent due to deeper depths to groundwater. The Solano Subbasin GSP shows that estimates of surface water and groundwater connectivity indicate the likelihood of disconnected conditions along much of Putah Creek (LSCE Team, 2021). Groundwater conditions along Putah Creek are of interest because of the important riparian forests in this part of the Subbasin, which is one of the underlying reasons that the GSP Technical Team recommended the Northwest Focus Area as an area for focused PMAs.

1.4.2. Agricultural Sector

Economics. A full 29 percent of Solano County's agricultural production revenue ("farm gate value") is generated from fruit and nut crops, 22 percent from vegetable crops, 19 percent from animal production, and 17 percent from field crops (Solano County Agricultural Commissioner, 2020). Almonds were the top grossing crop in 2020, followed by processing tomatoes, nursery products, cattle, alfalfa, and walnuts. By acreage, field crops (including alfalfa, pasture, and rangeland) accounted for 278,310 acres in Solano County in 2020. Almonds accounted for 18,300 acres, followed by walnuts (10,720 acres), tomatoes (10,400 acres), sunflower (6,610 acres), and grapes (4,000 acres). Crop compatibility is an important determinant in the feasibility of MAR on farm fields, described in detail in Section 3.3.2 below. Groundwater provides ~24 percent of the total irrigation supply in the Solano Subbasin, for an estimated ~170,000 irrigated acres of farmland use.

Demographics. The Solano Subbasin Snapshot (LGC, 2020) identifies the following demographic parameters relevant to the present analysis:

- Approximately 50,000 residents depend on groundwater for their drinking water. The Solano Subbasin has a total of ~4,086 wells, an estimated 130 public supply wells for drinking water, and an estimated 1,400 domestic wells
- Linguistic Isolation: Linguistic isolation, which is defined as any household in which all members aged 14 years and older speak a non-English language at home and speak English less than "very well", ranges from 2 to 15 percent throughout communities within the Subbasin (American Community Survey 2012-2016)

In summary, Solano Subbasin has a robust agricultural sector with a wide range of crops, soils that are generally suitable for agriculture, moderate winter rainfall, and reliable sources of irrigation water.

2. MAR AGRICULTURAL PRACTICE DESCRIPTIONS

This section summarizes the steps The Freshwater Trust (TFT) took to research, formulate, and ground-truth potential MAR scenarios prior to developing analytical models for MAR optimization. In general, this includes working with stakeholders to set goals and objectives, researching suitable practices, developing MAR approaches and scenarios that align with the National Resource Conservation Service (NRCS) Practice Standards, and conducting on-farm site visits to discuss potential scenarios with local growers.

During prior projects also funded through NRCS's Conservation Innovation Grant program, TFT worked with Dixon Resource Conservation District (RCD), Solano RCD, and NRCS to identify three priority conservation practices in the Solano Subbasin: cover crops, irrigation efficiency, and MAR. This technical memorandum focuses on MAR as a strategy to recharge groundwater in the Solano Subbasin.

2.1. Goals and Objectives

Goal: Develop multi-objective beneficial outcomes in the Solano Subbasin by identifying optimal locations for specific, voluntary agricultural management practices that have the potential to increase shallow aquifer recharge benefits and generate associated surplus stormwater use and/or flood water reduction benefits to ensure groundwater sustainability.

Objectives:

- Quantify the (a) potential economic implementation costs and (b) groundwater and surface water benefits of distributed recharge actions on suitable agricultural fields in the Solano Subbasin
- Provide analytical tools for GSAs to develop programs for targeted outreach, technical assistance programs, and incentives for distributed on-farm recharge practices in specific locations with maximum return on investment

2.2. Managed Aquifer Recharge

Types of Managed Aquifer Recharge. MAR is not currently defined by statute or regulation in California, but "groundwater recharge" is defined by statute as "the augmentation of groundwater, by natural or artificial means."[2] MAR represents a groundwater resource augmentation approach to maintain or improve aquifer conditions by capturing excess surface water and/or precipitation and moving this water through controlled conditions into aquifers. As an intentional management approach, MAR projects typically aim to meet one or more of the following objectives:

- Increase volume, rate, or both of groundwater infiltration
- Provide water security and resiliency against future droughts and climate change through storing excess surface water below ground
- Work towards SGMA compliance by mitigating groundwater storage reduction and increasing supply, both in the long- and short-term

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[2] CAL. WATER CODE § 10721(i).

- Support GDEs by ensuring wetland and riparian areas are not adversely affected by groundwater level decline

As this approach to improving groundwater conditions has become more widespread, it has taken on various forms.[3] Two MAR practices are described in this TM which are "Ag-MAR" and "Rain-MAR". These are primarily distinguished by the respective source of water used for recharge: Ag-MAR is intended to divert excess surface water flows from rivers or drainage canals onto agricultural lands and working landscapes for infiltration. By contrast, Rain-MAR is intended to maximize the infiltration of precipitation that falls on agricultural fields with the potential to reduce flood peaks or events. The modeled practices are defined below.

NRCS Practice Standards.

- *NRCS Interim Practice Standards for groundwater recharge*. NRCS has prepared two interim practice standards (815 and 817) relating to groundwater recharge. NRCS Practice Standard 815 is called "Groundwater recharge basin or trench" and is an off-channel impoundment with a permeable base underlain by an unconfined aquifer. NRCS Practice Standard 817 is called "On Farm Recharge" and is the periodic application of surface or stormwater to cropland with connectivity to an unconfined aquifer. These are currently still being tested and reviewed, and not yet eligible for general use in NRCS projects
- *Related practices*. In addition to the two NRCS draft practice standards mentioned above, the MAR practices are also incorporate elements of NRCS Practice Standards 378 (Pond), 477 (Tailwater Recovery), 644 (Wetland Wildlife Habitat Management), and 356 (Dike)

Modeled practices. The following MAR practices were incorporated in modeling scenarios for fields within the Solano Subbasin:

- *"Rain-MAR."* Rain-MAR, a term coined by TFT, refers to a form of MAR that involves maximizing the retention or collection of precipitation on or adjacent to agricultural fields, without any application of delivered surface water. Two variations of Rain-MAR were modeled:
  - *Berms*: relying on existing or newly graded 18" berms on the field perimeter that collect water for infiltration on the cropped area of a field
  - *Sumps:* excavating (or re-purposing) field-adjacent sumps, trenches, or tailwater recovery systems for infiltration
- *"Ag-MAR."* Ag-MAR is the practice of delivering surface water to an agricultural field for the purpose of infiltrating water to the aquifer. Ag-MAR is generally expected to occur in the winter when crop water demands are lowest. Two variations of Ag-MAR are modeled. MAR-High Volume assumes delivery of 2 acre-feet (AF) of water for each acre enrolled (including modeled seasonal precipitation) between December and March, and MAR-Low Volume assumes delivery of 1 AF of water for each managed acre (including modeled seasonal precipitation) over the same period. The simulated application volumes are conservative due to uncertainties about the annual availability of excess flows, the feasibility of delivering surface water during winter, and the period of ponding on fields

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[3] For specific examples of each type of MAR project, see: Central Coast Reg'l Water Quality Control Board, Staff Report on Managed Aquifer Recharge in the Central Coast Region (June 21, 2017), www.waterboards.ca.gov/rwqcb3/board_info/agendas/2017/july/item11/item11_stfrpt.pdf.

Stakeholder input. TFT conducted field visits with four growers in the Dixon RCD (a drainage district within the Solano Subbasin) with large agricultural holdings north of I-80 to better understand their perceptions of two potential Rain-MAR practices: berms and sumps. A fifth grower in the same region was interviewed by phone. The growers indicated where their existing sumps and/or tailwater recovery systems are located, and they were asked a series of questions about benefits and risks to their operations, maintenance implements, and economics. The growers represent large land holdings and variable crop and irrigation systems including perennial orchards and asparagus, and annual tomato, sunflower, and grain rotations. The growers' fields included furrow, sprinkler, and drip irrigation systems, and they were already familiar with berms and tailwater systems.

Perceptions of MAR with berms. In general, three of the four the growers interviewed were averse to using berms to manage stormwater directly on their fields in winter, regardless of potential incentives or penalties. The primary concerns cited include the potential for anoxic soil conditions, reduced yields, and increased disease pressure due to MAR. One grower was open to using berms on fields with row crops (tomatoes and sunflowers), provided he could drain the water in time to till the soil in spring.

Perceptions of MAR with sumps. All interviewed growers were open to using sumps to manage stormwater; however, several expressed a preference for using cover crops to infiltrate water and mitigate flooding, especially on orchards. Each of the growers interviewed had fields with existing tailwater pits and were familiar with the concept. In cases with a pre-existing sump, implementation costs would be lower, and no land would be taken out of production. While several growers noted that re-purposing existing sumps for Rain-MAR would require investment for operations and maintenance, in general, their feedback indicated that using sumps may be worth the added complexity if it earned them "credit" in the event that limits were placed on the apportionment of groundwater in the future, or if it allowed increased irrigation flexibility or regulatory relief.

2.3. Relationship to SGMA

The analysis of these MAR practices for a Project and Management Action (PMA) is intended to provide implementation tools for GSAs to maintain groundwater sustainability and prevent undesirable results in the Solano Subbasin. Rain-MAR has the potential to redirect un-utilized winter runoff to the local aquifer to supplement groundwater supply and benefit the overall water budget. Applied appropriately, MAR also has the potential to recharge groundwater for the benefit of GDEs and domestic well users.

3. METHODS AND RESULTS

This section summarizes the approach TFT used to determine where to implement groundwater recharge actions in the Subbasin for the maximum benefit at the least implementation cost.

TFT's approach to developing MAR programs involves five basic steps (Figure 2). The first step is to analyze all agricultural fields in the Area of Interest, identify the crop type, and classify other environmental and management conditions from multiple spatial datasets. Next, MAR feasibility is analyzed for each field based on crop compatibility, water quality risk, and mounding risk. The feasible fields are then modeled with and without the practice to quantify recharge benefits and net present cost of the practice. The results of the field-scale analysis can be aggregated to estimate cumulative benefits and costs of the practice to address local priorities. Based on these priorities, example implementation scenarios are developed for a proposed demonstration project, and for a hypothetical MAR program that a GSA could implement to maximize recharge within a GSA's cost constraint.

Figure 2. Analytical Steps

- Identify & classify agricultural fields
- Assess groundwater recharge feasibility
- Model each field's recharge benefits and practice costs
- Assess basin-scale costs and benefits
- Optimize to meet targets within constraints

3.1. Scale of Analysis and Area of Interest

MAR opportunities are presented at two scales in the present analysis (Figure 1). The two areas of interest (AOIs) are as follows:

- *MAR Suitability.* Areas of the subbasin containing cultivated fields. For this portion of the analysis, TFT delineated the northern and eastern boundaries of the Subbasin, the southern boundary of the Solano Resource Conservation District (RCD), and the western boundary of Solano Irrigation District because they had the highest concentration of irrigated agricultural land and delivery and drainage canals.
- *Northwest Focus Area*. Based on feedback from the Solano GSP Technical team (see Solano GSP, draft Chapter 8, August 2021), the Northwest Focus Area, which has experienced some local groundwater level declines, was selected for Rain-MAR scenario purposes.

3.2. Rain-MAR Data

Individual agricultural fields are the primary unit of analysis for modeling recharge practices. This section describes the datasets used to classify field types, recharge potential, and management attributes of each agricultural field in the Area of Interest.

3.2.1. Data Aggregation and Field Classification

Field attributes are derived primarily from publicly available datasets from the US Department of Agriculture (USDA), the US Geological Survey (USGS), NRCS, and the University of California, Davis (UC Davis).

Agricultural Field Boundaries & Acreages. Boundaries and acreages were determined using the DWRs' Statewide Crop Mapping dataset (DWR, 2021b). This dataset was originally developed by Land IQ, LLC and subsequently revised by the DWR using a combination of aerial photography, remote sensing multi-spectral imagery, agronomic analysis, and ground verification. Areas that appeared to have non-agronomic land uses are excluded from field polygons and incorporated into its Land Use Viewer tool. Fields typically contain a single crop type and are not intersected by, or inclusive of, any other features, such as houses, irrigation and fertilization structures, barns, roads, canals, etc. Each field's acreage was then calculated using ArcGIS.

Crop Type. The crop or crops grown on each field are classified according to the USDA Cropland Data Layer (Han et al., 2014). The majority crop type for each field polygon is used when this dataset shows multiple crops within a field polygon. Intra-annual rotations are classified, but inter-annual rotations are not (Figure 3).

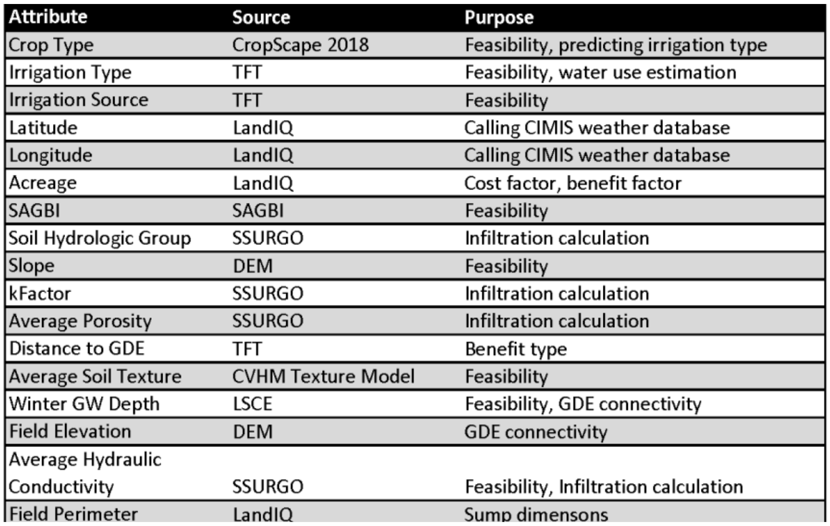
Crop QA/QC. Remotely sensed crop data from the sources described above went through a Quality Assurance/Quality Control (QA/QC) procedure and ground-truthing process. First, a random subset of these datasets was checked against 2019 satellite imagery and Google Earth "street view" images to look for inconsistencies (i.e., orchards or vineyards identified as row or field crops, evidence of misclassified irrigation systems based on visible infrastructure, summer-time green fields identified as non-irrigated, etc.). Second, 'reasonableness' checks were performed between the crop types identified on all individual fields to identify unlikely combinations (e.g., "alfalfa" irrigated with high efficiency irrigation, non-irrigated orchards, etc.). Finally, NRCS and Dixon RCD project partners verified the crop and irrigation type for a random subset of Solano County fields based on their own knowledge of the area. The project partner input, aerial imagery analysis, and Google Earth "street view" imagery were used to rectify data issues identified through the above procedures.

Soils & Field Slope. The majority slope within each field polygon is calculated in ArcGIS using the U.S. Geological Survey 10-meter digital elevation model (DEM), and the majority soil type within each field polygon is determined using the NRCS SSURGO Database (Soil Survey, 2021).

Surface Suitability for Recharge. The Soil Agricultural Groundwater Banking Index (SAGBI) dataset is used to assess suitability of recharging groundwater (O'Geen, 2015). A team of researchers at the University of California Davis and the UC Cooperative Extension developed SAGBI, which incorporates soils and topography data to compute a spatially explicit index of the suitability for groundwater recharge. The SAGBI is calculated using five major factors that are critical to successful agricultural groundwater banking: deep percolation, root zone residence time, topography, chemical limitations, and soil surface condition. The SAGBI is derived from parameters like slope classes, soil electric conductivity (EC), and soil hydraulic conductivity (Ksat) from the SSURGO Database. UC Davis' modified SAGBI scores, accounting for six-foot 'deep tillage' that eliminates near-surface confining soil layers, were used for all analyses.

__Source of Irrigation Water__. For Ag-MAR analysis, each field's source of irrigation water is classified as not irrigated, surface water, groundwater, or "mixed" (i.e., the field has the potential to be irrigated by both surface and groundwater). The field classification method was trained with machine learning methods using the Land Use Surveys and five predictor variables, including surface water diversions (SWRCB, 2021) water conveyance infrastructure data from the National Wetlands Inventory (USFWS, 2021), surface water districts (DWR, undated), and irrigation wells (DWR, 2021f). Irrigation source classifications were cross-referenced with the DWR California Land Use Surveys dataset (DWR, 2021b) using 2003 and 2000 source data for Solano and Sacramento Counties respectively, to verify that source water assumptions were consistent with land use classifications.

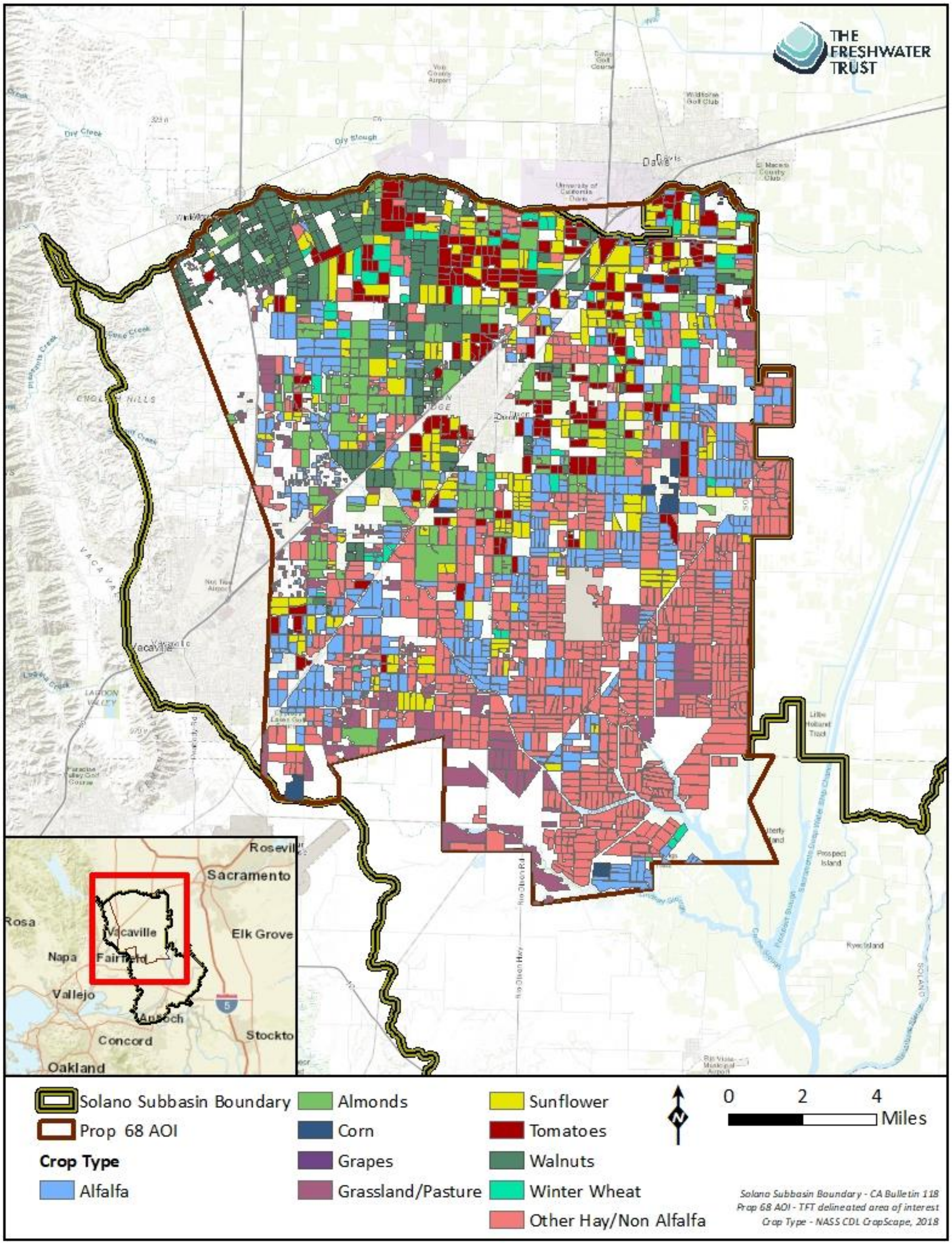
Table 1. Field Classification



Attribute	Source	Purpose
Crop Type	CropScape 2018	Feasibility, predicting irrigation type
Irrigation Type	TFT	Feasibility, water use estimation
Irrigation Source	TFT	Feasibility
Latitude	LandIQ	Calling CIMIS weather database
Longitude	LandIQ	Calling CIMIS weather database
Acreage	LandIQ	Cost factor, benefit factor
SAGBI	SAGBI	Feasibility
Soil Hydrologic Group	SSURGO	Infiltration calculation
Slope	DEM	Feasibility
kFactor	SSURGO	Infiltration calculation
Average Porosity	SSURGO	Infiltration calculation
Distance to GDE	TFT	Benefit type
Average Soil Texture	CVHM Texture Model	Feasibility
Winter GW Depth	LSCE	Feasibility, GDE connectivity
Field Elevation	DEM	GDE connectivity
Average Hydraulic Conductivity	SSURGO	Feasibility, Infiltration calculation
Field Perimeter	LandIQ	Sump dimensons

The resulting field-scale spatial dataset incorporates specific attributes from each dataset into an ArcGIS geodatabase for further analysis and modeling, as shown in Table 1. Figures 3 (Crop Types), 4 (SAGBI), 5 (Irrigation Types), 6 (Irrigation Sources), and 7 (Soil Texture).

Figure 3. Crop Types in the Solano Subbasin.



Solano Subbasin Boundary - CA Bulletin 118
Prop 68 AOI - TFT delineated area of interest
Crop Type - NASS CDL CropScape, 2018

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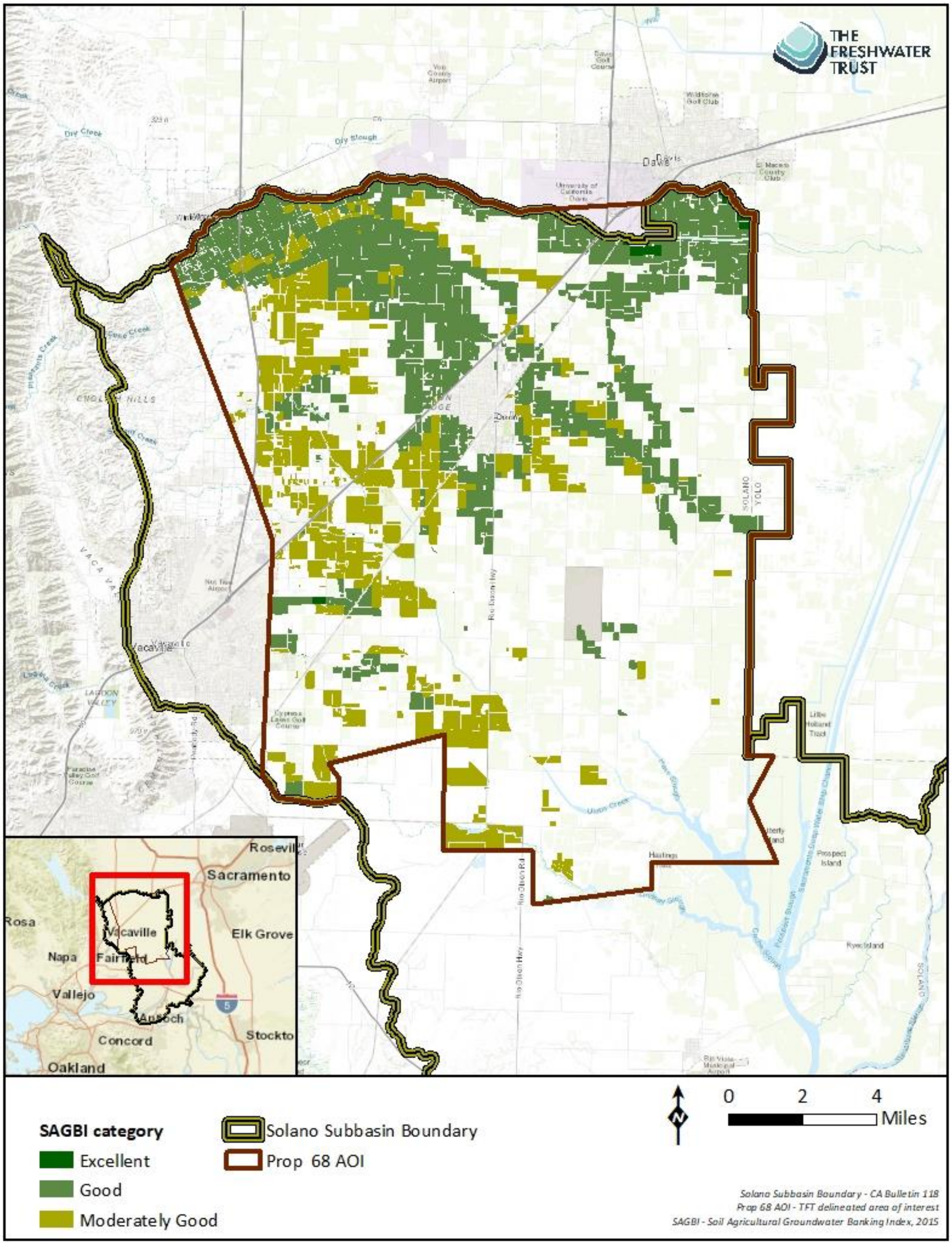
Figure 4. Soil Agricultural Groundwater Banking Index (SAGBI) in the Solano Subbasin.
Fields displayed have a SAGBI rating of Moderately Good, Good, or Excellent.



Solano Subbasin Boundary - CA Bulletin 118
Prop 68 AOI - TFT delineated area of interest
SAGBI - Soil Agricultural Groundwater Banking Index, 2015

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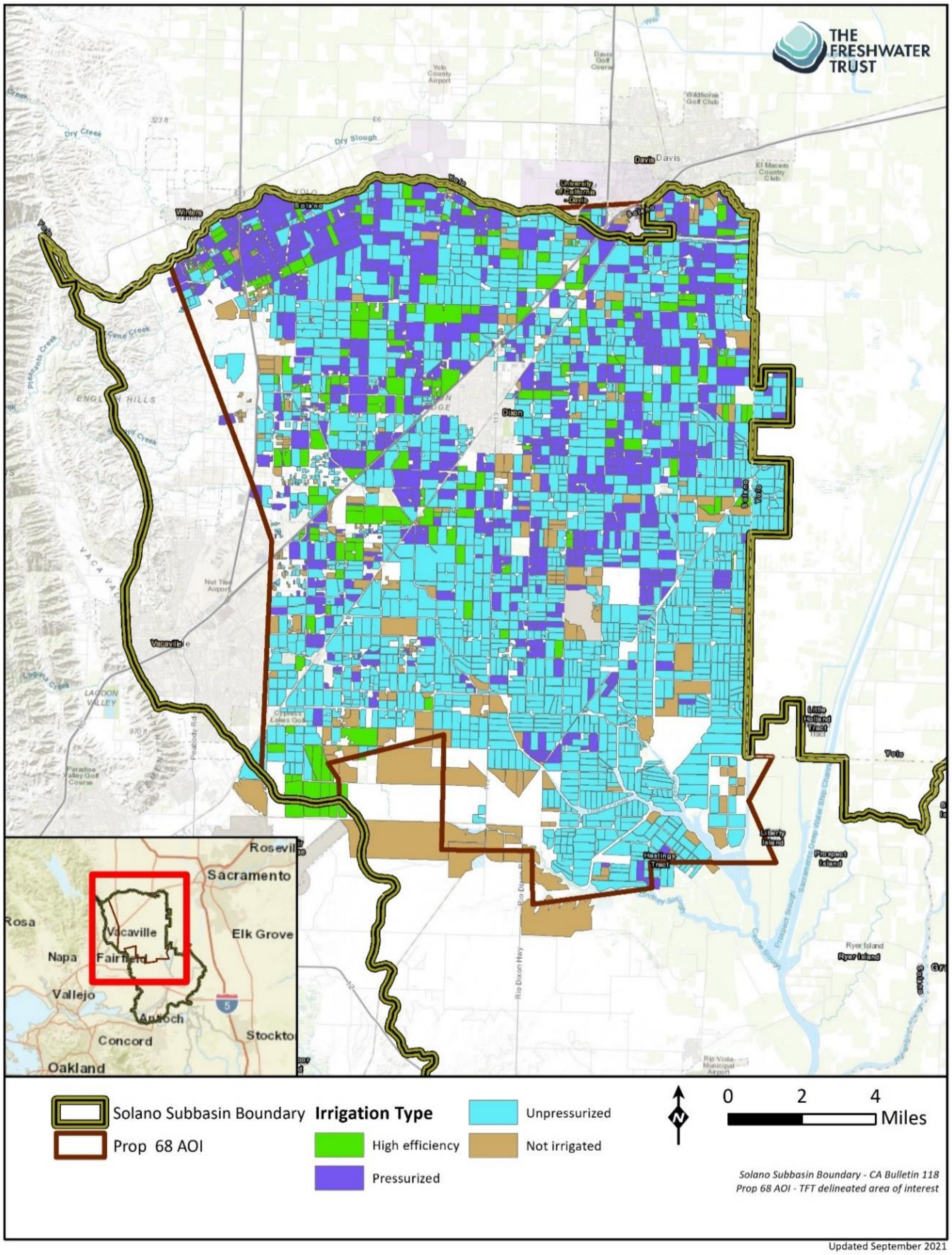
Figure 5. Irrigation Types in the northern Solano Subbasin.

Irrigation type can be used as a proxy for berms because gravity systems (flood, furrow) often use berms to retain irrigation water.



Solano Subbasin Boundary - CA Bulletin 118
Prop 68 AOI - TFT delineated area of interest

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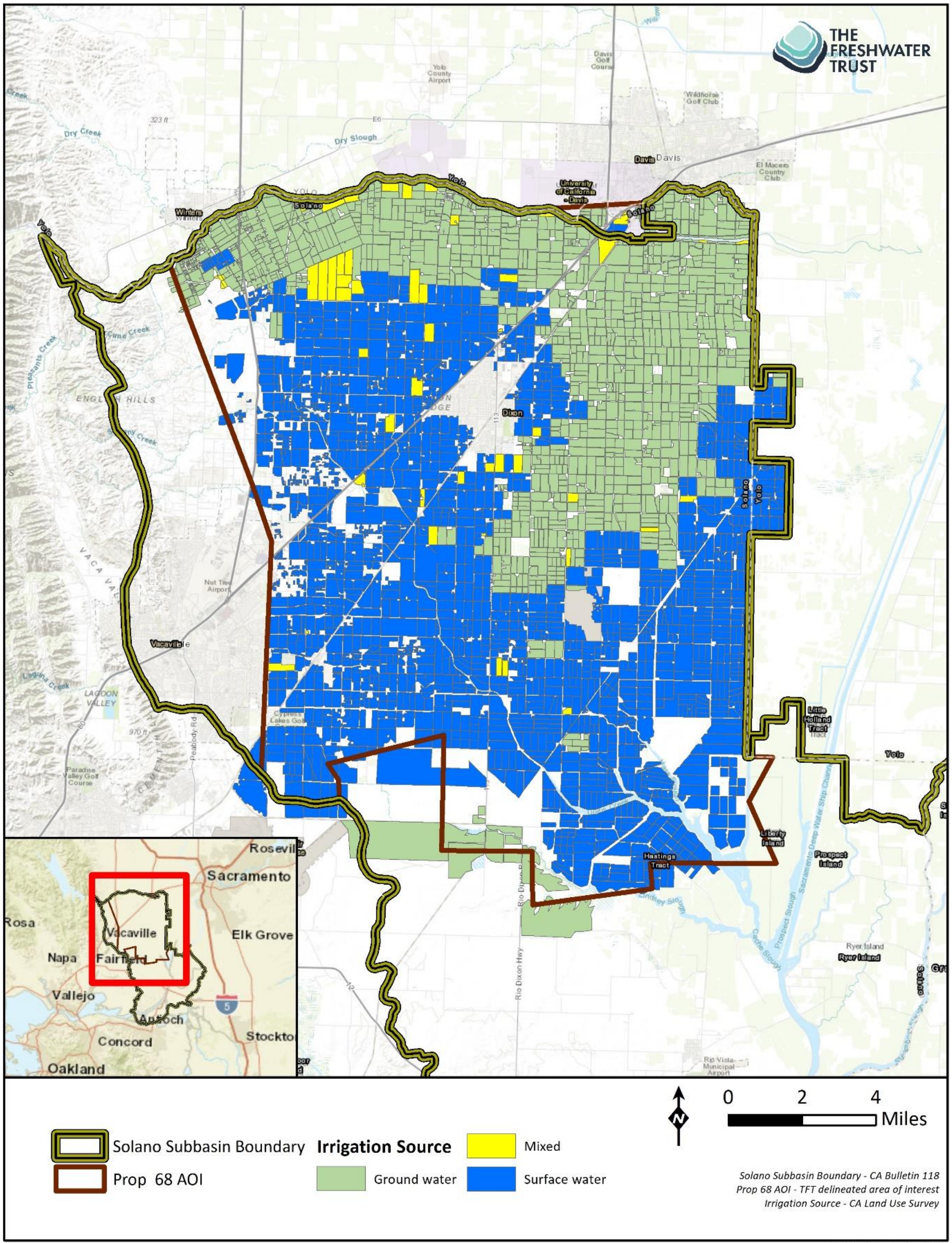
Figure 6. Irrigation Sources in the northern Solano Subbasin.

Irrigation source is used to determine feasibility for Ag-MAR, since only surface water fields are eligible.

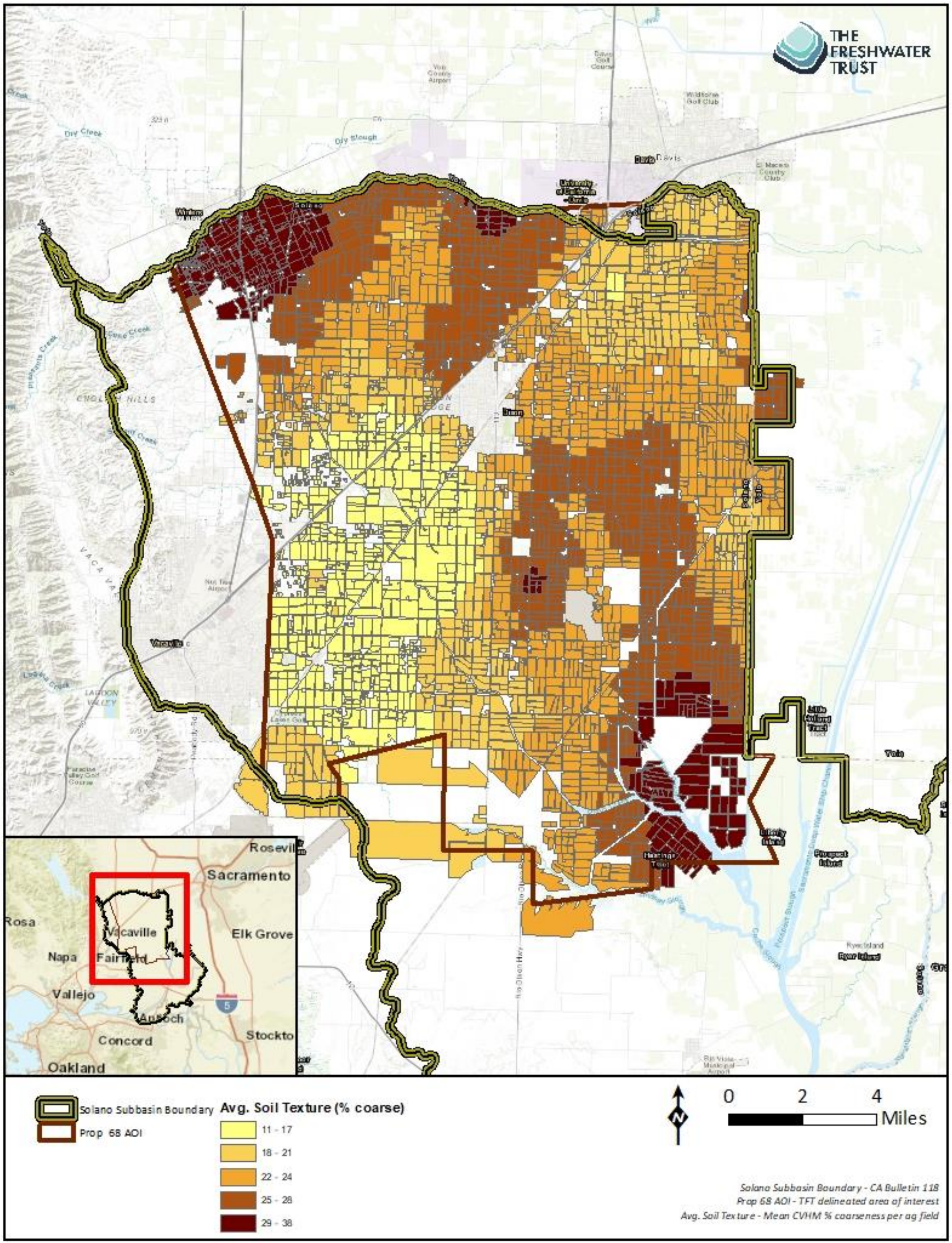


Solano Subbasin Boundary - CA Bulletin 118
Prop 68 AOI - TFT delineated area of interest
Irrigation Source - CA Land Use Survey

Updated September 2021

Figure 7. Average Soil Texture in the vadose zone in the northern Solano Subbasin.

Soil texture is a feasibility metric for infiltration.



Solano Subbasin Boundary - CA Bulletin 118
Prop 68 AOI - TFT delineated area of interest
Avg. Soil Texture - Mean CVHM % coarseness per ag field

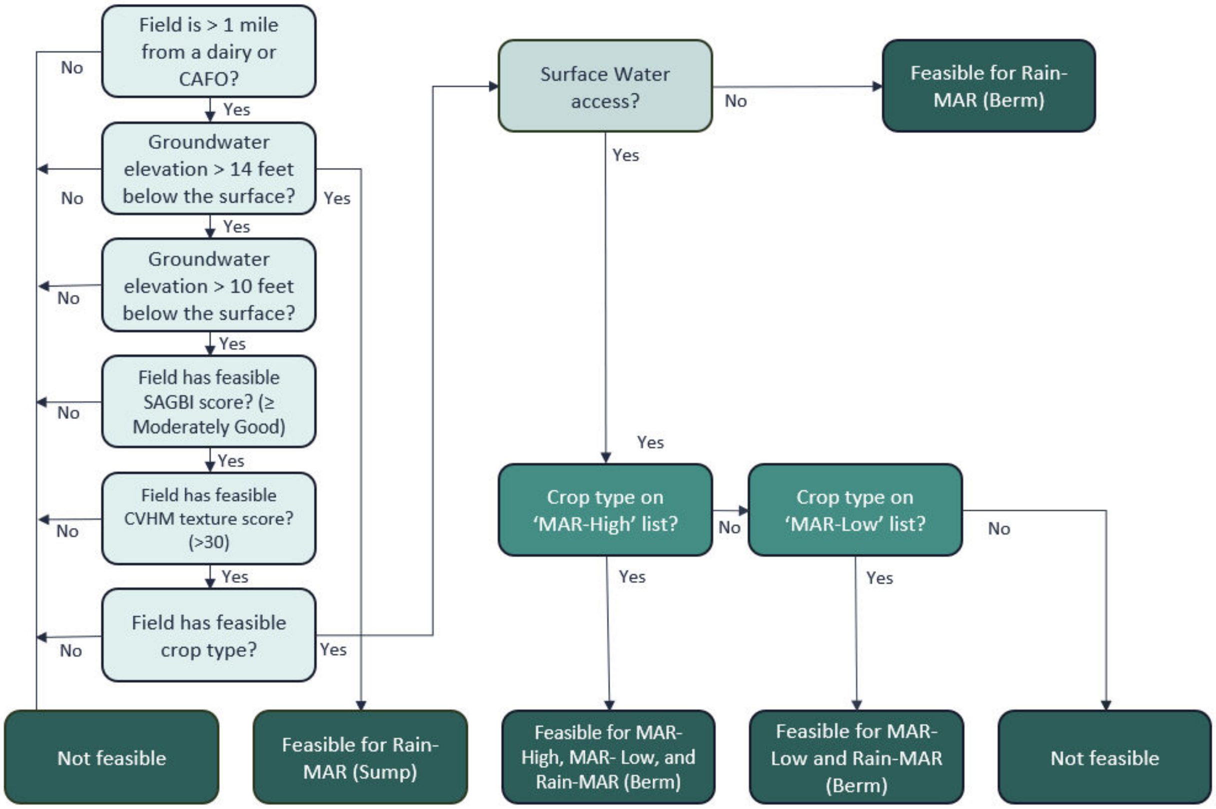
Updated September 2021

3.3. Analysis of Managed Aquifer Recharge

3.3.1. Feasibility Analysis

The recharge feasibility analysis excludes fields not suitable for recharge by defining thresholds for factors that would constrain recharge, impact farm operations, or pose a potential risk for flooding or drinking water quality. For example, fields are determined infeasible for recharge if they have mounding risk (shallow groundwater elevations, low SAGBI scores, fine textured soils deeper in the vadose zone), or are planted in crops that are intolerant to flooding. While groundwater quality constraints were not evaluated for the AOI (apart from salinity metrics in SAGBI), potential effects of future recharge operations on contaminant migration should be considered where applicable. These, and other legal/regulatory constraints (e.g., zoning, permitting, easements, etc.) would need to be assessed at a site level during the project implementation phase. The flow chart below illustrates the logic that is applied to each field to determine which actions are feasible. Rain-MAR actions include Rain-MAR Sump and Rain-MAR Berm, and Ag-MAR actions include MAR-High Volume and MAR-Low Volume.

Figure 8. Feasibility Analysis Flow Chart



3.3.2. Screening Potential Constraints and Risk Factors

There are several risk factors associated with MAR practices that require consideration to ensure that all fields are suitable for the practice. Three of these factors, mounding risk, crop compatibility, and water quality, are common to both MAR practices. Ag-MAR has additional constraints associated with access to surface water. Only fields classified as using surface water (either fully or in conjunction with groundwater) are considered feasible for Ag-MAR.

Mounding risk. Groundwater mounding refers to a concentration of near-surface groundwater that forms when localized infiltration gets perched above a layer of low hydraulic conductivity, or when localized infiltration causes a rise in the water table (Poeter et al., 2005). Stormwater infiltration basins can create groundwater mounding if the infiltration rate of water exceeds the soil's capacity to dissipate water to the water table through unconfined flow (Thompson and Nimmer, 2007).

TFT screened fields for groundwater mounding risk to ensure MAR projects do not impact infrastructure or result in saturated conditions in the root zone. Three metrics were applied to assess fields for mounding risk: 1) depth to groundwater, 2) SAGBI rating, and 3) soil texture.

Depth to groundwater screening. Groundwater elevation relative to the ground surface is a key criterion for mounding risk because a shallow depth to groundwater may impede the dissipation of water infiltrated by MAR. TFT assumed the mounding risk would differ between MAR with berms (holding water on the field surface) and MAR with sumps (holding water in excavated depressions). For this analysis, the threshold for MAR with berms was set at a depth to groundwater of 10' or less, and MAR with sumps was set at a depth to groundwater of 14' or less. Fields with groundwater depths below these thresholds were deemed infeasible for those respective practices and removed from those analyses.

LSCE provided TFT with depth to groundwater data for the subbasin five water years (LSCE, 2021b). To determine these thresholds, TFT analyzed the depth to groundwater for each field using data from the 2005 Water Year (classified by DWR as an above average Water Year) to apply a conservative criterion that would minimize potential mounding risk.

SAGBI screening. Fields with a modified SAGBI rating of Excellent, Good, or Moderately Good were screened as potentially feasible for MAR. Fields rated as moderately poor, poor, and very poor were eliminated.

Soil texture analysis. Soil texture in the vadose zone (also referred to as "coarseness percentage") is indictive of the ease of water movement through the soil system. It is positively correlated to hydraulic conductivity, so soils with higher coarseness percentage have higher hydraulic conductivity. Coarseness percentage was used to screen out fields with low hydraulic conductivity to reduce mounding risk. TFT applied the following six steps:

1. Choose the design storm and determine the volume and duration of precipitation.
2. Choose a threshold of time required for that volume of ponded water to infiltrate.
3. Use the outputs from steps 1 and 2 and calculate the required hydraulic conductivity (Ks) velocity to infiltrate that volume within the required time threshold.
4. Define the association between Ks and coarseness percentage using a machine learning algorithm.
5. Select the coarseness percentage associated with the required Ks as the threshold for determining which fields are feasible for MAR.
6. Vertically and horizontally interpolate coarseness percentage based on a soil texture model and calculate the average texture for each field.

For Step 1, the design storm chosen was based on the NOAA Atlas 14 (Perica, 2014) ratings for duration and intensity of a storm event in Winters, California. A "10-year storm" intensity was chosen with a duration of 24 hours, and the volume of precipitation from such a storm was estimated.

For step 2, the threshold time limitation chosen for the ponded water to infiltrate was two days. The selection of two days was based on anoxic tolerances of selected perennial crop (see crop compatibility section below).

For step 3, the required Ks for that storm's volume to infiltrate was calculated. To do this, it was assumed that the soil was saturated at the onset of the rain event and that, in a saturated state, the infiltration rate would be same as the hydraulic conductivity. The resulting formula is:

*hydraulic conductivity (Ks) = (rainfall intensity * rainfall duration)/(time allowed for ponding)*

For step 4, Ks data was associated with coarseness percentage data. Both datasets were provided by LSCE and calibrated for the Solano Subbasin.[4] TFT applied a machine learning algorithm that used a multi-layer Perceptron regressor from the "sklearn" python package. The independent variable was the coarseness percentage, and the dependent variable was hydraulic conductivity (Ks). The analysis was constrained to the first two soil layers (0- 25' and 25-75' respectively). An arithmetic mean of the coarseness percentage and a harmonic mean of the hydraulic conductivity was taken for each layer to get average values for each field. The data was split into training data and validation data. Once the model was trained, it was run to find a corresponding coarseness value for the required Ks value that would drain a 10-year storm within 48 hours. The resulting coarseness value was 30%.

For step 5, TFT selected the coarseness percentage of =>30% as the threshold to screen fields for mounding risk.

For step 6, TFT applied these results to the Central Valley Hydrological Model, known as CVHM (Faunt, 2009). The CVHM soil textural model comprises one-mile pixels with 46 layers, which are each 50 feet deep. TFT vertically and horizontally interpolated the data to determine each field's average coarseness percentage within the vadose zone, from the ground surface to the depth of groundwater. The coarseness percentage ultimately used to assess mounding risk was downloaded from the CVHM's texture model, a USGS developed 3-dimensional hydrological model for the Central Valley in California.

Crop Compatibility. Crop-specific suitability criteria applied were: 1) the amount of time the crop can withstand saturated soil, 2) the crop's rooting depth (shallow rooting depths are less susceptible to water logging), and 3) crops with planting dates earlier than March 15th. Fields in Solano excluded from consideration for MAR implementation altogether included: non-agricultural (nursery), olives, pistachio, rice, small grains and winter crops such as winter wheat. Almonds and walnuts were considered feasible for the MAR-Low Volume but not MAR-High Volume scenario because they have a low tolerance (but not intolerance) for saturated soils and because the amount of water-soluble nitrate typically applied would pose high risk for nitrate leaching with excessive water application. Crops considered feasible for all crop scenarios include alfalfa, citrus, corn, dry beans, grapes, grassland, pastures, mixed vegetables,

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[4] LSCE Team. 2021b. Coarseness percentage and conductivity data for the Solano Subbasin, provided by Nick Watterson (LSCE) to Stephanie Tatge (TFT) on 5/3/21.

oilseed, hay, orchard (excepting almond and walnut), row crop, soybean, stone fruit, sunflower, and tomatoes.

Water Quality. MAR has the potential to improve groundwater quality via dilution in certain circumstances, however, it also has the potential for mobilizing nitrate, other salts, and anthropogenic or geogenic contaminants that could pose risks to domestic wells and community water systems (Waterson et al., 2020; Bachand et al., 2016). MAR projects should consider historical land use, current nitrogen management, and soil permeability class (Waterson et al., 2021) when assessing water quality risk factors, along with the general PMA Implementation Considerations noted in the Solano GSP, Section 8, Appendix F.

One potential water quality risk factor is proximity to confined animal feeding operations (CAFOs) and dairy operations (Ransom et al. 2018, DeMarco, 2014; Harter et al. 2002). Likewise, a recent study used surficial nitrogen data layers from the UC Davis Center for Watershed Sciences to calculate a nitrogen balance[5] for the years 1990, 2005, and 2020 and found the small, discrete legacy nitrate loading to groundwater exactly overlapped with the footprint of dairies, confirmed by satellite imagery](Balmagia, et al., 2020). Findings from the Central Valley Dairy Representative Monitoring Program indicate substantially higher N loading per acre from dairy lagoons in comparison to croplands (LSCE, 2015). For the purposes of the feasibility analysis, TFT applied an example metric of a 1-mile buffer around dairy facilities, as a preliminary screen for potential nitrogen mobilization. TFT identified CAFOs and dairies in the Solano Subbasin using the "California Central Valley Dairies (CAFOs)" dataset (CVRWQCB, 2006) created by the Central Regional Water Quality Control Board (CRWQCB) during dairy inspections from 2005 to 2006 and hosted by the EPA.[6] TFT confirmed the presence of the three dairies manually using 2020 NAIP imagery. Aerial interpretation indicated that many fields surrounding the dairy and lagoons appear to be forage and corn fields, which are commonly spread with manure solids and slurry. It should be noted, however, that the buffer is a coarse screening tool and the boundary is not adjusted to account for factors such as groundwater flow direction, hydraulic gradient, depth to groundwater, site level nutrient management, groundwater travel time, and historical land use practices.

Numerous other tools are being developed for assessing water quality risk. Adapting these tools for a subbasin-wide analysis of MAR feasibility was beyond the scope of this effort, however, they are important for site level evaluation of MAR projects. For instance, the State Water Resources Control Board's GeoTracker database contains records for a variety of documented sites (e.g., underground tanks, clean-up sites, etc.) and environmental data from water quality regulatory programs (SRWCB,

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

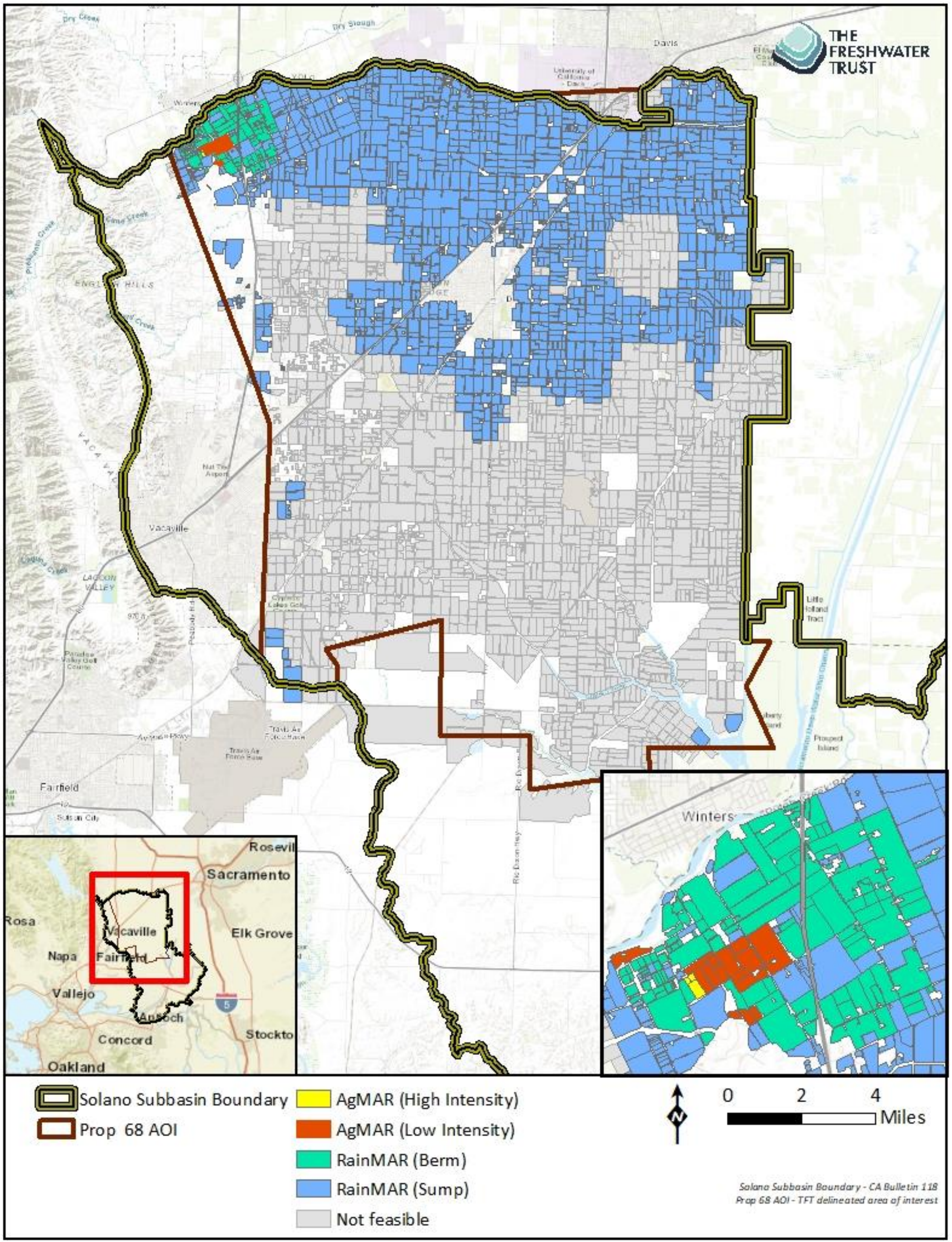
[6] The CVRWQB General Waste Discharge Requirements (WDR) Board Order R5-2010-0118 (as revised by Order R5-2011-0091), in accordance with federal law, defines animal feeding operations (AFOs) as operations with confined livestock for a total of 45 days or more in any 12-month period, and where vegetation is not sustained in the confinement area during the normal growing season. Size categories for dairy CAFOs are defined as large (700 mature dairy cows), medium (200-699 mature dairy cows) and small (less than 200 mature dairy cows). CVRWQB WDR Order R5-2007-0035 defines "Existing milk cow dairies" as dairies that were operating and filed a complete Report of Waste Discharge in 2005.

2021a). The Groundwater Ambient Monitoring and Assessment (GAMA) program provides groundwater quality data from the State's network of monitoring wells and various tools to assess groundwater risk for domestic wells and small systems (SWRCB, 2021b). Geogenic contaminants, including naturally occurring iron, manganese, arsenic, chromium, uranium, vanadium, and selenium, each have a unique set of risk factors for groundwater quality that necessitate a thorough understanding of the site-specific geochemical and hydrological conditions at MAR project sites (Fakhreddine et al., 2019). These water quality risk factors should be assessed on a site-specific basis to determine whether they occur at the site and, if so, whether application of MAR would positively or negatively impact water quality conditions.

<u>Access to Surface Water</u>. In contrast to Rain-MAR, Ag-MAR involves the application of surface water to the field for recharge. This introduces several constraints, including the need to verify water rights, the need for surface water delivery infrastructure, coordination with an irrigation district to utilize and time the delivery of water, or the obtaining of regulatory permits if water is diverted from streams. The availability of surface water is incorporated into the field classification process (Section 3.2). Other of these constraints, such as water rights, permitting requirements, and delivery infrastructure require site-specific analyses beyond the scope of this report. The result of the screening analyses is a collection of "feasible fields" as shown in Figure 9 below.

Figure 9. MAR Feasibility in the northern Solano Subbasin.

The colors of the fields below represent which fields are feasible for various types of MAR.



Updated September 2021

3.3.3. Infiltration Analysis - Methods

Once fields are classified and unsuitable fields are ruled out, the fields where MAR is feasible are analyzed for their relative infiltration capacity. A water balance equation is applied to incorporate precipitation data, evapotranspiration, and NRCS' Runoff Curve.

Water Balance equation. TFT's infiltration model uses a water balance equation at the field level to estimate the changes in water distribution given the implementation of agricultural practices. The water balance approach is a flexible method that allows various component water sources and sinks to be defined for a unit of analysis (ag fields in this case) and is manipulated to estimate how agricultural practices impact the distribution of water. The model uses field specific input volumes of precipitation and irrigation to estimate the various discharges through crop evapotranspiration, surface runoff, subsurface flows, and percolation to groundwater.

Precipitation. Daily precipitation depth (P_{tj}) is estimated for each agricultural field using an inverse distance weighted average total daily precipitation from the three nearest California Irrigation Management Information System (CIMIS, 2021) reporting stations (Figure 10). The spatial centroid of each field is used to determine the three nearest stations and the distance to them. Using an inverse distance weighted average is a scientifically accepted approach that avoids extreme values that may otherwise be observed by simply taking data from a single nearby station yet preserves the influence of distance-from-measurement overall. The estimated benefits include a range of values in representative DWR Water Years, "Critical" and "Wet", as classified for the Sacramento Valley (DWR, 2021a). CIMIS data from Water Years 2015 and 2017 were used to represent a Critical and Wet Year, respectively, representing both ends of the precipitation spectrum.

Evapotranspiration. Crop evapotranspiration represents the volume of water that a crop uses for growth and cooling. This is estimated using a modified version of the Consumptive Use Program Plus (CUP+ version 6.1), developed by DWR (Orang, 2005). Irrigation inputs are the predominant source of non-precipitation water entering the water balance equation, but applications could also include the volume of water applied for MAR. Irrigation is assumed to be applied in situations where crop demand exceeds precipitation; this excessive demand is also referred to as Et_{aw}. To meet Et_{aw}, it is assumed that producers apply this volume, plus an amount equal to the inefficiencies of a given irrigation system. Efficiencies are assumed to be 65, 75, and 90 percent efficient for flood/furrow, sprinkler, and drip irrigation, respectively.

Runoff Curve. The quantity of water leaving the field as runoff is estimated using the runoff curve method as described in the National Engineering Handbook (USDA-NRCS, 2004). Runoff curves estimating the quantity of direct runoff (surface, channel, and subsurface flow) are defined for various curve numbers, which are a function of a hydrologic soil group, land use class, and the hydrologic condition. Hydrologic soil group describes the types of soil underlying an area of interest by assigning a letter identifier ranging from A-D retrieved from the NRCS web-soil survey, where A soils have the lowest runoff potential, and D soils have the highest (USDA-NRCS, 2019). Soil types are estimated for a given field using zonal statistics to calculate a majority soil type of that field. Land use class describes the type of use occurring on a given field in terms of the general crop class (row, grass, orchard, etc.) and the treatment (practices like conservation tillage, no-till, contour farming, etc.) occurring on that field that affect runoff. Land use classes are derived from CropScape data during the field classification stage.

Treatment class is a function of the practices modeled and the crop type as tillage method is a crop-based assumption in the model. Hydrologic condition qualitatively (good, fair, or poor) describes the infiltration potential of a field as a function of land cover (both density and frequency), field slope, crop residue, and grazing intensity. An additional adjustment is made to the initial assignment of a curve number to account for 5-day antecedent runoff condition (ARC) for precipitation and irrigation. This ARC adjustment is made to account for the increased likelihood of soils either being saturated or dried out. The ARC adjustment is made to the curve number and shifts it down in the case of low precipitation, which lowers expected runoff, and up in the case of high precipitation, which increases expected runoff (Schiariti, 2021).

Given the mass balance requirement of water in the hydrologic cycle, the remaining volume of water is assumed to be storage in the soil and groundwater. Following the definition of runoff using the curve number method, a portion of that runoff represents subsurface flow. Therefore, the remaining balance is assigned to the atmosphere and groundwater, with 85 percent of the storage value to groundwater, and 15 percent to remaining storage.

Calculations for Sumps. The inclusion of sumps on a Rain-MAR field adds an additional complication to the calculations as water entering the sump, infiltration rates, and a sump's water holding capacity need to be included.

Due to lack of reliable data for which fields have existing sumps, it was assumed that when this practice exists as a feasible alternative, a sump is added to the edge of the field. Adding a sump requires the following assumptions:

1. Length of the sump is ¼ the perimeter of the field area as determined using GIS
2. Width of the sump is 40 ft.
3. Depth of the sump is variable with the field's winter ground water depth, with a limiting condition that there remains 10 ft. between the bottom of the sump and the water table estimate. The sump is assumed to have 1:2 slopes on the side and represents a trapezoidal/v shaped sump.
4. Infiltration rate of the sump is equal to the field's average daily vertical k_{sat} from SSURGO.

The impact of these assumptions is evident beyond the infiltration modeling as shown in the following cost analysis section.

3.3.4. Infiltration Analysis - Results

The foregoing methods were applied to all suitable fields to determine the relative efficacy of MAR across the Solano Subbasin. This section summarizes the results.

A map of the feasibility of Rain-MAR and Ag-MAR in the Solano Subbasin is presented in Figure 8 In general, the feasibility of Rain-MAR was higher because Ag-MAR has increased risk for causing standing water on cropped fields. Additionally, Rain-MAR is not restricted by access and operational constraints associated with surface water delivery.

Further analysis was conducted on the MAR feasibility Rain-MAR-feasible fields to visualize the distributions of resulting infiltration volumes. Histograms were generated for both infiltration volumes (acre-feet) and infiltration in linear feet (i.e., infiltration volume normalized by field area) as shown in

Figures 11 and 12. Here, infiltration refers only to *additional* infiltration resulting from MAR practices. The scenarios include Rain-MAR with sumps, Rain-MAR with berms, Ag-MAR with high volumes and Ag-MAR with low volumes. Each feasible field may be represented multiple times based on the different variations of MAR scenarios that were modeled.

In Figure 11, the left and right histogram distributions are to be expected for volume and feet (respectively) of infiltration, with most field scenarios infiltrating smaller volumetric amounts because they are smaller in acreage. However, examining the summary statistics in Table 2 more than half of the scenarios produced zero additional infiltration (e.g., the median infiltration is zero). This finding is true for both volumetric infiltration and linear infiltration (controlling for field area). This finding is likely related to the ARC calculation described in the methods section above. The ARC is an adjustment to the Curve Number method based on the estimated soil moisture resulting from the preceding five days' rainfall patterns estimating soil moisture. (The Curve Number method is a simple procedure developed by NRCS to estimate the total storm runoff from total storm rainfall in an ungauged watershed.)

By recalculating these summary distributions for Wet Years and Critical Years separately (normalizing by field area), this ARC effect becomes clearer, as seen in Figure 12. The model assumes most short and infrequent rainfall events, which are the most common rainfall event during drier years, do not generate any runoff because the soil moisture is so low that the small precipitation volume remains in the vadose zone. This low soil moisture in drier water years means that implementing Rain-MAR during those years would not produce any *additional* infiltration benefits (nor any prevented runoff benefits) for many of the field scenarios.

Table 2. Summary Statistics of Infiltration Benefits

	Min	1st Quantile	Median	Mean	3rd Quantile	Max
Acre Feet	0	0	0	1.79	0.22	94.56
Feet	0	0	0	0.05	0.04	1.06

Figure 10. Precipitation.

Precipitation means, by month, for a Critical Year and Wet Year. Rain-MAR is only simulated for the months of December, January, and February. Precipitation data from CIMIS (DWR, 2021c); Water years from DWR Hydrologic Classification Indices (DWR, 2021a): critical year: 2015; wet year: 2017.

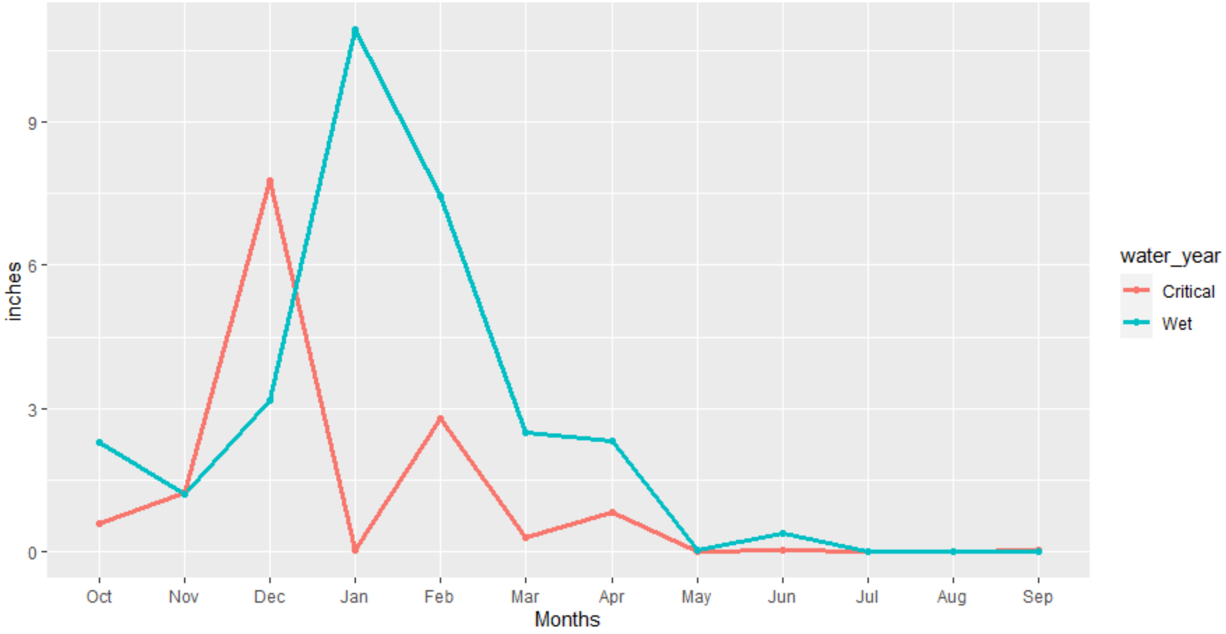


Figure 11 a & b. Summary statistics of infiltration.

Summary statistics of additional infiltration on each field due to MAR implementation. Top histogram shows the count of fields with the acre-feet volumes on the y-axis, bottom histogram shows the count of fields with acre-feet per acre infiltration (e.g., the infiltration normalized by area).

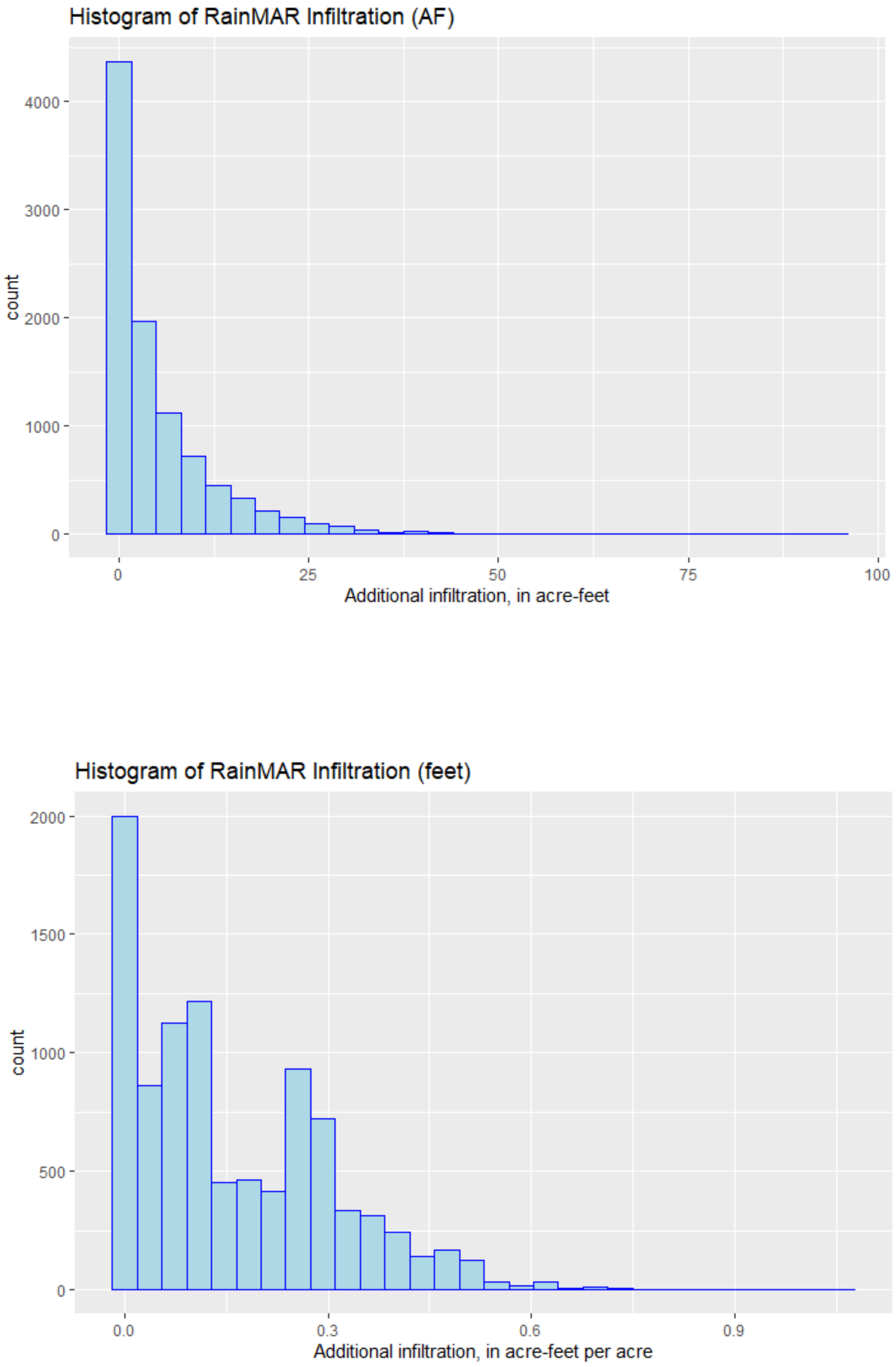
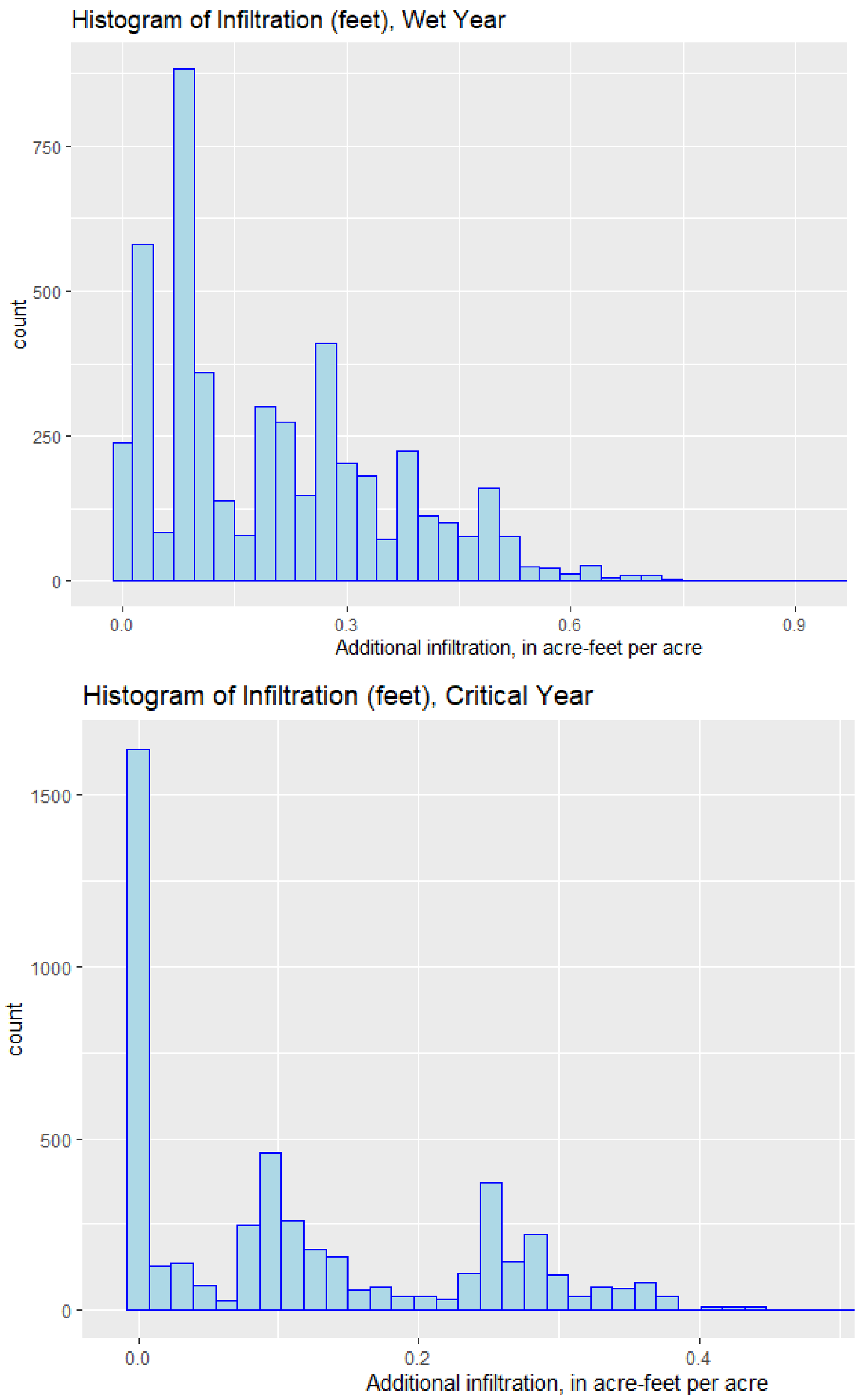


Figure 12 a & b. Summary statistics of infiltration, AF/acre, by water year.

Top histogram shows the count of fields in a wet year, bottom histogram shows the count of fields in a critical year (infiltration is normalized by area in both histograms). Over 1,500 fields had 0 infiltration benefits during the critical year.



3.3.5. Cost Analysis - Methods

A cost-benefit analysis framework[7] was used to inform priority-setting and investment decisions in planning agricultural management practices focused on recharge. It aggregates annual costs with practice implementation over a defined period. The economic components of adding recharge practices to a farming operation is dependent on several field level details and existing practices. Aggregated annual values are output as a net present value (NPV), using a 3 percent discount rate of implementing a single or multiple actions over a defined period; for the purpose of this analysis, 10-years is used. Field level costs and benefits are evaluated as private (incurred/realized by producers), resulting in a more comprehensive analysis that is useful to producers, conservation planners, and various state and federal agencies. Researching, organizing, standardizing, and aggregating the data needed to complete the cost/benefit analysis requires a wide variety of sources. Crop enterprise budgets from the University of California Cooperative Extension and NRCS practice standards provided the basis for many of the values used in the module, but technical reports, peer-reviewed literature, professional opinion, and USDA data were used to develop the final values. All values were transformed into standardized units.

Net benefits. The model development starts with identifying the net benefits associated with any given recharge practice on an annual basis. A partial budgeting approach (ISU, 2018) described/quantified the changes in expected cash flows, given the implementation of a recharge action; this resulted in a baseline cost of $0. When benefits are not monetized, the resulting net benefit is negative, indicating a cost.

The economic components of adding MAR to a farming operation depend on numerous unobserved field level details and existing practices. Therefore, the costs considered are expected to represent a conservative situation where the field has no existing/useable infrastructure and is not currently performing any of the necessary operation/maintenance tasks needed for this practice. The MAR practice is analyzed in two contexts (Ag-MAR and Rain-MAR), with multiple economically unique scenarios in each dependent on the management method (sump or berm) and the MAR source (applied water or precipitation).

The model calculates the present value of costs over the defined period based on various combinations[8] of the following components:

Rain-MAR (Sump)

- Operation (Sump Preparation)
    - This is an annual cost for clearing vegetation from the sump via mowing. Costs are informed by both California NRCS practice standards and interviews with landowners in Solano County.
- Operation (Sump Excavation)
    - This is an establishment cost for initial excavation of a sump. Because there are insufficient data to determine which fields have a sump, all fields were assumed to need a sump constructed to use this practice. Excavation costs are based on $/cubic yard estimates from California NRCS practice scenarios.

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[7] As applied, with no monetized benefits, the analysis functions as a present value cost analysis, and the reporting metric is the net present cost.

[8] See Figure 13 for cost schedules used in the analysis

- Operation (Field Preparation)
    - This is an annual cost for grading land after harvest of annual crops to facilitate water flowing into the sump. The cost estimates are based on multiple sources for general field operations, and do not represent the use of any specific implement or method.
- Maintenance
    - This is an annual cost to remove sediments that are loaded into the sump and eventually decrease its holding capacity. The current assumption is that the maintenance is performed annually, but sumps may only require clean-out every 5 yrs. Excavation costs for cleanout are estimated as 20 percent of initial excavation costs.
- Flashboard Riser
    - Flashboard riser is assumed to be necessary in each sump. This is to prevent flooding on adjacent fields and control the water levels in the sump. Cost estimates are applied from California NRCS practice scenarios.

Rain-MAR (Berm)

- Operation (Field Preparation)
    - Field preparation is assumed to consist of construction of temporary berms/checks to retain precipitation in the field area. The costs are taken from the California NRCS practice scenario for the construction of temporary habitat ponds through, “Separat[ing] portions of a field with a newly constructed internal levee.” It is assumed these berms would be dismantled with normal field preparations, so no additional costs are incurred.

3.3.6. Data Limitations/Uncertainties/Issues not Addressed

Field data from the full AOI resulting from the analysis were quality-checked to determine if the values were within an appropriate and expected range and re-analyzed as needed. However, there are several data limitations and sources of uncertainty that cannot be addressed with the data available, as discussed below.

Water Rights. The screening tool does not account for water rights that may be required to do MAR. Some practices, particularly Ag-MAR, would require the verification of water rights, or permission to use private or district-owned canal systems. This would need to be done on a case-by-case basis and is not included in the analysis; therefore, it represents a possible future cost to the practices affected by water right constraints. The following agencies may have roles for recharge projects in general: the respective GSA, Solano County, and the State Water Resources Control Board (SWRCB).

Regulatory Permits. The screening tool does not define regulatory permits that may be required for certain forms of MAR. State and local public agencies in California are required to comply with the California Environmental Quality Act (CEQA) when they take discretionary actions, such as implementing a project or program that makes a significant change to the environment that is not otherwise exempted. Likewise, diversions from creeks and streams may require federal or state regulatory permits.

Water rights. Some practices, particularly, would require the verification of water rights, or permission to use private or district-owned canal systems. This would need to be done on a case-by-case basis.

Existing sumps: Through direct farmer outreach, TFT identified existing sumps on numerous fields, however, no comprehensive dataset is available to positively identify sumps across the Subbasin. Due to the lack of data and/or methods to estimate existing sumps, it was assumed no fields currently have sumps and thus require establishment of new sumps. This assumption may overestimate the excavation costs of implementing sumps, on fields where sumps already exist.

Other Physical Conditions. The assessment of conditions used in the feasibility analysis is limited to the quality and reliability of the data. TFT was unable to accurately assess existing infrastructure in many cases. Land uses change over time, which can affect the feasibility criteria, and/or the physical characteristics (size, shape) of delineated field areas. Currently, land ownership records do not exist in a form that would allow combining fields into more efficient units of analysis. On-site verification is required to inform these critical pieces of information.

3.4. Assessment of Potential MAR Benefits

The potential benefits of infiltration resulting from MAR activities on any given field were assessed. This section presents methods and analyses of potential benefits to GDEs and Drinking Water Wells in SDACs. These tools can be applied during GSP implementation to assess the potential benefits of MAR activities for specific habitats or drinking water systems within the Subbasin.

3.4.1. Potential Benefits to Groundwater Dependent Ecosystems (GDEs)

The National Communities Commonly Associated with Groundwater (NCCAG) dataset (Klausmeyer et al., 2018; DWR, 2021d) uses phreatophyte vegetation and the surface expression of groundwater (such as springs and seeps) to estimate potential GDE polygons.

Identifying GDEs under SGMA: Best Practices for using the NC Dataset (TNC, 2019) includes six best practices to identify GDEs. The first is establishing a connection to groundwater, noting, "…it is important to consider local conditions (e.g., soil type, groundwater flow gradients, and aquifer parameters) and to review groundwater depth data from multiple seasons and water year types (wet and dry) because intermittent periods of high groundwater levels can replenish perched clay lenses that serve as the water source for GDEs." Two extreme cases were considered: 3 consecutive drier years 2014-2016, and 3 consecutive wetter years 1997-1999. The DWR Chronological Reconstructed Sacramento and San Joaquin Valley Water Year Hydrologic Classification Indices (DWR, 2021a) were used to choose the wetter and drier periods. Likely GDEs are mapped in Figure 6-4 of the Surface Water and Groundwater Conditions Technical Memo for the Solano GSP (LSCE Team, 2021).

Using LSCE's GDE data, TFT applied a workflow embedded in ESRI ArcGIS 10.7 based on Darcy's Law (ESRI, 2021a, b) to estimate direction and distance of groundwater flow and distance to GDEs from each agricultural field in the Subbasin, as shown in Figure 13. When determining each field's MAR benefit type, fields whose infiltrated water eventually flows to a GDE are considered MAR fields that benefit GDEs. The output of these workflows produces a numeric "hydraulic distance to GDE" metric that is either zero or nonzero. If the field's GDE distance metric is non-zero, that field gets classified as MAR-GDE benefit.

3.4.2. MAR Influence of Domestic Wells

Summary of Community Outreach. The Freshwater Trust and Local Government Commission (LGC) engaged with groundwater-dependent communities that may be most vulnerable to changing conditions to ensure their needs and concerns are incorporated in the development of the Solano Subbasin GSP. Using publicly available datasets, TFT conducted a detailed geospatial analysis of the Solano Subbasin to identify the distribution of groundwater dependent communities[9]. The initial analysis included federal and state datasets and an analysis of socioeconomic vulnerability indicators (Houlihan, 2020; DWR, 2021g). Vulnerability indicators and more information about wells and public water systems within the Solano Subbasin can also be explored at groundwaterguide.com/map.

Findings from the above outreach generated questions from community members about shallow domestic wells going dry, inter-basin coordination on groundwater planning efforts, groundwater-surface water interactions (e.g., stormwater run-off impacting groundwater quality), water quality monitoring for private domestic wells, and land-use impacts on groundwater (particularly in relation to new housing developments). Quantitative analyses are possible to address these qualitative findings.

Following the same ESRI workflows described above for GDE benefits, TFT assessed the potential for infiltrated water from MAR areas with a high density of domestic wells. Using DWR's Online System for Well Completion Reports (DWR, 2021e), domestic well density is grouped into four categories by PLSS Section: 0-15; 16-50; 51-100; 101+ as shown in Figure 2-13 of the GSP (LSCE Team, 2021).

Figure 14 provides an example of how groundwater infiltration from MAR could potentially influence domestic wells on Sections in the latter three categories. Specifically, the map identifies each field where (i) MAR is feasible and (ii) the field is hydrologically connected to a Section with higher well density. If a field is connected to more than one higher density Section, the model defaults to the Section to which the field is hydrologically closest. These findings could be used to target MAR toward fields with potential to benefit domestic wells, or to avoid fields if potential for contaminant mobilization could impact nearby wells.

This method could also be used to assess the influence of MAR on domestic wells in DACs and SDACs (or other priority areas), however, these designations may change periodically so DAC and SDAC areas would need to be updated following the methods described in Appendix 2a of the Solano GSP Section 2 (Plan Area).

3.4.3. Potential Benefits to Aquifer Storage

One of the primary intended benefits of MAR is groundwater recharge to benefit domestic and public water supplies and irrigation. For the purposes of this analysis, groundwater storage is broadly defined as waters infiltrating primarily to unconfined aquifers. Likewise, any water that infiltrates beyond the root zone is considered a potential benefit for unconfined groundwater recharge and storage.

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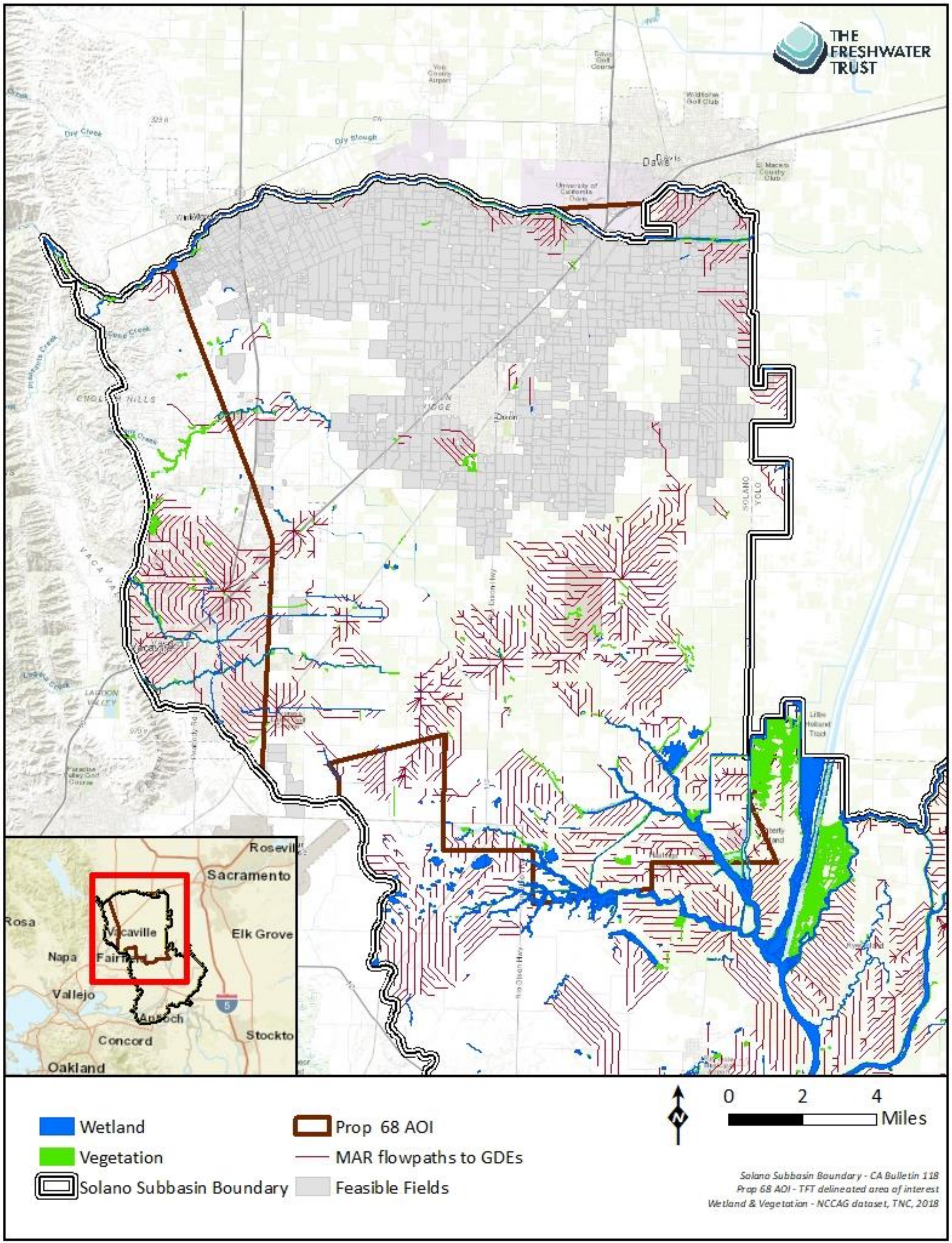
[9] Webmap created by TFT for this purpose here: https://freshwatertrust.maps.arcgis.com/apps/MapSeries/index.html?appid=b7f3791641dc4f3e8719d3ecde3a071c

Figure 13. Potential MAR influence on GDEs.

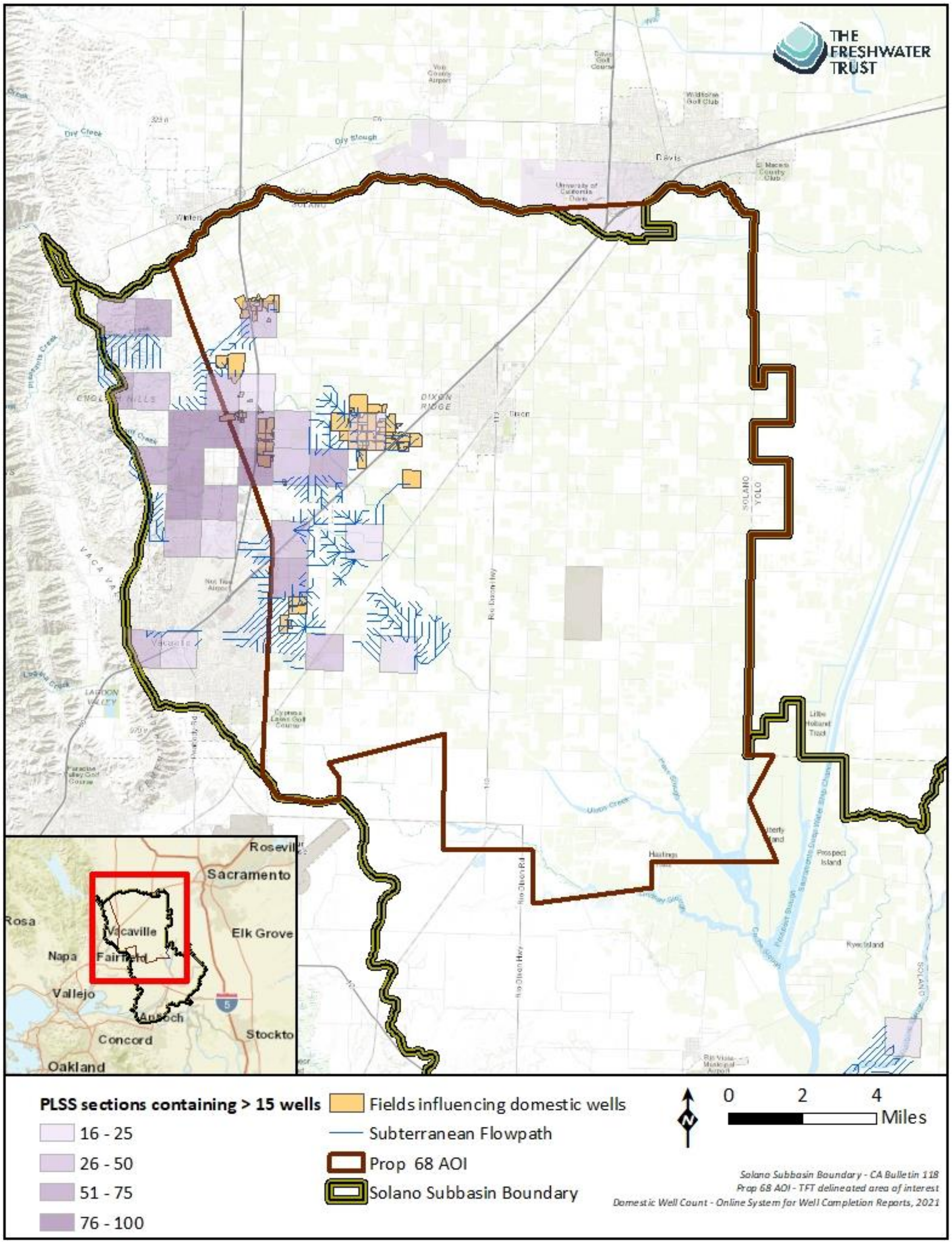
The lines below represent flow paths of infiltrated water reaching a groundwater dependent ecosystem.



Updated October 2021

Figure 14. Potential MAR influence on Domestic Wells.

Potential influence of groundwater infiltration from MAR on domestic wells Solano Subbasin with higher density of domestic wells. Red areas show the locations of a dairy/CAFO with a 1.0-mile radius buffer.



Solano Subbasin Boundary - CA Bulletin 118
Prop 68 AOI - TFT delineated area of interest
Domestic Well Count - Online System for Well Completion Reports, 2021

Updated September 2021

4. DISCUSSION

The preceding sections discuss TFT's methods for defining and modeling MAR practices at a field scale and preliminary results of MAR analyses in the Solano Subbasin. The following section demonstrates the potential application of these methods for developing projects to support groundwater management and tools that can be used to incentivize and prioritize MAR projects and other projects that benefit groundwater.

4.1. Applications to GSP

This Technical Memorandum describes approaches that can be used to implement distributed recharge strategies on lands suitable for recharge. This initial work also provides input for a potential demonstration project to field test this strategy using Rain-MAR, and management tools for GSAs to develop recharge programs during GSP implementation, as described in GSP Section 8, including:

- Overview of multi-benefit recharge projects and field-level MAR data for development of Projects and Management Actions (PMAs)
- A PMA for a proposed Rain-MAR demonstration project in the Solano Subbasin Northwest Focus Area
- A policy memo with a Credit Framework and the legal background for crediting groundwater recharge actions to create incentives for practice adoption
- A summary of the Solano Agricultural Scenario Planning System. This tool can be used by GSAs to develop cost-effective programs for implementing MAR and other conservation practices

4.2. Rainfall Managed Aquifer Recharge (Rain-MAR) in the Northwest Focus Area

The Rain-MAR PMA is a voluntary demonstration project intended to evaluate the use of specific MAR activities on local farms to generate multiple benefits for groundwater sustainability and stormwater management in the Northwest Focus Area (Figure 1). Rain-MAR was selected for assessment in this area because the practice can be implemented on an individual farm without the need for external water, delivery infrastructure, or permits, and because the implementation costs are lower than other forms of MAR. This analysis supports two components to the Rain-MAR PMA: (1) a demonstration project designed to test the practice on a small number of fields and (2) a hypothetical MAR incentive program to illustrate the recharge benefits and practice costs associated with implementing distributed MAR practices across a larger landscape.

4.2.1. Demonstration Project

The Rain-MAR Demonstration Project will involve working with willing landowners to develop and test methods for reducing sheet runoff from agricultural fields during winter storm events and managing the water for infiltration. In addition to recent localized groundwater level declines, the Northwest Focus Area drains to areas identified in the Dixon Watershed Management Plan as having floodwater and stormwater management issues.

Applying the methods described in previous sections, 108 agricultural fields are suitable for Rain-MAR within the targeted area of the Northwest Focus Area. These include five fields where both the sump and berm methods are feasible, and 103 fields where only the sump method would be feasible. The Demonstration Project will identify up to three fields where willing landowners will implement MAR to assess the benefits and costs on-the-ground within or in the vicinity of the Northwest Focus Area.

The objectives of the Rain-MAR Demonstration Project are to:

A. Implement two methods of Rain-MAR (each on at least one field): (i) using a pre-existing end of field sump or (ii) grading temporary 18-inch berms along the field edge, to reduce runoff and increase infiltration of rainwater between December and February for up to three years. Water will be sourced by capturing winter precipitation that falls directly onto the field.

B. Design Rain-MAR practices so that they avoid or minimize impacts to the normal use of the demonstration fields for growing healthy and abundant agricultural crops, and to avoid the potential for adverse impacts to neighboring fields.

C. Evaluate the (i) volume and rate of groundwater infiltration, and (ii) the volume of prevented runoff resulting from the practice on each demonstration field as compared with similar control fields where the practice is not applied.

D. Monitor and evaluate depths to groundwater and crop health on both demonstration and control fields.

Demonstration Project: Expected Volumetric Benefits. Two representative fields were chosen to estimate the volumetric benefits of the proposed Rain-MAR demonstration project, including one field for the sump method and for the berm method. The sample fields were selected because they had among the largest modeled amounts of additional precipitation retained per acre (within each practice type). Table 4 summarizes the estimated volumetric benefits and implementation costs for each method on the demonstration fields.

The estimated benefits include a range of values in representative DWR Water Years, “Critical” and “Wet”, as classified for the Sacramento Valley. CIMIS data from Water Years 2015 and 2017 were used to represent a Critical and Wet Year, respectively, representing both ends of the precipitation spectrum. The estimated costs include implementation and maintenance of the sump and berm practices on the representative treatment fields. The sump method assumes use of any pre-existing on-farm basin.

The cost estimate reflects expenses for implementation of the practice and does not include costs for outreach, recruitment, and the design and deployment of project monitoring. In general, an additional 20 percent should be added for these tasks.

As shown in Table 4, the volumetric benefit of both forms of Rain-MAR, even when optimal fields are chosen, result in less than one acre-foot of additional infiltration per year. To have an impact on groundwater level, baseflows, or GDEs—or to have co-benefits of floodwater accumulation downstream—MAR practices would need to be implemented on a substantial number of fields distributed across the Northwest Focus Area.

Table 4. Demonstration project: estimated volumetric benefits of Rain-MAR (acre-feet)

	SUMP		**BERM**	
	Wet Year	Critical Year	Wet Year	Critical Year
Field acres (typical field)	141		117	
Annual infiltration total (AF)*	95.9	53.0	65.6	40.7
Infiltration per acre (AF)*	0.68	0.38	0.56	0.35
Prevented runoff (AF)*	112.8	62.3	77.1	47.9
Total cost per year**	$13,270	$13,270	$1,975	$1,975
Cost per AF infiltration per year	$138	$250	$30	$49

**Additional volume over what would naturally occur without MAR*

***Cost estimation methods are described below in paragraph 8.5.3.2.6 (“Economic Factors”)*

4.2.2. Modeling a Hypothetical Rain-MAR Incentive Program

To illustrate the efficacy of distributed MAR practices over a broader area, a hypothetical scenario was developed for the Northwest Focus Area to calculate the expected benefits of a multi-benefit incentive program.

Following the feasibility criteria described above and based on results of field-level Rain-MAR feasibility and cost-benefit analysis, a simulation of potential programmatic implementation of Rain-MAR throughout the Northwest Focus Area was conducted. Results are summarized in Table 5 below.

This example program scenario assumes $100,000 is available annually to implement Rain-MAR practices within the targeted portion of Northwest Focus Area over ten years. The resulting optimized landscape-level scenario includes 13 fields and results in an additional 466 acre-feet to 860 acre-feet of additional infiltration per year, depending on precipitation. The most cost-efficient feasible projects were included in this optimized scenario, which included five projects using the berm method and eight projects using the sump method of Rain-MAR. Overall, the cost of achieving additional infiltration is approximately $113/acre-foot in a Wet Year and $208/acre-foot in a Critical Year. The program would also result in a significant amount of flood mitigation via prevented annual runoff during the rainy months. The costs of achieving the additional infiltration will likely increase as recruitment of the most optimal sites is not likely to be achieved.

Table 5. Hypothetical MAR Program: estimated volumetric benefits of Rain-MAR (acre-feet)

	Wet Year	**Critical Year**
Total program acres	1,098	
Infiltration total (AF)*	860	466
Infiltration per acre (AF)*	0.78	0.42
Prevented runoff (AF)*	1,011	548
Total cost per year	$96,940	$96,940
Cost per AF infiltration per year	$113	$208

**Additional volume over what would naturally occur without MAR*

The Solano Subbasin GSP (Section 8) describes the development of a related model scenario that assumes that up to 50 percent of growers with fields suitable for recharge within the Northwest Focus Area would participate in the program in an average year.[10] The field selection was further filtered to exclude permanent crops, rice, and non-agricultural areas. Based on those criteria, a total potential recharge area for the hypothetical Rain-MAR program in the Northwest Focus Area was estimated to be approximately 6,100 acres. Across the 6,100-acre area, the analysis simulated an average annual increase in deep percolation of precipitation on participating fields of approximately 3,000 AF/yr.

The volumes per acre of infiltration resulting from both scenarios were in a similar range (TFT: 0.78 AF in a representative Wet Year and 0.42 AF in a Critical; and GSP Technical team: 0.49 AF average for the Integrated Hydrologic Model period from 1991-2018), indicating consistency across approaches. The additional recharge from either of these hypothetical programs could help stabilize simulated groundwater levels over the projected future water budget period.

Fields are typically optimized by cost-efficiency, which is completed by dividing each field's environmental benefit (modeled infiltration volume) by the estimated annual cost and sorting fields in descending order. TFT's cost estimates assume consistent costs from year to year, whereas environmental benefits vary based on Water Year. As indicated in Table 5, the annual cost efficiency rates are projected to be between $113 per acre-foot in a Wet Year and $208 per acre-foot in a Critical (dry) Year, assuming wide variation in precipitation from year to year.

A key purpose of the *demonstration project* proposed above is to identify site level infiltration benefits through observed infiltration measurements and verify on-farm implementation costs, thereby improving understanding of the benefits and costs of the practice on-the-ground and generating a more accurate understanding of the cost efficiency when developing incentive programs and forecasting results.

4.3. Solano Agricultural Scenario Planning System

During GSP implementation, GSAs can identify optimal fields to implement Rain-MAR, as wells other practices that benefit sustainable groundwater management, using a scenario planning tool customized for the Solano Subbasin.

The Solano Agricultural Scenario Planning System (SASPS) is a web-based application that GSAs and other local agencies can use to design voluntary programs to engage agricultural producers in on-farm sustainable groundwater management projects. Developed by TFT, with support from NRCS and in collaboration with the Dixon and Solano RCDs, the SASPS is customized for the Solano Subbasin. The SASPS was developed with funds from the Solano County Water Agency grant (Contract 18/19-08) and matching funds from a NRCS Conservation Innovation Grant *Streamlining Regulatory Compliance and Conservation Planning: Data Analytics Applications for Producers, Planners, and Agencies* (Award Number 69-3A75-17-287).

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[10] TFT has developed a separate optimization model based on the assumed rate of recruitment success will affect cost, and therefore must be defined

GSAs that need to engage the agricultural community in on-farm sustainable groundwater management projects can use the SASPS to view key agricultural metrics in their area of interest, design custom programs to meet their management objectives or budget and identify optimal areas for efficient recruitment of landowners. Practices covered by the tool focus on distributed recharge, including MAR and cover crops, and demand reduction via irrigation efficiency upgrades. GSAs can identify specific agricultural fields where these practices are feasible, view the site-specific economic cost burden to farmers implementing these practices (over 10 years), and see the impact across a suite of water resource metrics, including farm-level changes in the annual volume of: 1) groundwater or surface water use, 2) infiltrated water, and 3) runoff. GSAs can use these data to develop programs that contribute to sustainable groundwater management by reducing or delaying the need for expensive infrastructure-based projects, or by contributing complementary groundwater benefits in the project area.

To develop the SASPS, TFT classified all farm fields across the Solano Subbasin by agricultural type, irrigation system, and other physical characteristics (including soils, subsurface texture, and topography). Then a field-scale feasibility assessment was completed to determine which, if any, of these on-farm practices can be implemented on each field, either alone or in combination in the Subbasin. Environmental and economic modeling were then completed for all potential on-farm "projects" and for multiple program design scenarios, which can be evaluated against comparable current condition scenarios.

The SASPS allows users to design a custom program in one of two ways: (i) the user sets a target benefit (such as volume of water infiltrated) and SASPS determines the lowest cost scenarios to meet that target, or (ii) the user sets a budget limit and the SASPS determines scenarios that achieve the optimum level of environmental benefit within that cost constraint. The user can also select a boundary for their area of interest, including the five GSA boundaries, Special District boundaries, and the Subbasin as a whole. Further, the user can specify an expected level of landowner participation to obtain realistic cost and benefit scenarios.

A SASPS User Guide will be provided to the Solano County Water Agency upon completion of that separate grant-funded project, however, the resulting tool will be available for use by the GSAs in Solano Subbasin. Likewise, some of the analyses that are included in the SASPS (i.e. irrigation efficiency, cover crops) were developed via prior grant projects. The methodologies that underly those analyses are described in the final grant report for NRCS Conservation Innovation Grant 69-3A75-17-287, completed in 2020. (https://www.thefreshwatertrust.org/wp-content/uploads/2020/10/Final_Report_2017_National_CIG.pdf; https://www.thefreshwatertrust.org/wp-content/uploads/2020/10/Scenario-Planning-System-Methodology.pdf)

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Appendix A

NRCS Interim Practice Standard 815

GROUNDWATER RECHARGE BASIN OR TRENCH

Appendix B

NRCS Interim Conservation Practice Standard 817

ON FARM RECHARGE