Title
Modeling the Effects of Multi-Benefit Agricultural-Managed Aquifer Recharge in Colusa County, California

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Modeling the Effects of Multi-Benefit
Agricultural-Managed Aquifer Recharge in Colusa County, California

By

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THESIS

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Committee in Charge

2022

ABSTRACT

Intensive use of groundwater in the last century, as well as persistent and severe droughts, have diminished California's groundwater resources to alarming levels over the last decade. Rising in prevalence as a way of both maintaining and improving groundwater levels is agricultural-managed aquifer recharge (ag-MAR), a technique that involves actively spreading water on the ground to encourage deep percolation to underlying aquifers. In the coming years, ag-MAR may be seen as a powerful tool in sustainable groundwater management. However, ag-MAR is not only a tool to replenish our groundwater resources, as the technique also provides multiple benefits to the environment, including nearby communities and wildlife. Flooded agricultural fields can provide temporary wetland habitats while recharging water to underlying aquifers. The goal for this study was to develop groundwater models using MODFLOW to quantitatively and qualitatively assess the benefits of ag-MAR for a groundwater basin in northern California in addition to being a wetland habitat for migratory birds. Through the development of a regional parent model and a more refined child model, we simulated the effects of ag-MAR and tested scenarios of increasing recharge rates and recharge duration. From the results of the model scenarios, we determined that increasing recharge rates, either by flooding more fields in a project area or prolonging the flooding periods, will yield a significant – and positive – hydrologic effect on groundwater levels and storage. With the analysis of the groundwater models' results, it is possible to understand the hydrologic and environmental impacts of multi-benefit recharge projects, and how it can be scaled up spatially and temporally to increase the benefits to migratory birds and our groundwater resources for future projects across California.

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I am also grateful to The Nature Conservancy (TNC) for providing the funding that supported this project and myself during my two years as an M.S. student. I was greatly inspired by the initiative and reach that TNC has on projects that positively impact people, animals, and the environment. Specifically, I thank Julia Barfield, the Program Manager at TNC for the BirdReturns program, for her insights and helpful feedback over the past two years. I also thank the staff at Davids Engineering Inc., Jeff Davids and Chris Harter, for providing us with the data needed to complete this project.

Lastly, I would like to thank my parents for supporting me throughout all my years of schooling and for pushing me towards being a successful, intelligent and independent woman. I especially thank my dad, who has been instrumental during my time in graduate school, helping me stay on track with planning coursework, reading and re-reading my thesis, and being my captive audience for my seminar rehearsals. The support of everyone I mentioned above has made my time in graduate school some of the most influential years of my life.

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1. INTRODUCTION AND OBJECTIVES

1.1 Introduction

Increasing groundwater use for agriculture and public utilities in the last century have put pressure on and diminished groundwater storage in California's aquifers. The severe droughts that occurred over the last decade were exceptionally warm and dry, including some of the driest years since the late nineteenth century, further exacerbating the adverse effects of decreased groundwaterwater resources (Hanak et al., 2015). Years of decreased precipitation and increased groundwater extraction have rendered many of California's groundwater basins and subbasins to be in a state of groundwater overdraft, where outfluxes of groundwater through pumping or other natural processes (e.g. return flow to streams, evaporation) greatly exceed influxes to groundwater storage. State agencies recently tasked with achieving groundwater sustainability by 2040, known as Groundwater Sustainability Agencies (GSAs), have taken action to correct how we can locally manage groundwater resources in California in order to combat groundwater overdraft through the Sustainable Groundwater Management Act (SGMA). Given how crucial groundwater is to California's growing population and massive agricultural industry, it is imperative to practice sustainable management of this vital resource. The consequences of mismanagement of California's groundwater resources are the driving force behind the implementation of methods that can help restore and increase groundwater storage in aquifer systems across the Central Valley.

Rising in prevalence as a way of both maintaining and improving groundwater levels is managed aquifer recharge (MAR), a process that intentionally places more water into groundwater aquifers than would naturally occur using surface spreading or injection (e.g.

aquifer storage and recovery, drywells) methods (Dillon, 2005). The method of MAR used in this project, agricultural-managed aquifer recharge (ag-MAR), spreads diverted surface water onto fallow agricultural fields to recharge groundwater supplies and store water for future use. The feasibility of MAR in agricultural settings depends on water availability, infrastructure, crop tolerance, and the suitability of soil to allow for deep percolation (Dahlke et al., 2018). The suitability of soil in agricultural fields can be assessed using the Soil and Agricultural Groundwater Banking Index (SAGBI) to determine if ag-MAR would be a viable and successful method of replenishing groundwater in a certain area, depending on the rate of deep percolation through the material, residence time of water in the root zone, soil chemistry, as well as topographic and other surface conditions (O'Geen et al., 2015). As long as conditions are viable, ag-MAR can be implemented annually, providing a reliable and sustainable source of stored groundwater to be used in times of drought when other water sources are deficient.

In the coming years, GSAs may look towards ag-MAR as a powerful tool in sustainable groundwater management. However, ag-MAR is not only a tool to replenish our groundwater resources, as this application has multiple benefits to an environmental system, including nearby communities and wildlife. There are a limited number of studies that assess the multiple benefits of ag-MAR projects in addition to the apparent hydrologic response in a field's underlying water table. Although ecological benefits may be harder to measure than hydrologic benefits, considering benefits to wildlife and the environment as design outcomes may have a positive influence on gaining stakeholders to implement more ag-MAR projects. MAR projects undoubtedly have the potential to bridge the gap between two distinct but connected fields of science. Ag-MAR projects are important, especially in California's Central Valley, because they provide a sustainable way to manage and store groundwater while also being an ecological asset to migratory birds and other organisms that depend on wetland habitats (The Nature Conservancy, 2021).

Across California, groundwater extraction accounts for 40% of the water supply for farms and cities (Chappelle et al., 2017). Colusa County, like many counties in the Central Valley, is highly dependent on pumping groundwater to support their agricultural production. Increased groundwater pumping has resulted in groundwater level declines of >20 ft over the last decade, which highlights the necessity of practicing sustainable groundwater management at the local level. Implementing ag-MAR in Colusa County gives support to farmers while recharging groundwater resources for local communities' future water usage. The Nature Conservancy (TNC), in partnership with Colusa Groundwater Authority, has developed a multi-benefit recharge program to compensate farmers that volunteer their fields to be flooded during the fall season when water resources are limited but migratory bird and waterfowl habitat are in high demand during the fall migratory season (The Nature Conservancy, 2021). Desirable conditions in the fields that are conducive to both recharge and bird stopovers are those that best mimic a natural wetland habitat. The idea of the TNC project is to convert agricultural fields to temporary wetland habitats that have enough standing water and are free of orchards and other trees that would limit space in the fields and inhibit the bird's eye view of the fields from above, as migrating birds are more inclined to stop in open flooded fields (The Nature Conservancy, 2021).

Incentive programs like TNC's on-farm multi-benefit recharge program or BirdReturns, are known to produce a large proportion of open water habitats in post-harvest rice fields during times of drought (Reiter et al., 2018). BirdReturns and other incentive programs were responsible for providing, on average, 35% of the wetland habitat on the landscape during the 2013-2015 drought, with a few days even reaching up to 100% of the wetland habitat (Reiter et al., 2018). Previous results of TNC's incentive program have shown some of the largest average densities in shorebird presence in this agricultural region when wetland habitat was provided for migratory birds that are usually unable to stop in fallow rice fields (Golet et al., 2017). The timing of flooding during the fall also makes these ag-MAR sites valuable habitats for birds during migration season when habitats are in deficit, especially during drought (Golet et al., 2017). Just as incentive programs provide a means of sustaining migratory bird populations during dry years, they also provide a way of restoring groundwater resources for use during drought, which further highlights the importance of multi-benefit recharge programs.

1.2 Thesis Objective and Research Questions

The goal for this study was to develop two groundwater models using MODFLOW in order to simulate and understand the effects of conducting ag-MAR on selected field sites in Colusa County during the fall season. The first model developed was a large-scale regional model, called the parent model, which was built to derive a more refined, and local child model, which mainly focused on selected recharge sites. The development of the parent and child models allowed us to quantitatively and qualitatively assess the benefits of ag-MAR on the study area's groundwater resources, the water supply of nearby communities, and as a wetland habitat for migratory birds. In addition to quantifying the effects to these beneficial users, with the results of our models we aimed to answer the following key research questions:

1. Through the process of groundwater model development and analysis of results, what guidelines can we provide for optimizing the design of multi-benefit groundwater recharge projects like this in the future?
2. How does the timing, frequency, and amount of recharge affect the results of our model, and what are the benefits of changing each factor? Also, what would we need to monitor to measure these benefits?
3. In what ways can we use groundwater models in the context of understanding hydrologic and environmental impacts in multi-benefit recharge projects, and what answers can we derive from such models?

2. BACKGROUND

2.1 Study Area

The project area is located in Colusa County, California, in the northern Sacramento Valley region (Figure 1). Located in the Colusa groundwater subbasin of the Sacramento Valley groundwater basin, the project area is bounded by the foothills of the Coast Ranges in the west, and the Sacramento River and other surface water features in the east near the Sutter Buttes. The topography of the project area is mostly flat agricultural land, with higher topography in the southwestern area near the foothills of the Coast Ranges and in the east near the Sutter Buttes. With the exception of a few major urban centers and wildlife refuges, the land use in the area is predominantly agricultural. Agriculture in the area is supported with irrigation water supplied to growers via surface water features like canals and supply systems (Figure1).

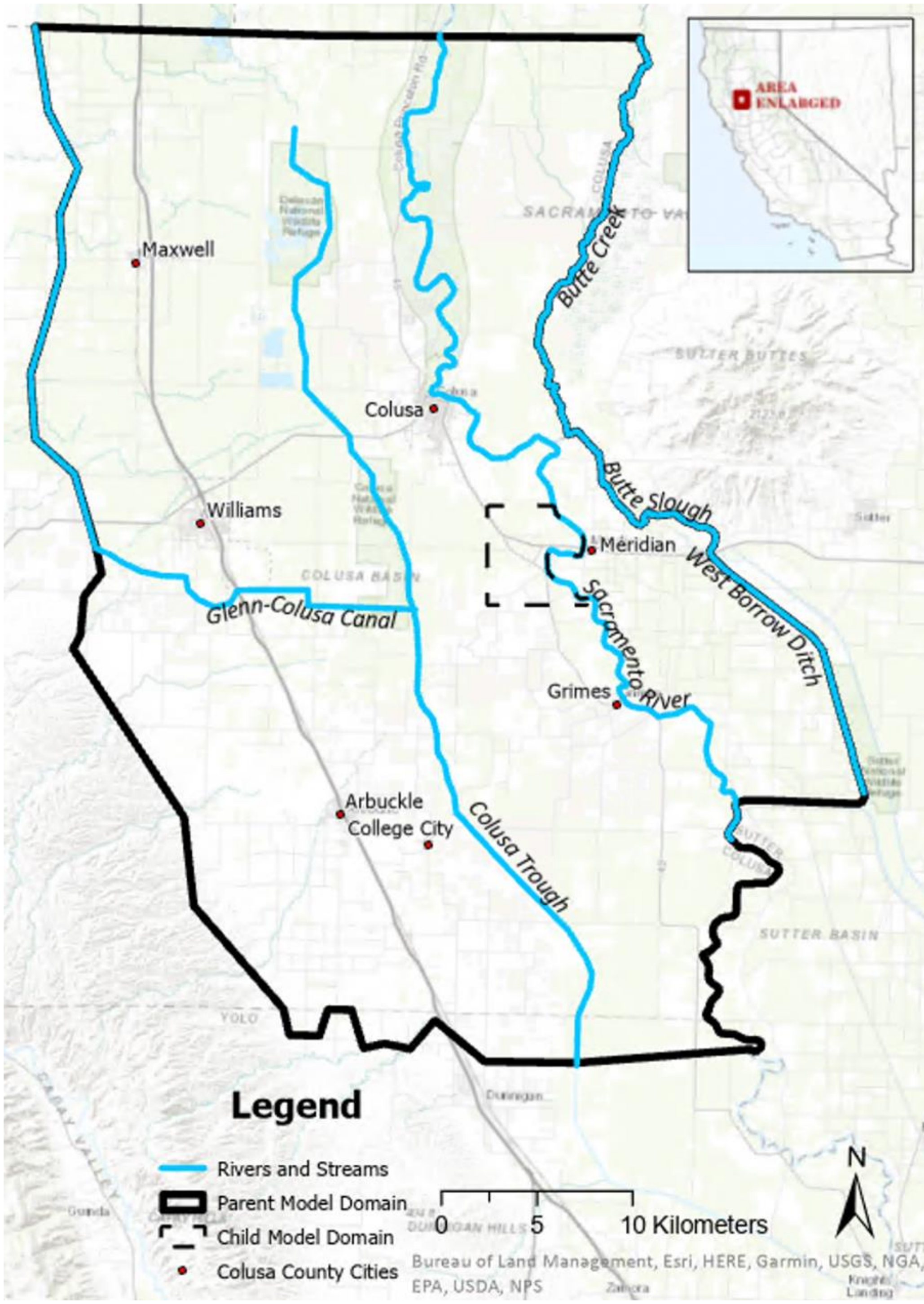


Figure 1: Map of project area, including the parent and child model domains, major cities, and major surface water features.

Major surface water features in the study area include the Sacramento River, Butte Creek, Butte Slough, the West Borrow Ditch, the Colusa Trough, and the Glenn-Colusa Canal. The Sacramento River flows north to south along the eastern border of the parent model domain (Figure1) and serves as the principal stream in the Colusa Subbasin, significantly contributing to California's water supply (Colusa Subbasin GSP, 2021). Regionally, streams that drain the Coast Ranges and Sierra Nevada serve as tributaries to the Sacramento River (Colusa Subbasin GSP, 2021). The Sacramento River is a vital source of water for landowners and irrigation water suppliers in the Colusa Subbasin in addition to providing 80 percent of inflow to the Sacramento-San Joaquin Delta (Colusa Subbasin GSP, 2021). The Glenn-Colusa Canal originates from the Sacramento River and flows through the Colusa Subbasin into Colusa County via the local canal system, providing irrigation water for the Glenn-Colusa Irrigation District, which is the largest irrigation district in the Sacramento Valley (Colusa Subbasin GSP, 2021).

The only principal aquifer in the Colusa Subbasin is contained in the freshwater-bearing sediments and stream channel deposits of the Modesto Formation, Tehama Formation, Riverbank Formation and Tuscan Formation, with the majority of the fresh groundwater in the project area contained within the Tehama Formation (Colusa Subbasin GSP, 2021). Soils conducive to recharge, based on the SAGBI rating, range from excellent to very poor suitability, with the most suitable soils in the project area falling within the good to poor suitability range (Figure 2).

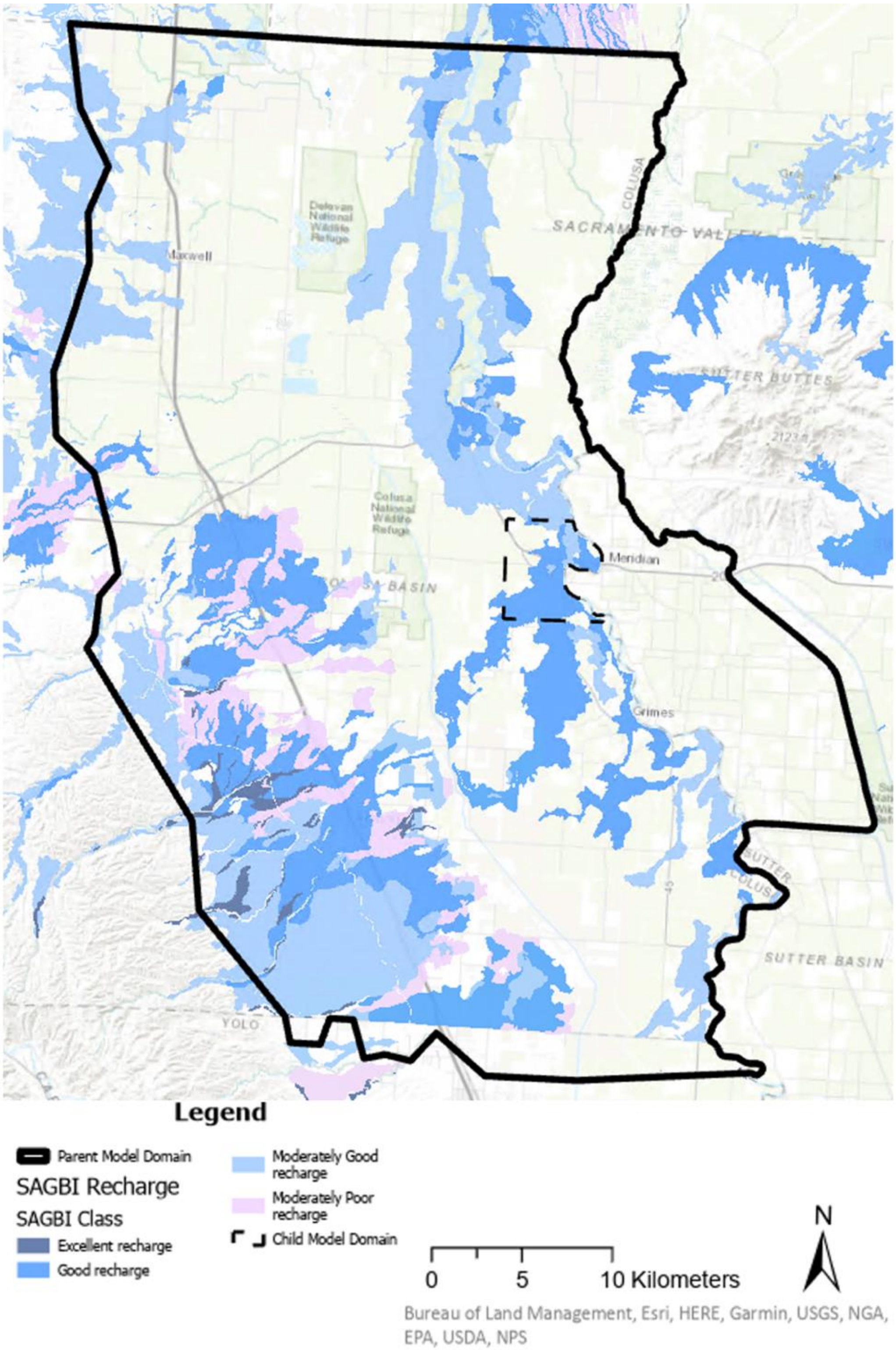


Figure 2: Map of SAGBI ratings of soils in the project area.

Hydrologic conditions of interest in the project area include a natural cone of depression in groundwater elevation levels in the middle to southern half of the parent model domain (Figure 3). Based on recent groundwater monitoring data from the California Department of Water Resources (DWR), seasonal variations in groundwater elevation (head) contours show a cone of depression forming in the center of the parent model domain during the Fall 2020 season due to stresses to the aquifer, such as excessive groundwater pumping for agriculture during the summer. Groundwater levels usually recover in the springtime, depending on how much precipitation occurred during the winter, but Spring 2021 contours still show lower groundwater levels in the same area with steeper groundwater head gradients, as opposed to other areas in the parent model domain. Groundwater typically flows away from topographically high areas like the foothills of the Coast Ranges in the west, away from the Sacramento River in the east, and flows towards the topographically low areas where the cone of depression forms. This area is heavily influenced by agriculture, and high amounts of pumping for agricultural use may be the cause of groundwater level depletion and the subsequent formation of the cone of depression and areas of low groundwater elevation.

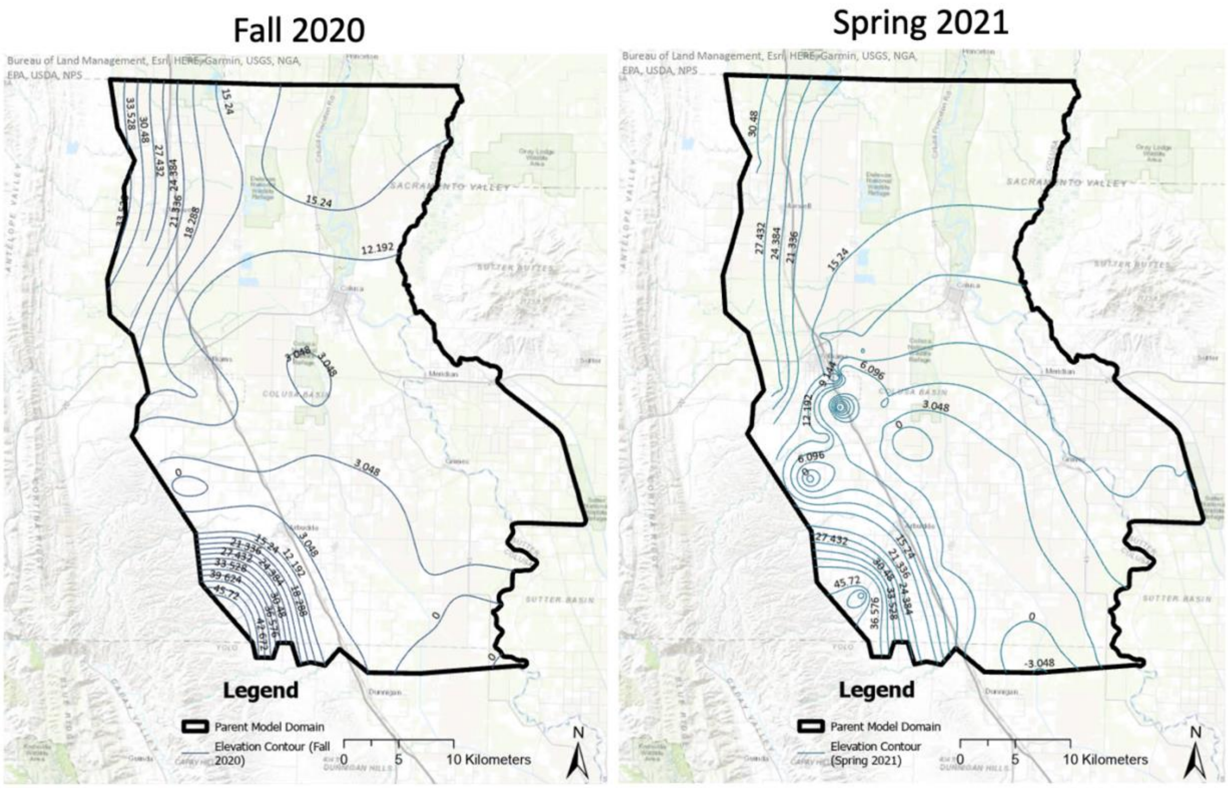


Figure 3: Map of groundwater heads, or groundwater elevation, contours (meters above sea level) from the California Department of Water Resources (DWR) showing Fall 2020 and Spring 2021 head contours within the parent model domain.

2.2 Ag-MAR Study Sites

In 2019 and 2020, TNC recruited several landowners into their fall season bird habitat and ag-MAR incentive program. A total of 8 field sites were enrolled in TNC's incentive program, which are all located in Colusa County, California (Figure 4). The nearest major cities to the ag-MAR sites are Williams, Colusa, and Meridian. The field sites modeled in this study are located near the city of Meridian, along the western bank of the Sacramento River (Figure 5). The fields (Field 2 and Field 15) are part of the Davis Ranches property. This area was chosen for the child model domain because Field 2 was the only field site that participated in flooding during consecutive years (2019-2020). The crop type grown on these fields is rice, but the fields were fallow during the period of flooding during the fall. The SAGBI recharge rating for the area in and around Field 2 and Field 15 are good to moderately good suitability for deep percolation in the soils (Figure 6). All ag-MAR field sites were chosen based on SAGBI suitability prior to flooding.

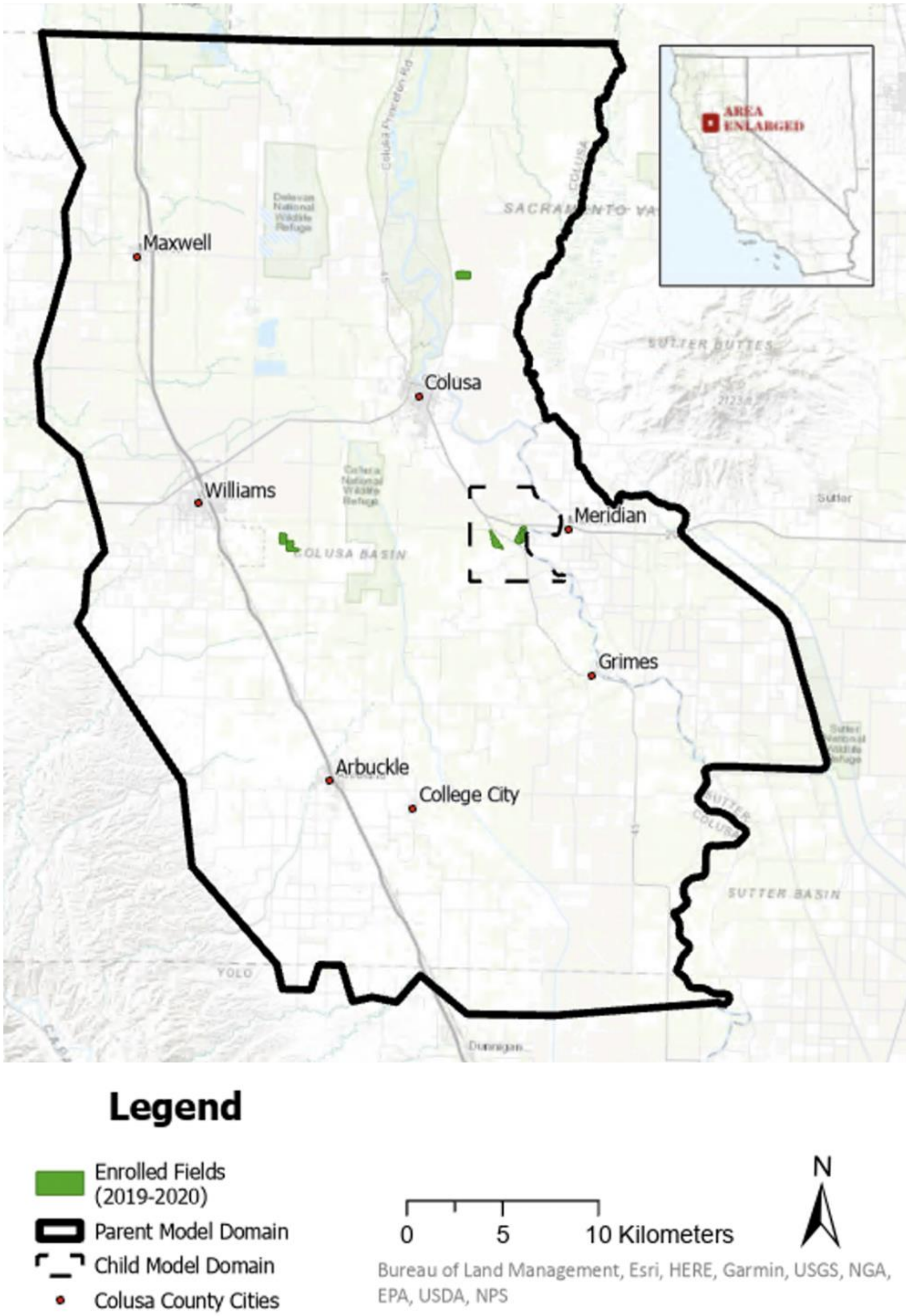


Figure 4: Map of all field sites enrolled in TNC's BirdReturns incentive program during 2019 and 2020. Only one field (Field 2), located in the child model domain adjacent to the Sacramento River, participated during both years.

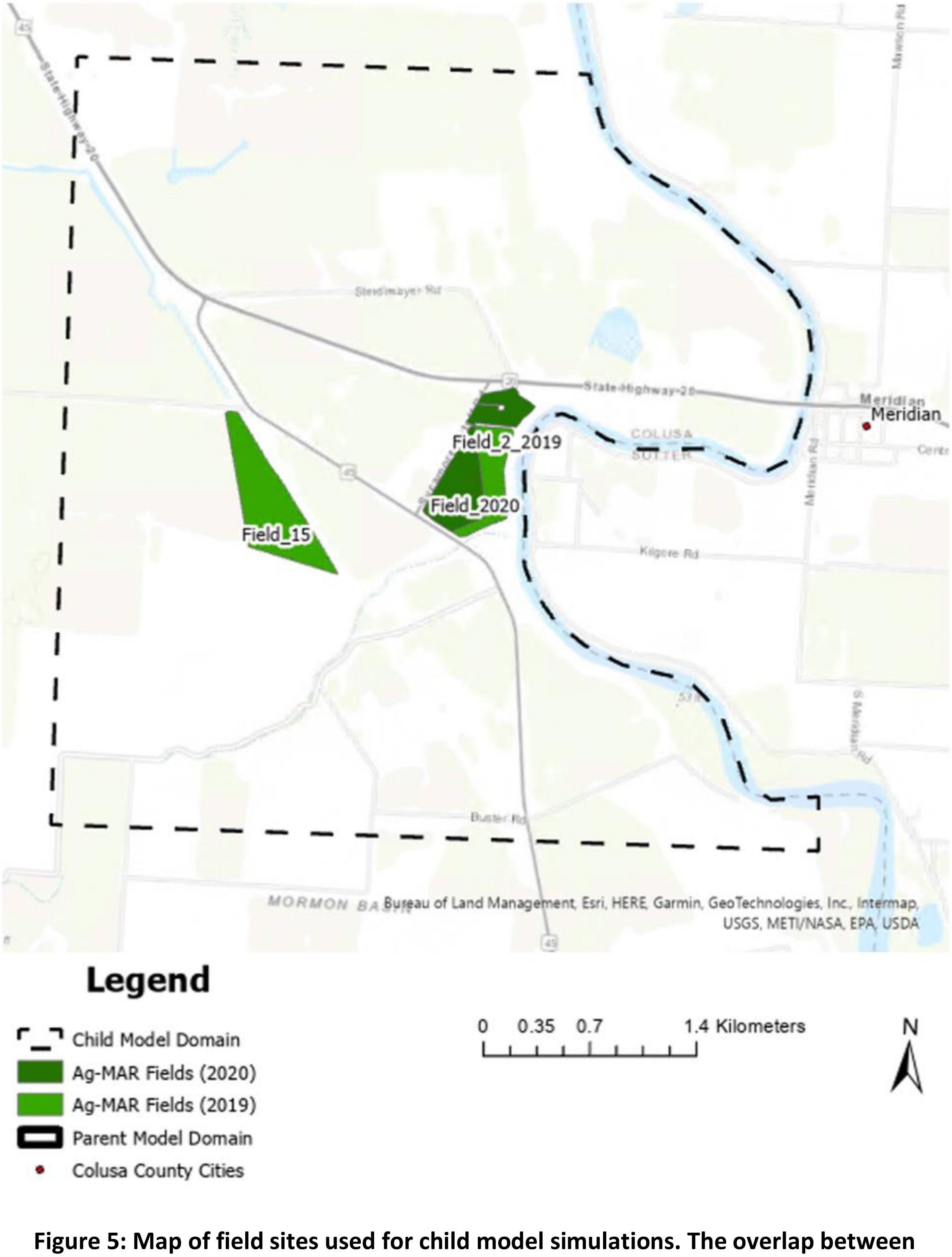


Figure 5: Map of field sites used for child model simulations. The overlap between Field_2_2019 and Field_2020 indicates that Field 2 participated in flooding during both 2019 and 2020.

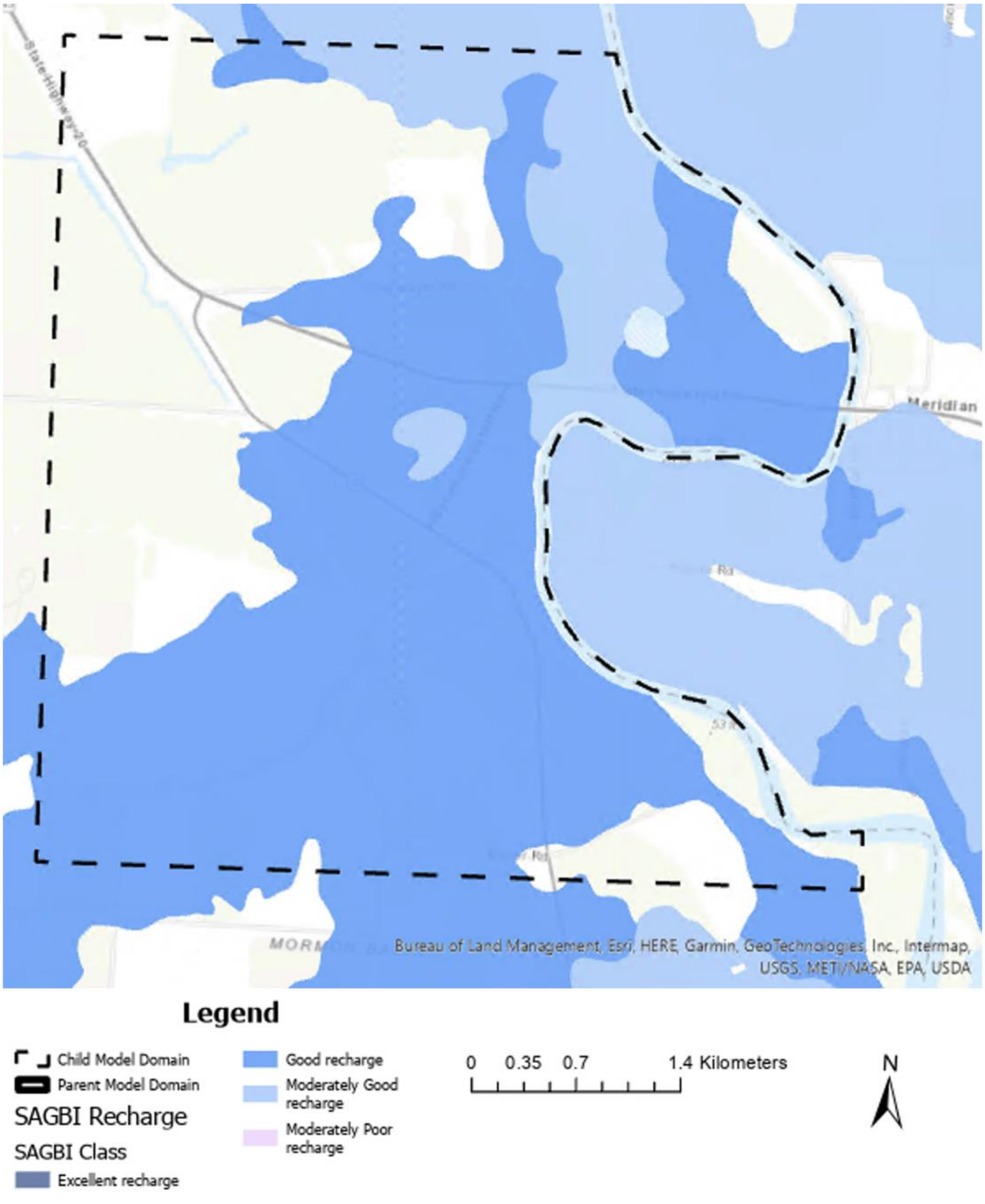


Figure 6: SAGBI map of recharge suitability of soils in child model area.

3. METHODS

3.1 Data Acquisition and Usage

The data collected and used for the two groundwater models were primarily extracted from the Sacramento Valley Groundwater-Surface Water Simulation Model (SVSim) (Bond et al., 2018), which is similar to the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim). Both SVSim and C2VSim were developed by the California Department of Water Resources, but SVSim is more specific to the northern Sacramento Valley, while C2VSim encompasses the entire Central Valley. Other sources of data include the California DWR, the United States Geological Survey (USGS), and Davids Engineering, Inc., the consulting company hired by TNC to conduct the field methods and technical analysis of the recharge program at each field site during 2019 and 2020. The data extracted from these sources were used in the MODFLOW model development process for parameterizing the packages for the parent and child models. More information on the development and calibration of C2VSim and SVSim can be found in Brush et al., 2013, and California Department of Water Resources, 2022, respectively.

Layer stratigraphy data was extracted from SVSim, as were the layer and aquifer parameters, such as specific storage (S_S), specific yield (S_Y), and vertical and horizontal hydraulic conductivity (K). The layer stratigraphy and parameter data were used to define the aquifer parameters of all 9 groundwater model layers in both the parent and child models in their discretization (DIS) packages. The uppermost layers in both models are relatively thin, with an average thickness ranging from 10 to 50 m. The lower layers are the thickest, ranging from about 50 to 200 m thick. The total thickness of all layers combined in both models is approximately 600 m (Table 1).

Table 1: Layer stratigraphy and average thickness of the layers in the parent and child models.

Layer	Average Thickness (m)	Average Thickness (ft)
1	11	36
2	10	35
3	12	40
4	24	78
5	53	170
6	80	260
7	53	170
8	80	260
9	210	690

Each field site was flooded with a depth of 4 inches of water maintained for 30 continuous days during the fall, and 60 days of deep percolation data was collected (30 days during flooding and 30 days after flooding), with deep percolation rates calculated for each site (Davids Engineering, 2020). These calculations were made using a mass balance approach – in which the inflows to the system are equal to the outflows – along with groundwater level measurements that were taken either periodically or continuously throughout the flooding period at groundwater monitoring wells adjacent to the field sites (Figure 7). Recharge took place at Field 2 during two periods, 9/18/2019-11/16/2019 and 9/17/2020-11/16/2020. Recharge took place at Field 15 during one period, 9/18/2019-11/16/2019. The average recharge rates at the three field sites ranged from 0.011 to 0.023 m/day (Table 2). Deep percolation rates for all other days, or model stress periods, in the remainder of the domain are rates averaged by month from SVSim. Davids Engineering also monitored groundwater levels in four wells adjacent to the field sites (Figure 7). We used the groundwater level data provided by Davids Engineering for our child model's head observation (HOB) package. The average depth to groundwater between all four of the monitoring wells ranged from 5.3 to 7.7 m of depth (Table 3).

Table 2: Average deep percolation (recharge) rate calculated at each field site.

Ag-MAR Site	Average Recharge Rate (m/day)	Average Recharge Rate (ft/day)
Field_15	0.011	0.034
Field_2_2019	0.017	0.056
Field_2020	0.023	0.075

Table 3: Average depth to groundwater from the ground surface for each of the four groundwater monitoring wells.

Monitoring Well Name	Average Depth to Groundwater (m)	Average Depth to Groundwater (ft)
Field_15	6.4	21
Field_2_2019	5.3	17
Well_34	6.6	22
Well_2b	7.7	25

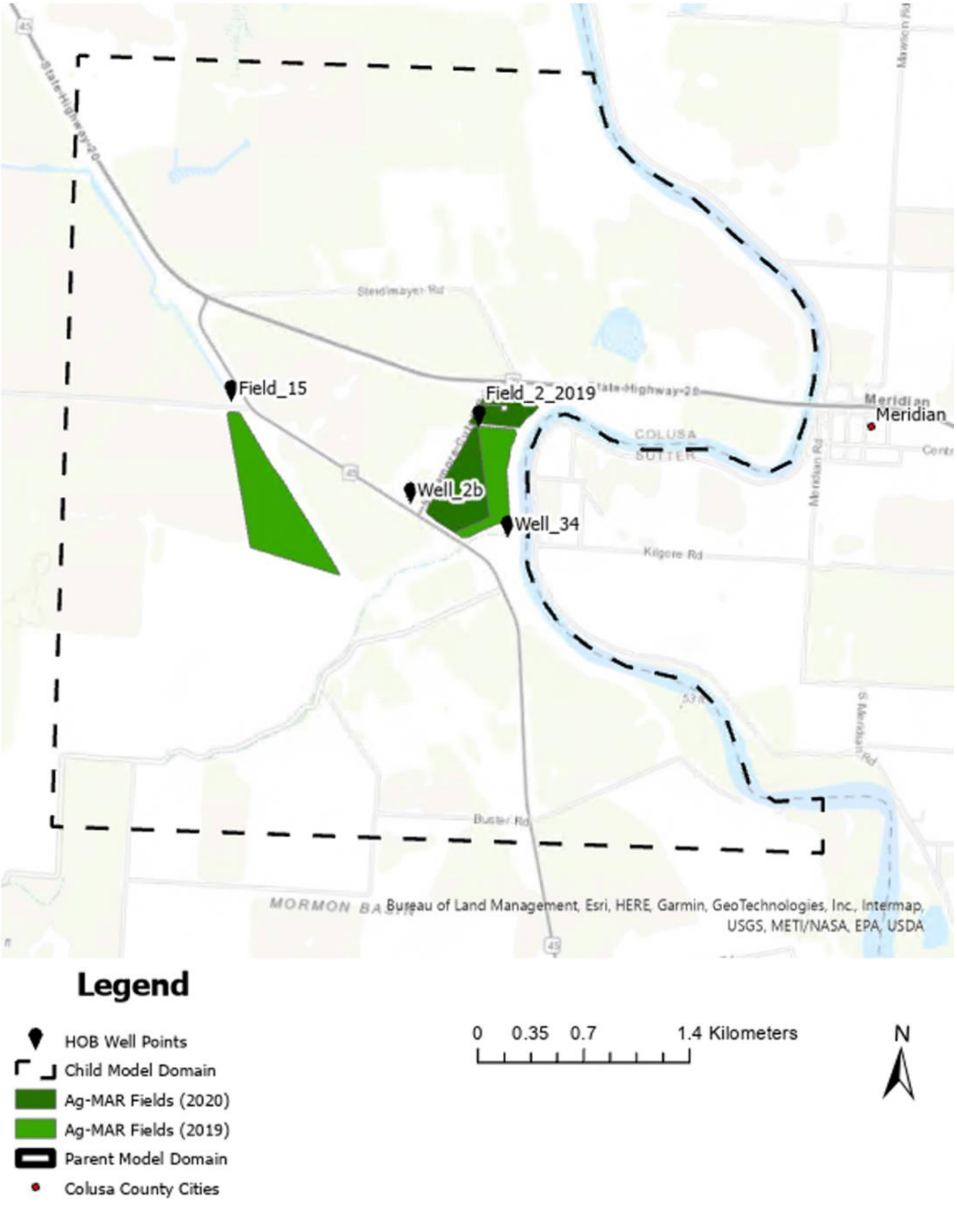


Figure 7: Map of groundwater monitoring wells and field sites.

3.2 The Numerical Groundwater Flow Model (MODFLOW)

The software used for the models constructed for this study is the MODFLOW-2005 Three-Dimensional Finite-Difference Ground-Water Model developed by the U.S. Geological Survey (Harbaugh, 2005). MODFLOW-2005, hereafter referred to as MODFLOW, uses packages that simulate the effects on groundwater flow processes of wells, rivers, lakes, and other relevant aspects and boundary conditions. A list of the packages used in both models is included in Table 4. MODFLOW can also vertically simulate aquifer systems with different geologic layers that may be specified as confined or unconfined. MODFLOW's mathematical solution for simulating groundwater flow through the center of each cell in a model follows the partial-differential groundwater flow equation (Equation 1).

Equation 1: Partial-differential groundwater flow equation.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

$S_s\frac{\partial h}{\partial t}$ = 0 in a steady-state model

The variables K_{xx}, K_{yy}, and K_{zz}, are specified hydraulic conductivity values along the x, y, and z coordinate planes (in units of L/T) (Harbaugh, 2005). The potentiometric head (in units of L) is denoted by h in the equation above, and W is the volumetric flux per unit volume that represents sources and/or sinks of water into or out of the system (in units of T^{-1}) (Harbaugh, 2005). S_s represents the specific storage of the earth material (units of L^{-1}), and t (units of T) is time (Harbaugh, 2005).

Table 4: Parent and child model packages included in both models, with a list of data used and data source for each package.

Parent Model Packages	Child Model Packages	Package Names	Data Used	Data Source
DIS	DIS	Discretization File	Layer Thicknesses	SVSim (Bond et al., 2018)
BAS6	BAS6	Basic Package		
LPF	LPF	Layer-Property Flow Package	HK, VKA, SS, SY	SVSim (Bond et al., 2018)
RCH	RCH	Recharge Package	Recharge Rate	SVSim (Bond et al., 2018), Davids Engineering
WEL	WEL	Well Package		
GHB	GHB	General-Head Boundary Package	Reference Head	California DWR
RIV	RIV	River Package	Stream Bed Conductivity, Stream Bottom	SVSim (Bond et al., 2018)
HOB	HOB	Head-Observation Package	Well Locations, Observed Head	SVSim (Bond et al., 2018), Davids Engineering
OC	OC	Output Control Option		
PCG	PCG	Preconditioned Conjugate-Gradient Solver		
RVOB		River Observation Package	Stream Gage Locations, Discharge	USGS
CHD		Time-Variant Specified-Head Package	Starting Head	California DWR

3.3 Parent Model Setup

The larger of the two models developed for this study was a steady state model that encompassed most of the area of Colusa County (Figure 9). As is the case with steady state models, all model parameters remained constant over a specified amount of time, so all input data that varied over time were averaged to one value for input. The purpose for making the large model steady state was to have all inputs to the system equal to the outputs, stabilizing the system as a whole. This provided a more general simulation of the regional hydrologic processes (Figure 8), which allowed for faster model runs and processing times. The results of this large steady state model provided information on flow magnitude and direction that was used to constrain the boundaries of the child model.

The domain for the large model spans an area of approximately 160,000 square meters and includes 9 layers, modeled after the layers in SVSim. The coordinate system used to define the parent model was NAD83 California Albers. The parent model has 140 rows and 113 columns, with a cell size of 400 m $\times$ 400 m. The number of stress periods, or days, is 1 since the parent model is run under steady state conditions. The boundary conditions used to define the model domain include 2 general head boundaries (GHB), 2 constant head boundaries (CHB), and the river package (RIV) to simulate the effects of rivers, streams, and canals that flow through the model domain (Figure 9).

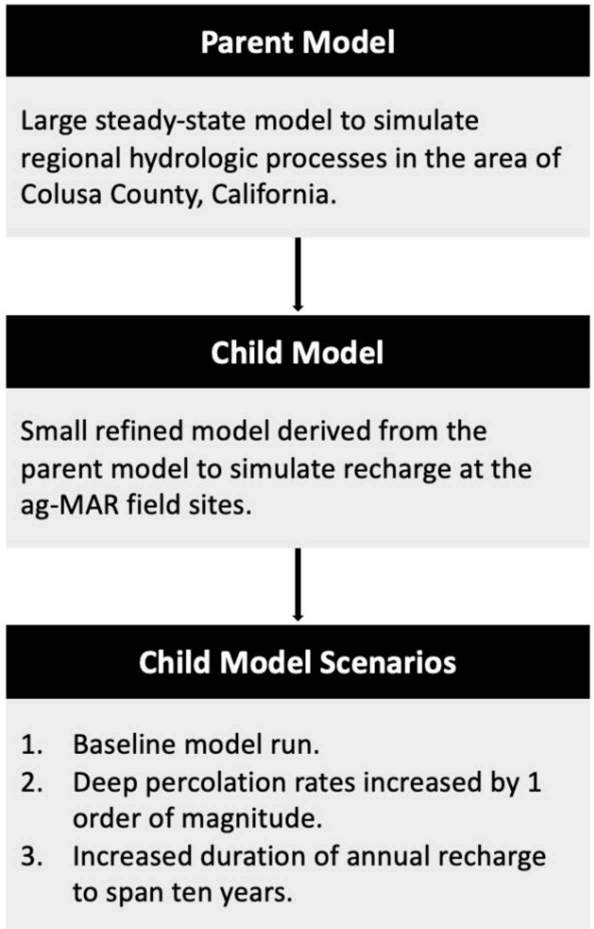


Figure 8: Flow diagram summarizing the main project components and methodology.

Figure 9: Map of parent model domain and boundary conditions.

3.4 Child Model Setup

The smaller of the two models developed for this study was a transient model that was located within the area of the parent model domain, including the ag-MAR field sites (Figure 10). Since the child model is transient, all data input for each package varied over time. The starting date of the child model was defined to be 8/18/2019, one month before the flooding occured, and the end date of the model is 11/16/2020, the last day of the flooding period. Like the parent model, the coordinate system used to define the child model was NAD83 California Albers. The child model has 58 rows and 58 columns, and each cell in the model has a size of 100 m $\times$ 100 m. The number of stress periods, or days, included in the child model is 456. Groundwater fluxes and directions of flow were extracted from the results of the parent model in order to inform the boundary conditions of the child model (Figure 11). The well (WEL) package was used to simulate those fluxes. We defined the flux from each well in all model cells on the child model's boundaries to represent the general flow that occurred in the same area of the parent model. In more specific terms, cell-by-cell flow data was extracted for each cell in every layer from the parent model, and the cell-by-cell flows were used to inform the groundwater fluxes at the boundaries of the child model. We also used the River (RIV) package to represent the small part of the Sacramento River that acts as the eastern boundary of the child model. However, the RIV package is only present in the first layer of the model, so we used the GHB package for the eight layers directly below the river cells. The recharge (RCH) package was used to represent the 2019 and 2020 ag-MAR field sites, with deep percolation data from Davids Engineering.

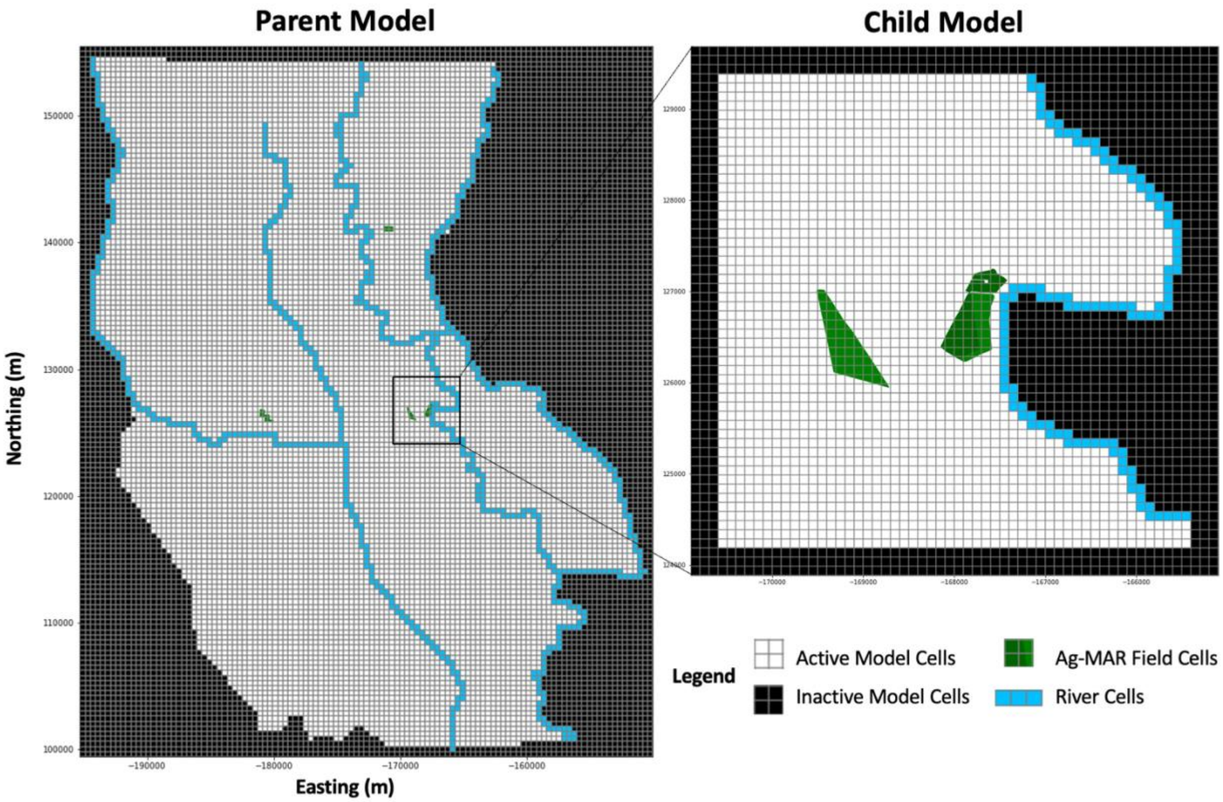


Figure 10: Map of the parent and child model cells and locations of the ag-MAR field sites.

Figure 11: Map of child model domain, ag-MAR field sites and boundary conditions.

3.4.1 Child Model Scenarios

Three different scenarios were run using the child model to test different parameters and their influence on the hydrologic response seen in the model outputs. The three scenarios were designed to assess whether the timing, frequency, and amount of recharge significantly influences the hydrologic results of the child model. Scenario 1 was the baseline model run, using the original and unaltered deep percolation data from Davids Engineering. No alterations or calibrations to the model inputs were made for this scenario. For Scenario 2, we increased deep percolation rates from Davids Engineering by one order of magnitude (multiplied rates by ten) to ascertain whether we could see a significant hydrologic response. Only the deep percolation data was altered for Scenario 2; all other inputs remained the same as Scenario 1. It should also be clarified that a tenfold increase in recharge rates is not realistic. However, we wanted to test this hypothetical extreme solely to see a significant response. For Scenario 3, we increased the duration of recharge to span ten years. We chose to use the 2019 deep percolation data, and repeated that year ten times to see how increasing the duration of recharge would affect the child model results. The 2019 deep percolation data input for Scenario 3 was unaltered; only the duration of recharge and the time discretization of the child model was increased to span ten years. Scenario 3 was designed to represent ten consecutive years of implementing ag-MAR on these field sites.

4. RESULTS

4.1 Parent Model Results

The results analyzed from the steady-state parent model include model performance plots and model outputs. We assessed the performance of the parent model with a one-to-one plot of the observed heads that were input into the model, with the simulated equivalent heads that the model calculated at each groundwater monitoring well in the parent model domain (Figure 12). The different colors on the plot represent the binned data of the residual heads, which were calculated as the difference between the observed and simulated equivalent heads. The different bins represent different groups of residual data ranges. The gray line represents the line of equal values, or one-to-one line, between the observed and simulated equivalent heads.

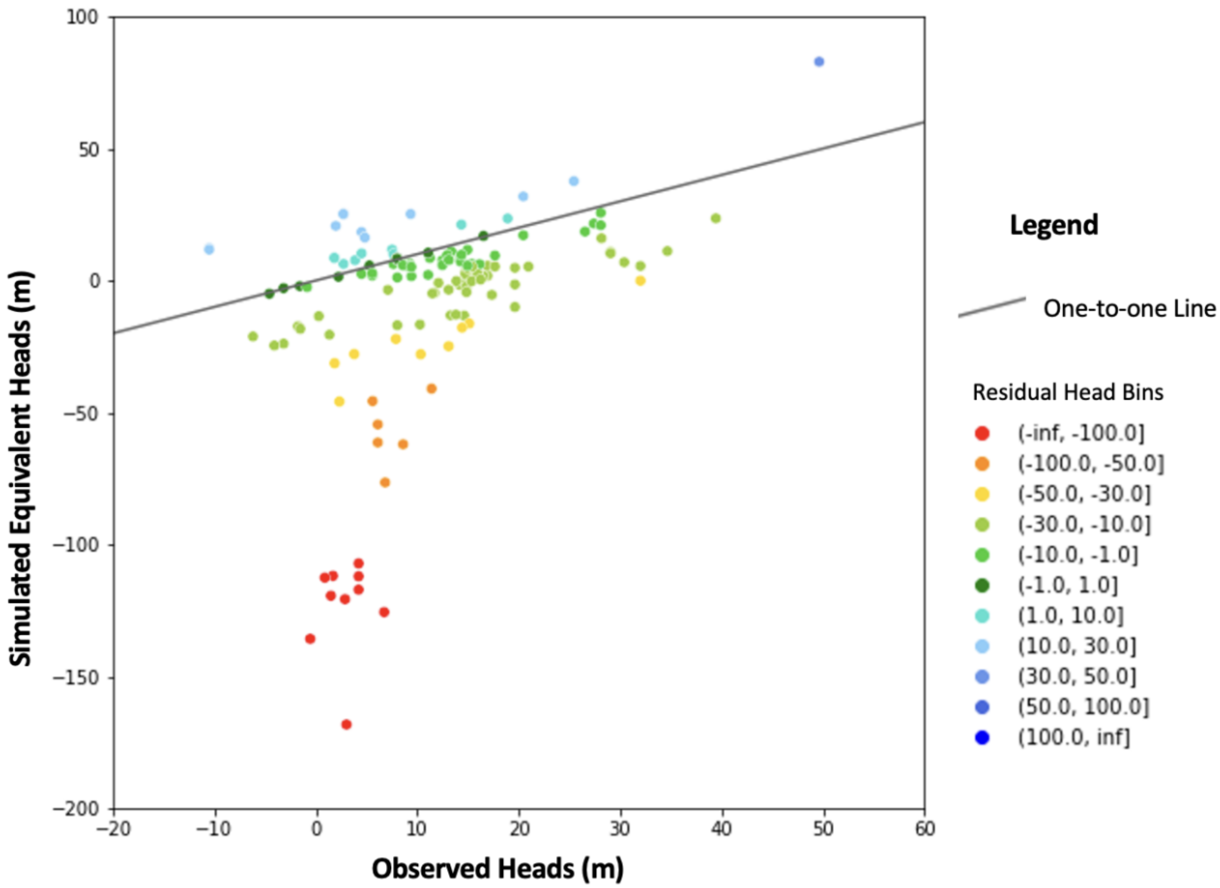


Figure 12: One-to-one plot of observed vs. simulated equivalent heads for the parent model performance.

The same binned residual head data were plotted on a map of the parent model domain, showing the location of the groundwater monitoring wells and the residual head value (Figure 13). Like the residual head bins plotted in the one-to-one plot in Figure 12, the bins for the residual map were calculated from the difference between the observed and simulated equivalent head values at each groundwater monitoring well on the map. By plotting the residuals on a map of the parent model domain, we were able to assess the distribution of wet and dry wells in our model. Blue colors indicated an excess of water in certain wells, red and orange colors indicated wells that were more "dry," and green colors represent a satisfactory residual value. A satisfactory residual value means that the difference between the observed and simulated equivalent heads were small, indicating good model performance. The black square on the residual map is a reference point for the area of the child model domain's boundary.

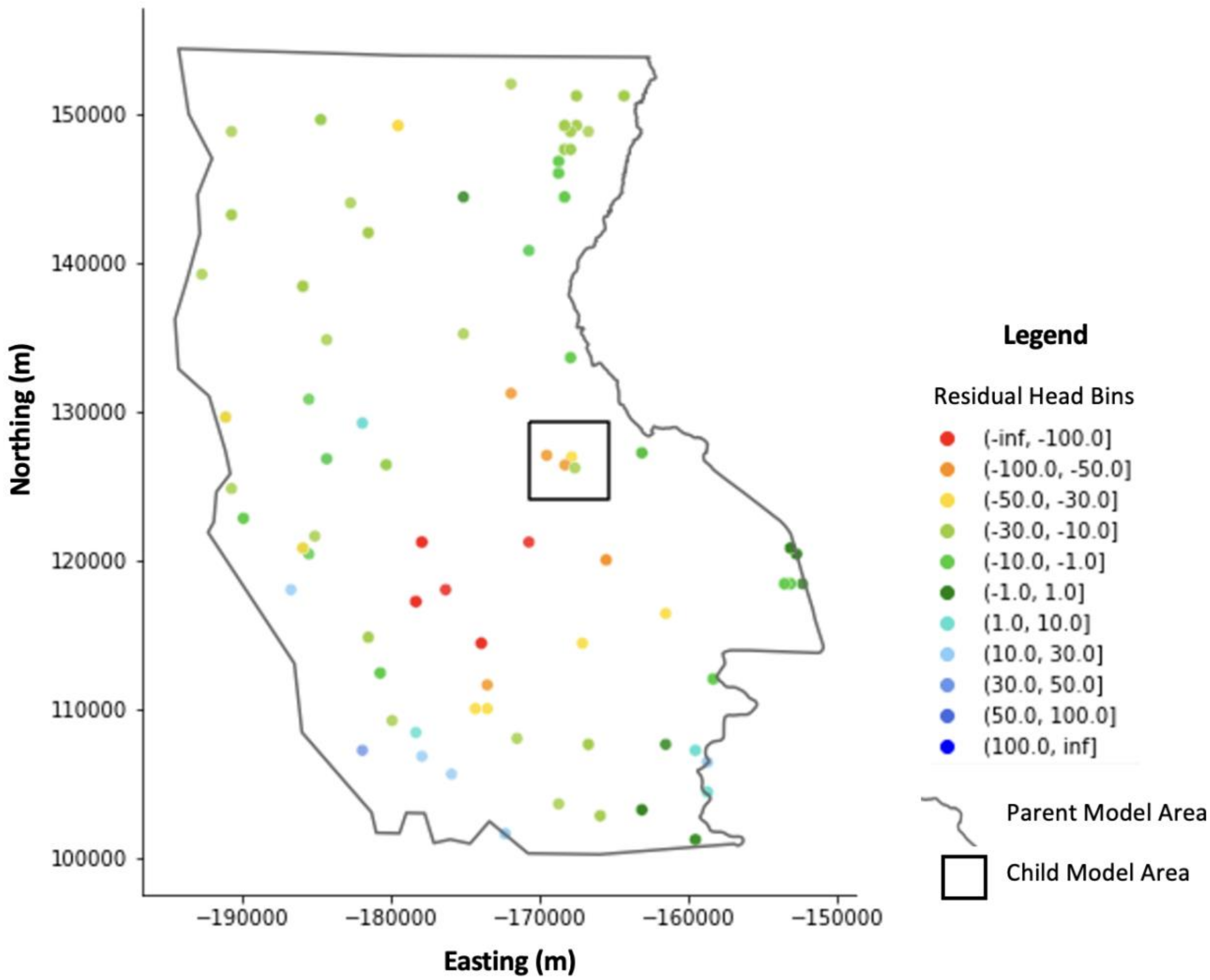
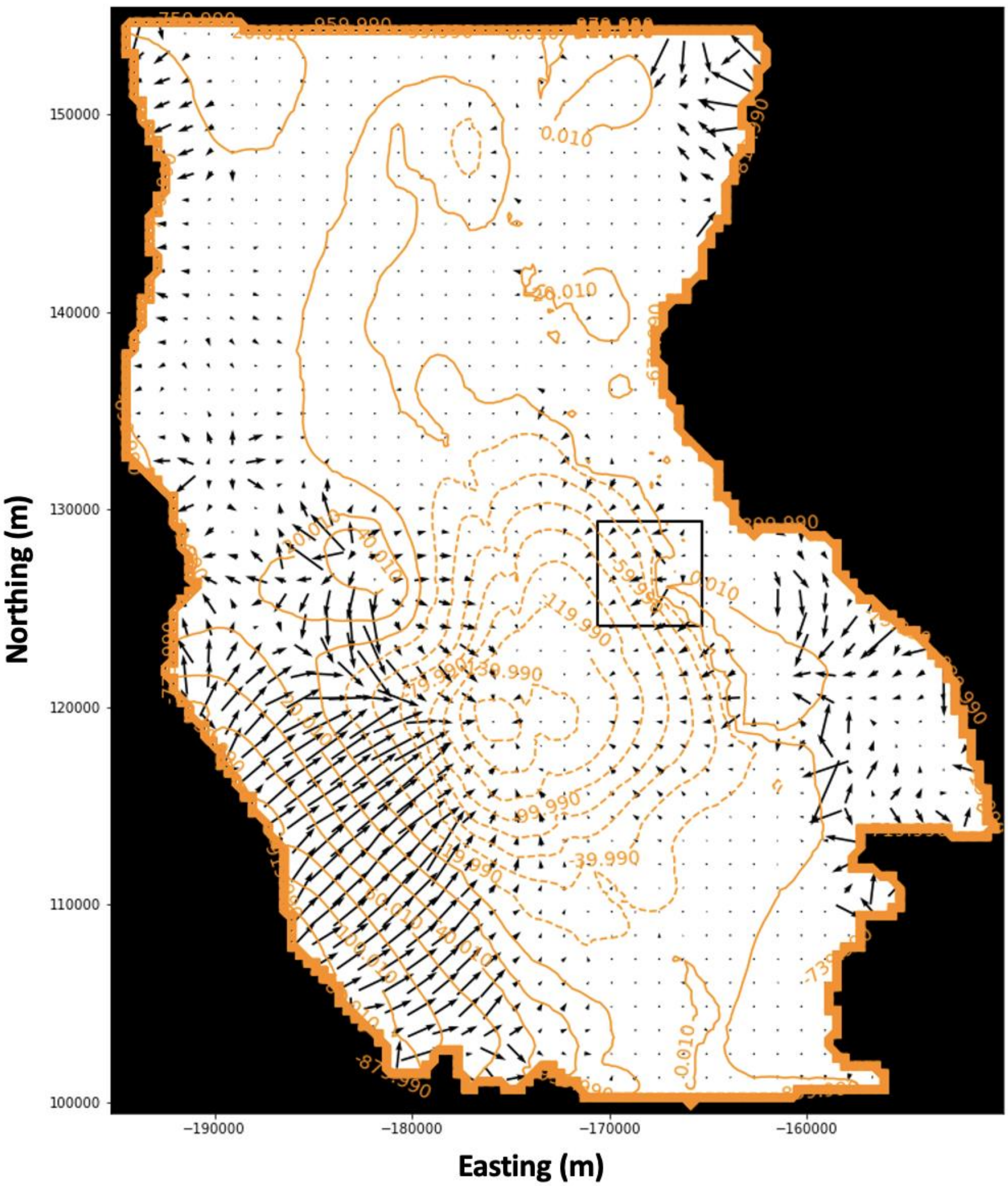


Figure 13: Residual map of heads for the parent model.

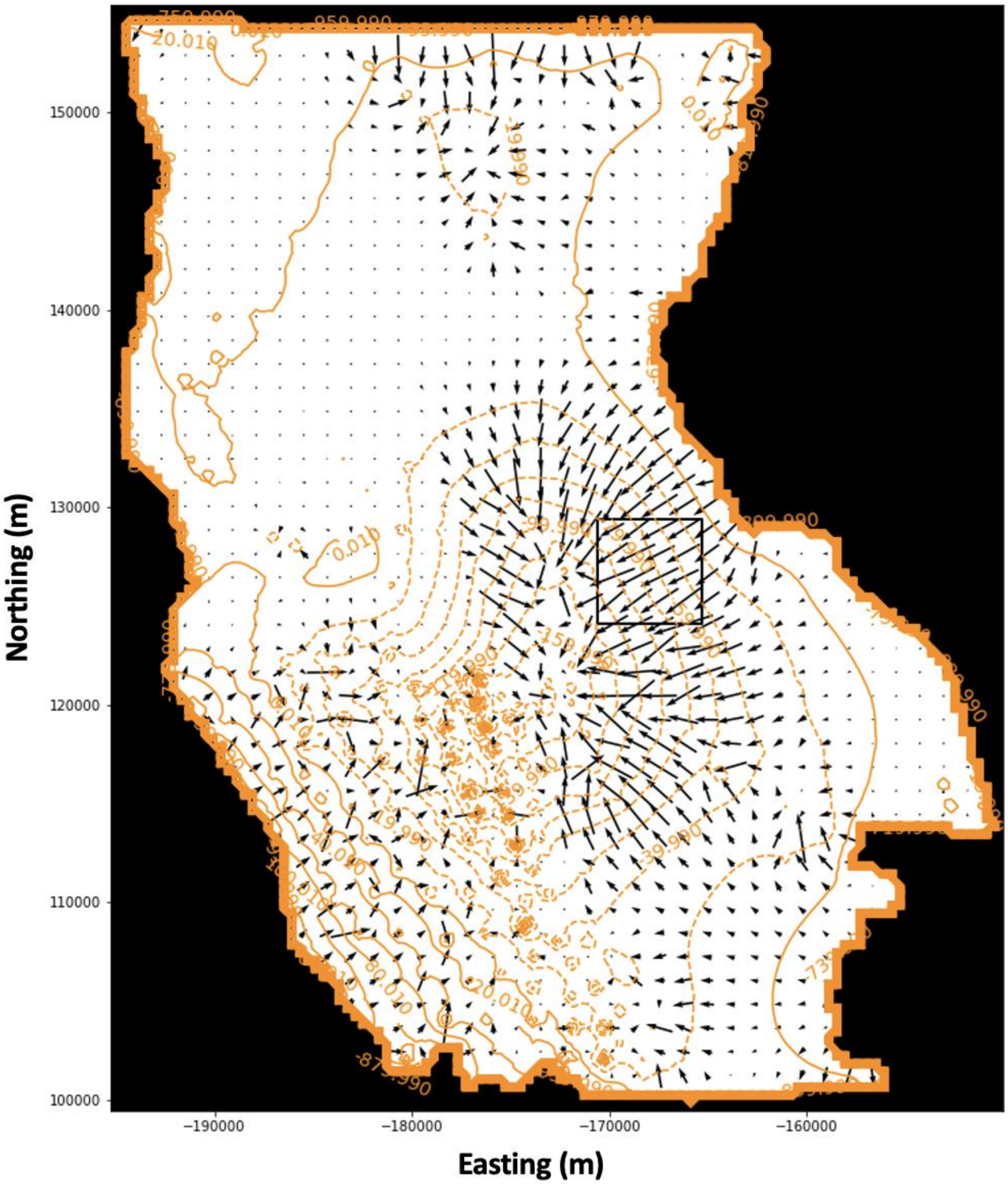
The outputs of the parent model are data of groundwater fluxes, which includes the magnitude of volumetric flow through each model cell and the direction. The groundwater flux was calculated at each cell in every layer of the model for each stress period (the parent model has only one stress period since it is steady state). The hydraulic head, or groundwater elevation above sea level (ASL) in meters, was plotted as orange contours with the magnitude and direction of groundwater flux for Layers 1, 6 and 9 with black arrows (Figure 14). These three layers were chosen out of all nine layers because they were deemed representative of the top, middle, and bottom of the model's layers. The length of each arrow represents the magnitude of groundwater flux, with the arrow pointing in the direction of flow. The map also includes a black square that serves as a reference point of the child model area, and the flow that occurs at and around the child model's boundary at each layer. The maps show that the general flow of groundwater in the parent model is towards the cone of depression and the pumping wells in that area, with water flowing away from the Sacramento River near the recharge sites in the child model area.

Layer 1



Northing (m)
150000
140000
130000
120000
110000
100000
Easting (m)
−190000
−180000
−170000
−160000
0.010
-119.990
-99.990
-39.990

Layer 6



Northing (m)
Easting (m)
150000
140000
130000
120000
110000
100000
−190000
−180000
−170000
−160000

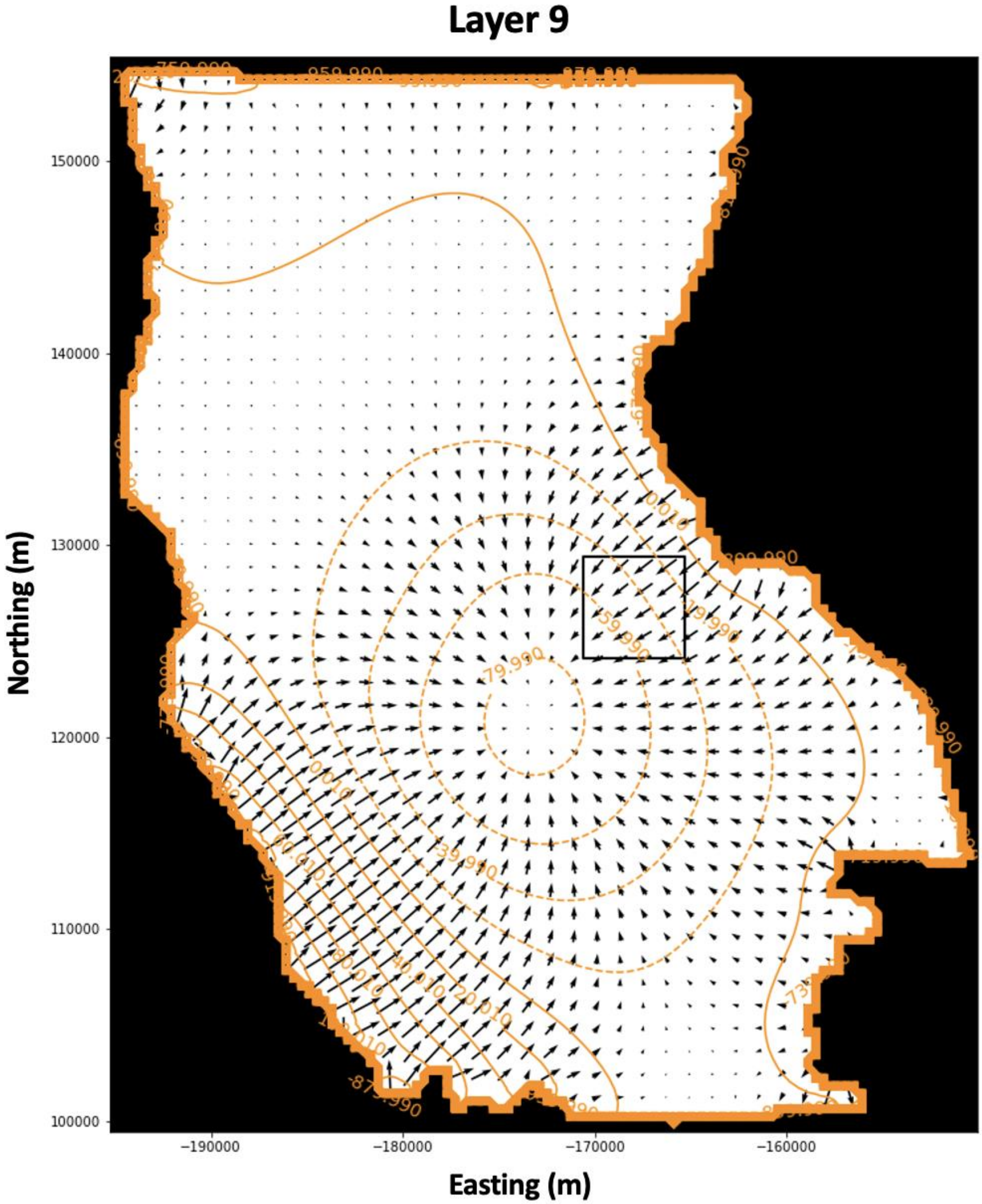


Figure 14: Map of head contours and flow magnitude and directions for Layers 1, 6, and 9 in the parent model domain. The depth ranges for each layer with respect to the ground surface

elevation are 0 m – 11 m for Layer 1, 110 m – 190 m for Layer 6, and 323 m – 533 m for Layer 9.

4.2 Child Model Results

4.2.1 Scenario 1 Results

The results of Scenario 1, which was run using the child model, represents the baseline model run performance and outputs, using the original and unaltered deep percolation data from Davids Engineering. For this baseline scenario, we assessed the model performance using a similar analysis to the parent model performance. The one-to-one plot for the child model is a plot of the observed and simulated equivalent heads with a gray line indicating the line of equal value (Figure 15). The colors of the dots represent the binned residual head data.

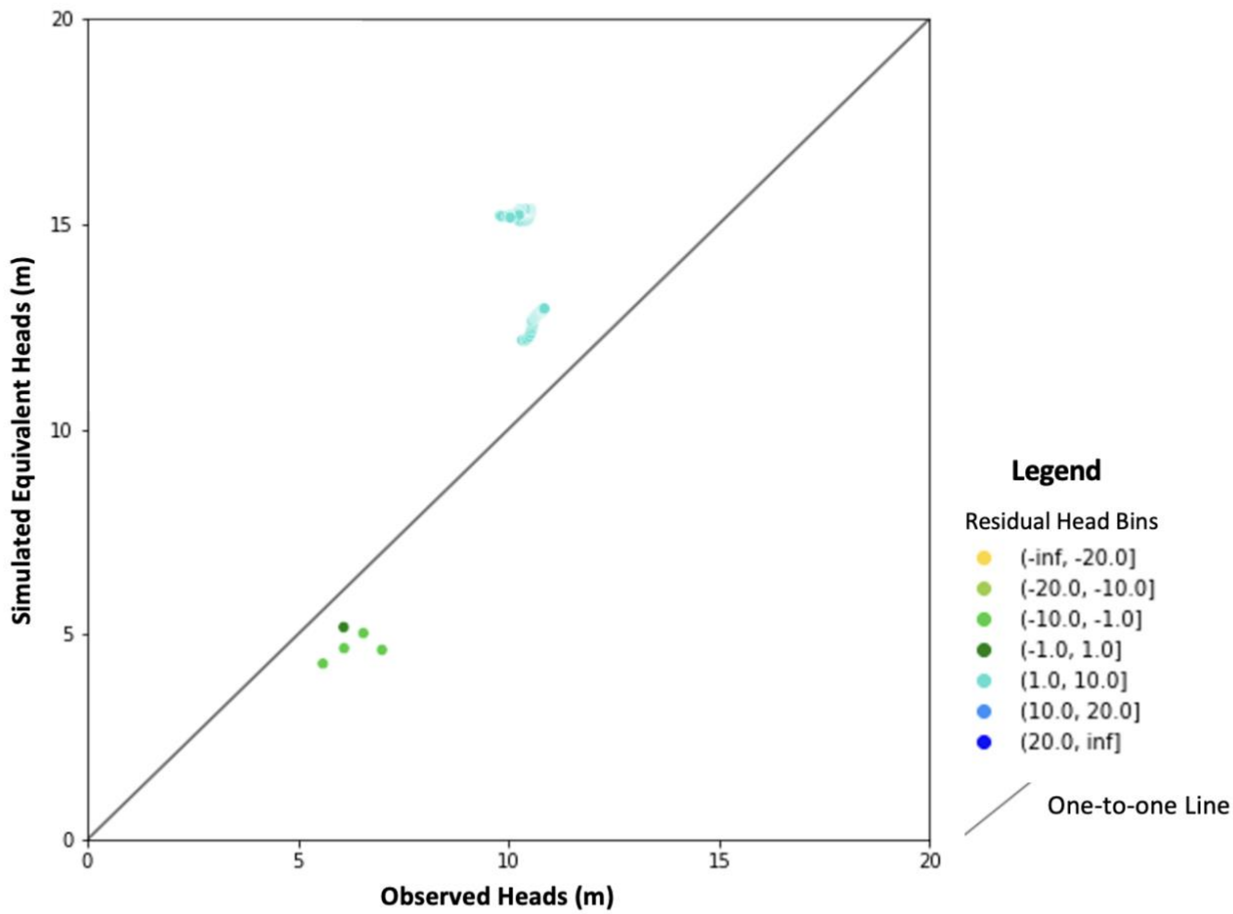


Figure 15: One-to-one plot of observed vs. simulated equivalent heads for the child model performance.

The binned residual heads were also plotted on a map of the child model domain, indicating the location of the four groundwater monitoring wells used to collect continuous and periodic groundwater elevation data during the recharge studies at each ag-MAR field site (Figure 16). The location and shape of the field sites are outlined in black, and the four colored dots show the location of the groundwater monitoring wells and their average residual simulated head value. Yellow colors indicate “dry” wells (where there is a difference between the observed and simulated equivalent head values greater than 20 m), green colors represent good model performance (small difference between observed and simulated equivalent heads), and blue colors indicate “wet” wells (where simulated equivalent heads are overestimated).

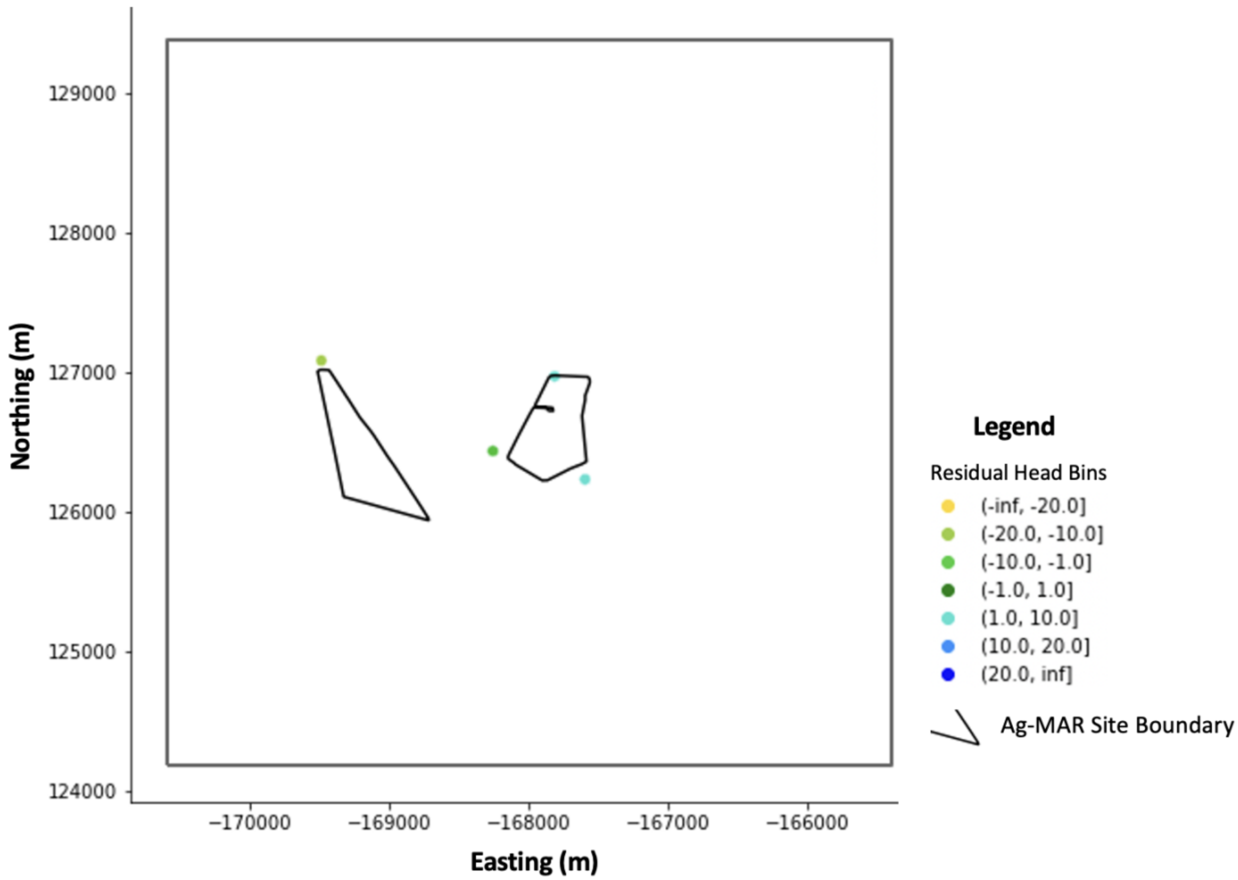


Figure 16: Residual map of the average residual simulated heads for the child model.

The child model outputs of Scenario 1 include the magnitude and flow direction of volumetric groundwater fluxes in each model cell, calculated using MODFLOW’s groundwater flow equation at each stress period in the model run; the child model is transient and has 451 stress periods, or days, that it simulated in its model run. Head contours are plotted as orange lines and flow magnitude and direction plotted as black arrows illustrate the direction and magnitude of groundwater flow (Figure 17). Groundwater generally flows southwest, with water flowing away from the Sacramento River in the area near the recharge sites. Only the first layer was plotted, since this is the only layer of interest due to it being the layer of the child model in which the RCH package defines recharge to occur.

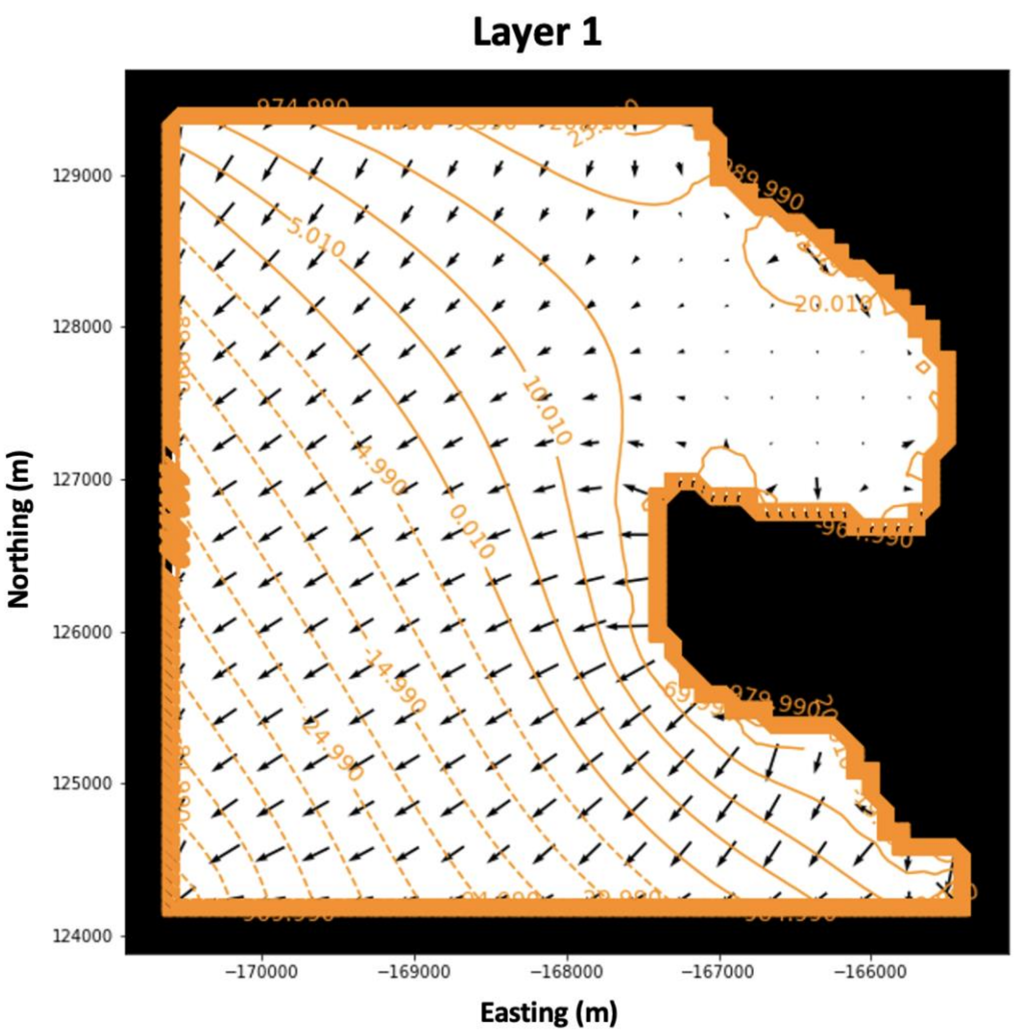
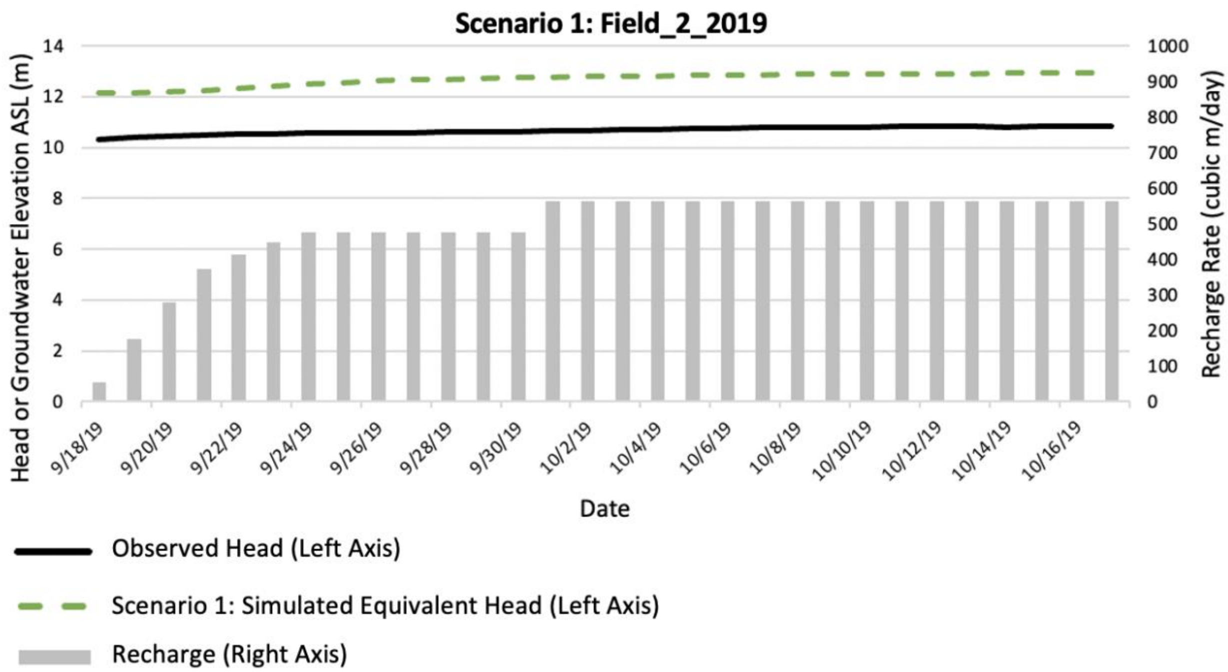
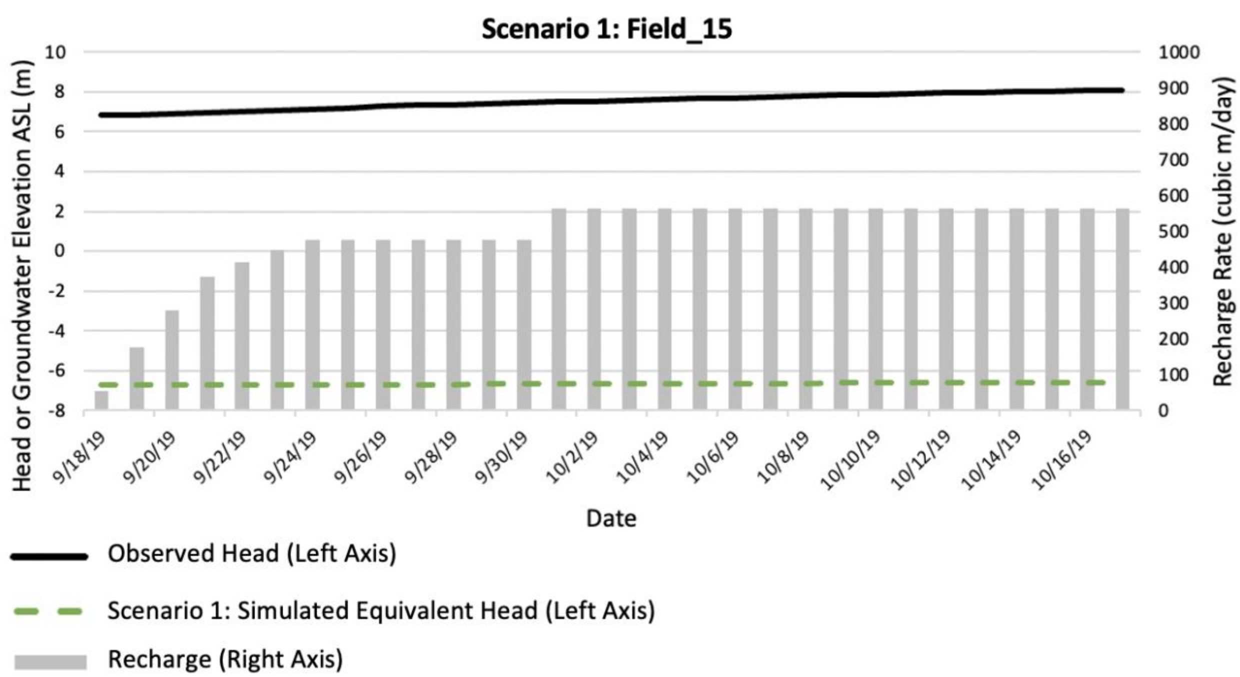


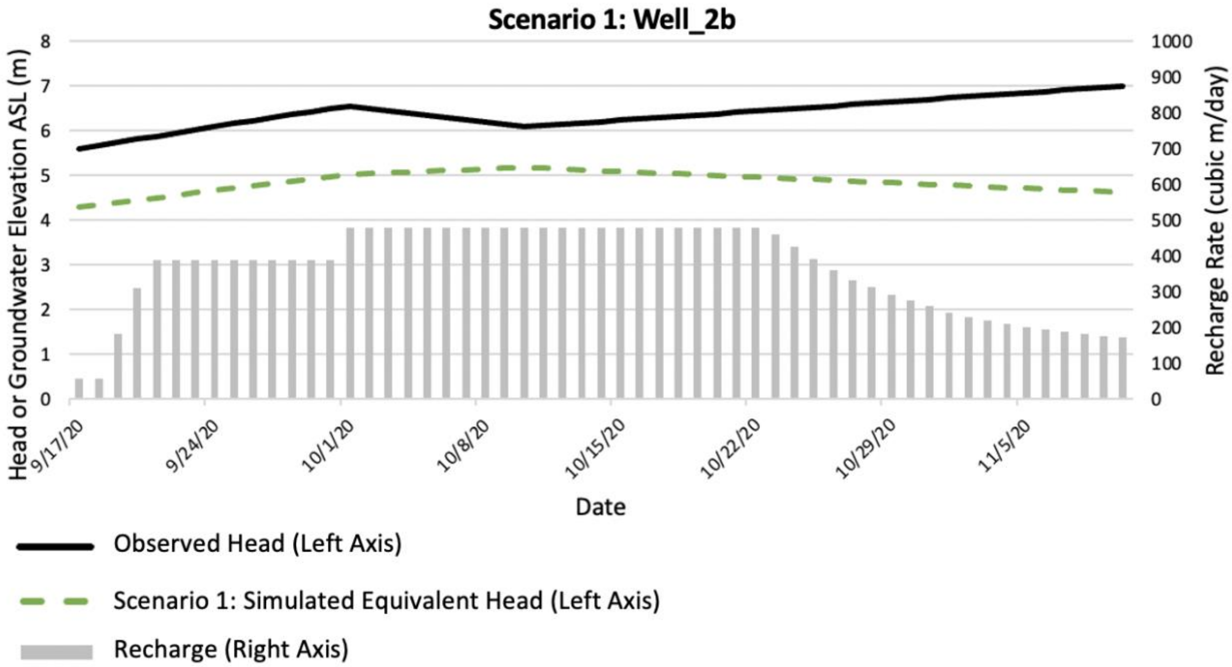
Figure 17: Map of head contours and flow magnitude and directions for Layer 1 in the child model domain.

A more in-depth analysis of the model performance was conducted to understand how the observed and simulated equivalent heads change over time at each of the four groundwater monitoring wells in the child model domain. Hydrographs of the observed and simulated equivalents were plotted for each groundwater monitoring well; the head, or groundwater elevation ASL (m) was plotted on the primary y-axis, while recharge rates (cubic m/day) was plotted on the secondary y-axis as a bar plot (Figure 18). Hydrographs and recharge rates were plotted together for each well to illustrate the relationship between groundwater elevation and recharge rate over time. In half of the groundwater monitoring wells (Field_2_2019 and Well_34) we observed simulated equivalent values greater than the observed values, and in the other half of the wells (Field_15 and Well_2b) we observed simulated equivalent heads less than the observed values. The difference between the observed and simulated equivalent head values were the greatest for the Field_15 well, with a 12-14 m difference, while the difference between the observed and simulated values for the other three wells were significantly less, with a 2-6 m difference. This discrepancy may arise from the spatial variation in where the groundwater monitoring wells are located (Figure 7). The Field_2_2019, Well_2b, and Well_34 monitoring wells are all located near each other, near the Sacramento River. In contrast, the Field_15 well is located the farthest away from the Sacramento River and the other three wells.

Recharge rates varied over time among the four groundwater monitoring wells. For Field_2_2019 and Field_15, recharge gradually increased in mid- to late September of 2019 and remained constant throughout the remainder of the flooding period in October of 2019. For Well_2b and Well_34, recharge rates increased rapidly in September of 2020, remained fairly constant through October of 2020, and slowly decreased during November of 2020 (the post-flooding period).







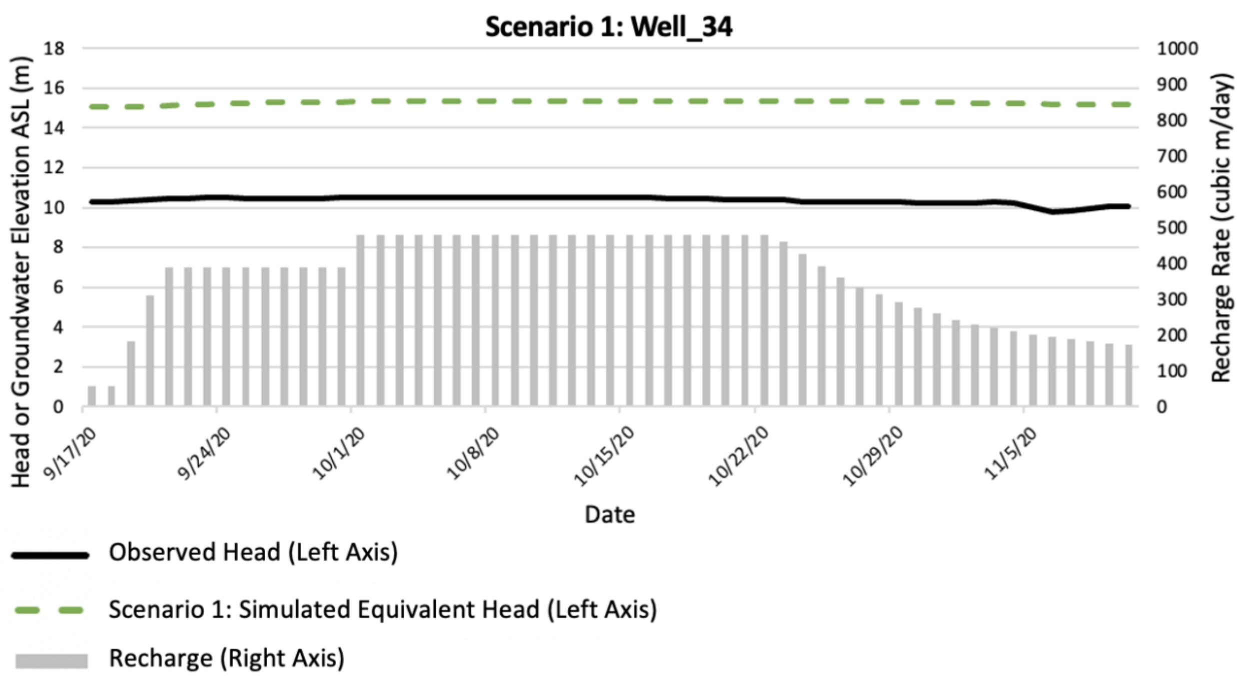


Figure 18: Combined hydrographs and recharge plots at each groundwater monitoring well for Scenario 1.

Additional child model outputs from Scenario 1 include the water budget components that flow into and out of the model's cells, calculated during each stress period of the model run. The water budget components plotted include storage (In), river leakage (In), recharge (In), storage (Out) and river leakage (Out). A stacked bar chart was made to represent the magnitude of the rates (cubic m/day) of each water budget component over time (Figure 19). Water that flows into the model cells from storage, river leakage, and recharge are plotted in light green, light orange, and blue, respectively. These inflows are specified as positive rates on the y-axis. Water that flows out of the model cells and are transferred to storage and river leakage are plotted in dark green and dark orange, respectively. These outflows are specified as negative rates on the y-axis. The rates of each component were plotted to see the variations over time, such as seasonal differences in recharge or storage.

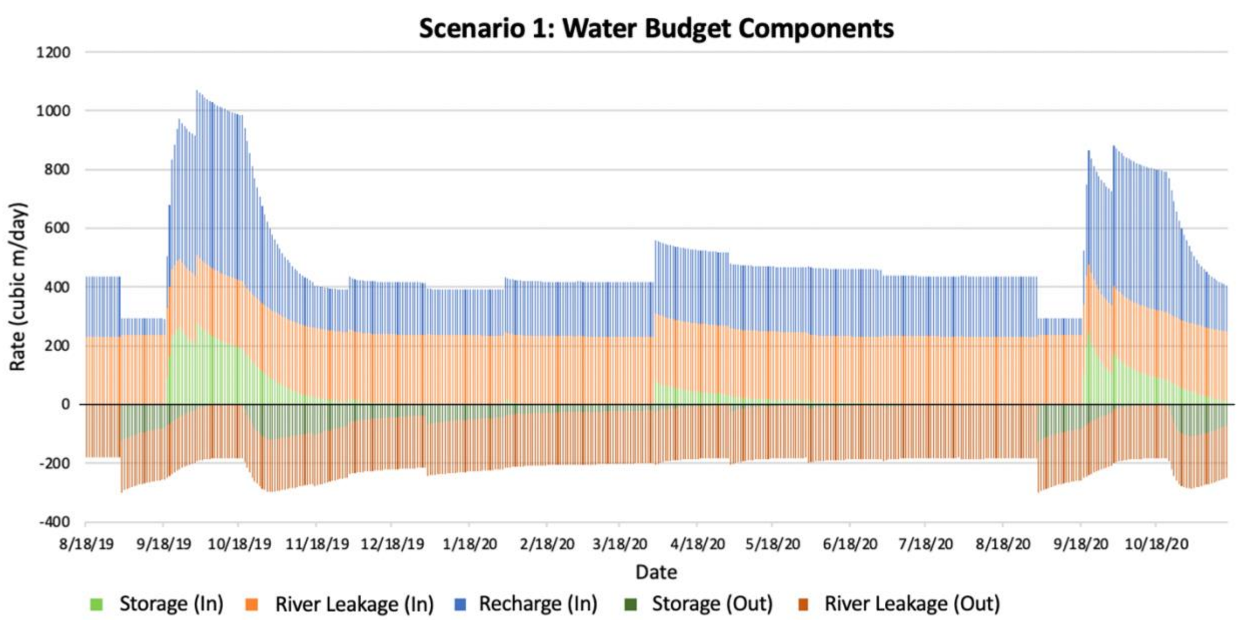
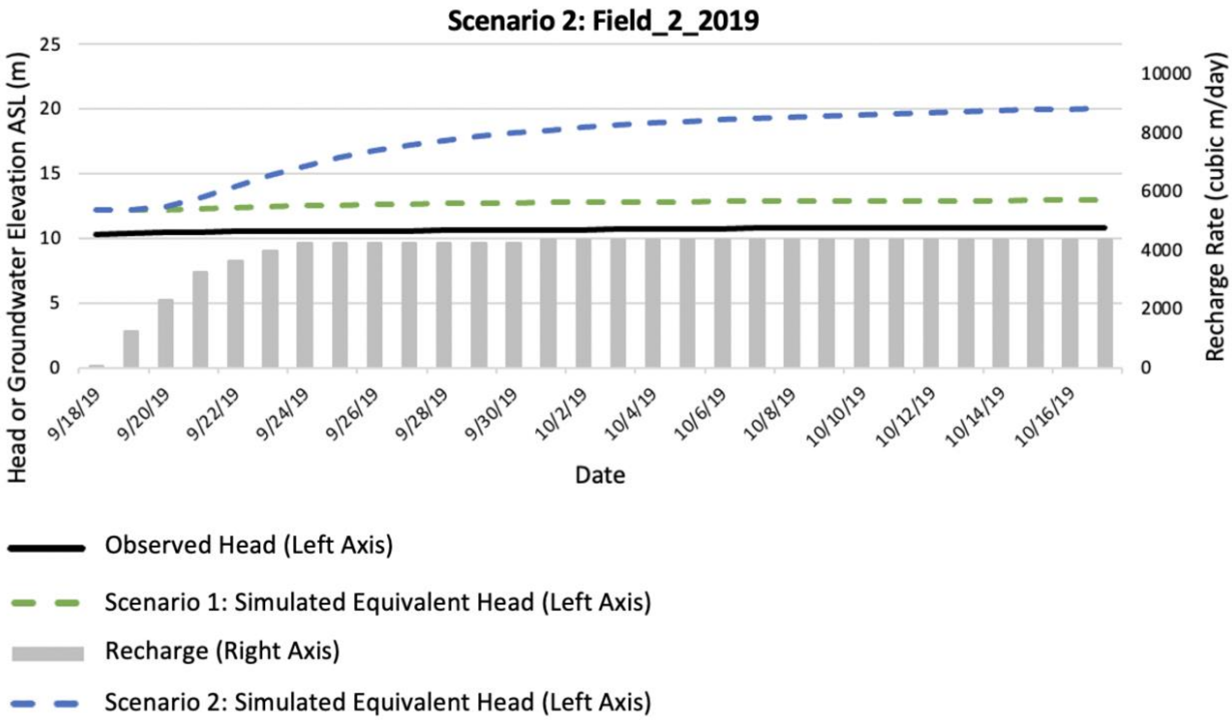


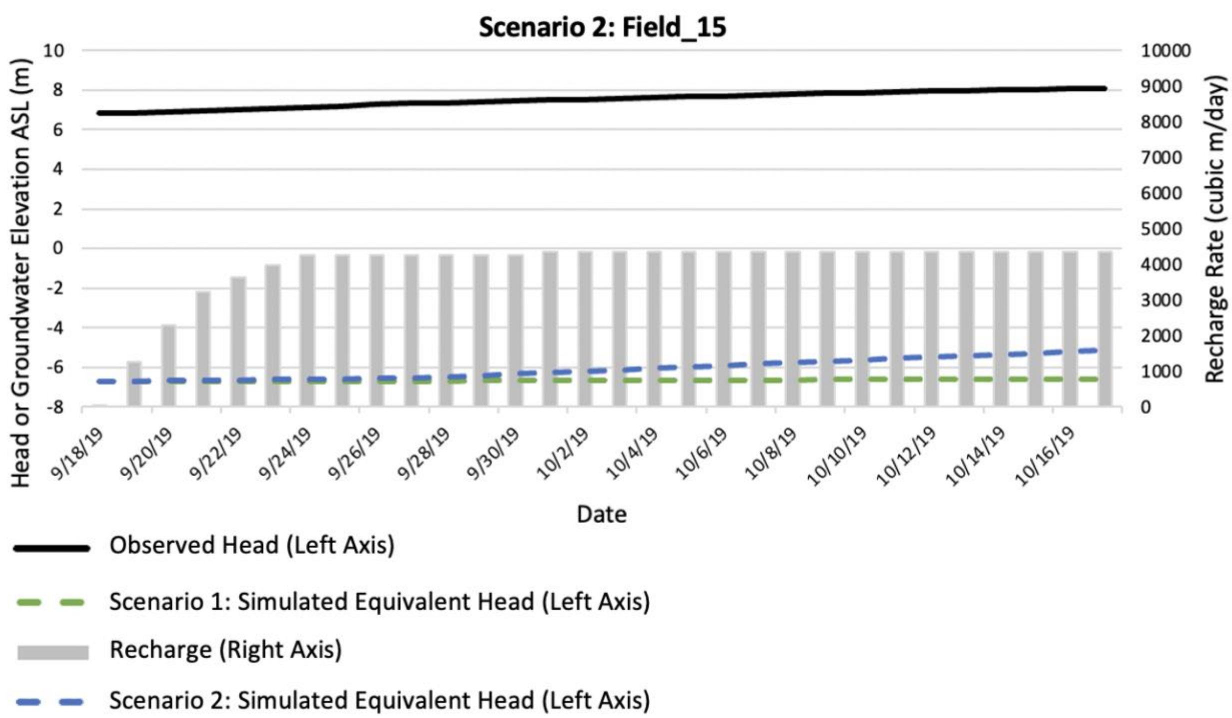
Figure 19: Graph of water budget components for Scenario 1.

4.2.2 Scenario 2 Results

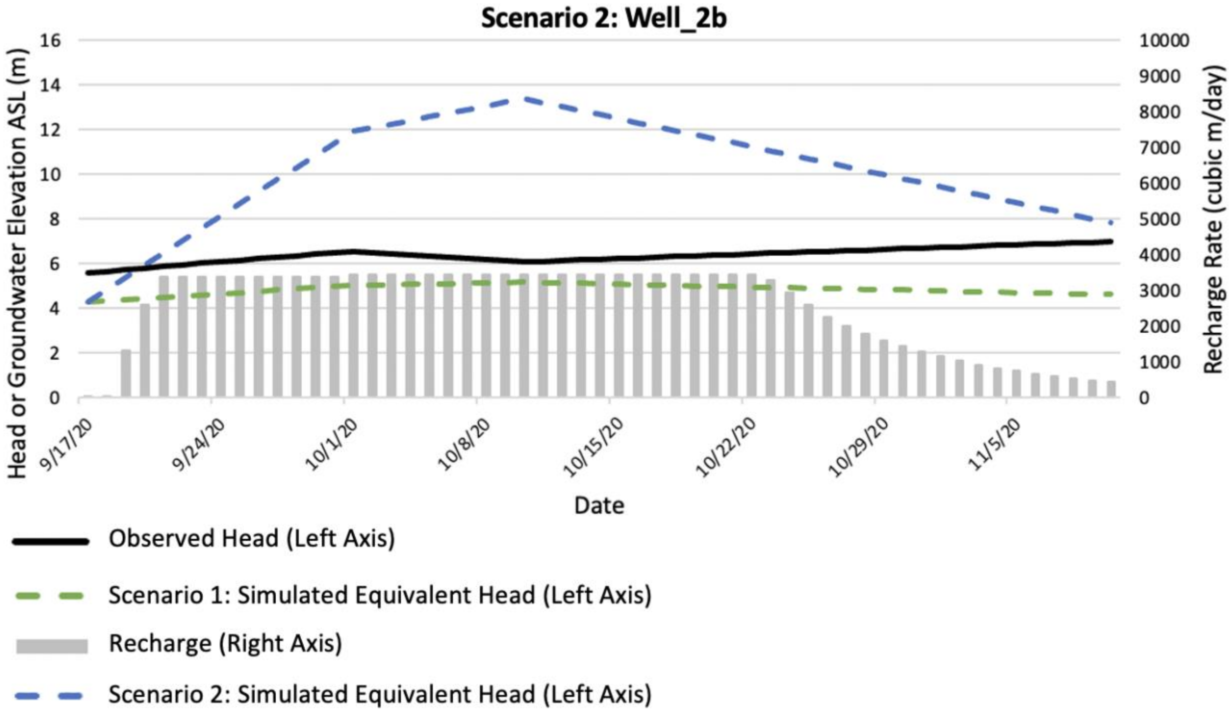
The child model results of Scenario 2 represent increased rates of deep percolation during the same recharge periods as Scenario 1, where deep percolation values were increased by one order of magnitude. Similar to Scenario 1, we analyzed the hydrographs of observed and simulated equivalent heads over time at each of the four groundwater monitoring wells (Figure 20). Groundwater elevation levels were plotted on the primary y-axis, and recharge rates were plotted as a bar chart on the secondary y-axis to compare the observed and simulated equivalent heads with recharge rates over the course of each recharge period. Both simulated equivalent head values were plotted from Scenario 1 (green) and Scenario 2 (blue) to display the hydrologic difference between the two scenarios. Overall, the hydrographs of the simulated equivalent heads for Scenario 2 are consistently higher than those of Scenario 1. Recharge rates varied over time among the four groundwater monitoring wells for Scenario 2. For Field_2_2019 and Field_15, recharge gradually increased in mid- to late September of 2019 and remained constant throughout the remainder of the flooding period in October of 2019. For Well_2b and Well_34, recharge rates increased rapidly in September of 2020, remained fairly constant through October of 2020, and slowly decreased during November of 2020 (the post-flooding period).



Scenario 2: Field_2_2019
Head or Groundwater Elevation ASL (m)
Recharge Rate (cubic m/day)
Date
9/18/19
9/20/19
9/22/19
9/24/19
9/26/19
9/28/19
9/30/19
10/2/19
10/4/19
10/6/19
10/8/19
10/10/19
10/12/19
10/14/19
10/16/19
Observed Head (Left Axis)
Scenario 1: Simulated Equivalent Head (Left Axis)
Recharge (Right Axis)
Scenario 2: Simulated Equivalent Head (Left Axis)



Scenario 2: Field_15
Head or Groundwater Elevation ASL (m)
Recharge Rate (cubic m/day)
Date
9/18/19
9/20/19
9/22/19
9/24/19
9/26/19
9/28/19
9/30/19
10/2/19
10/4/19
10/6/19
10/8/19
10/10/19
10/12/19
10/14/19
10/16/19
Observed Head (Left Axis)
Scenario 1: Simulated Equivalent Head (Left Axis)
Recharge (Right Axis)
Scenario 2: Simulated Equivalent Head (Left Axis)



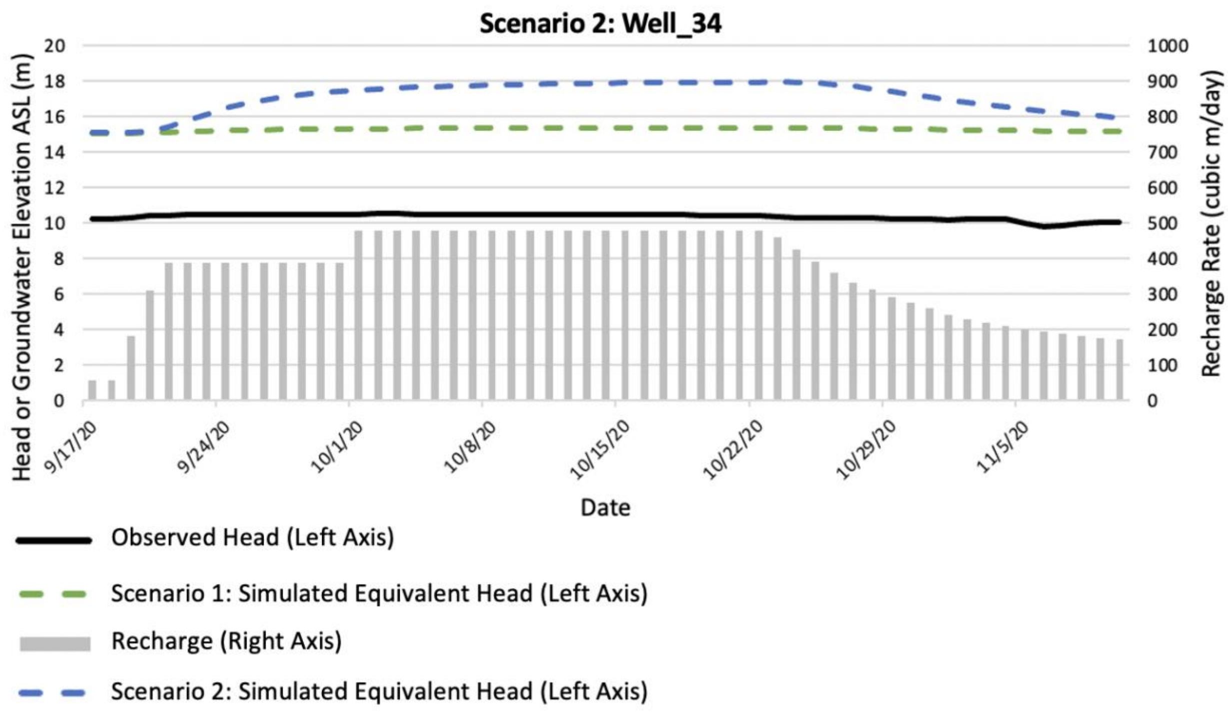


Figure 20: Combined hydrographs and recharge plots at each groundwater monitoring well for Scenario 2.

The water budget components extracted from the child model results of Scenario 2 were represented with a stacked bar chart (Figure 21). Each of the components plotted are the same as the components plotted for Scenario 1. The water budget components plotted are storage (In), river leakage (In), recharge (In), storage (Out) and river leakage (Out). The main difference is that the scale of the rates (cubic m/day) of the components is several times larger than that of Scenario 1. Recharge rates are largest during the flooding periods at the ag-MAR field sites. Inflows to the model cells from storage are also greatest during the periods of high recharge rates, and outflows from the model cells to storage start to increase after a few weeks of recharge. The inflows and outflows of river leakage appear to remain fairly consistent over time.

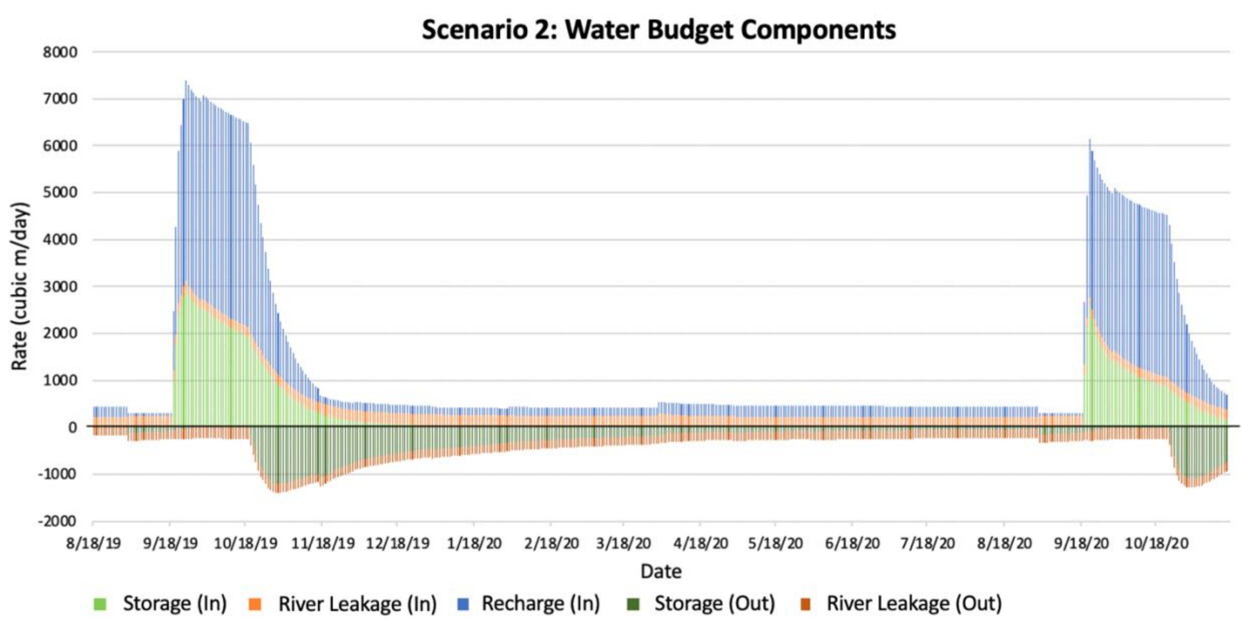
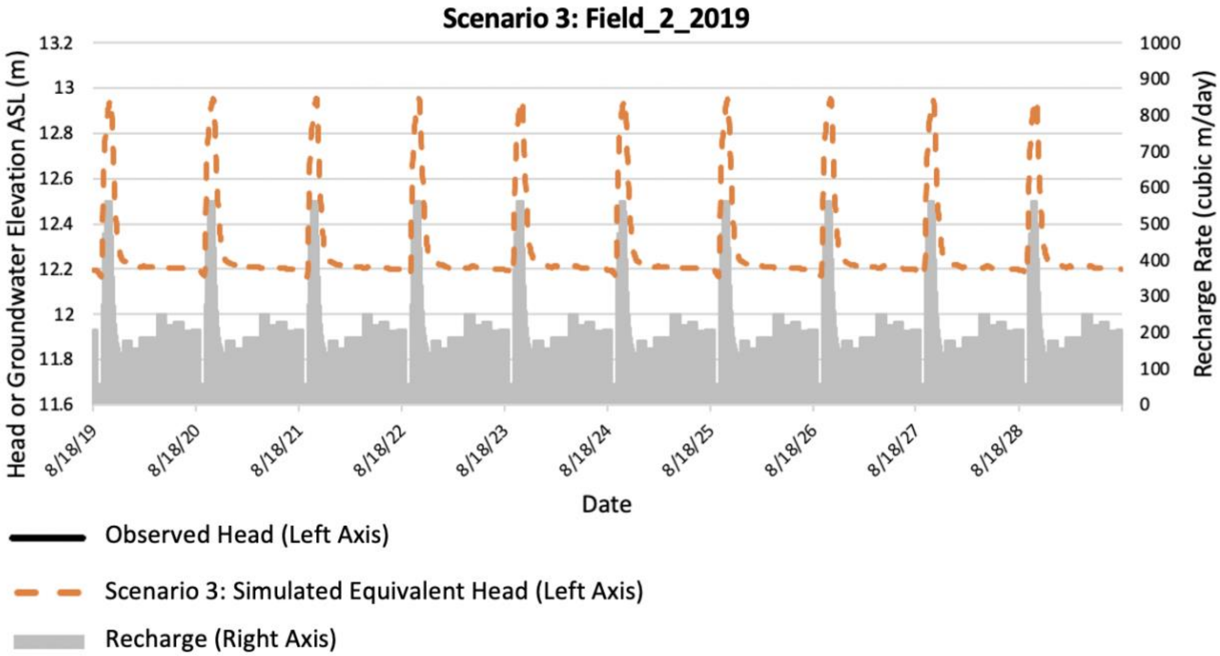
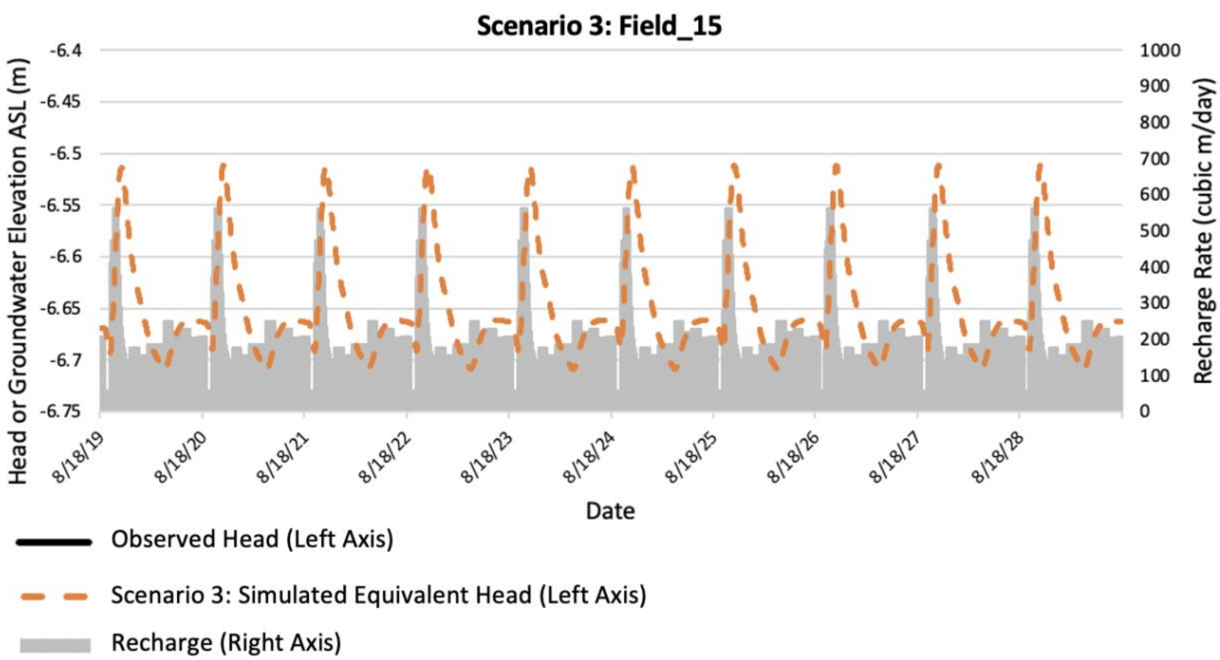


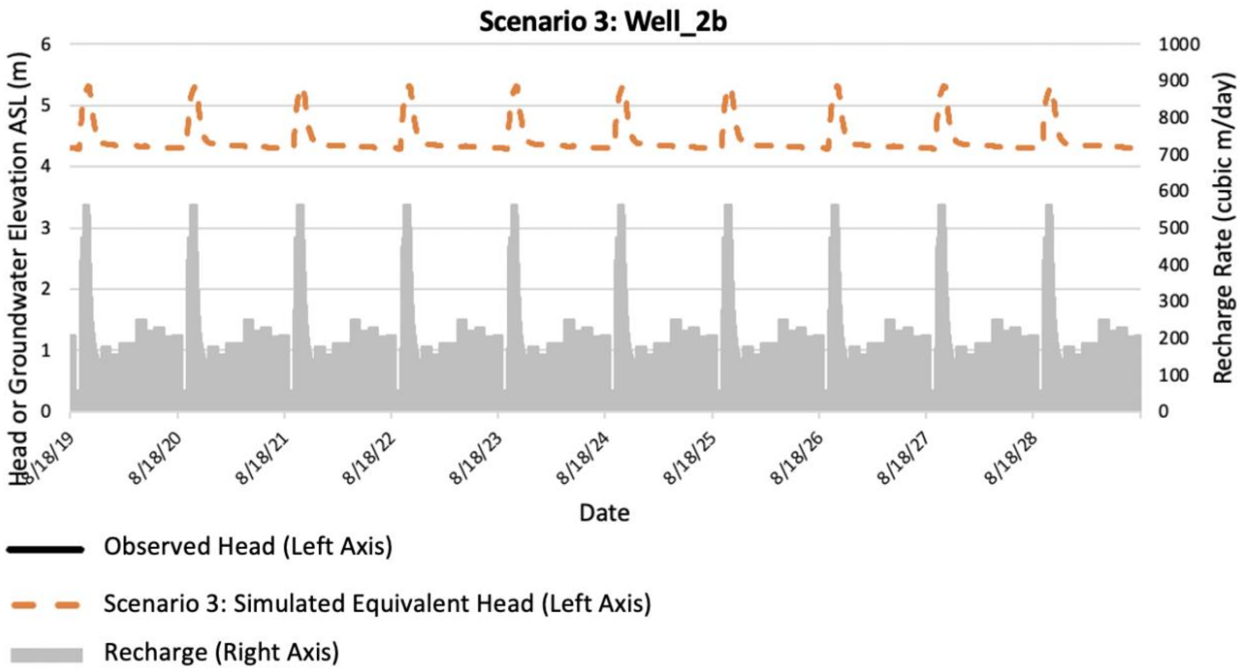
Figure 21: Graph of water budget components for Scenario 2.

4.2.3 Scenario 3 Results

The results of Scenario 3 represent a repetition of the 2019 recharge program for ten consecutive years. Because of the large difference in time discretization between Scenarios 1 and 2 and Scenario 3, the analysis of the model performance of Scenario 3 was conducted individually without an initial comparison with the first two scenarios. Hydrographs of the observed and simulated equivalent head values (in units of meters) were plotted for each groundwater monitoring well on the primary y-axis, while recharge rates (cubic m/day) were plotted on the secondary y-axis (Figure 22). The groundwater elevation and recharge rates were plotted together to demonstrate their relationship over the course of the ten years. The simulated head values were plotted alone for this ten-year model run because there are no projected groundwater elevation data from the year 2020 to 2029. The pattern of the hydrograph is repetitive, as each consecutive year is a replication of the previous one. The same can be said for the bar chart of the recharge rates. As recharge rates peak, the simulated heads also reach their peak.


Scenario 3: Field_2_2019
Head or Groundwater Elevation ASL (m)
Recharge Rate (cubic m/day)
Date
8/18/19
8/18/20
8/18/21
8/18/22
8/18/23
8/18/24
8/18/25
8/18/26
8/18/27
8/18/28
Observed Head (Left Axis)
Scenario 3: Simulated Equivalent Head (Left Axis)
Recharge (Right Axis)


Scenario 3: Field_15
Head or Groundwater Elevation ASL (m)
Recharge Rate (cubic m/day)
Date
8/18/19
8/18/20
8/18/21
8/18/22
8/18/23
8/18/24
8/18/25
8/18/26
8/18/27
8/18/28
Observed Head (Left Axis)
Scenario 3: Simulated Equivalent Head (Left Axis)
Recharge (Right Axis)



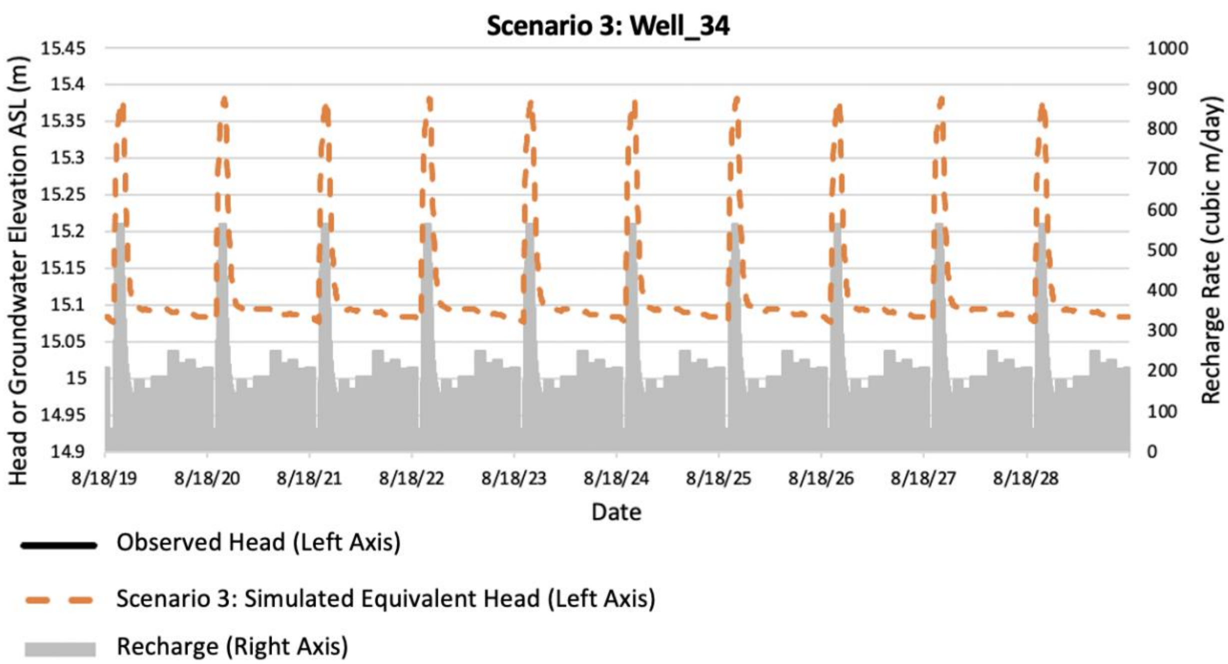


Figure 22: Combined hydrographs and recharge plots at each groundwater monitoring well for Scenario 3.

The water budget components that were an output of the child model for Scenario 3 are plotted as a stacked bar chart (Figure 23). The components of interest that were plotted as rates (cubic m/day) either into or out of the child model's groundwater system included storage (In), river leakage (In), recharge (In), storage (Out) and river leakage (Out). The rates of these inflows and outflows to the groundwater system span the ten years that the model was run for Scenario 3. The graph follows a consistent pattern, for each component, as the whole ten years is a replication of the first year (the 2019 recharge program). There is no visible increase in any of the water budget components' rates over time, as the pattern is very consistent.

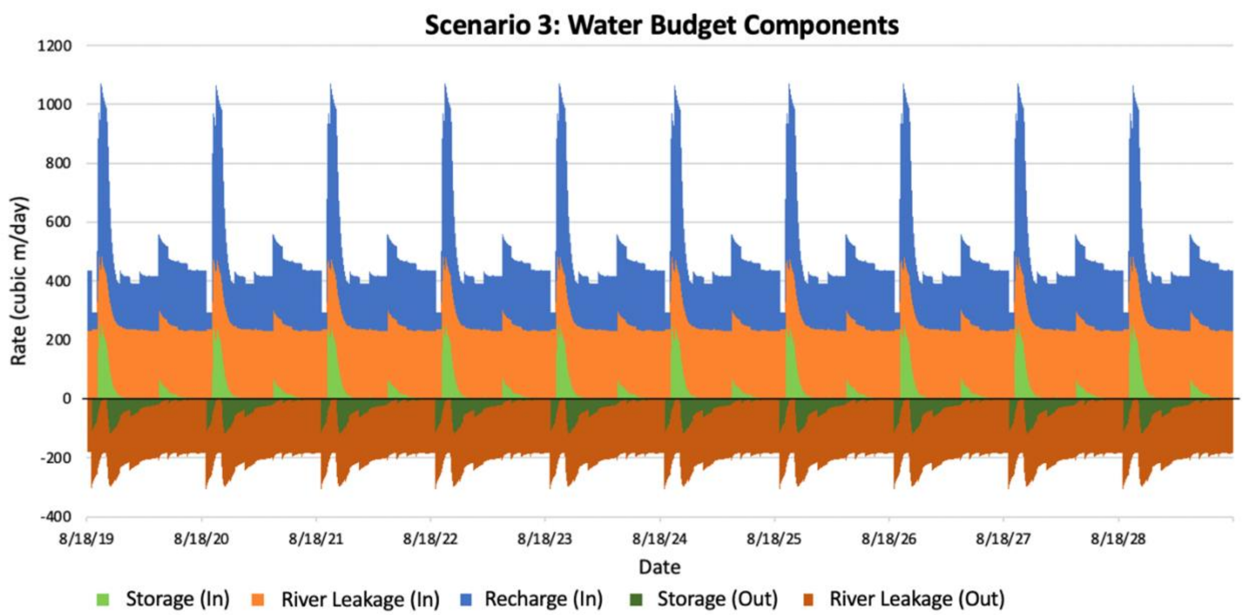


Figure 23: Graph of water budget components for Scenario 3.

5. DISCUSSION

5.1 Discussion of Parent Model Results

From analyzing the model performance of the parent model through the one-to-one plot of observed and simulated equivalent heads (Figure 12), it is evident that most of the data are a good fit to the one-to-one line, with the exception of the cluster of red dots in the lower left area of the plot. This group of heads had a residual greater than -100 m, meaning the difference between the observed and residual heads at these groundwater monitoring wells were greater than -100 m. Other than this cluster of red residuals, the binned residual head data indicated that the majority of the values of the observed and simulated equivalent heads were fairly close, with a difference of less than -100 m to 30 m. The overall shape of the distribution of dots on the one-to-one plot suggest that we were mostly underestimating the heads in certain areas, resulting in a more conservative estimation of heads in the parent model domain.

The residual map of the parent model shows the distribution of groundwater monitoring wells and how dry or wet they are according to the color of the well points (Figure 13). The northern half of the parent model domain showed good to fairly good model performance, with the green and yellow colored residual points indicating a small difference between the observed and simulated equivalent values of head. Within the black square, the area of the child model domain, most of the groundwater monitoring wells indicate an underestimation of heads (shown by the two orange, one yellow, and one light green colored points). The areas where the residuals were smallest (green colored points) were areas near surface water features along the eastern boundary of the parent model domain, such as Butte

Creek, Butte Slough and the West Borrow Ditch, as well as some parts of the Sacramento River in the domain area. The cluster of red dots that were shown in the one-to-one plot (Figure 12) are seen in the middle to southern half of the parent model domain (Figure 13). The red dots indicate an area of low groundwater elevation, forming a cone of depression.

The cone of depression shown by the parent model results is not a surprising discovery. As discussed previously, a natural cone of depression occurred in the same area during the fall 2020 season, with low groundwater elevations in the same area occurring in the spring 2021 season, as shown by real-world groundwater monitoring data from the DWR (Figure 3). This finding is further supported by the parent model outputs of groundwater flux (magnitude and direction of flow) seen in Figure 14. The general trend of groundwater flow in the parent model is away from the model boundaries and towards the center of the model, where the cone of depression occurs; water always flows from areas of high hydraulic head to low hydraulic head. The cone of depression in our model is more exaggerated than the natural cone of depression that occurs in the same area. Therefore, we have identified it as a systematic error in this model. We want to emphasize that this underestimation in heads can create uncertainties for the fluxes in the child model; for the current state of the project, we were more interested in running the child model scenarios than prioritizing the calibration of the parent model.

Flow magnitudes in Layer 1 are very high in the southwest corner of the parent model domain, indicating high magnitudes of flux away from the foothills of the Coast Ranges (Figure 14). The steep gradient and high-magnitude fluxes in that area could be a result of the topography of the ground surface, or a "pulling" of water towards the cone of depression due to high amounts of groundwater pumping in the central area of the parent model domain, where a lot of pumping for agriculture occurs. Both are plausible explanations, and both may contribute to the presence of the cone of depression. Flow in Layer 6 illustrates the influence of pumping wells that extract groundwater from the shallow to middle layers of the model, with the cluster of concentrated head gradients displaying the “pull” of water from groundwater pumping wells. All layers (Layers 1, 6 and 9) indicate flow away from the Sacramento River near the child model domain area where the ag-MAR field sites are located. This is significant because in the area of interest, the Sacramento River is a losing stream, meaning it does not take water from the surrounding groundwater as it flows downstream. This finding suggests that although the ag-MAR sites are located close to the Sacramento River, most of the recharged groundwater is not at a great risk of being diverted to the Sacramento River as surface water flow.

We were able to construct the parent model and analyze the results to understand the regional groundwater flow in the parent model domain. These regional flow patterns and magnitudes were extracted to serve as the child model’s boundary conditions that were informed by the natural geography and hydrology of the region. Essentially, the parent model results were a credibility check for the child model. Since we successfully replicated the parent model’s flow patterns in the child model, we gained confidence in the results of our three recharge scenarios that were used to test different parameters using the child model. Despite the cone of depression observed in the parent model, the flow directions do make sense, but the magnitude of fluxes might be skewed because of how exaggerated the cone of depression is.

5.2 Discussion of Child Model Results

Each of the three scenarios were run using the child model, and the flow in the child model domain was a direct result of the flow that occurred in the same area of the parent model domain. As such, the results and flow directions observed from the child model were influenced by the results of the parent model. It is important to note that each of the child model scenarios was affected in the same way by the cone of depression that occurs in the parent model, which was merely a systematic error in the parent model. Analyzing the flow direction and magnitudes of flux in the child model results from Scenario 1 make it clear that groundwater flows southwest, away from the Sacramento River and towards the cone of depression in the parent model. Although the cone of depression occurs naturally, as seen in real-world data, we should reiterate that the cone of depression in our parent model is exaggerated, which may have influenced the magnitude of the groundwater flux in our child model scenarios.

Scenario 1 was the baseline model run with unaltered deep percolation data. The one-to-one plot of observed and simulated equivalent heads (Figure 15) and residual map for the child model indicated that the model performed very well in the baseline scenario model run, since the simulated values are close to the observed head values. In Scenario 1, we noticed that proximity to the river affected the variation in simulated head values. For example, the hydrograph and recharge bar chart for Well_34 (Figure 18) showed very little variation in groundwater elevation (in both the observed and simulated heads) since that well is located so close to the Sacramento River. The hydrograph and recharge bar chart for Well_2b (Figure 18) showed more of a response (in the form of a change in groundwater elevation) to recharge rates.

In the child model run for Scenario 2, deep percolation rates were increased by one order of magnitude (multiplied each value by 10) to assess whether a significant hydrologic response would be observed within the same time frame (same recharge periods as Scenario 1). From the combined hydrographs and recharge bar charts for Scenarios 1 and 2, we saw a significant difference in the water table elevation between the two scenarios. The simulated heads in Scenario 2 (Figure 20) were consistently higher than the simulated heads in Scenario 1 (Figure 18). It is clear that increasing the magnitude of recharge, as we did in Scenario 2, shows a significant hydrologic response through a raised water table when compared to the simulated heads plotted from Scenario 1. In the case of Well_2b in Scenario 2, we even noticed that the simulated heads exceeded the observed values, unlike the simulated heads from Scenario 1. We also want to clarify that for Well_2b, the spike in simulated head would realistically flood that monitoring well by approximately 2 m. However, since Scenario 2 is purely hypothetical, we want to emphasize that our goal was to test an extreme increase in recharge rates in order to see a significant response.

The water budget component graphs of both Scenario 1 and Scenario 2 exhibited the same pattern, but as expected, the rates in Scenario 2 are extremely scaled up when compared to Scenario 1. In Scenario 1, we observed that as recharge rates increased, water levels rose in the model. When recharge rates declined, water began to drain out from the model cells and flow out to storage. In Scenario 2, we also noticed the same pattern of increased outflows from the model cells to storage after recharge rates started to decline. It was difficult to compare the results of Scenario 3 to the results of Scenarios 1 and 2, since the time discretization of Scenario 3 was ten times larger, and only simulated heads were analyzed since there were no projected groundwater elevation data that could be used as input observed heads. We initially hoped to see at least a slight and gradual increase in storage inflows and groundwater levels over the course of the ten years for Scenario 3, but the water budget graph indicated that just simply replicating the 2019 recharge program year did not provide enough variability to show any significant improvement in groundwater storage or water levels over time. Perhaps gradually increasing recharge rates with each consecutive year would have shown an overall positive hydrologic response by the end of the ten years.

Although we did not observe the response we had hoped to see for Scenario 3, we learned what does and does not work for the context of designing that hypothetical scenario. What may work in a future scenario might be gradually increasing recharge rates with each consecutive year, which might show a significant hydrologic response by the end of the ten years. We also believe that the plots of the hydrographs and recharge bar charts for Scenario 3 did not show any changes in groundwater levels over time because the amount of recharge was so little. And unfortunately, the sites that have been flooded are located very close to the Sacramento River. This is an issue in the context of this model because the river package acts as a boundary condition, which does not allow for much movement of water near that boundary. Theoretically, Scenario 3 showed results that should have been expected, since it was essentially a ten-year replication of Scenario 1, which had such small deep percolation rates from flooding that we saw very little hydrologic effects. In a future scenario, replicating the design of Scenario 2 for ten years, instead of Scenario 1, might show a significant difference.

After comparing the results of the three scenarios, it is evident that increasing deep percolation rates yields the most significant hydrologic response. The results of Scenario 2 yielded the most positive response, increasing the simulated equivalent heads at each of the four groundwater monitoring wells.

6. CONCLUSION

Through the model development process, we were able to simulate and understand the effects of applying ag-MAR to field sites in Colusa County. With the results of our parent model, we were able to visualize the regional hydrologic characteristics of our project area, while applying those regional flows in the creation of our child model. With the more refined nature (spatially and temporally) of the child model's discretization, we simulated recharge at the ag-MAR field sites and tested three different scenarios to provide useful insights on how recharge projects like this can be improved upon in the future. From the results of our models, it is evident that multi-benefit recharge projects are influential to groundwater storage in addition to wildlife.

This study focused on the more technical side of this multi-benefit recharge project, with the development of the groundwater models as a tool of assessing the hydrologic effects of ag-MAR. Now that we have two working models, this project – and the models themselves – are flexible enough that this study could be expanded in the future to answer different research questions and run additional scenarios. The models could be used to model nitrate transport if stakeholders are interested in seeing the potential risks of nitrate contamination as a result of ag-MAR near disadvantaged communities by analyzing the particle tracking of recharged water to trace where recharged water flows.

Based on our results, and learning through the model development process, we can provide suggestions and guidelines for optimizing the design of multi-benefit recharge projects like this in the future. Changing the timing, frequency, and amount of recharge would have significant effects on our model results. Although it is understood that fall is an appropriate time for flooding fallow rice fields, it would be interesting to see what would result from having the same fields flooded during different seasons or all year. If possible, using the same fields multiple times (during consecutive years) will also establish a baseline and allow for a comparison of recharge at the same fields every year. Increasing rates of recharge, either by flooding more fields in a project area or prolonging the flooding periods, will have a positive effect on groundwater storage and groundwater elevation.

Lastly, we realize that our models can never be truly “perfect,” but the way we build, use, and interpret the results of our models to answer questions is what makes our models invaluable tools. Learning what model designs work well, like Scenario 2, and the designs that do not yield anticipated results, like Scenario 3, proved that knowledge is ultimately gained through the successes and the failures. We were able to simulate the effects of TNC’s multi-benefit recharge program and hypothetical recharge scenarios. The purpose of our groundwater models was to understand the hydrologic and environmental impacts of multi-benefit recharge projects, and how it can be scaled up spatially and temporally to increase the benefits to migratory birds and our groundwater resources for future projects across California. This study provided great insight on the effect small-scale recharge projects can have in a local setting. Studying the effects and continuously improving upon the design of multi-benefit recharge projects make ag-MAR a more accessible and viable approach to achieving a sustainable management of our state’s groundwater resources.

REFERENCES

Brush, Charles & Dogrul, Emin. “User’s Manual for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG.” June 2013.

California Department of Water Resources. *Periodic Groundwater Level Measurements*, April 2022. Accessed At: https://data.cnra.ca.gov/dataset/periodic-groundwater-level-measurements.

California Department of Water Resources. “SVSim: Sacramento Valley Groundwater-Surface Water Simulation Model.” June 2022. Accessed At: https://data.cnra.ca.gov/dataset/svsim

Chapelle, Caitrin, Hanak, Ellen, Harter, Thomas. “Groundwater In California.” Public Policy Institute of California. May 2021. Accessed At: https://www.ppic.org/wp-content/uploads/JTF_GroundwaterJTF.pdf

Colusa Groundwater Authority & Glenn Groundwater Authority. “Colusa Subbasin Groundwater Sustainability Plan.” December 2021. Accessed At: https://colusagroundwater.org/projects/groundwater-sustainability-plan/

Dahlke, Helen E., et al. "Managed Aquifer Recharge as a Tool to Enhance Sustainable Groundwater Management in California: Examples From Field and Modeling Studies." Elsevier Enhanced Reader, 2018. https://doi.org/10.1016/bs.apmp.2018.07.003. Accessed 15 May 2022.

Davids Engineering, Inc. *TNC Colusa Recharge Analysis*. Technical Report, Colusa Recharge Analysis Pilot Monitoring, December 2019.

Davids Engineering, Inc. *TNC Colusa Recharge Analysis*. Technical Report, 2020 Colusa Multi Benefit Recharge Monitoring, December 2021.

Dillon, Peter. “Future Management of Aquifer Recharge.” Hydrogeology Journal 13.1 (2005): 313–316. Web.

Golet, Gregory H., et al. “Using Ricelands to Provide Temporary Shorebird Habitat during Migration.” Ecological Society of America, vol. 28(2), 2017, pp. 409–26.

Hanak, Ellen, et al. "What if California's Drought Continues?" Public Policy Institute of California. August 2015. Accessed At:

https://www.ppic.org/wp-content/uploads/content/pubs/report/R_815EHR.pdf

L. Bond, T. Durbin, and C. Bonds. *Sacramento Valley Groundwater-Surface Water Simulation Model Technical Memorandum 1B (SVSim TM-1B)*. Technical report, California Department of Water Resources, April 2018. URL https://data.cnra.ca.gov/dataset/svsim.

O'Geen, A. T., et al. "Soil Suitability Index Identifies Potential Areas for Groundwater Banking on Agricultural Lands." California Agriculture, vol. 69, no. 2, Apr. 2015, pp. 75–84. DOI.org (Crossref), https://doi.org/10.3733/ca.v069n02p75.

Reiter, Matthew E., et al. "Impact of Extreme Drought and Incentive Programs on Flooded Agriculture and Wetlands in California's Central Valley." PeerJ, vol. 6, June 2018, p. e5147. DOI.org (Crossref), https://doi.org/10.7717/peerj.5147.

U.S. Geological Survey. *National Water Information System*, April 2022. Accessed At: https://waterdata.usgs.gov/nwis.