Agricultural Managed Aquifer Recharge: Fate, Transport and Distribution

Amber Bonarrigo
University of California Davis
HYD-243
June 10, 2021

Abstract

Climate change and population growth require innovative management strategies to meet water demands while sustaining resources for future generations. Agricultural managed aquifer recharge, a water banking method for farmers to store excess surface water in aquifers during wet periods and extract the stored water during drying periods, was tested on one field site in 2019. Two fields were flooded with diverted surface water for 30 days. Field data and data from local weather stations were incorporated into a mass balance to determine total deep percolation (recharge) to the aquifer. A regional MODFLOW model is in development to better understand AgMAR recharge rates and fate and transport of the recharged water. The Sacramento Valley Water Allocation Model (SacWAM) was used to extract long-term estimated groundwater storage in the Colusa groundwater basin. The storage data will be used to calibrate and validate the MODFLOW model which will better the understanding of MAR recharge pathways in Colusa basin.

Introduction (Literature Review)

California's climate is characterized by the largest precipitation and streamflow variability observed within the conterminous United States (US) [8]. As a result, the state is susceptible to recurring droughts and floods that threaten the quality and quantity of the state's groundwater reserves. Groundwater accounts for approximately 38% of California's water supply during a normal year and upwards of 48% during a dry year [4]. This reliance upon groundwater creates vulnerability - if groundwater resources are not sustained. Taxation of California's groundwater reserves stresses the agricultural sector, particularly during dry years, when there is a heavier reliance upon groundwater to supply water for irrigation. Managed aquifer recharge (MAR) is a method implemented to boost groundwater supply, particularly during dry seasons, by creating conditions for more water to recharge aquifers than would occur naturally [2, 3, 9, 10, 12]. This is achieved via infiltration basins, injection wells and on-farm recharge [9, 11]. On-farm recharge, otherwise known as agricultural groundwater banking or AgMAR, is a form of MAR where farmland is flooded with excess surface water in winter to intentionally recharge groundwater [1, 6, 10]. Though effective, this method poses risks to groundwater quality if fertilizers and pesticides applied to the land surface are carried down to the water table via the percolated AgMAR flood water. Groundwater models that account for the specific pathways of a potential flood field, pesticide and nutrient loading in the root zone, and nitrate transport dynamics can add quantitative data to assist the cost-benefit analysis when considering AgMAR.

One of the challenges of groundwater models, however, is determining overall inputs from the land and surface water systems. Particularly in agriculturally dense areas where many different crop types with varying irrigation demands and evapotranspiration (ET) rates are present. While MODFLOW includes various packages to estimate recharge, ET, crop use, surface water interactions etc. the Water Evaluation And Planning (WEAP) tool can handle all of those components in one package [15]. WEAP is a water balance and accounting model [16]. It uses the water balance approach to determine groundwater recharge from precipitation after all other users have been met [16]. It includes an interface for linking to MODFLOW and MODPATH models to couple the water resources management and water balance outputs to a groundwater flow and particle-tracking simulation. The Sacramento Valley Water Allocation Model (SACWAM) is a fully calibrated and validated WEAP model developed by the Stockholm Environmental Institute (SEI) in partnership with the California State Water Resources Control Board (SWRCB) [14].

The SACWAM model was developed to evaluate how management decisions involving the State Water Project and Central Valley Project allocations would affect the Bay-Delta watershed [14]. The model domain extends north to the California-Oregon border and just south of Stockton, CA (Figure 1). The SACWAM domain is much larger than the Colusa basin area of interest, however this means fluxes in and out of the basin will be better captured by larger regional system dynamics, allowing for improved calibration of the MODFLOW model.

Figure 1: SACWAM model domain adapted from the Sacramento Valley Water Allocation Model Documentation [14].

Basin Setting

Colusa County is located in Sacramento Valley, the northernmost portion of the greater Central Valley complex. It is bounded by the Coastal Ranges to the West and the Sutter Buttes and the Sacramento River to the east. Glenn County lies to the north and Yolo county to the south.

The Sacramento River is the major natural surface water feature, flowing north to south through Colusa County. The Colusa Trough is a man-made surface water feature that flows north to south through the middle of the county and is the main drainage feature for irrigation in the area. To the west, is the Glenn-Colusa Canal which provides much of the irrigation water to northwestern users in the county. A dense network of man-made canals and ditches used for routing irrigation water and return flows is interspersed throughout.

The geologic setting of the Sacramento Valley generally consists of continental sediments accumulated from the Coast Range to the West and the Sierra Nevadas to the East underlain by marine sediments [5]. Fresh water is stored in the continental sediments which range from 700 to 900 m thick [5]. In the western portion of the valley where Colusa County is located, the Tehama Formation, derived from the Coast Range is most prevalent. The Tehama Formation is described as predominantly silts and clays with thin/discontinuous lenses of sand and gravel [5]. Depth to groundwater varies, it is typically deeper with proximity to the coast ranges and shallows proceeding eastward towards the Sacramento River, it is 9 meters below ground surface (m bgs) on average [5]. The base of fresh water typically coincides with the base of the continental sediments i.e. 700 to 900 meters below ground surface. As this analysis is primarily concerned with AgMAR effects on shallow groundwater, only the more surficial continental sediment geology was incorporated in the model.

Methods

This analysis consisted of field-scale implementation of AgMAR at three different sites in Colusa County, CA in 2019 and extraction of long-term Colusa groundwater basin storage estimates from the SACWAM model. The purpose of the analysis was to project what affect local AgMAR implementation within the Colusa basin would have on regional storage to set a benchmark for calibration and validation of a future MODFLOW groundwater flow model.

Field Tests

To better understand the effects of AgMAR on groundwater systems, a field-scale test was implemented on two agricultural fields in 2019 in Colusa County, California (CA) [7]. The field locations are shown in Figure 2. The field test consisted of flooding the fields for 30 days and maintaining approximately 10 centimeters (cm) of ponded flood water above the fields for the entire duration [7]. Surface inflows, surface outflows and precipitation were measured on a daily basis [7]. ET was estimated as the reference ET (ETo) of the closest CIMIS weather station and multiplied by a crop coefficient of 1.1 for open water surface [7]. The changes in surface and root zone storage were estimated on a daily basis, from the measured and ET data, which were all used to determine the amount of recharge to the groundwater basin over the 30 day period [7]. Based on the mass balance analysis, Davids Engineering estimated that 40 to 75 cm of flood water recharged as deep percolation to the underlying water table from the AgMAR tests [7].

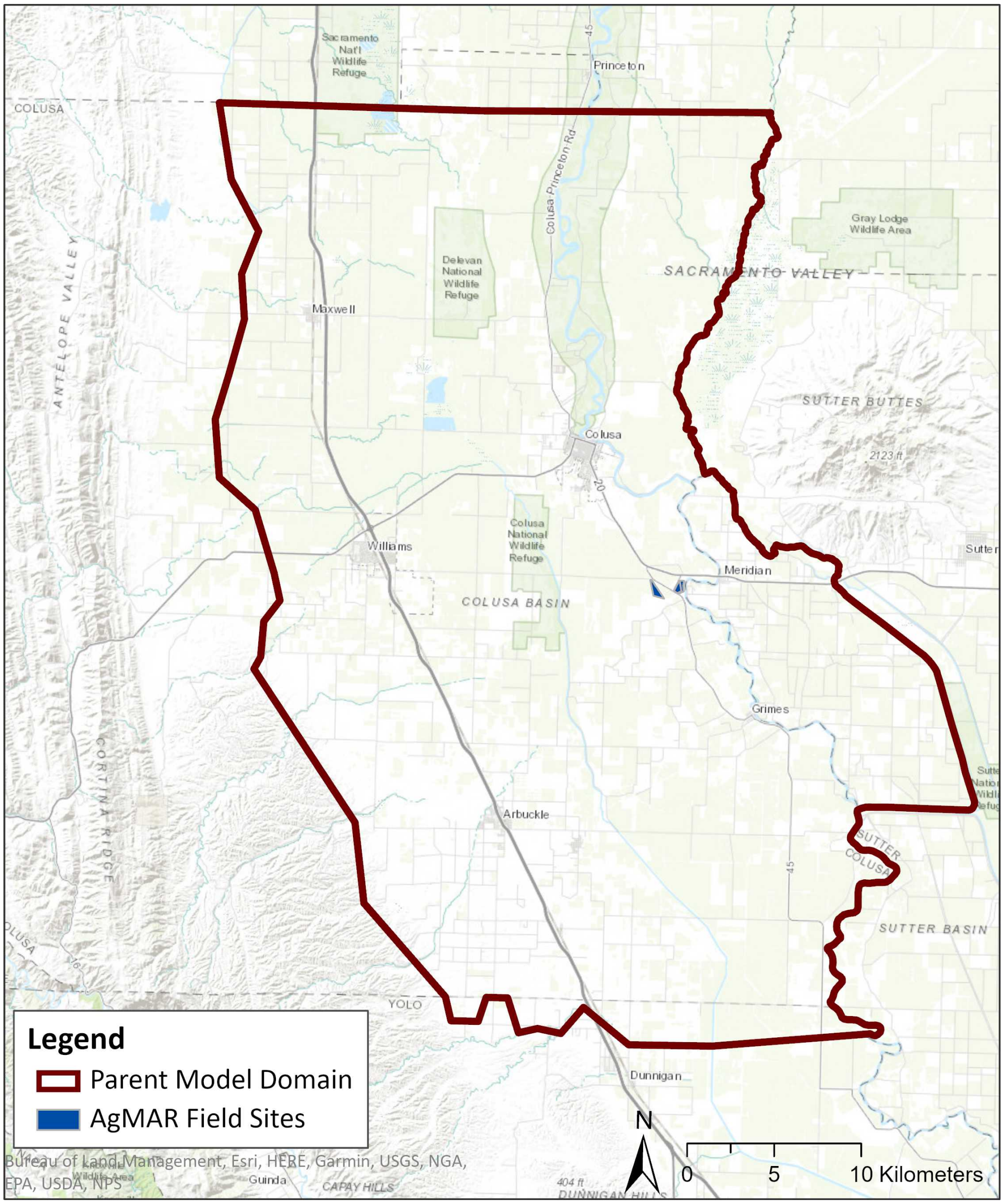

Figure 2: MODFLOW model domain (maroon) and field locations for AgMAR tests in Colusa County, CA.

Sacramento Valley Water Allocation Model (SACWAM)

The SACWAM model is publically available for download from the California State Water Resources Control Board [13]. The model was calibrated to and simulates historical data from 1921 through 2015 [14]. The Colusa groundwater basin is one of the ten groundwater basins simulated in the model [14]. For the purposes of this analysis, the proposed MODFLOW model domain was imported into the SACWAM model to identify nodes of interest and the Colusa Groundwater Basin node isolated for further analysis. Figure 3 is a zoomed in snippet of the SACWAM model overlying the proposed MODFLOW model domain with the Coluas groundwater basin node and all the connected demand sites identified. Once the nodes of interest were identified, inflows, outflows and long-term storage data were extracted from the nodes and exported for further analysis.

Preliminary Results

The SACWAM model indicated that the Colusa groundwater basin was connected to 16 demand sites - 12 agricultural, 1 rural and 4 urban. The demand sites are located as far north as Tehama county and as far south as Yolo County (Figure 3). Isolating the inflows and outflows from these sites indicated the community dependence on groundwater from the Colusa basin vs surface water as shown in Figures 4.

Figure 4 indicates major surface water inflows are from the Sacramento River and water project deliveries from the Glenn Colusa and Tehama Colusa canals. Major surface water outflows are to the Colusa Basin Drain and return flow to the Sacramento River. Most of the inflow to these demand sites comes from Colusa groundwater and the Glenn Colusa Canal while most outflow goes to the Colusa Basin Drain. While there is a nearly equal dependence on surface water and groundwater in this system, the disproportionate amount of water returning to groundwater may be expected to result in a decline in groundwater resources over time. This expectation was confirmed by the estimated groundwater storage in the Colusa Groundwater basin returned by the SACWAM model as shown in Figure 5.

The groundwater storage data shows that the Colusa Basin was initially estimated to contain approximately 3.7×10^8 million m^3 of water beginning in 1921. From 1921 to 1978 approximately 6.0×10^7 m^3 of groundwater were mined from this resource, over 16% of the total supply. Following conservation efforts in the 1970s, storage in the Colusa basin was relatively stable from 1978 to 2009. However with the 2011 drought, there was a greater reliance upon groundwater such that storage in the Colusa basin declined by approximately 2.0×10^7 m^3 in the final modeled years from 2009 to 2015. Thus the SACWAM model indicates a total of 1×10^8 m^3 of water have been mined from the Colusa Basin, resulting in a decline of 27% of the supply since 1921. This data demonstrates historical mining of groundwater and confirms that in times of drought this region extracts more from the Colusa Basin than is recharged resulting in a net decline in storage.

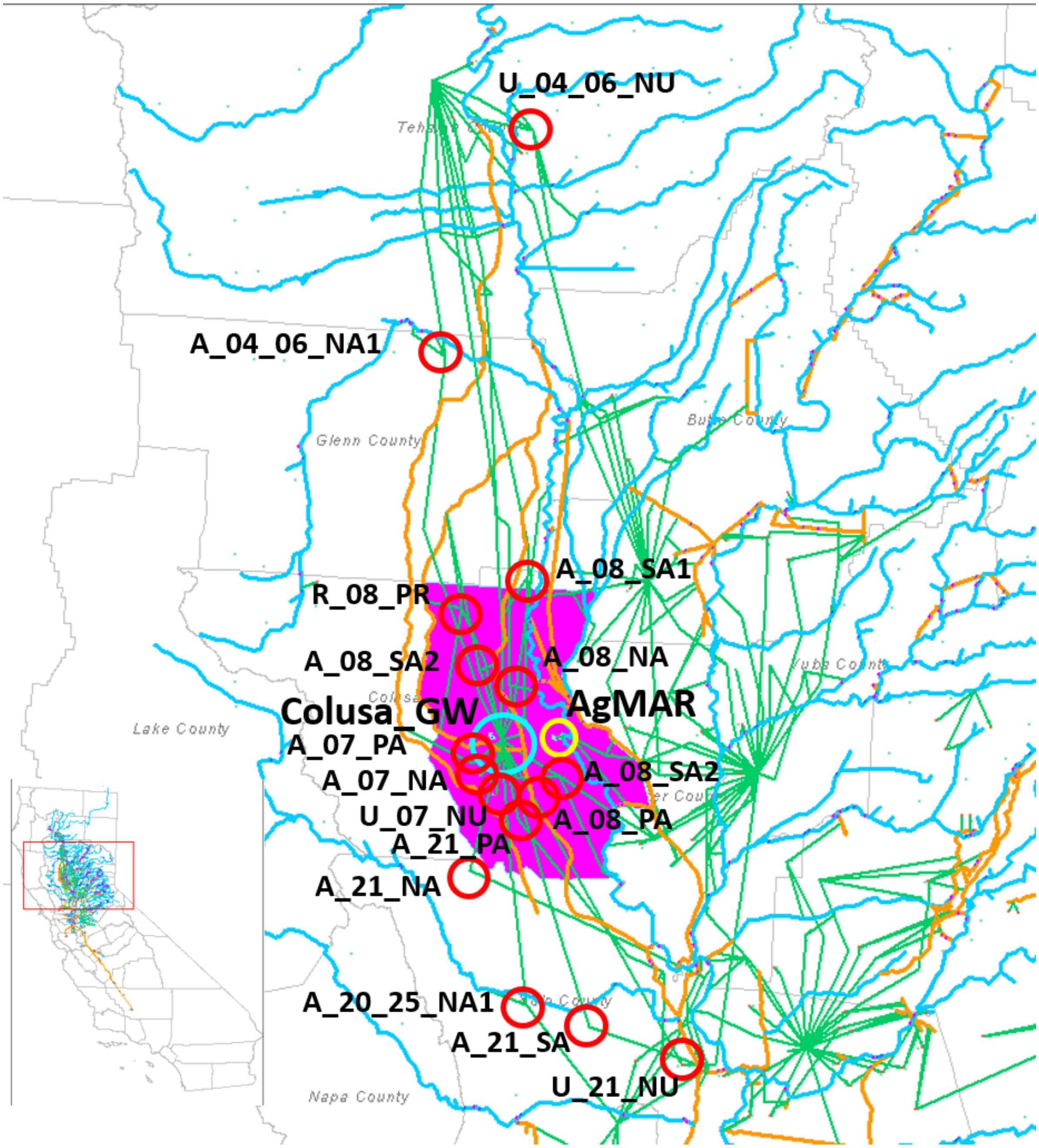

Figure 3: SACWAM model overlying MODFLOW model domain with Colusa Groundwater basin node and connected demand sites highlighted.

AgMAR may curb the decline. The field tests indicated 40 to 75 cm infiltrated as deep percolation to the subsurface. Given the two fields had a total combined area of approximately 5.8×10^5 m^2 this equates to 4.5×10^5 m^3 of deep percolation. While this is only a drop in the overall Colusa Basin bucket (0.17%), if implemented on a wider level it could have a greater impact. However, this is complicated by local recharge pathways and residence times in the basin. Just because water is recharged in Colusa Basin, does not mean it stays in Colusa Basin.

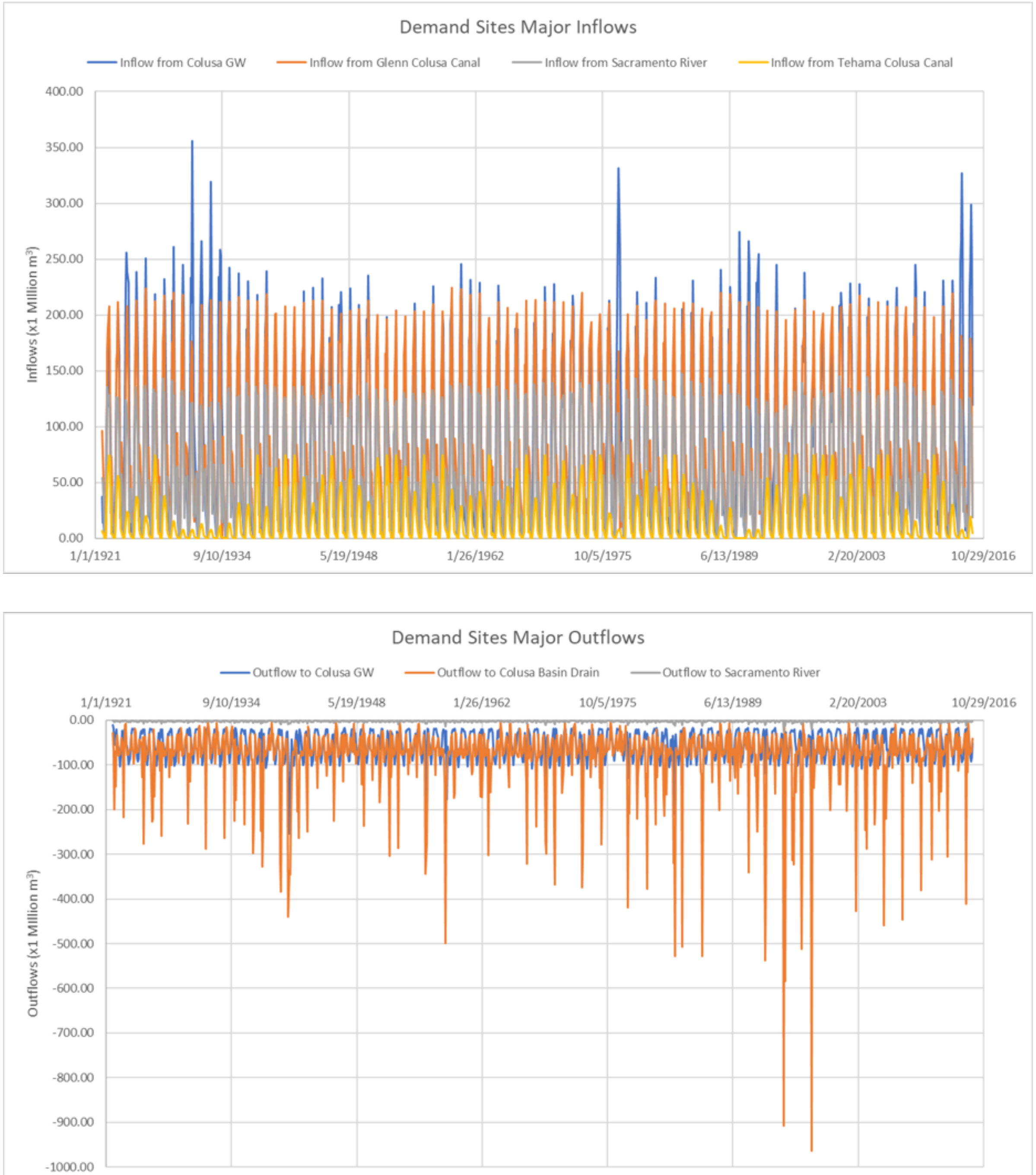

Figure 4: Major inflows (top) and outflows (bottom) to demand sites connected to the Colusa Groundwater Basin node in the SACWAM model.

The AgMAR tested fields were located approximately 360 to 1,750 m from the Sacramento River. Though the closer field (Field 2) was estimated to recharge approximately 35% more than the field located over a kilometer away from the river, the farther field (Field 15) observed over double the increase (2.4x) in water levels (Table 1). Thus further analysis of recharge pathways via a MODFLOW groundwater flow model will add valuable information regarding where to implement

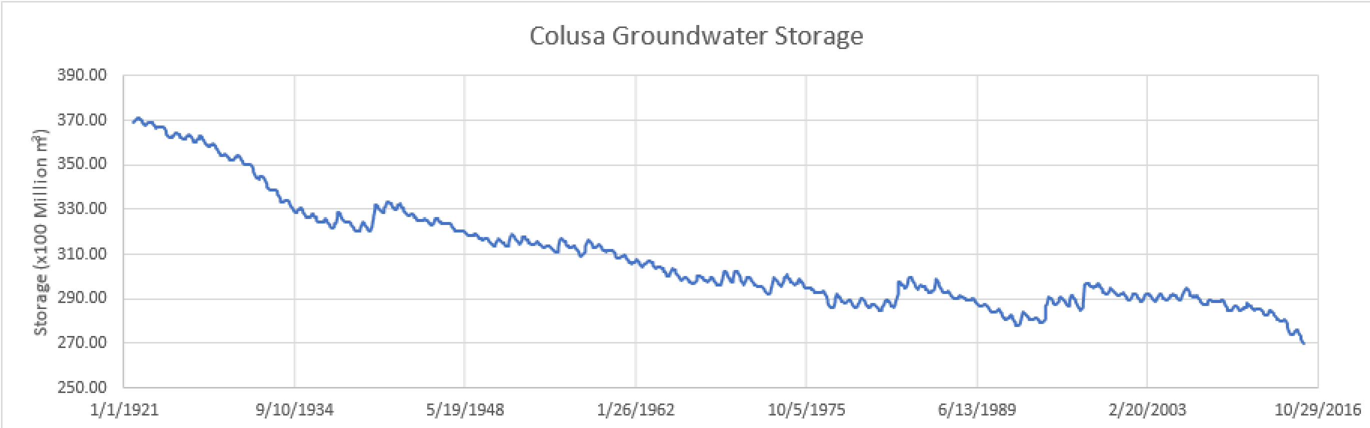

Figure 5: Total storage estimated in the Colusa Groundwater basin by SACWAM for model years 1921 through 2015.

Table 1: Recharge estimates from 2019 AgMAR field test in Fields 2 and 15.

	Field 2	Field 15
Area (m^2)	2.7×10^5	3.1×10^5
Proximity to River (m)	360	1,750
Total Calculated Deep Percolation (m^3)	2.6×10^5	1.9×10^5
Total Observed Change in Water Level (m)	0.5	1.3

AgMAR to get the most benefits in the basin.

Conclusions

Climate change predictions indicate droughts like that experienced from 2011 to 2015 in California will only become more intense and more frequent in years to come [8]. The Colusa basin groundwater storage data extracted from the SACWAM model indicates despite past conservation efforts, in times of drought groundwater reliance increases such that more water is extracted from the basin than is replenished. With increasing frequency and intensity of droughts, this practice is not sustainable long-term. New management practices like AgMAR may alleviate those shortages by recharging and banking more water in times of plenty for use in times of need. A field test demonstrated applying 10 cm of flood water to relatively conductive agricultural fields for 30 days, recharged 40 to 75 cm of water. While these gains are only felt locally i.e. at the field scale, more widespread use could have larger impacts. More work is needed to evaluate risks of AgMAR contributing to pollution by agricultural pesticides and nitrates. Additionally further research is in development to assess where the recharged water ends up via a MODFLOW groundwater flow model and MODPATH particle tracking. Whether or not AgMAR is the answer, innovative water management practices are in dire need to meet water demand in California when supply is increasingly uncertain.

References

1. Philip AM Bachand, Sujoy B Roy, Joe Choperena, Don Cameron, and William R Horwath. Implications of using on-farm flood flow capture to recharge groundwater and mitigate flood risks along the Kings River, CA. *Environmental science & technology*, 48(23):13601–13609, 2014.

2. Herman Bouwer. Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal*, 10(1):121–142, 2002.

3. RF Brown and DC Signor. Artificial Recharge—State of the Art. *Groundwater*, 12(3):152–160, 1974.

4. California Department of Water Resources. California's most significant droughts: comparing historical and recent conditions, 2015. URL: `https://cawaterlibrary.net/wp-content/uploads/2017/05/CalSignficantDroughts_v10_int.pdf`.

5. CH2M Hill and MBK Engineers, Inc. Sacramento Valley Finite Element Groundwater Flow Model User's Manual. Technical report, February 2015.

6. Helen Dahlke, Andrew Brown, Steve Orloff, Daniel Putnam, Toby O'Geen, et al. Managed winter flooding of alfalfa recharges groundwater with minimal crop damage. *California Agriculture*, 72(1):65–75, 2018.

7. Davids Engineering, Inc. Colusa Recharge Analysis Pilot Monitoring. Technical report, December 2019.

8. Dettinger, Michael. Climate change, atmospheric rivers, and floods in California–a multimodel analysis of storm frequency and magnitude changes. *JAWRA Journal of the American Water Resources Association*, 47(3):514–523, 2011.

9. Peter Dillon. Future management of aquifer recharge. *Hydrogeology Journal*, 13(1):313–316, 2005.

10. Tiffany N Kocis and Helen E Dahlke. Availability of high-magnitude streamflow for groundwater banking in the Central Valley, California. *Environmental Research Letters*, 12(8), 2017.

11. Tess A Russo, Andrew T Fisher, and Brian S Lockwood. Assessment of managed aquifer recharge site suitability using a GIS and modeling. *Groundwater*, 53(3):389–400, 2015.

12. Bridget R Scanlon, Robert C Reedy, Claudia C Faunt, Donald Pool, and Kristine Uhlman. Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. *Environmental Research Letters*, 11(3):035013, 2016.

13. State Water Resources Control Board. San Francisco Bay/Sacramento-San Joaquin Delta Estuary (Bay-Delta) Program, 2019. URL: `https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/sacwam/sacwam_download.html`.

14. Stockholm Environment Institute. Sacramento Valley Water Allocation Model. Technical report, 2019.

15. Stockholm Environment Institute. WEAP Features, 2021. URL: `https://www.weap21.org/index.asp?action=202`.

16. Stockholm Environment Institute. Why WEAP?, 2021. URL: https://www.weap21.org/index.asp?action=201.