Leveraging Access to Historic Geologic and Monitoring Data to Determine Impact of Heterogeneity and Model Upscaling on Local-Scale MAR Model Results

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Abstract

With the ongoing efforts throughout California to achieve a sustainable management of groundwater, managed aquifer recharge projects have been largely considered by stakeholders to supplement current groundwater use. However, lack of data, time, water resources, or understanding of subsurface characteristics can make finding suitable recharge sites challenging.

This project focuses on a case study of three vineyards in Elk Grove, California. It is unique in that there is a developed monitoring network, decades of pre-existing research, permits to allow for the recharge project to occur, and extensive collaboration to fully characterize the subsurface and flow pathways. One hundred geologic realizations of the study area were generated utilizing a transition probability/ Markov chain geostatistical software (T-PROGS) and was informed by over 500 discretized well completion reports and previous knowledge of mean lengths. The 1-foot vertical discretization of the geologic model and the number of raw data used to inform the model lends well to understanding the impact of the heterogeneity on recharge results at a local scale.

This portion of our work focuses specifically on the impact of the geologic heterogeneity on results obtained from a numerical groundwater flow model (developed with MODFLOW), and the variance of recharge impacts due to the geologic uncertainty. All one hundred realizations of the geologic model were input into the groundwater model. Steady state runs with natural recharge were analyzed for all realizations and head results were compared throughout the domain. The geologic realizations were also upscaled vertically to determine when the upscaling causes a substantial difference in results compared to the un-upscaled run.

Introduction/ Literature Review

In 2014, the state of California passed the Sustainable Groundwater Management Act (SGMA), which required critically overdrafted basins to create plans to sustainably manage groundwater resources for the future. In these plans, agencies are required to consider and account for specified undesirable outcomes related to groundwater decline (California State Legislature, 2014). In addition to using less groundwater in critical months, stakeholders are exploring ways to divert excess surface water and store it in groundwater systems for longer-term sustainability of the system.

This report focuses specifically on Managed Aquifer Recharge (MAR), which involves diverting excess surface water during wet seasons (normally winter months) to areas with high conductivity, which hopefully results in rapid recharge to the groundwater table below (Bouwer, 2002; Dillon et al., 2009). A subset of MAR is the practice of flooding agricultural fields during dormant seasons, termed Agricultural MAR (Ag-MAR). This method of MAR has great promise to boost groundwater levels before the growing season, and in crops such as alfalfa, the practice of Ag-MAR has not affected crop yield (Dahlke et al., 2018). In regard to water quality, studies have also been conducted to test how Ag-MAR practices have impacted water quality, and crops such as vineyards also show great potential for effective recharge projects without harming water quality (Waterhouse et al., 2020).

MAR projects pose a number of challenges, such as the cost of building the recharge infrastructure and finding suitable locations close to a water source. Surface maps that characterize highly conductive soils in the region, such as the Soil Agricultural Groundwater Banking Index (SAGBI) (O'Geen et al., 2015) have been used to identify suitable sites for recharge projects and are useful when just focusing on recharge, with no consideration for where the water will eventually go. However, when considering recharge to the water table in alluvial depositional systems, analysis of the deeper geology is needed to identify highly conductive connected pathways that have the potential to move a large amount of water from the surface to the groundwater table quickly (Weissmann et al., 2004).

Most groundwater models use a very simplified version of geologic conditions, and don't account for these interconnected pathways (Weissmann et al., 2004). The groundwater models that have taken this heterogeneity into consideration have found that these coarse-grained connected systems are responsible for high efficiency water movement in this particular study area (Meirovitz, 2010; Weissmann et al., 2004).

In the overall case of MAR success, it is not really known what specific characteristics are most important when determining suitability and viability of potential recharge sites. The potential variability of recharge success at a site due to the uncertainty in the geology is also not known. This study area and project is unique in that there is a large amount of geologic data, access to monitoring data, and a large amount of stakeholder engagement. Because of this, the study area in this report could prove to be a very informative case study that fully explores all dynamics of MAR and focuses on what specific characteristics result in successful and effective recharge projects.

Objective

The main objective of this report is to generate a groundwater model utilizing geologic and monitoring data in the area that can be used to characterize the range of potential recharge efficiency that we can expect for the vineyard recharge sites. The following is a list of expected deliverables for this report:

1. A description of the data included in the creation of the geologic model and an example of the realizations created
2. The MODFLOW packages used in this model, and all assumptions included in the generation of the input files for these packages
3. Head results of the steady state groundwater model for all realizations
4. Comparison of head results of 5 of the 100 realizations at 2, 4, 8, 10, and 20 times upscaling

Study Area

This study area focuses on three vineyards located in Elk Grove California. These vineyards have been approved as MAR sites and have been flooded with excess surface water from the Cosumnes River. The geologic model used for this report was influenced by 551 well completion reports, and those well locations are also shown below (Figure 1):

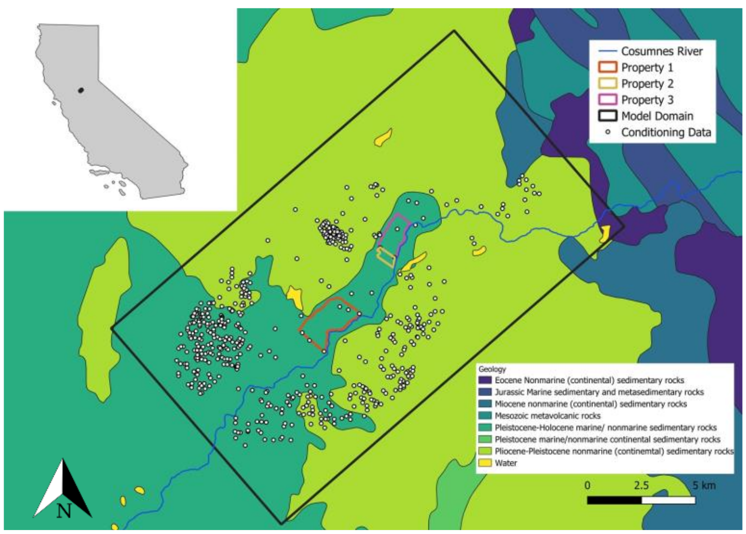

Figure 1: Location of model domain, conditioning data, Cosumnes River, and vineyards approved for MAR project

This location was chosen because of its proximity to a water source (the Cosumnes River), willingness from farmers to allow for the recharge to occur, and reports that suggest that vineyards could serve as ideal locations for Ag-MAR, without too much harm to water quality.

Hypothesis

The hypothesis of this report Fis that the geology plays a very important role in determining how successful recharge projects will be in one area. I also believe that there will be a point in upscaling in which the domain acts as a homogeneous system, in which the bulk flow in and out of the model domain is the same, but there is no way to identify where in the domain recharge will be most successful.

Data Sources

Geology

The location and pdfs for the Well Completion Reports used in the geologic model were found from the California SGMA Data Viewer (*SGMA Data Viewer*, n.d.). This website was created after SGMA became legislation and was vital in giving the public access to many previously proprietary documents.

The mean lengths for the four geologic facies in this model were found from pumping tests and other analysis completed by past UC Davis students (Fleckenstein, 2004; Meirovitz, 2010).

All of the raw geologic data was input into the software called Transitional Probability Geostatistical Software (T-PROGS). The input and expertise of developer Steve Carle and professor Graham Fogg were instrumental in ensuring the completion of this geologic model (Carle, 1999).

Pumping and Recharge Data

Pumping and Recharge Data were extracted from the regional groundwater model *California Central Valley Groundwater-Surface Water Simulation Mode*l (C2VSim). This model was developed by DWR for use by stakeholders when creating more local groundwater models for GSP’s. (Brush, C.F., and Dogrul, E.C. June 2013).

River Package Data

The shapefile for the river package was modified from the Major Rivers and Creeks Shapefile obtained from the National Hydrography Dataset (NHD) (*National Hydrography Dataset (NHD) - NHD Major Rivers and Creeks - California Natural Resources Agency Open Data*, n.d.). My colleague in the research group, Andrew Calderwood, performed data collection campaigns in which he characterized the Cosumnes River. His data was also included in the river package for this model run.

Constant Head Boundary Conditions

The Constant Head Boundary Condition data was specified through a given Digital Elevation Model (DEM) with projection EPSG:3310. This DEM was provided to the graduate group by a post-doctoral researcher, Brad T. Gooch.

Methods and Assumptions

Geology

The creation of the geologic model is not the main focus of this project, but the process is useful when understanding the potential problems associated with very data dense and discretized modeling. The Well Completion Reports were digitized and discretized into one foot increments. The geology was then simplified from over 100 characterizations to four hydrofacies, with specific proportions and mean lengths. This geologic data was input into T-PROGS, and 100 realizations of the subsurface were generated. Mode detail about the geologic model process can be found in a recent publication (Rodriguez et al., 2021).

Pumping and Recharge Data

Post-doctoral researcher Giorgos Kourakos extracted monthly pumping and recharge data from C2VSim to the given model domain. This data, in the form of csv file, provided monthly pumping data and recharge data from October 1973 to September 2015. Because this model run is steady state, the first step was to take the average value of pumping and recharge at each cell over the full time period.

The grid in C2VSim does not match with the grid chosen for our model domain (Figure 2). To remedy this, code was written in Python to calculate the proportion of the C2VSim grid cells that intersected with our structured grid cells. This proportion was then used to calculate the relative pumping and recharge values for each model domain cell.

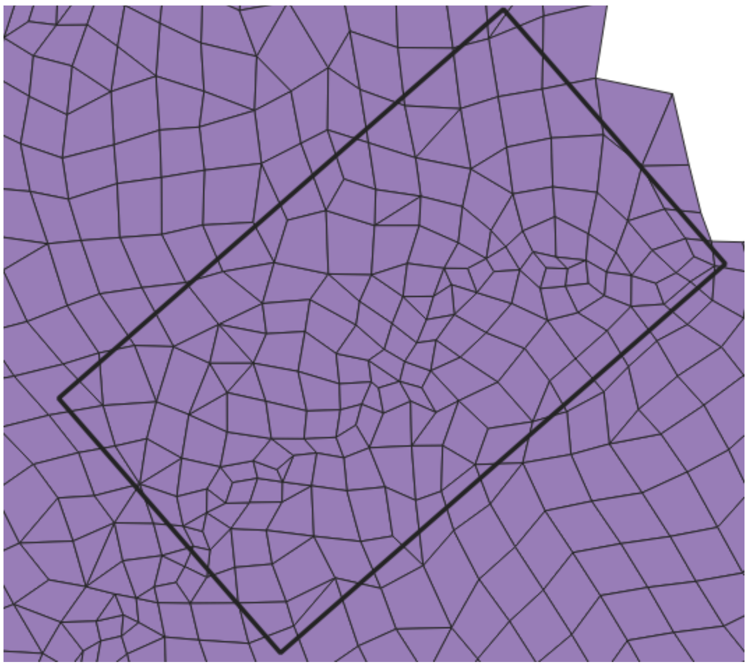

Figure 2: C2VSim unstructured grid overlayed with model domain

Flopy is a python shell used to run MODFLOW. This shell requires specific inputs for packages. Extra care was taken to ensure that the recharge values were input correctly as a rate and normalized by the area of influence.

The final output for this exercise was a rate of recharge for each 200 m x 200 m structured grid cell, and a volumetric pumping loss value for each structured grid cell.

River Package Creation

The shapefile for the river was modified from a larger Cosumnes model currently being created in parallel in the research group. Each river reach within the model domain has a specified length, stage, river bottom, and conductance. The conductance for each reach is calculated from the cross sectional area, conductance, and width of the cell.

Boundary Conditions

The Constant Head Boundary Condition is calculated directly from the DEM. For the eastern-most boundary, it is assumed that the mountainous area acts as a constant head boundary, in which the water table is at the same elevation of the mountain. The elevation values for this eastern boundary were extracted from the DEM and input as boundary conditions. A plot showing the variability of the elevation along this boundary is given in Figure 3.

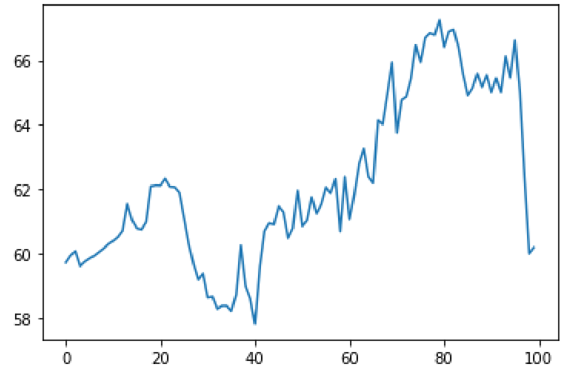

Figure 3: Elevations of Eastern Constant Head Boundary Condition

The general head boundary conditions are a bit less precise. There are no real features within the domain that act as a known water level boundary. Because of this, the general head boundary conditions were based on water surface elevation levels outside of the domain, such as outflow to the Delta.

Calculation/Results

Geologic Model

Four of the 100 geologic realizations created are visualized for comparison in Figure 4.

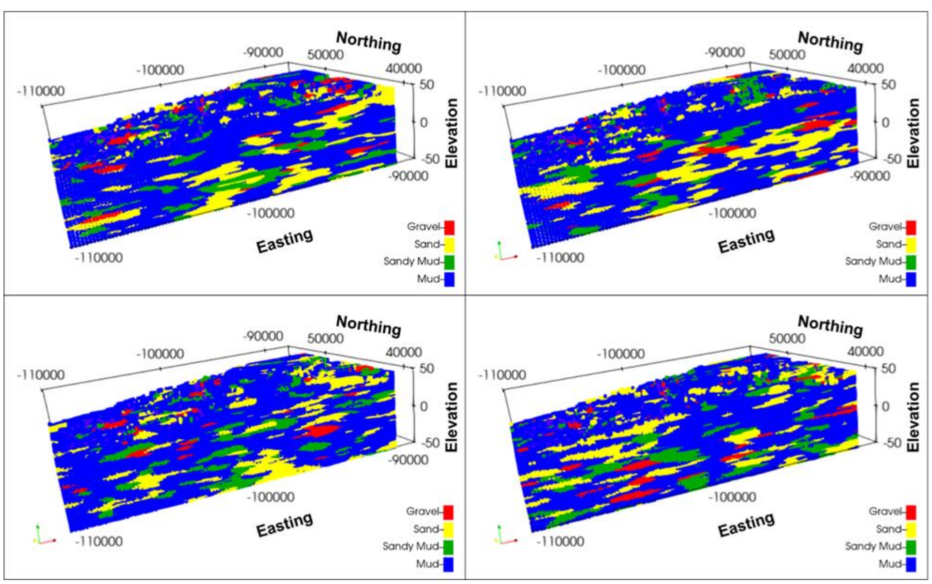

Figure 4: Visualization of four of 100 geologic realizations of the study area

As shown, all realizations have the same characteristics. The conditioning data is the same for all realizations, as well as the mean lengths and proportions of facies. The main difference is the location of high conductivity pathways that would provide for quick recharge to the water table below. The difference in recharge results between realizations will be very helpful in determining the potential range of recharge, especially when considering the heterogeneity of the subsurface.

MODFLOW Model Results

The model was run at steady-state and resulted in a convergence error (Figure 5).

```
         TIME SUMMARY AT END OF TIME STEP    1 IN STRESS PERIOD    1
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH  86400.      1440.0      24.000      1.0000     2.73785E-03
 STRESS PERIOD TIME  86400.      1440.0      24.000      1.0000     2.73785E-03
         TOTAL TIME  86400.      1440.0      24.000      1.0000     2.73785E-03
1
 FAILURE TO MEET SOLVER CONVERGENCE CRITERIA
 BUDGET PERCENT DISCREPANCY IS  -23.6658
 STOPPING SIMULATION

 Run end date and time (yyyy/mm/dd hh:mm:ss): 2022/05/18 11:19:31
 Elapsed run time:  1 Minutes,  9.560 Seconds
```

Figure 5: Example of solver convergence error

There are many solvers that one can choose when running MODFLOW, and some have more abilities to iterate over very small cell thicknesses than others. After a few more iterations, there was a solver that gave a mass balance output:

```
  CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
  ------------------                 ------------------------

        IN:                                      IN:
        ---                                      ---
          STORAGE =           0.0000               STORAGE =           0.0000
    CONSTANT HEAD =    19972204.0000         CONSTANT HEAD =    19972204.0000
            WELLS =           0.0000                 WELLS =           0.0000
    RIVER LEAKAGE =           0.0000         RIVER LEAKAGE =           0.0000
  HEAD DEP BOUNDS =       25709.7500       HEAD DEP BOUNDS =       25709.7500
         RECHARGE =     5034494.0000              RECHARGE =     5034494.0000

         TOTAL IN =    25032408.0000              TOTAL IN =    25032408.0000

       OUT:                                     OUT:
       ----                                     ----
          STORAGE =           0.0000               STORAGE =           0.0000
    CONSTANT HEAD =    17057114.0000         CONSTANT HEAD =    17057114.0000
            WELLS =     8351030.0000                 WELLS =     8351030.0000
    RIVER LEAKAGE =     4922266.0000         RIVER LEAKAGE =     4922266.0000
  HEAD DEP BOUNDS =      893987.8750       HEAD DEP BOUNDS =      893987.8750
         RECHARGE =           0.0000              RECHARGE =           0.0000

        TOTAL OUT =    31224398.0000             TOTAL OUT =    31224398.0000

         IN - OUT =    -6191990.0000              IN - OUT =    -6191990.0000

PERCENT DISCREPANCY =         -22.01     PERCENT DISCREPANCY =         -22.01
```

Figure 6: Mass Balance Output for the run with least discrepancy

After 15 runs, this output was the one that resulted in the least percent discrepancy in the mass balance. It appears that the constant head boundary condition, as well as the general head boundary condition, require too much water to be maintained. In the case of the constant head boundary, this makes sense. The mountain elevation is significantly higher than that of the vineyards and floodplain. It is also possible that the general head boundary is too far away from the model domain that it is no longer meaningful. The constant head boundary was simplified and modified many times, but there was still no convergence.

Take 2: Simplified MODFLOW Model

The MODFLOW model was simplified in an attempt to get convergence. In this model run, pumping was completely removed, recharge was made constant over the domain, and the river package was simplified. This set up removed the issues with the constant head boundary condition, because the domain was flooded with more than enough water to keep the constant head boundary at the mountain elevation. It is obvious that the head results from this model study will not be accurate to real world conditions. However, the spread of head results is potentially useful for understanding where in the model domain the results are most varied. To show these results, head values for each cell in the two main vineyards, Teichert and Rooney, were extracted for all 100 realizations. Probability Density Functions (PDF's) were created for each cell utilizing the head values from all realizations. These PDF's were ranked based on spread. The PDF's with the highest peak had the most certainty in head values, and those with the largest spread had the least certainty (Figure 7).

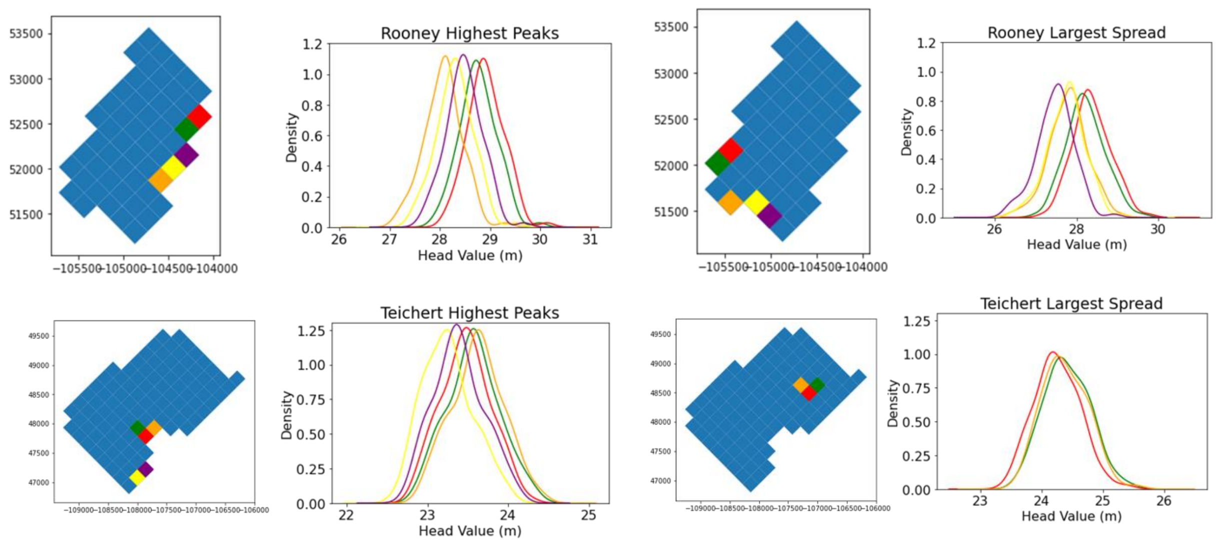

Figure 7: Most and Least Varied PDF's for head results and both Teichert and Rooney for all 100 realizations

From these results, it appears that the head values are most consistent near the river. This makes sense because in this simplified model scheme, the river package was the dominant driver of the model. However, the areas with the largest spread are loosely around the areas in which the geologic data is consistent among all realizations, which would require more thorough analysis to understand.

Conclusions/ Recommendation/Limitations

Unfortunately, I was unable to generate the desired results from the more detailed groundwater model I worked on this quarter. However, the exercise itself was a very interesting practice in understanding the potential pitfalls of attempting to model areas using a large amount of data and very detailed geology, when there is not as much known about the boundary conditions. At this stage, I am confident in the physical accuracy of the geologic model, the Cosumnes River set-up, and the pumping and recharge results from C2VSim. The boundary conditions seem to make sense in theory, but it is obvious that more work needs to be done to depict them more accurately for this model to run and converge.

The questions being asked of scientists now are interesting and complicated and will require the use of more detailed groundwater models. It is up to us to be patient and diligent when creating these models and utilize all resources available to us to represent the physical world as well as we are able to.

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