PROJECT DESCRIPTION

Water management and long-term sustainability is a significant concern in the project study area. Anticipated increases in population growth, projected changes to precipitation intensity and duration due to climate change, heavy reliance on imported water, and already overstressed groundwater aquifers present a difficult challenge to water resource managers. Engineered systems such as infiltration basins, bio-infiltration networks, and artificial wetlands collect surface stormwater and promote infiltration into the subsurface. However, infiltration basins do not treat the water, and the infiltration process is slow and can be ineffective if the water level decreases throughout the year. Bio-infiltration networks and artificial wetlands naturally treat stormwater only, have a minimum load capacity, require ample open space, and require costly maintenance. Our project proposes utilizing a decentralized wastewater treatment to treat residential wastewater (tertiary) and simulate the injection in three dimensions as it enters the unconfined aquifer below. Modeling shows the effect of the injected treated wastewater on the water table depth and helps predict the time frame of beneficial impacts. The benefits of this project include reduced reliance on imported water, reversing harmful land subsidence due to over-pumping, and reduced risk of briny water incursion along the oceanic shoreline. The specific tasks are (1) site selection, (2) designing a decentralized facility that requires minimal space, (3) developing a collection system to treat all the wastewater generated from 13,000-14,000 residents in the five nearby cities, (4) designing the injection well, (5) performing hydrologic modeling of the injection well scenarios, (6) considering environmental impacts, (7) and performing cost analysis.

Site Selection: Site selection involved several steps including data acquisition, data processing, and geospatial analysis in 2- and 3-dimensions. The region had an abundance of boreholes, water table monitoring wells, and geological maps. Borehole data from the U.S. Bureau of Land Management provided 1210 sites with stratified soil information up to 30.5 m below the surface. Soil maps were also available from the U.S. Department of Agriculture National Resources Conservation Services (USDA NRCS) dataset[1]. Monitoring wells from Regional Water Agency A provided 210 sites with groundwater observations over time. Geological maps detailed the location of fault lines, approximate thickness of confined and unconfined aquifers, and depth to bedrock. This location lies directly above an unconfined aquifer approximately 30.5 m below ground with thickness ranging from 10 to 20 m. This region was also void of any fault lines making it an ideal location. With these observations, we were able to identify our study site represented in Figure 1. The study area is approximately 61 km^2 and serves a population of approximately 13,000 to 14,000 individuals[2].

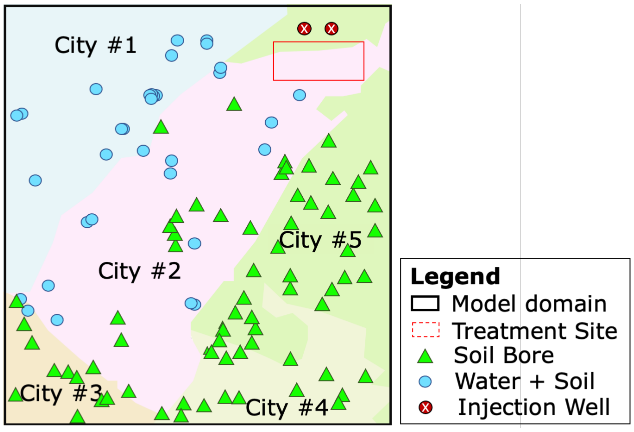

Figure 1. Model domain with soil and water table observations, decentralized treatment location, and injection wells

Decentralized Facility Design and Collection System: To mitigate the massive amounts of energy to meet demand and the extensive financial resources required for operation, we selected a decentralized water treatment system to address the collection, treatment, and distribution of the processed water (Figure 2). We will use the community's existing gravity sewer network consisting of 20.32 cm diameter pipes and approximately 59.5 km of sewer lines to gather wastewater and distribute it under pressure towards one of our eight packaged wastewater treatment plants for processing. The packaged plant consists of five tanks, which include an equalization tank to prevent hydraulic overload (individual capacity of 33,405 gal. or 267,000 gal. combined), a sludge holding tank (22,612 gal. capacity) that will store the excess waste activated sludge (we will periodically empty by a contract septage hauler once full), a 100,081

[1] *Geospatial Data Gateway:Home*. USDA. (2021, May 8). https://datagateway.nrcs.usda.gov/.

[2] The United States Census Bureau (2021, May 8). TIGER/Line Shapefiles. https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html

gal. aeration tank to activate the sludge and remove organic wastes, a chlorine/clarifier tank to disinfect and return the activated sludge to the aeration tank (19,385 gal. capacity), and tertiary treatment tanks to reduce biological oxygen demand (BOD) and suspended solids (S.S.; total capacity of 20,435 gal each). Plant managers will release water under gravity into wells that inject directly into the underlying aquifer to rejuvenate groundwater levels.

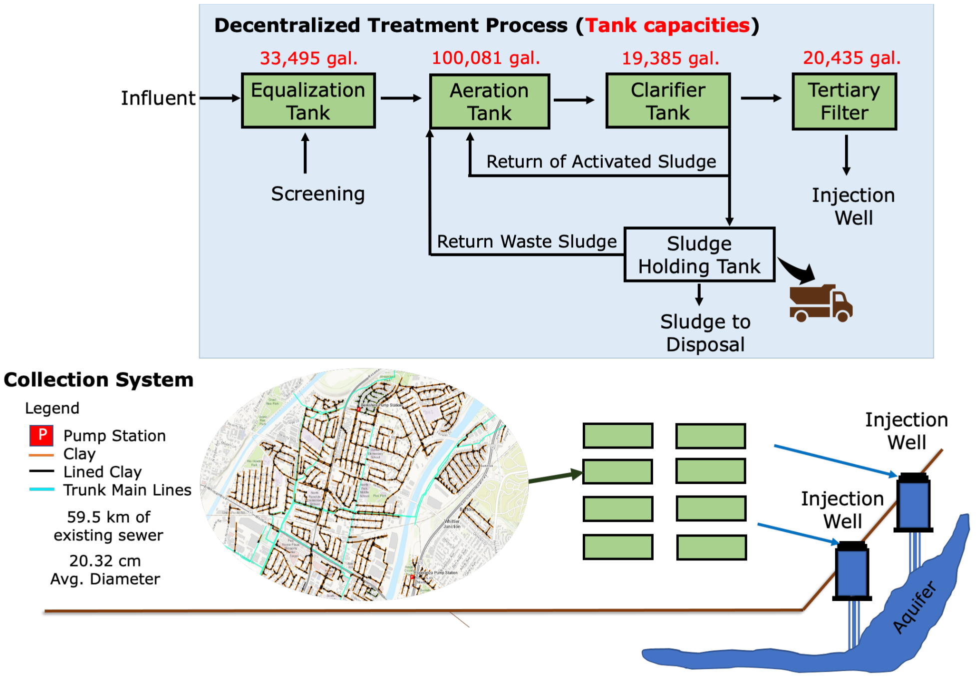

Figure 2. Collection system and decentralized treatment process

The expected treatment facility size is 1.46×10^4 m^2 (3.6 acres), utilizing a vacant area between the community and a river. The site is adjacent to land already incorporated into the regional water management system. The facility uses eight modular, prefabricated wastewater treatment systems in parallel to treat 800,000 gallons per day (GPD). The overall wastewater generation rate per capita is approximately 265 liters/capita/day[3]; the wastewater generated from a community of 13,000 residents is around 910,000 GPD (Eq. 1). We anticipate an 80% retention of the wastewater for reuse (727,600 GPD); this facility will handle that capacity with the expectation of population (P) growth.

$$Q = (P * 69.96) \quad [\text{GPD}] \qquad (1)$$

Injection Well: The depth to bedrock is approximately 30.5 m and provided a threshold for our well depth. We decided to develop three well scenarios to evaluate the costs and change in water table depth. Scenario 1 involved one well drilled to 21.3 m injecting 800,000 GPD, scenario 2 included two wells drilled to a depth of 21.3 m injecting 400,000 GPD each, and scenario 3 included two wells drilled to a depth of 27.4 cm injecting 400,000 GPD each. The well pipe diameter was 15.24 cm.

For our analysis, we used the steady-state unconfined aquifer equation to calculate injection rate and the radius of influence, found to be 0.62 m from the center of the injection well. The radius is relatively small; however, the subsurface material is sandy gravel with high permeability, which is a reasonable result. The well screen will be fitted to the bottom 15.24 m of length, a wire width of 1.19 mm, and a slot size of 0.89 mm. This screen is necessary to the sandy/sandy gravel subsurface from entering the well. The screen will be made of PVC since it is light, strong, easy to install, and inexpensive.

Hydrologic Modeling of Injection Scenarios: We used ParFlow, an open-source, object-oriented, physically-based, three-dimensional (3D), parallel hydrologic model to simulate the surface and subsurface

[3] Ellis, T. G. (2004). Chemistry of wastewater. *Encyclopedia of Life Support System (EOLSS)*, *2*, 1-10.

hydrologic processes. ParFlow solves for variable saturation (vadose and groundwater) in the subsurface using the Richard's equation and can include injection or extraction wells in the domain. After collecting data and site selection, we performed geospatial analysis to generate 2D datasets (i.e., water table depth, directional slopes), obtain model parameterization (i.e., saturated hydraulic conductivity), and forcing (i.e., precipitation) needed for the hydrologic model.

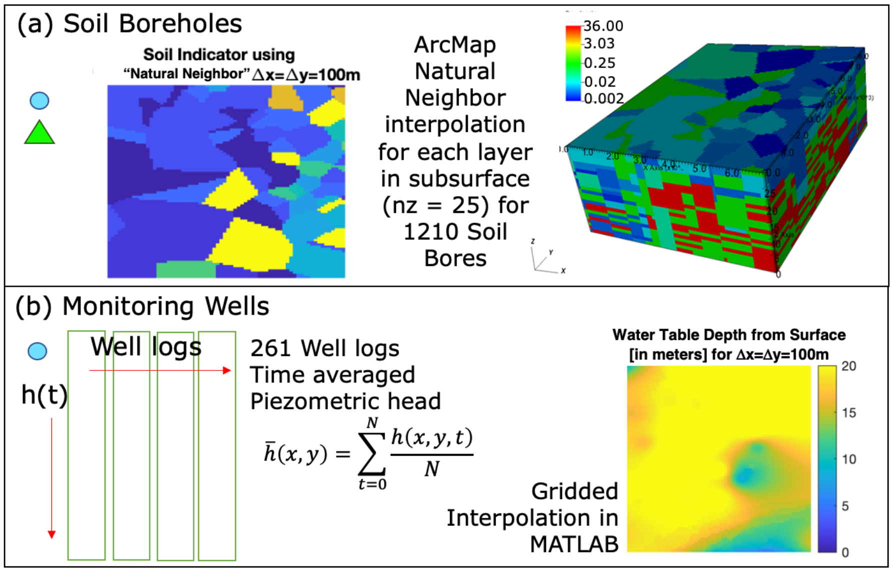

Figure 3. Geospatial analysis of (a) soil boreholes and (b) water table monitoring wells using ArcMap and/or MATLAB

The blue circles and green triangles represent the processed sites found in Figure 1. The soil bores had scattered observations up to 30.5 m in the subsurface. We used the Natural Neighbor interpolation tool to determine the soil classification throughout the domain for each subsurface layer (in 1.2 m increments). Figure 3a shows a sample of the method at a 100 m spatial resolution for the soil surface. The polygons represent the soil type assigned to that region. The 3D image in Figure 3a shows the twenty-five layers compiled to create the subsurface configuration. Each monitoring well log had random observations throughout our simulation period. The water table depth did not significantly vary throughout the observation period ($\pm 0.5\ m$). Therefore, we temporally averaged the logs for each well and used the gridded interpolation function in MATLAB to generate a 2D constant water table depth to define our boundary conditions on the x- and y- faces of the 3D domain. The boundary condition at the bottom of the domain was set as a no-flux boundary because of the existence of a confining layer according to the geological maps for the region.

The final two components needed to build the model domain were the digital elevation model, used to calculate the x- and y-directional surface slopes required to resolve the terrain-following grid, and meteorological observations (i.e., precipitation) needed to drive the simulations. The USDA NRCS dataset[2] provided the digital elevation map. We downloaded NASA's North American Land Data Assimilation System Level 2 dataset (NLDAS-2) for hourly precipitation observations[4]. NLDAS-2 provides hourly observations for at an 0.25-degree spatial resolution across the contiguous United States. The dataset required developing a bash script to mass-download hourly files from the FTP site. We then extracted and processed precipitation in a specific format for ParFlow using MATLAB for our domain's coordinates.

Any model configuration is defined by the number of grid cells in the x-, y-, and z-direction; the finer the discretization, the more detailed representation of area at a high computational cost. We used the model configuration of 69x90x25 in the x-, y-, and z-direction, respectively, resulting in 155,250 grid cells for our modeling simulations. The grid cell discretization or cell thickness was 100 m, 100 m, and 1.2 m in the x-, y-, and z-direction, respectively.

The modeling cohort had to "spin up" the model domain to achieve hydrologic equilibrium (or a steady-state condition) before considering any injection scenarios. This step is essential to assure our model domain is behaving realistically. Our model domain ran for 39,048 hours or ~4.5 years before reaching hydrologic equilibrium; spin-up took approximately three days to complete. We were able to obtain twelve years of hourly precipitation from 2007 - 2018.

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[4] NLDAS: Project Goals. NASA (2021, May 8). https://ldas.gsfc.nasa.gov/nldas

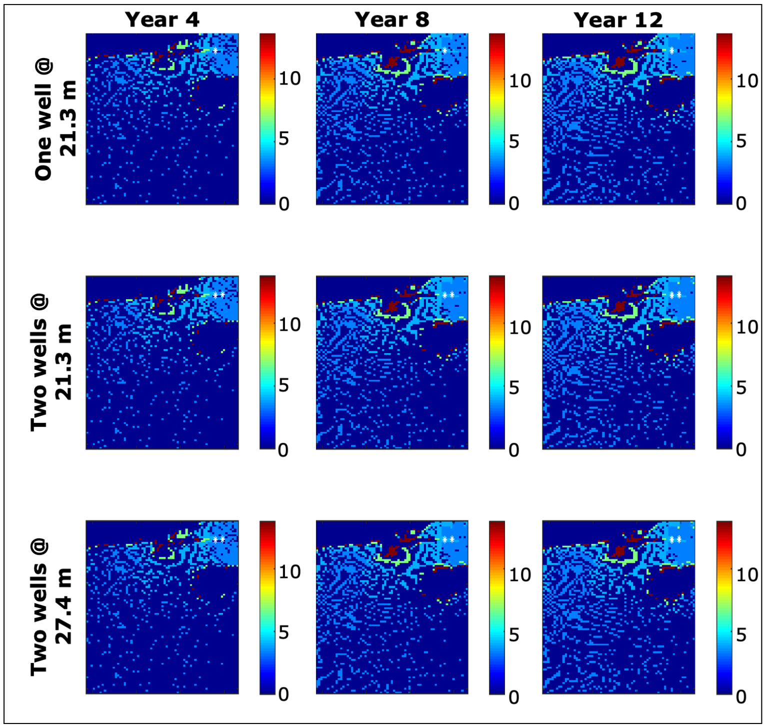

Figure 4. Change in water table depth over time given the three modeling scenarios. The white dots in the upper right corner are the location of injection well(s).

The three injection well scenarios simulated in ParFlow were:

Scenario 1: Well #1 injected 800,000 gallons per day (GPD) at 21.3 m depth.

Scenario 2: Wells #1 and #2 injected 400,000 GPD each at 21.3 m depth.

Scenario 3: Wells #1 and #2 injected 400,000 GPD each at 27.4 m depth.

All scenarios were compared to a *no-injection* simulation to quantify the changes to water table depth and specific storage in the subsurface.

To identify which scenario provided the best results, we determined the change in water table depth due to each injection scenario (Eq. 2) where (x,y) represents each gridded coordinate in the domain and h is the water table depth in meters.

$$h_{injection}(x,y) - h_{no\ injection}(x,y) \tag{2}$$

In Figure 4, we can see the water table level is rising (resulting in a positive calculation from Eq. 3) for each scenario; this trend improves as we continue to inject water into the subsurface. The differences were minimal (mostly 0) between the scenarios. We also calculated the change in specific storage from the injection scenarios to the no injection case (Figure 5) and found the difference in subsurface storage was ~10^3 m^3 when the increase in subsurface storage is three orders of magnitude higher; the difference between the scenarios is considered relatively negligible. This figure shows the positive change in subsurface storage due to the injection wells over time. **Considering the one injection well case significantly reduces the infrastructure and pumping costs by purchasing and operating only one injection well. We chose the single well scenario injecting 800,000 GPD as the best solution for our project.**

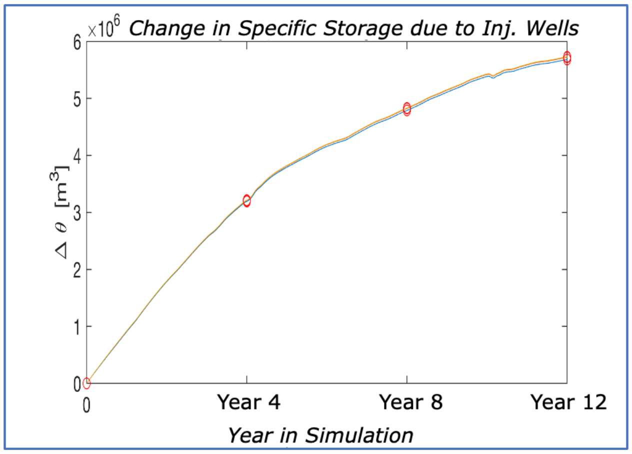

Figure 5. Change in specific storage [m³] relative to the no injection scenario due to the injection wells.

The simulation period of this project was limited to twelve years because downloading the hourly precipitation observations was time-intensive. Future teams can continue this modeling work further back in time to get a 50-year perspective. Future scenarios could include climate variability, changing precipitation frequency, and intensity. We understand the model did not include an extraction well, which is likely the case considering the relatively shallow unconfined aquifer. Future work can evaluate the long-term effectiveness of injecting reclaimed water at this site and other known extraction sites.

PROJECT DESCRIPTION

Environmental Impacts: Based on the California Environmental Quality Act (CEQA), we determined we must address aesthetics, noise, and air quality issues because of the project. The aesthetic impact of the facility is not limited to the finished product itself but also the construction. In building this facility, some local vegetation will be cleared away and use landscaping with plants compatible with the area. Doing so will improve the aesthetic of the facility while reducing the cost of maintenance to the landscape. Due to the proximity of the site to residents and local businesses, it is essential to coordinate with the local jurisdiction on land use. Residents in the area and local businesses will be exposed to above-average sound during construction and waste disposal leaving the facility. It is important to coordinate with the local region to reduce exposure and find the time that such noise would be less inconvenient and minimize the impact on local traffic. Transportation and project construction can impact air quality. We will use EPA Tier 4 compliant diesel engines for heavy machinery on-site to reduce construction impact. Transportation will require a class six medium single axle dump truck. Solid waste will be extracted once a week from an on-site storage unit to reduce the number of trips while still using a smaller diesel engine.

Cost Analysis: The total cost estimate for an eight-modular decentralized treatment facility performing tertiary treatment and a single injection well was $28.95 million U.S. dollars. The costs considered environmental mitigation (12%), inspection (6%), design (6%), contingency (18%), well costs (<1%), equalization tank (<1%), treatment plan (26%), pump station (3%), collection system (29%), permits (<1%). The highest cost is from the developed collection system ($8.5 Million). Operation and maintenance will cost approximately $1.6 million U.S. dollars annually. If we were to assign a monetary gain based on the amount of reclaimed water, the community gains approximately $600,000 U.S. dollars per year. The money saved <u>by not sending wastewater to the centralized treatment facility</u> was $1.4 million U.S. dollars per year.

COLLABORATION OF FACULTY, STUDENTS, AND LICENSES PROFESSIONAL ENGINEERS

Students maintained constant communication with their water resources faculty mentor, other University Civil Engineering faculty, industry partners, public works departments, dataset contacts, and Professional Engineers. Here is a list of our collaborators with their professions and a description of our interaction:

1. Civil Engineering faculty member in Hydrology and Water Resources (Ph.D.) secured project funding to support the Senior Design instructors and a Graduate Student on the project. They provided Linux and TCL tutorials and designed ParFlow training exercises in the Fall. They provided access to a 64-core Linux machine to run model simulations.
2. Senior design instructor A and Professional Engineer (P.E.) at a regional water agency guided the educational components of the project (i.e., format project plan). They provided personal contact information for other professionals to assist on the project.
3. Senior design instructor B and Professional Engineer (P.E.) at a regional water agency guided the educational components of the project (i.e., format project plan). They assisted with the overall flow of the final presentation to industry professionals.
4. Senior design instructor C, Professional Engineer (P.E.) and Ph.D. at a Geological Engineering firm assisted with the geotechnical analysis.
5. Geotechnical Engineering faculty member (Ph.D.) verified the hydrostatic pressure for the pad footing needed to support the treatment system. They also assisted in analyzing the soil bore logs from the study area.
6. Structural Engineering faculty member (Ph.D.) assisted in designing the rectangular pad footings to support the water treatment system. The footing design will withstand one-way shear.
7. Environmental Engineering faculty member (Ph.D.) assisted in determining the amount of water to be treated. They also assisted in designing the decentralized treatment system (primary, secondary, and tertiary treatments).

8. Manager of Hydrogeology at Regional Water Agency A (P.E.) advised the team on setting the domain size of the groundwater model. They also helped extract large quantities of well data required to model groundwater flow.
9. Principal Public Affairs Representative at Regional Water Agency B (P.E.) provided the team with a tour of a nearby decentralized treatment facility south and outside of our model domain. This interaction helped the team get a better concept of water treatment plants in general. This meeting also allowed the team to confirm the design considered all laws and regulations relating to such structures.
10. Graduate Civil Engineering Student assisted in MATLAB coding and ParFlow simulations. This student was pivotal in helping the team develop innovative scripts to work around the shortcomings inherent in the ParFlow software.

The pandemic required students to utilize various forms of networking and communication approaches to acquire critical information efficiently. Emails, Zoom meetings, Google Hangouts, Teams were standard methods of communication. The final interaction with industry partners and faculty occurred online via a two-hour zoom presentation to present our final design. Over 100 participants in attendance consisted of students, faculty, engineering industry partners, internal and external advisors, and several members of the funding agency.

PROTECTION OF HEALTH, SAFETY, AND WELFARE OF THE PUBLIC

See *Environmental Impacts*. We made several considerations to address aesthetics, noise, and air quality issues because of the project. The primary goal of this project was to provide safe and sustainable drinking water for the patrons in our study area. Our project does that and includes additional benefits:

Local benefits: Aquifers injected at a faster rate than they are replenished experience lateral movement of water via the hydraulic gradient. When coastline aquifers are injected, this prevents salty or briny water from entering the aquifer because we reverse the hydraulic gradient away from the well and towards the coastline. Using sustainable management recharge keeps the aquifer at a pressure that provides a barrier to seawater encroachment and protects the water supply. Recharging the aquifer will also help raise the water table, which will keep surface water in ponds and lakes on the surface where it can provide habitat for wildlife, rather than seeping down into an overtaxed aquifer where it is out of reach to flora and fauna. A modular, distributed network of treatment and reinjection facilities would divert a significant amount of water currently disposed at sea back into the water table. This allows the region to retain the benefit of treatment and eliminate any environmental risk associated with releasing the effluent into the ocean. Both the construction and operation of treatment and reinjection facilities will create short and long-term jobs both locally and regionally. Local water treatment and reinjection will remove pressure from the large centralized facility. This will allow the central facility to act as the backstop for emergency conditions such as significant rainfall events. It will also provide flexibility to the system enabling nearby treatment nodes to help during maintenance or outages. This project is repeatable throughout the U.S., which will reduce dependency on outside water acquisition and create a regionally sustainable and resilient water management scheme. The current practice involves moving large volumes of water great distances, which involves significant financial expenses. Keeping the water treatment localized as much as possible will significantly reduce this energy burden and economic cost to the region.

Regional benefits: In addition to the local impact, this type of decentralized, modular water treatment will benefit adjacent regions. One benefit will be the reduction of demand on the upstream water supply. This can allow water to be diverted to communities upstream for their use. Should other communities around the region switch to this type of infrastructure, it will reduce imported water demands further- saving money and allowing the water upstream to be used for agriculture and providing habitat for wildlife in the communities. Habitat restoration from reduced demand will help restore water tables and natural wetlands, creating productive havens for local flora and fauna and stopover habitat for migratory birds. Reinjection of the water used locally in other parts of the region will help with subsidence in those communities also. Land subsidence is a problem statewide.

Global benefits: This approach to water management is scalable and applicable in communities around the world. The success of the modular, decentralized approach in our region can serve as a model for water treatment systems worldwide. This development could be incredibly impactful to impoverished or water-stressed countries. Local wastewater treatment and reinjection facilities would reduce the dependency on external water sources and potentially lower energy and costs and provide local positive environmental impacts.

MULTIDISCIPLINE PROFESSION PARTICIPIATION

Students collaborated with graduate students, and professionals outside of areas of Civil Engineering. Here is a list of our multidisciplinary collaborators with their professions and a description of our interaction:

1. Mechanical Engineering graduate student assisted with the design of the equalization pumps, float switches, sludge diversion valves, a lag pump, blowers, and an airlift pump essential to the collection system.
2. Electrical Engineering graduate student helped determine the amount of power needed for the decentralized system.
3. Computer Science graduate student assisted with debugging issues in ParFlow and MATLAB. They also assisted in downloading NLDAS-2 data by setting up a bash script on a Linux computer.
4. Professional Geologist A (P.G.) suggested a specific bulletin providing the geological map for our study area. The team was able to find the geological composition 152.4 m below the surface. This document ultimately led to the identification of the confined aquifer and the location of our study site.
5. Professional Geologist B (P.G.) provided groundwater contour maps for the modeling work. These up-to-date maps allowed the team to define our boundary conditions better.

KNOWLEDGE OR SKILLS GAINED

This project helped students work more closely with professionals and professors in a setting distinct from the typical classroom environment. This course required students to create due dates for tasks and assign work amongst each other. The design of the decentralized treatment facility required a multi-dimensional application of knowledge from environmental engineering courses, fluid mechanics/water resource engineering, numerical methods, economics, construction management, structural and geotechnical engineering. The hydrologic modeling scenarios involved numerical methods, water resource engineering, and geotechnical engineering. The modeling scenarios required students to learn Linux and TCL commands to run the model on a computing cluster. Students were required to make extensive use of contacts and search open access data repositories to obtain borehole observations, river flow, rainfall, groundwater table levels, water contours, injection and extraction wells, aquifer locations, and soil parameters. Several of these datasets had varying coordinates systems or needed to be geospatially processed to fit a 2D grid or extract hourly observations. This task required students also to learn ArcMap and other mapping tools in MATLAB. ArcMap is not software taught in any Civil Engineering courses; students would not have acquired this skill without this opportunity.

CONCLUSION

In reducing the need for imported water, we are reducing impacts on the environment. Such effects include the reduction of greenhouse gas emissions since less water will be pumped from distant facilities. In reducing imported water, fisheries, wetlands, and other natural environments will benefit from the available water conserved at the source. Our design will increase the local drinking water supply by treating wastewater locally and injecting it into the unconfined aquifer below. This new infrastructure will also reduce the dependency on imported water. Lastly, the reinjection of water will eliminate land subsidence and saltwater intrusion.