FRESNO STATE

California Water Institute

Shallow Subsurface Artificial Groundwater Recharge (SSAGR)

Shallow Subsurface Artificial Groundwater Recharge (SSAGR)

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A
CSU Agricultural Research Institute
Research Report

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EXECUTIVE SUMMARY

California is a conjunctive use state, meaning that its water supply consists of both surface water and groundwater. Surface water, supplied by snowmelt from the Sierra Nevada, is collected in its numerous dams and distributed through a vast network of pipelines and canals, is used for both agricultural irrigation and domestic/municipal uses. Groundwater is also used for irrigation and for domestic/municipal needs when surface water is not available because of drought. For some farms, communities, and individuals, groundwater is the sole source of clean, affordable water. Groundwater supplies 41% of California's average annual water use, or approximately 17.6 million acre-feet of water (Department of Water Resources, Natural Resources Agency 2021). During droughts, groundwater increases to 58% of the State's water use (Department of Water Resources, Natural Resources Agency 2021).

Groundwater quality and quantity has diminished in many parts of California due to over reliance on groundwater. This has been particularly true during the recent droughts of 2012-2016 and 2019-2022. The diminished quantity of groundwater has resulted in the decline of water tables, which has resulted in domestic, municipal, and agricultural wells going dry. As a result of the declining groundwater tables throughout the State, the Legislature enacted the Sustainable Groundwater Management Act (SGMA) in 2014 (Department of Water Resources 2023). The purpose of the Act is to arrest groundwater table decline to avoid adverse impacts.

There are tools and technologies available to accomplish SGMA's goal. They include reducing groundwater use through fallowing agricultural land, reducing domestic and municipal uses, and the use of groundwater recharge technologies. Groundwater recharge technologies include recharge basins, Flood Managed Aquifer Recharge (FloodMAR), and Shallow Subsurface Artificial Groundwater Recharge (SSAGR). This report focuses on SSAGR and how it compares to the traditional recharge basin technology. The research results indicate that SSAGR is both more efficient in delivery of recharge water to the aquifer and that it is less expensive than recharge basins using a present worth comparison.

This report is an abridged version of a full technical report that is available uppon request by emailing cwi@mail.fresnostate.edu.

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List of Acronyms and Abbreviations

Hr	hour or hours
Ib	pound or pounds
Ksat	Saturated hydraulic conductivity
g	gallon or gallons
gpm	gallons per minute
ft	foot or feet
ft^2	square foot or square feet
ft^3	cubic foot or cubic feet
in	inch or inches
MAR	Managed Aquifer Recharge
PPIC	Public Policy Institute of California
SAGBI	Soil Agricultural Groundwater Banking Index
SC	Clayey Sand
SGMA	Sustainable Groundwater Management Act
SM	Silty Sand
SP	Sand, poorly graded
SP-SM	Sand, poorly graded with Silt
SSAGR	Shallow Subsurface Artificial Groundwater Recharge

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The Center for Irrigation Technology at Fresno State who provided the Jain spin filter at no cost to support this research.

Introduction

California is a conjunctive use state, meaning that its water supply consists of both surface water and groundwater. Surface water, supplied by snowmelt from the Sierra Nevada, is collected in its numerous dams and distributed through a vast network of pipelines and canals is used for both agricultural irrigation and domestic/municipal uses. Groundwater is also used for irrigation and for domestic/municipal needs when surface water is not available because of drought. For some farms, communities, and individuals, groundwater is the sole source of clean, affordable water. Groundwater supplies 41% of California's average annual water use, or approximately 17.6 million acre-feet of water (Department of Water Resources, Natural Resources Agency 2021). During droughts, groundwater increases to 58% of the State's water use (Department of Water Resources, Natural Resources Agency 2021).

Groundwater quality and quantity has diminished in many parts of California due to over reliance on groundwater. This has been particularly true during the recent droughts of 2012-2016 and 2019-2022. The diminished quantity of groundwater has resulted in the decline of water tables, which has resulted in domestic, municipal, and agricultural wells going dry. As a result of the declining groundwater tables throughout the State, the Legislature enacted the Sustainable Groundwater Management Act (SGMA) in 2014 (Department of Water Resources 2023). The purpose of the Act is to arrest groundwater table decline to avoid adverse impacts.

There are tools and technologies available to accomplish SGMA's goal. They include reducing groundwater use through fallowing agricultural land, reducing domestic and municipal uses, and the use of groundwater recharge technologies. Groundwater recharge technologies include recharge basins, Flood Managed Aquifer Recharge (FloodMAR), and Shallow Subsurface Artificial Groundwater Recharge (SSAGR). This report focuses on SSAGR and how it compares to the traditional recharge basin technology.

The report presents the various theoretical basis for the analysis of the SSAGR and recharge basin technologies, the installation and monitoring of a SSAGR system, the recharge efficiency and economic comparison of the SSAGR system with a recharge basin, and the conclusions, recommendations, and observations developed through the research of SSAGR and its comparison with the recharge basin technology.

Methodology

This Methodology section will describe the general SSAGR system, the site selection process, the follow-up site stratigraphy investigation and results, a description of the installation of the various elements of the SSAGR system, and finally, the present worth of a hypothetical 40-acre SSAGR system. It will then describe a hypothetical 40-acre traditional groundwater recharge basin and its present worth. The present worths of the two systems will be compared on a per cubic foot of recharge water per year in the *Results* section.

General SSAGR System

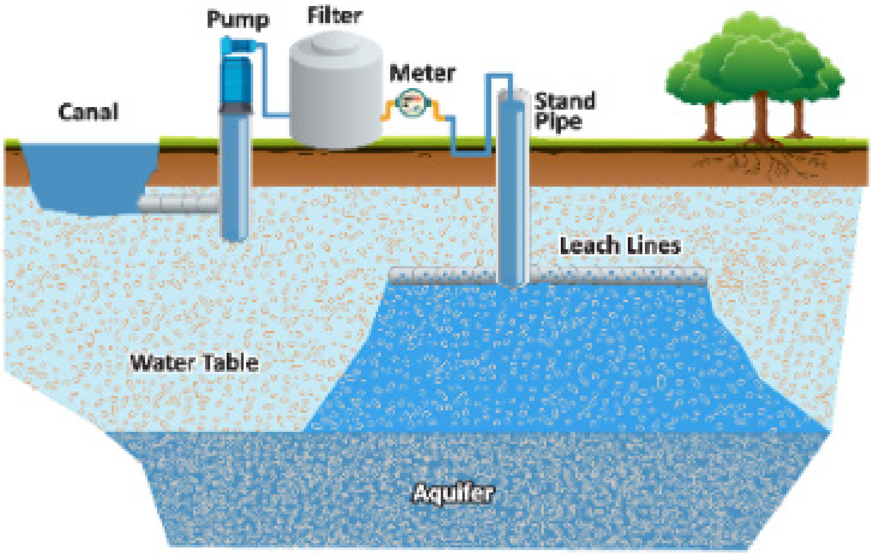

Figure 1- Cross section of a SSAGR system

A general SSAGR system consists of a surface water source (the Helm Canal in this case), a connection from the canal to a pump wet well, a lift pump, a flow meter, a delivery pipeline, a standpipe, and a distribution pipeline consisting of solid wall header pipes and perforated recharge pipe. The SSAGR system is illustrated in Figure 1.

The recharge water starts in the Helm Canal. It is conveyed from the canal to the pump wet well through a gated headworks and connecting pipeline under gravity head. The recharge water is lifted by pump from the wet well through a pressure pipe system to the SSAGR distribution standpipe where it was distributed by gravity flow to the three perforated system pipelines. The recharge water passes through a filtration system and a magnetic resonance flow meter on its way to the standpipe. The pump is a Grundfos submersible capable of delivering 60 gallons per minute at the operating point. The pump was provided by Grundfos, Inc. as part of their support for research at Fresno State. The filtration system is a 4x10-6 inch Jain spin filter that was provided by the Center for Irrigation Technology at Fresno State in support of this research. The flow meter is a 2-in diameter magnetic resonance meter that measures instantaneous discharge rates to one gallon per minute. Three valves are located in the system to isolate the perorated pipes from the distribution header pipeline.

Figure 2 illustrates the SSAGR installation at the Fresno State Farm.

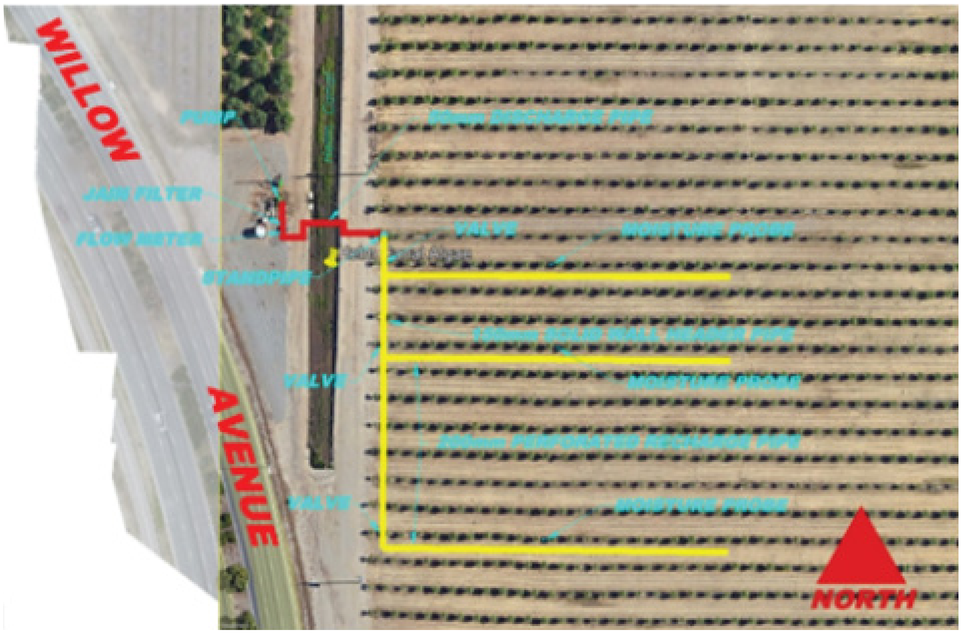

Figure 2 - SSAGR Site (Google Maps 2020)

Site Selection

Mary Church describes the site selection for this SSAGR system in detail (Church 2021). The process involved locating open land on the Fresno State Farm that fit three criteria: 1) the land was currently unplanted; 2) the land would be planted at some date in the near future; and 3) the stratigraphy of the site was conducive to groundwater recharge. Fresno State Farm Manager, Mark Salwasser, was approached in the fall of 2020 by the research team with the proposal to site the SSAGR system on the Fresno State Farm. He agreed to consider partnering with the research team on a presently fallow tract of land located at the southwest corner of East Bullard Avenue and North Willow Avenue. This tract of land is part of the Fresno State Farm, close to campus, and was scheduled to be planted with almond trees during the winter of 2020/2021. Figure 3 illustrates the location of the SSAGR system.

Figure 3 - SSAGR Site Location (Google Maps 2020)

This site was then screened for its recharge site potential using the Soil Agricultural Groundwater Banking Index (SAGBI). The SAGBI mapping was developed by A.T. Green et. al. in 2015 to assist the agricultural community in selecting land for potential groundwater recharge sites. Figure 4 is a portion of the SAGBI mapping depicting the site and its index of 93 (Church 2021) (University of California, Davis 2021).

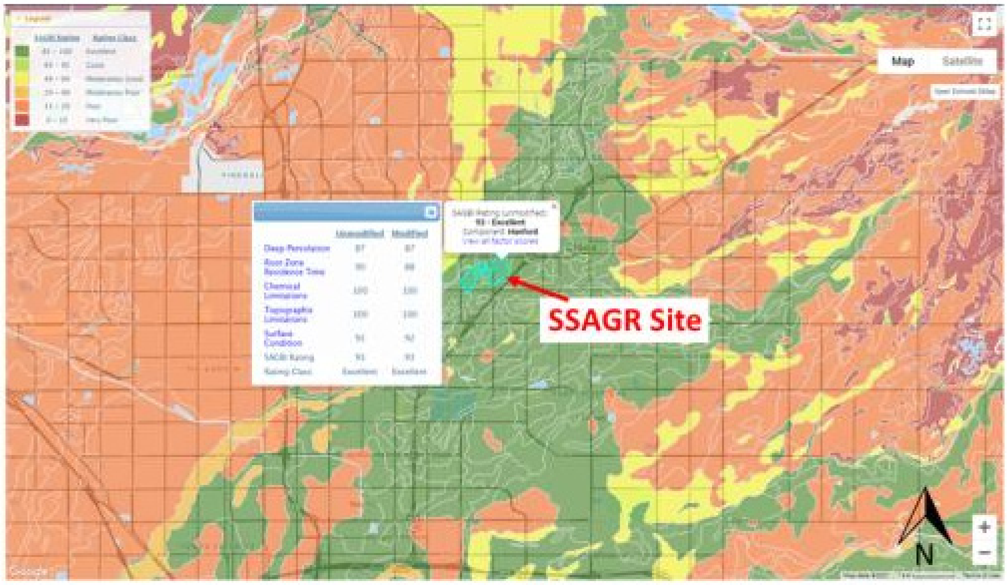

Figure 4 - SAGBI Rating for SSAGR Site (Church 2021) (University of California, Davis 2021)

Existing Stratigraphy

The existing stratigraphy of the site was investigated by the research team and the Moore Twining Associates drill rig crew in 2020 (Moore Twining Associates 2023). The drill rig was equipped with an 8-in diameter flight auger. The research team collected samples of the auger tailings at 5-ft intervals. Ten sets of samples were collected. The tailings were sight categorized by the Principal Investigator (PI) and Professional Civil Engineer, Cordie Qualle, and 5 lbs. samples at each 5-ft interval were bagged for laboratory analysis. The laboratory analysis was conducted by Mary Church and Gabriella Bonilla, research team members in the Lyles College of Engineering Soils Laboratory. The results of the laboratory are reported in Ms. Church's MSCE Project Report (Church 2021).

The site soil classification by the PI is listed in Table 1.

Table 1 - Site Stratigraphy Boring Sample Description

Depth Below Ground Surface meters	Site Description
0.0	Silty sand, dry, tan
1.5	Medium sand, brown, wet, no cohesion
1.8	Coarse sand, wet, no cohesion
3.0	Silty sand, wet, brown to tan, some cohesion
5.8	Clay sand with grey clay flecks, brown, damp, cohesive
6.7	Clay sand, brown, damp, cohesive
7.6	Clay with grey pebbles, brown, damp, very cohesive
8.5	Clay sand, brown, damp, cohesive
9.1	Clay, moist, hard
10.1	Clay sand, brown/green, damp very cohesive
10.7	Clay, brown, damp, very cohesive
11.3	Clay sand, brown, damp
12.2	Sandy clay, brown, hard drilling, cohesive
13.7	Clay sand, brown, damp
14.0	Clay, brown, damp, very cohesive
14.6	Clay sand, brown, damp very cohesive
15.2	Clay, brown, damp, very cohesive
15.8	Dense sand, grey, cemented – Bottom of boring

The saturated hydraulic conductivity, Ksat, of each 5-ft of soil depth was determined in the LCOE Soils Lab using the falling head test method (Elementary Engineering Library 2022) using a soil sample that was retrieved from the site stratigraphy boring. The boring was driven to a total depth of 50-ft resulting in ten samples. These are the same soil samples that were tested by Church and previously discussed in this report. The saturated hydraulic conductivity for each sample was determined five times using the same apparatus set up and the resulting saturated hydraulic conductivities were averaged to determine the representative value for that soil sample. The results of the saturated hydraulic conductivity investigations are presented in the Results section of this report.

SSAGR Recharge System

The pipeline system was installed by Lidco, Incorporated, a research partner, in October 2020 (Lidco, Inc 2023). Figures 5 and 6 illustrate the installation of the perforated pipeline systems.

Figure 5 - Lidco excavator installing perforated SSAGR pipeline 1

Figure 6 - Lidco excavator installing perforated SSAGR pipeline 2

The installation of the SSAGR underground pipeline system occurred prior to planting almond trees to allow for maximum access to the site by the equipment. The system can be installed in existing orchards, but that requires a specialized excavator and additional time due to access restrictions to avoid damaging the existing trees.

The installation was valued at $38,000 US in 2020.

Pump and Discharge System

A submersible pump capable of delivering 60 gpm was donated to the project by Grundfos Pump, Inc., a research partner. The pump was installed in an existing wet well adjacent to the Helm Canal with the assistance of the Fresno State Farm Manager, Mark Salwasser, and his staff. The Fresno State Farm is a research partner. A discharge pipeline system was installed by the research team from the pump to the filter system, flow meter, and then to the stand pipe which delivers the water to the underground pipeline system. The flow meter is a Seametrics WMP-101 2-indiameter plastic-bodied magmeter (Seametric, Inc. 2019). A pressure transducer was included in the discharge system prior to the filter to monitor the pump discharge pressure head. A telemetry system to capture and report the flow meter and the pressure transducer readings was installed by RedTrac, Inc., a research partner. The magmeter measures the discharge rate using a current-sinking pulse set for the minimum reading of 1 gpm (Seametric, Inc. 2019).

The telemetry output from the pressure transducer and the flow meter are uploaded to the cloud using a Davis Instruments, Inc. gateway (Davis Instruments, Inc 2023). Davis, a research partner, allowed Redtrac to use the Application Programming Interface (API) to download the telemetry data and store and display that data on their site.

The Jains 4x10-6 inch spin filter (Jains, Inc. 2023) was donated to the project from Charles Hiller, director of the Center for Irrigation Technology at Fresno State (Center for Irrigation Technology 2023). The status of the filter was monitored indirectly by monitoring the pump pressure head. Excessive pressure head indicated that the filter needed cleaning. Cleaning was achieved by removing the filter canister from the housing and pressure washing the canister.

The last elements of the research project to be installed were 30-ft long Sentek moisture probes. The probes were installed in an adjacent tree row and near the middle of each of the perforated pipe reaches. They were installed by the research team with the help of Gill Costa, sales engineer for Sentek, Inc., Kalyan Pollard, sales representative for Davis Instruments, Inc., and the drill rig crew from Twining Laboratories, Inc. headed by Drilling Manager, Josh Sheddan. The installation of the moisture probes required the drilling of an 8-in diameter hole using a flight auger to an approximate depth of 35-ft. The probe polyvinyl Chloride casing was installed in the hole and backfilled with a soil slurry. The moisture probe array was then installed in the casing. The casing was then backfilled using a soil slurry consisting of the drilling tailings from the flight auger, which were segregated by depth. This was to allow the soil slurry backfill to be placed around the casing in the same order in which it was removed to accurately represent the soil stratigraphy surrounding the probe. A slurry was used to insure intimate contact of the soil with the casing. Figure 7 illustrates the installation of a probe casing into a hole. The drill rig and crew are in the figure along with Gill Costa. This was the first installation of a 30-ft moisture probe in the United States. Figure 8 depicts the PI, Cordie Qualle, and Kaylan Pollard pouring a batch of soil slurry into the hole to backfill around the moisture probe casing. In the background are members of the research team preparing the slurry in 5-gallon buckets.

Figure 7 - Installation of a Moisture Probe Casing

Figure 8 - Pouring Soil Slurry Backfill around Moisture Probe Casing (Thune 2021)

SSAGR System Costs for a Hypothetical 40-acre SSAGR System

The first costs of a hypothetical 40-acre SSAGR system include the canal turnout, the turnout pipeline, pump standpipe, pump, filter system, discharge pipeline system, flow meter, and the recharge pipeline system, installed in place and complete. The SSAGR system costs are complicated by the fact that the cost of the turnout, turnout pipeline, pump standpipe, pump, and filter are typically also used for the drip irrigation system for the orchard. Apportioning the costs between the drip irrigation system and the SSAGR system can be accomplished by prorating the costs based on operational days. For the purposes of cost accounting, we assume that the SSAGR system will be operational from January through April independent of the drip system and together with the drip system from May through June in the years in which it is used. The drip irrigation system is assumed to be used in July and August independent of the recharge system. Therefore, out of 243 days of use per year, 151 of those days are attributed to the recharge system and 91 are attributed to the drip system. The 151 days are the days within January, February, March, April, and half of the days between May and June. The 91 days are half of the days between May and June and all the days of July and August. For the purposes of this analysis, it is assumed that recharge can occur every year. Using the days of use to apportion the costs between the SSAGR system and the drip system results in 62-percent of the cost attributed to the SSAGR system and 38% attributed to the drip system.

Cost of canal turnout, pipeline, and standpipe

Standard construction cost estimating was used to determine a cost for the turnout, turnout pipeline, pump standpipe, and the discharge system from the pump to the SSAGR system for a hypothetical 40-acre SSAGR system. The cost estimate is included in Appendix A of this report. The unit prices are based on standard, in-place costs used in the Civil engineering community in the Fresno, California area. They are not intended to be the exact construction cost, but an order of magnitude indication of the cost. Sixty-two percent of the cost of these items is attributed to the SSAGR system. The remaining 38 percent is attributed to the drip system.

Cost of pump and replacement interval

The discharge rate for the project SSAGR system was used to extrapolate a 11.3 cubic feet per second discharge rate 5100 gpm for a hypothetical 40-acreSSAGR system. The cost estimate is included in Appendix A of this report. The cost of the pump is based on standard, in-place costs used in the Civil engineering community in the Fresno, California area. No salvage value was assumed for the pumps at the end of their lives. They are not intended to be the exact construction cost, but an order of magnitude indication of the cost. Sixty-two percent of the cost of these items is attributed to the SSAGR system. The remaining 38-percent is attributed to the drip system.

The replacement interval of the pump is estimated to be once every 15 years (Hydraulic Institute, Europump, U.S. Department of Energy 2001).

Cost of filter and replacement interval

The cost of the in-place sand filter system was estimated using cost data from drip irrigation systems installed in the Central Valley using information from the State of California, Department of Agriculture, State Water Efficiency and Enhancement Program. Sixty-two percent of the cost of these items is attributed to the SSAGR system. The remaining 38% is attributed to the drip system.

Cost of SSAGR system

The cost of the in-place SSAGR system was provided by Glenn Drown, Project Manager for LIDCO, Inc., a research project sponsor (Lidco, Inc 2023). Mr. Drown indicated that the cost to design and install a SSAGR system is constrained by the site factors, which include the site stratigraphy, the limiting percolation rate, the available discharge rate from the recharge water source (typically an irrigation canal turnout), and the physical site constraints. Mr. Drown stated that current installation costs are estimated using the design site discharge rate as the discharge rate as it drives the size and extent of the pipe system. Current pricing for a SSAGR system ranges from $100 per gallon per minute discharge rate to $175 per gallon per minute discharge rate. The average cost is $138 per gallon per minute. One hundred percent of this cost is attributed to the SSAGR system. The estimated discharge rate for the 40-acre site is 5100 gpm.

Construction costs of the SSAGR System

The estimated construction cost of the hypothetical, installed SSAGR system for a 40-acre site is $700,800.

Operations and Maintenance Costs of SSAGR System

The operations and maintenance costs for the SSAGR system are minimal. There are some system start-up and shutdown costs, which can be absorbed into normal field operations at the site. The major cost is for electrical power to operate the pump when recharge is occurring. The power use for the pump was extrapolated from the power use of the project SSAGR system, which was calculated as 80.6 Kilo-watt hour (KWh) per acre foot of applied recharge water. The cost per KWh was obtained from the Electric Schedule AG published by the Pacific Gas & Electric Company (Pacific Gas & Electric Company 2021).

The applied water, power, and cost for an average recharge season were estimated as presented in Table 2.

Table 2 - Estimated Power Use and Costs for Hypothetical SSAGR System

Month	Hours/Month hr	Discharge Rate ft^3/sec	Discharge Volume a-f	Energy Consumption KWh	Energy Cost $/KWh	Monthly Energy Cost $
January	0	11.3	0	0	0.22	21.08
February	0	11.3	0	0	0.22	19.04
March	380	11.3	355	28,225	0.22	6,331.63
April	480	11.3	448	35,644	0.22	7,989.69
May	368	11.3	344	27,338	0.22	6,133.31
June	368	11.3	344	27,338	0.25	6,745.00
July	368	11.3	344	27,338	0.25	6,745.68
August	368	11.3	344	27,338	0.25	6,745.68

The published off-peak price per KWh was used as it was assumed that the recharge operations would occur between 9 p.m. at night and noon the following day. The published rate per KWh is higher in June, July, and August. No recharge was assumed to occur in January and February as the source of recharge water is assumed to be primarily excess surface water, which is generally not available until March. The total estimated cost of electrical power for an average recharge year is estimated to be $40,700.

The Present Worth of a Hypothetical 40-acre SSAGR system based on a 50-Year Life

The Present Worth (PW) of the hypothetical, installed 40-acre SSAGR system with a 50-year life consists of the PW of the construction cost, the PW of the replacement of the pump, and the PW annual cost of electricity to operate the pump. The PW of the construction cost is merely the construction cost. The PW of the replacement of the pump is the sum of the present worths of a series of three pump costs occurring in the future, one replacement for every 15 years of pump life. The PW of the annual electrical costs is the present worth of annual series electrical costs. The long-term interest rate used in the analysis is the 10-year Daily Treasury Real Long-Term Rates as of April 2023, which was listed as 1.7% (U.S. Department of the Treasury 2023). The annual sand filter maintenance cost attributed to the SSAGR operations was estimated to be $2,000.

The PW of the hypothetical SSAGR system is $2,224,000. Assuming there is recharge water available for three years out of every seven years, the total recharge volume over the assumed 50-year life of the SSAGR system is 28,200 acre feet. Dividing the PW by the total recharge volume produces a cost of $79 per acre-foot of recharged water.

Traditional Recharge Basin System

A traditional recharge basin system consists of a turnout structure, a turnout pipeline, a pump standpipe, a pump system, a discharge system, and fenced excavated recharge basins. The discharge system consists of a standpipe, a discharge pipeline, a control structure at the recharge basins, and turnout structures for each basin. Figure 9 depicts a typical 40-acre recharge basin system.

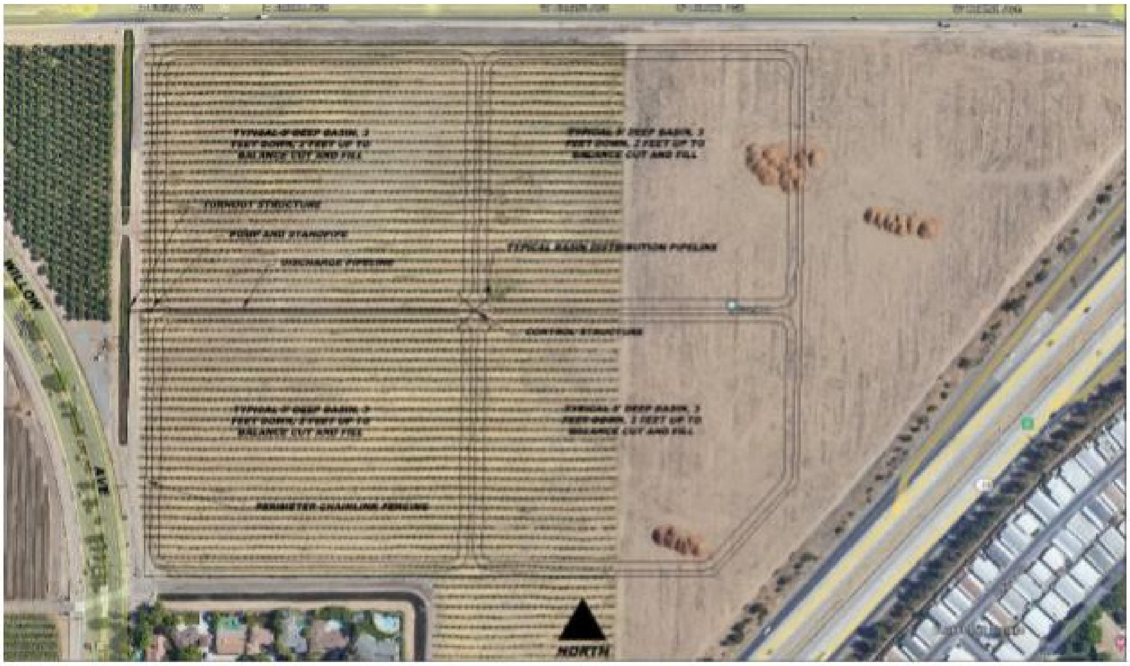

Figure 9 - Hypothetical 16-Hectare Traditional Recharge Basin (Google Maps 2020)

The construction costs for the recharge basin were based on the preliminary design illustrated in Figure 9. The construction cost estimates for the turnout structure, turnout pipe, pump standpipe, pump, electrical service, discharge system, control structure, distribution pipelines, basin excavation, and perimeter fencing were developed in the same manner as the SSAGR system, and the cost estimates are included in Appendix B of this report. The pump was assumed to be the same as that used for the SSAGR system. The application of recharge water will be approximately the same as the SSAGR system. Therefore, the annual electrical costs will be the same. The annual basin maintenance costs were assumed to be $50 per acre per year or a total of $2000 per year for the site.

Using the same long-term interest rate as for the SSAGR system of 1.7% and a 50-year life span, the PW value of the recharge basin was calculated to be $13,290,000. The 40-acre recharge basin is capable of recharging 27,115 acre-feet in 50 years, assuming 3 years of recharge in every 7-year interval, or a total of 21 years of recharge. That is equivalent to a PW of $490 per acre-foot of recharged water.

Moisture Probes

A total of three Sentek EnviroSCAN 10-meter moisture probes were installed, one adjacent to each of the three SSAGR perforated lines. Sentek moisture sensors were installed to observe the change in moisture above and below the SSAGR recharge lines. This was the first installation of the 34-ft moisture probe in the United States. The probe consists of 10 moisture meters, the sensor array, placed at approximately 3-ft intervals along the 34-ft length of the probe. Figure 10 illustrates the moisture probe equipped with moisture meters. Table 3 below lists the placement intervals of the moisture meters below the top of the probe casing.

In Figure 10, the moisture sensors, the gold-colored objects, are attached to a rail at the desired locations. The rail is inserted into a poly-vinyl chloride tube shown at the right side of Figure 10. The tube is equipped with a sealed end and a threaded cap. The sensor array is connected to a data interface card that transmits the moisture readings through a data cable to a solar-powered gateway. The gateway uploads the moisture information to a cloud data collection service. In this case, the Redtrac cloud data service was used. Redtrac is a research partner on this project.

Figure 10- Sentek moisture probe with moisture meters

The moisture sensors are calibrated to determine the volumetric moisture content of the surrounding soil based on the soil type by measuring the change in capacitance within the soil. The soil type was provided to the data aggregator, Redtrac, using the information from the soil boring log information from the project. Redtrac's proprietary analytic software algorithm converted the capacitance readings to volumetric moisture content, which is reported on their website dashboard for the project.

Table 3 – Moisture Meter Intervals in Sentek Moisture Probe Array

Probe Number	Depth Below Top of Casing
1	3-ft
2	6-ft
3	9-ft
4	13.5-ft
5	16.8-ft
6	20-ft
7	23.3-ft
8	26.6-ft
9	29.9-ft
10	33.5-ft

The moisture probes and their telemetry were activated soon after they were installed. The moisture probes sat idle for approximately a month to allow the moisture from the backfill slurry to equalize with the ambient moisture. Mary Church (Church 2021) began accessing moisture data from the moisture probes in September 2021, using the Redtrac data acquisition, analysis, and display system. Church monitored the resulting moisture probe data following the application of recharge water from September 19, 2021, to October 5, 2021 (Church 2021). The plots of the percent moisture content were erratic with little to no discernable trend as far as the changes in moisture content with depth except in the case of the south moisture probe. The data from this probe presented a dry soil at 10-ft, moderately wet soils at 13-ft, 20-ft, 23-ft, and dryer soils at 30-ft (Church 2021). The SSAGR system perforated pipe was installed at 12-ft. These trends seemed consistent with what one would expect. The north and middle probes did not exhibit this trend. The most probable explanation was that the moisture from the slurry backfill had equalized to the ambient conditions at the south probe, but not at the other two probes.

Data analysis for this report, which concerned 2022, began on January 1, 2022, and continued through to December 11, 2022. Data analysis was terminated on this date to isolate the data from the influence of pending rainfall events. The percent moisture content was collected every 15 minutes and reported by Redtrac as average hourly values. The hourly values were used to produce average daily values, average weekly, and average monthly values. The resulting trendlines were compared to determine if a longer time interval would provide sufficient definition and eliminate chatter in the data. The average weekly values were selected as providing adequate definition while moderating out the hourly and daily chatter in the data.

Results

This section will discuss the results of the following investigations undertaken in this research:

- The results of the recharge water volume from the June, July, and August 2022 run of the SSAGR system;
- The results of the water balance and system efficiency of the SSAGR system compared to a recharge basin system;
- The present worth economic comparison of a hypothetical 16-hectare SSAGR system compared to a hypothetical 16-hectare recharge basin. Note that the net recharge area for both sites is 15-hectares;
- The results of the laboratory investigation of the saturated hydraulic conductivity of the soil strata at the SSAGR system site; and
- The results of the data obtained from the moisture probes installed at the SSAGR site.

The analysis of the results will be presented in the following Analysis section.

SSAGR 2022 Recharge Results

One thousand two hundred and four hours of recharge were accomplished during the three months of June, July, and August of 2022. In other words, the SSAGR system was operating 55% of the time during those months. During that time period, the SSAGR system recharged a total of 10 acre-feet360 of water into the ground. The recharge rate was 361 cubic feet per hour or 16.1 ft per hour based on a total area of 0.50 acres. As will be discussed in the following subsection, 100% of the applied water became recharge water. The moisture probe data indicates that the recharge water moved down and probably horizontally, which means that it was not retained in the vadose zone (the layer of soil between the bottom of the root zone and the groundwater table).

Water Balance and System Efficiencies of the SSAGR System

A daily water balance calculation was performed for the SSAGR system assuming a distribution area of 0.50 acres from June 1 until July 20 and a distribution area of 0.17 acres from July 21 until August 31. The change in the distribution area occurred when only the North line was used after July 20 due to the system's limited run times. The water inputs to the SSAGR system area were the recharge water, tree drip irrigation water, and a small rainfall event that occurred during August. A total of 10 acre-feet of recharge water was applied by the SSAGR system. The drip irrigation applied another 0.17 acre-feet of water and the rainfall total was 0.002 acre-feet. This sums to a total of 10.172 acre-feet of applied water. The evapotranspiration of the young almonds was calculated to be 0.02 acre-feet and soil evaporation during this time period from the soil between the trees was taken as 0 acre-feet. A total of 0.02 acre-feet of water was lost from the area. The sum of the applied water minus the losses resulted in a net water balance of 10.152 acre-feet, which is greater than the applied SSAGR water, indicating that the SSAGR system was 100% efficient. The calculated recharge depth per acre of application area is 20 ft.

Discussion of the SSAGR 2022 Recharge and Water Balance Results

The results of the 2022 recharge run mean that the SSAGR system is able to deliver 100% of the applied recharge water to the ground where it is able to move both vertically and laterally through the soil stratigraphy.

Water Balance and Efficiencies of Hypothetical 40-Acre SSAGR and Recharge Basin Systems

The results of the comparison of a hypothetical 40-acre SSAGR system and a hypothetical 40-acre recharge basin are presented in the following table. The recharge rate for both systems was taken as the 0.016 ft/hr derived from the operation of the SSAGR research system

Table 4 - Comparison of Hypothetical SSAGR and Recharge Basin Systems

Criteria	SSAGR System	Recharge Basin System
Surface Area	40-acre	40-acre
Applied Recharge Water	1,323 a-f	1,375 a-f
Applied Irrigation Water	19.62 a-f	0 a-f
Precipitation	0.42 a-f	0.42 a-f
Evaporation Loss	0 a-f	83.84 a-f
Evapotranspiration Loss	1.10 a-f	0 a-f
Net Water Balance	1,343 a-f	1,292 a-f
Efficiency	100.0%	94.0%
Equivalent Calculated Recharge Depth	36.1 ft	34.45ft

Discussion of the Results of the Water Balance Comparison

The comparison of the two hypothetical recharge systems in a central San Joaquin Valley setting, one being the SSAGR system and the second being the traditional recharge basin provides interesting insights into the two systems. Based on the recharge rate used in this study, which was derived from the research site, the recharge basin system can handle more water at the site due to the storage capability of the basins, but it is not able to recharge the full amount of water delivered to the site because of the surface evaporation from the pond surfaces. The recharge basin loses approximately 84 acre-feet of water to evaporation during the summer months if recharge occurs during those months. This loss reduces the recharge basin's recharge efficiency to 94%. The resulting depth of recharge water that is applied to the two sites is 36 ft for the SSAGR site and 34 ft for the recharge basin site, the difference is wholly attributed to the evaporation losses.

Present Worth Comparison of Hypothetical 40-Acre SSAGR and Recharge Basin

The PW per acre-foot of water recharged for the hypothetical 40-acre SSAGR system was computed using the input parameters listed in the following table.

Table 5 - SSAGR Present Worth Parameters and Results

Description	Cost	Life Span	Interest Rate	PW
Canal Turnout	$7,390	50 Yrs	1.70%	$7,390
Discharge System	$57,226	50 Yrs	1.70%	$57,226
SSAGR System	$160,000	50 Yrs	1.70%	$700,800
Operations	$40,731	Annually for 50 Yrs	1.70%	$1,364,541
Sand Filter Maintenance	$2,000	Annually for 50 Yrs	1.70%	$67,002
Pump Replacement	$15,000	Yr 0-15	1.70%	$11,600
Pump Replacement	$15,000	Yr 15-30	1.70%	$9,000
Pump Replacement	$15,000	Yr 30-45	1.70%	$7,000
			Total PW	$2,224,500
		Total Recharge Vol in 50 years, a-f		28,230
			Total PW/a-f	$78.45

*Total average annual SSAGR recharge water volume from Net Water Balance in Table 4.

The PW per acre-foot of water recharged for the hypothetical 40-acre recharge basin system was computed using the input parameters listed in the following table.

Table 6 - Recharge Basin Present Worth Parameters and Results

Description	Cost	Life Span	Interest Rate	PW
Canal Turnout	$15,500	50 Yrs	1.70%	$15,500
Discharge System	$207,450	50 Yrs	1.70%	$207,450
SSAGR System	$11,607,900	50 Yrs	1.70%	$11,607,900
Operations	$42,731	Annually for 50 Yrs	1.70%	$1,364,541
Sand Filter Maintenance	$2,000	Annually for 50 Yrs	1.70%	$67,002
Pump Replacement	$15,000	Yr 0-15	1.70%	$11,600
Pump Replacement	$15,000	Yr 15-30	1.70%	$9,000
Pump Replacement	$15,000	Yr 30-45	1.70%	$7,000
			Total PW	$13,290,000
		Total Recharge Vol in 50 years, a-f		27,115
			Total PW/a-f	$490.00

*Total average annual Recharge Basin recharge water volume from Net Water Balance in Table 4.

Discussion of the Present Worth Analysis of the Hypothetical 40-Acre SSAGR and Recharge Basin Systems

The comparison of the present worth analysis of the SSAGR and the recharge basin systems indicates that the recharge basin's present worth is approximately 6 times greater than the SSAGR system. The difference is largely due to the construction costs of the two systems. The recharge basin construction cost is estimated to be $13.3 million in 2023 dollars. The SSAGR system is estimated to be $2.24 million, in the same dollars. The present worth per acre-foot of recharge water is estimated to be $74.45 for the SSAGR system and $490.00 for the recharge basin. The cost per acre-foot is both a function of the construction costs, which were previously discussed, and the efficiency of the two systems, which was discussed in the water balance analysis section.

The costs that were not discussed in this section were the cost of the lost property taxes and annual crop value. The annual crop value, which would be lost when land is converted from crop to basin, assuming that the land is planted with almonds can be estimated to be $29,000 per acre based on a five-year average (2017 through 2021) total of 1,174,000 bearing acres of almonds within the state of California and a total crop value of $5.5 billion (U.S. Department of Agriculture 2023). The annual loss of property taxes, assuming that the land is transferred from private ownership to public, varies with county tax structures and assessed valuation. Assuming an assessed value for almond acreage of $15,000 per acre and a 1% tax rate in accordance with Proposition 13, the loss in property taxes for a 40-acre site would be on the order of $6,000 per year.

See Next Page

Discussion of the Saturated Hydraulic Conductivity of the SSAGR Soil Strata

The saturated hydraulic conductivities (K-sats) are an indication of the permeability of the soil strata found within the SSAGR site. Higher Ksat values indicate high permeability rates, while low conductivities indicate low permeabilities. The Ksat values in the upper soils (0 to 3 meters) at the site are quite high averaging 0.40 ft/hr or 9.5 ft/day. The Ksat values decrease significantly below 10.5 feet by a factor of 10-4, to values as low as 2x10-4 ft/hr or 3.9 x10-3 ft/day. This change corresponds to the change in soil strata from sandy silts to silty clays. The SSAGR recharge pipelines are located at 12 feet, just above the silty clay layer and where the K-stats decrease. The significant change in the K-sat values indicates how important it is to do subsurface investigations such as borings and lab testing, Airborne Electromagnetic (AEM) surveys, or gravimetric surveys of the soil stratigraphy prior to selecting a site for groundwater recharge. Surface soils and even investigations down to 13.1 feet can yield results that are inconsistent with lower soil strata.

Moisture Probe Results

The percent moisture content for the three moisture probes, North, Middle, and South, are depicted in Figures 11, 12, and 13. The moisture content data for the probes above the depth of the SSAGR recharge pipelines have been removed. In addition, the 13.1 feet moisture meter for the North Probe and the 19.7 feet moisture meter for the Middle Probe are not currently reporting data. They are not shown in the following figures. The beginning and end of the application of recharge water are illustrated with red vertical lines in each figure. The week when the recharge water was only applied to the North Line is illustrated with a green vertical line in each figure. Week 19 corresponds to the week of May 29 through June 4, 2022, and Week 36 corresponds to the week of August 28 through September 3, 2022.

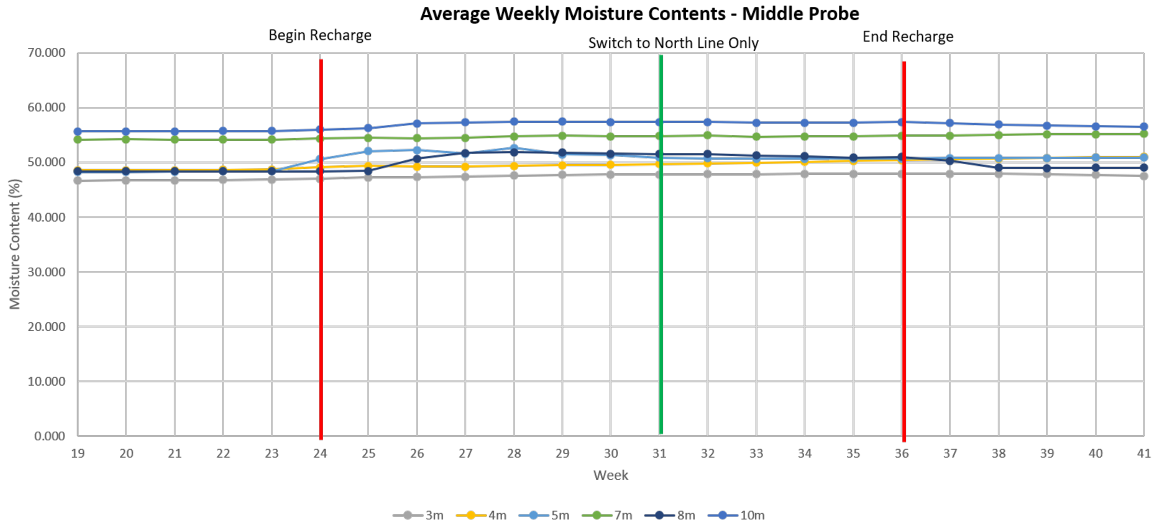

Figure 11- Average Weekly Moisture Content for the Middle Probe During the Application of Recharge Water

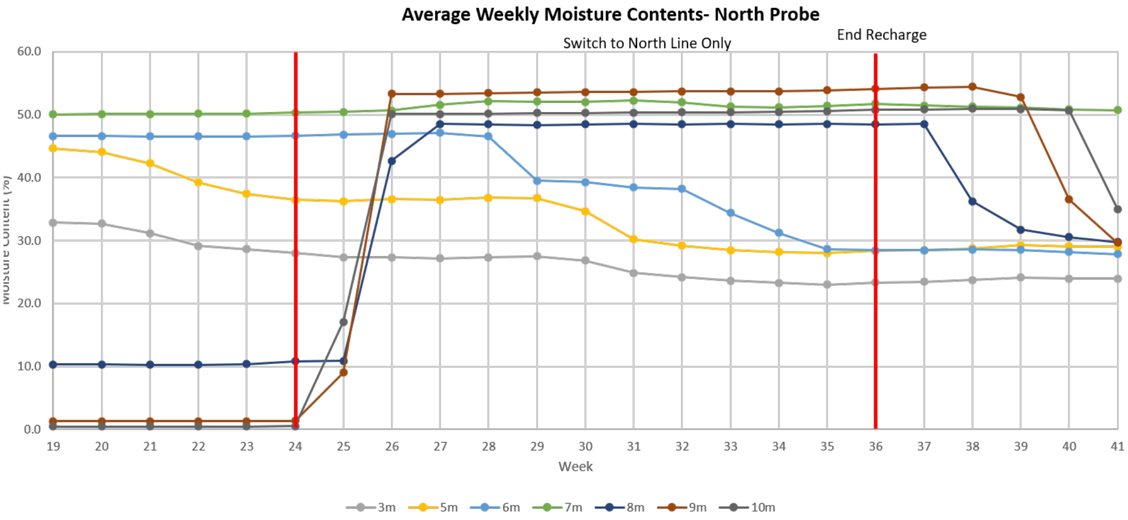

Figure 12 – Average Weekly Percent Moisture Content for the North Probe During the Application of Recharge Water

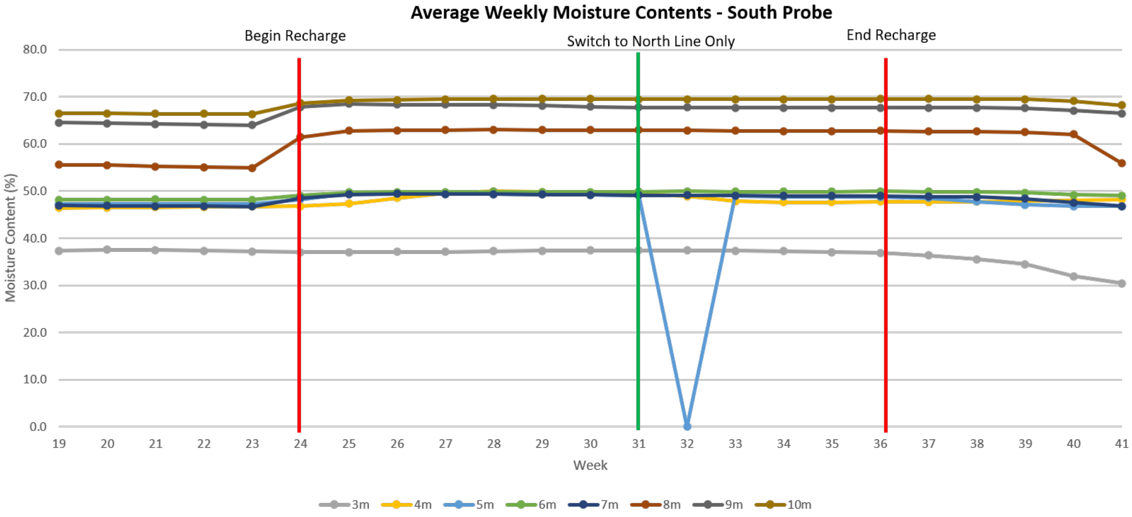

Figure 13 – Average Weekly Percent Moisture Content for the South Probe During the Application of Recharge Water

Discussion of the Moisture Probe Results

Probably the most interesting and perhaps enigmatic results from this project are the moisture probe data. The three plots of the moisture content of the soils adjacent to the moisture probes are presented in the previous section. They are interesting because they present the impact of the input of recharge water from the SSAGR system. Enigmatic in that it is difficult to understand exactly what the probe data is telling about the impact of the recharge water input. This section will attempt to provide some context for the data presented by the three plots.

Middle Moisture Probe (Figure 11)

As depicted in Figure 11, the moisture meters at 10 ft, 13 ft, and 23 ft show almost no reaction in percent moisture content to the start or cessation of recharge from the SSAGR system. For reference, the SSAGR system is installed at approximately 13 ft. The moisture meter at 16 ft registers a slight increase in percent moisture content at the start of the application of recharge water to the middle pipeline and a slight decrease in content when the application ceases. The 23 ft m and 33 ft meters also register a slight increase in moisture that corresponds to the start of recharge. The 23 ft moisture meter registers a decrease in percent moisture content that corresponds to the date when recharge stops. The 33 ft moisture meter does not register a decrease in percent moisture content.

The lack of response of the 10 ft moisture meter is understandable as it is placed one meter above the SSAGR pipe. The reaction of the 16 ft moisture meter is consistent with what should occur, except that the increase in moisture content is very small, on the order of 1%. The reaction of the 23 ft moisture meter is inconsistent given that the 16 ft and 26 ft moisture meters register increases in percent moisture content and the 26 ft percent moisture content is four times that of the 16 ft meter. Also, the 33 ft moisture meter registers the same four times greater percent moisture content as the 26 ft meter, but it registers that increase before the 26 ft moisture meter does.

One explanation is that the applied water does not linger long enough at the 16 ft level to significantly increase the moisture content. In other words, it finds a way to move either laterally or vertically downwards through a more permeable soil lens to a deeper stratum, in this instance, the 33 ft stratum where the lens encounters a low permeable stratum, causing the water to mound up to the 26 ft level before moving laterally, spreading out, seeking another pathway to deeper levels.

South Moisture Probe (Figure 13)

As with the Middle Moisture Probe, the South Moisture Probe appears to depict much the same response to the applied groundwater. The 10 ft moisture probe registers little to no response to the applied water. The deeper moisture meters display an increase in percent moisture content once recharge water is applied and a drop in percent moisture content once the application of recharge water ceases. The increase in percent moisture content is only 1-1.5% for the 13 ft, 16 ft, 20 ft, and 23 ft moisture meters whereas the 26 ft, 30 ft, and 33 ft moisture meters depict a 5% increase in percent moisture content. These moisture contents linger for two more weeks longer than the increased percent moisture content of the Middle Moisture Probe’s moisture meters.

The explanation of the Middle Moisture Probe data is applied to explain the data depicted by the South Moisture Probe. The movement of the water through the lower strata below the SSAGR pipeline is not significantly delayed at the 13 ft through 23 ft depths. However, once it encounters the lower strata, probably in the 33 ft depth range, it begins to mound and then moves laterally due to encountering a low permeable stratum.

North Moisture Probe (Figure 12)

The percent moisture content change is very dramatic as measured by the North Moisture Probe's moisture meters. When compared to the Middle and South Moisture Probes, it appears to be from a completely different project except that the trends are the same. The higher moisture meters, 10 ft, 13 ft, and 16 ft moisture meters register a declining percent moisture content, which indicates that the recharge water passed through these layers with no retention. The 23 ft moisture meter registered a slight increase in percent moisture, perhaps 1-1.5%. The 26 ft, 30 ft, and 33 ft moisture meters registered a 50-52% moisture increase. It is more probable that the increase was actually on the order of 20-22% as the moisture meters settled out at 30% after the application of recharge water ceased. The drop in percent moisture content was similar to the Middle and South Moisture Probes in time scale. The same low permeable stratum that affected the vertical downward movement of the recharge water at the Middle and South Moisture Probes is found at the North Moisture Probe, causing the recharge water to mound up at the 26 ft, 30 ft, and 33 ft moisture meters, at which depth, the water is assumed to have moved laterally. The higher permeable lens located at the Middle and South Moisture Probes appear to be larger and more connected near the North Moisture Probe, which explains the lower and declining percent moisture content in the higher moisture meters.

The data from the moisture meters are not wholly consistent with what you would expect given the K-sat values that were determined from the soiling boring samples. They indicate that a very low permeable stratum is located at 15 ft below the ground surface. The best explanation for this lack of correlation between the K-sat information and the data from the moisture meters is that this stratum is discontinuous throughout the SSAGR installation area. Essentially, there are lenses of more permeable material that penetrate to the lower, less permeable layers, but do not extend below the 33 ft depth, at least in the immediate vicinity of the moisture probes.

Conclusions

The results of the research prove that Shallow Subsurface Artificial Groundwater Recharge technology is a viable groundwater recharge method. SSAGR was able to recharge 100% of the water input to the system, which is an improvement over the efficiency of the traditional recharge basin technology, which achieved 94% efficiency. It also achieved an estimated cost of $78.45 per acre-foot of recharged water compared to a cost of $490 per acre-foot of recharge water for the traditional recharge basin technology based on a present worth analysis of the two systems. There are additional benefits to the SSAGR technology that are intuitive but were not studied as part of this research. They included:

- SSAGR can be implemented in almost any setting where the soil stratigraphy promotes groundwater recharge without disturbing the surface uses of the site, except that it probably should not be placed below buildings.
- SSAGR does not remove land from the property tax rolls.
- SSAGR is far enough below the root zone that legacy pesticides, fertilizers, and herbicides should not be mobilized by the recharge water and transported to the groundwater.
- SSAGR can be implemented where flood irrigation systems have been removed and replaced with drip irrigation systems.

There are some problems with the SSAGR system that can also be observed but were not specifically studied as part of this research. They include:

- SSAGR should be installed in open ground prior to planting trees or development of the site.
- The SSAGR system is not easily maintained, therefore, it is necessary to filter the recharge water prior to discharging it to the pipelines.
- The SSAGR system typically cannot be used at the same time as the drip irrigation system unless the water delivery and pump system have sufficient capacity to handle both systems.

The soil information determined in the laboratory was helpful in interpreting the data provided by the moisture probes. It was also helpful in understanding the ability of the recharge water to impact groundwater storage. It was also helpful when used to verify or disprove the recharge classification of the SAGBI mapping. In this case, the SAGBI mapping indicated that the location selected for the SSAGR system was favorable for recharge while the deep soil boring and subsequent testing in the laboratory indicated subsurface soils with low permeability.

Based on the experience with the soil investigations, it is recommended that each site selected for recharge should be verified with at least one, but probably three to five subsurface borings that penetrate 50 to 100 feet below the ground surface. The locations of the borings should be selected using the AEM mapping conducted by the State Department of Water Resources. The encountered stratum can be tested for permeability and this data be compared with the AEM classification of the soil strata at the site.

The moisture probes provided an interesting insight into the behavior of the soil moisture near the SSAGR system. Moisture levels, as recorded by the moisture probes, did increase while the SSAGR system was being operated and did decrease when the system was shut down. The differences between the moisture changes in the North Probe compared to the Middle and South Probes reinforce the non-homogeneous nature of soils. Conclusions from the moisture probe data are:

- The SSAGR system was able to input recharge water into the soil and percolate down into the lower subsoils until it encountered a highly impermeable layer.
- It is important to have good subsurface information when selecting a recharge site, regardless of which groundwater technology is implemented.
- The North Moisture Probe and the Middle Moisture Probe were located within 70 feet of each other while the South Moisture Probe was located 160 feet from the Middle Moisture Probe to observe whether the proximity of SSAGR percolation laterals had an impact on the soil moisture content. The moisture probe data seems to indicate that SSAGR recharge pipelines that are at least 70 feet apart do not influence each other as the Middle Moisture Probe's percent moisture content looks very much like the South Moisture Probe's percent moisture content and the North Moisture Probe's percent moisture content, while showing more reactivity than either of the other two moisture probes, did not increase significantly higher than the maximum moisture content of the other two.

Based on the experience with the installation of the moisture probes, the loss of signal from some of the individual moisture meters, and the data provided by the moisture probes, it is not recommended that they be installed as a standard feature of a SSAGR system. A simple groundwater monitoring well with a pressure transducer to record groundwater table elevation seems to be sufficient.

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Appendices

Appendix A – Evaporation coefficient Class A pan to large water body

Appendix B – Cost estimate for SSAGR system

Appendix C – Cost estimate for recharge basin

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