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Planning and Implementation of Groundwater Storage and Recovery Systems

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Abstract: The main objectives of all Groundwater Storage and Recovery (GSR) projects are to recharge, store and recover all or a portion of recharged source water. The groundwater recharge element of the system can be achieved by different direct methods, including infiltration basins, vadose zone wells, injection wells, dual-use wells that both inject and recover water, or a combination thereof. In-lieu recharge, which is the replacement of pumped groundwater with surface water supplies, is considered an effective indirect recharge method. The initial planning to develop a GSR project is driven by source water characteristics and amount, available aquifer storage and land for recharge facilities. The development of the GSR project is multi-phase effort that includes:

Phase1: Hydrologic Characterization of Potential Sites and Site Selection
Phase 2: GSR Facility Design and Construction
Phase 3: Operation, Maintenance and Monitoring
Phase 4: Project Evaluation and Improvement

GSR systems have a long successful history in California, mainly in the southern part of the state. Robertson-Bryan, Inc. (RBI) has developed a phase-based plan for a recharge pilot project in south Sacramento County, California, USA. Historic contour maps of the area show a significant drawdown at the center of the basin as a result of increased pumping. The initial phase of this project is underway and preliminary investigations revealed a great potential for the success of the recharge project.

Key words: Groundwater Storage and Recovery • Infiltration Basins • Injection wells • In-lieu recharge • Phase-based Plan

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INTRODUCTION

The increasing demand for water in the United States and other countries produced the realization that the vast underground reservoirs formed by aquifers are invaluable water supply sources, as well as water storage facilities [1]. Developing scientifically based strategies for sustainable use of our groundwater resources is essential in addressing growing demands of an increasing population and to prepare for the effects of climate change. One of the strategies that have been used and proved to be successful in mitigating depletion of natural groundwater reserves is the development of Groundwater Storage and Recovery (GSR) projects. GSR is a simple concept, in which surface water or recycled water is stored in subsurface permeable aquifers when water is plentiful and extracted during times of peak demand or drought. The main operations of all GSR projects are recharge, storage and recovery of all or a portion of source water recharged. The groundwater recharge element of the system can be achieved by different direct methods, including infiltration basins, vadose zone wells, injection wells, dual-use wells that both inject and recover water, or a combination thereof. In-lieu recharges-the replacement of pumped groundwater with surface water supplies-is considered an effective indirect recharge method.

Communities throughout the world are developing underground storage capacity to meet their growing water demands. In 2004, Topper *et al.* reported that artificial recharge was being “used in at least 32 states in the U.S. and at least 26 countries worldwide.” Many of these projects are implemented by state and local jurisdictions. GSR systems have a long and successful history in California, where artificial recharge of alluvial aquifers with storm runoff by use of spreading basins

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Corresponding Author: Ali. M. Elhassan, Robertson-Bryan, Inc. Elk Grove, California, USA began about the turn of the century and was a widespread practice by the 1930s, mainly in the southern part of the state [2].

Groundwater supports nearly 95 percent of all water demands in south Sacramento County. In the last four decades, groundwater levels in wells in the area have generally declined between 3 and 15 meters (10 and 50 feet). The average annual decline in water levels in the basin is 0.3 meters (1 foot). Historic contour maps of the south basin show an increase in the size of the cone of depression at the center of the basin as a result of increased pumping. Therefore, to protect the health and viability of this vital resource, interested stakeholders have come together to develop a management strategy for the groundwater resources in the area. In 2006, six stakeholders in the South Sacramento Basin entered into an agreement to produce a South Sacramento County Groundwater Management Plan. The common interest of these partners is to meet future water demand through comprehensive planning and collaboration with other stakeholders-including local, state and federal agencies-and with local academic institutions and residents in the area. One of the primary objectives of this planning process is to implement conjunctive use of groundwater and surface water. This includes planning for development of groundwater recharge projects in the area. Robertson-Bryan, Inc. (RBI) has developed a phase-based plan for a GSR project in south Sacramento County, California, USA, using recharge basins as the recharge method. The purpose of developing this phase-based plan is to provide a practical investigative planning approach for developing artificial recharge projects, which will allow agencies in south Sacramento County to pursue technically and fiscally sound recharge projects.

Development and Implementation of Gsr Projects: The initial planning to develop a GSR project is driven by source water characteristics (timing and amount) and available aquifer storage and land for recharge facilities. The study describes a four-phase process for development and implementation of the *recharge basins GSR* projects. This multi-phase approach allows agencies and stakeholders to cost effectively manage the project budget. These phases are:

Phase 1: Hydrologic Characterization of Potential Sites and Site Selection
Phase 2: GSR Facility Design and Construction
Phase 3: Operation, Maintenance and Monitoring
Phase 4: Project Evaluation and Improvement

The focus of this paper is on Phase 1, which provides the process and procedures for evaluating potential recharge locations for the Project. Subsequent phases are addressed more generally because specific design, operation, monitoring and project documentation depend on Phase 1 findings.

Phase 1: Hydrologic Characterization of Potential Sites and Site Selection: The objective of this phase is to hydraulically characterize potential recharge sites in specific basins to determine if any are appropriate for GSR projects. Site characterization should address the following questions:

- Are infiltration rates of the near-surface layers (within 3 meters (10 feet) of surface) sufficiently high for the project needs?
- Do lateral extensive low-permeability layers exist within the shallow vadose zone?
- What are the hydrologic properties of the predominant layer type?
- What is the potential for recovery?

Accordingly, at the end of this phase and by answering these questions, the detailed design criteria of the project facilities will be determined, project construction outlines will be laid, management and operation procedures will be formulated and a monitoring plan will be decided. An important outcome of this phase is a detailed project budget. The ensuing sections of this paper describe the field and modeling evaluations and the information that will be produced. These evaluations will be phased to include:

Hydrology and Hydrogeology Data Assembly: Available regional baseline basin data should be assembled and analyzed to determine potential initial recharge sites. These data should include basin hydrogeology and well logs; regional and local groundwater levels and groundwater contour maps; land use and land parcel availability for recharge projects; soil maps of the basin; hydrology data, including rainfall and evapotranspiration; surface water supply; water rights and pumping test results; and water quality data for the surface water source and the aquifer.

Near Surface Hydraulic Evaluations: The following field investigations are designed to determine the infiltration capacity and hydraulic conductivity of the top 3 meters (10 feet) of the soil profile.

- Backhoe Test Pits

Backhoe test pits allow visual observation of the soil horizons and overall soil conditions both horizontally and vertically. An extensive number of test pit observations can be made across a site at a relatively low cost and in a short time period. Soil samples from test pits should undergo laboratory testing to determine particle size distribution and soil permeability. At each test pit, the following conditions should be noted with depth measurements described as depth below the ground surface:

- Soil horizons (upper and lower boundary),
- Soil texture and color at each horizon,
- Color patterns (mottling) and observed depth,
- Observation of bores or roots (size, depth) and
- Near surface hardpan or limiting layers (clay layers).

The number of test pits varies depending on site conditions. In general, for infiltration basins, multiple test pits should be evenly distributed at the rate of 5 to 8 test pits per site. Additional tests should be conducted if local conditions indicate significant variability in soil types. Similarly, uniform site conditions indicate that fewer tests are required.

Particle Size Distribution Analysis: Sieve analysis of particle size distribution from soil samples collected during test pit excavations allows estimation of soil permeability and normalized infiltration. The sieve analysis uses a graded series of wire screens [3].

The gradation data yields the percentage of fines (percent passing the number 200 sieve (0.075 mm)). Soils with higher percentage of fines indicate a higher percentage of clay materials, which makes the soil unsuitable for recharge basins. The effective grain size D_{10} (diameter for which only 10 percent of the sample particles are finer), will be determined and used to estimate the saturated hydraulic conductivity using the Hazen formula:

$$K = C\,(D_{10})^2 \qquad (1)$$

Where:

K = Hydraulic conductivity (cm/sec)
C = A constant and unit conversion factor that varies from 1.0 to 1.5
D_{10} = Effective grain size diameter (mm)

Spreading basin approximate maximum infiltration rate q_A can be calculated using the following equation:

$$qA = (k)\,(A) \qquad (2)$$

Where:
q_A = infiltration rate
A = The total infiltration area of the soil interface

This equation is acceptable for estimation purposes, as studies have shown that under ponding, the long-term vertical infiltration rate of a soil usually approaches a steady value equal to the saturated hydraulic conductivity.

Double-ring Infiltrometer Test: Infiltration is the major process that affects groundwater recharge. A double-ring infiltrometer is the instrument most often used for measuring infiltration rates in the field. These tests sharpen estimates made for sites selected from the sieve analysis. A double-ring infiltrometer consists of two metal cylinders with the inner and outer cylinder diameter of 30.5-61.0 centimeters (12-24 inches), respectively [4]. Both rings are driven partially into the soil about 5 to 10 centimeters (2 to 4 inches) and filled with water. The rate at which the water moves into the soil is measured. The infiltration rate is determined as the amount of water that penetrates the soil per surface area over time. The infiltration rate becomes constant when the soil becomes saturated. The double-ring infiltrometer minimizes the error associated with the single-ring method because the water levels in the outer ring forces vertical infiltration of water in the inner ring. The ASTM standard D3385, the standard test method for infiltration rate of soils in field using a double-ring infiltrometer, describes a procedure for measuring infiltration rate with a double-ring infiltrometer.

Small-scale Infiltration Basins: Small infiltration basins are usually 9-by-9-meter (30 by 30 feet) basins with a depth of 1 to 2 meters (3 to 7 feet). To measure infiltration rates, the same principles and equations as cylinder infiltrometer can be applied. The water level is raised until it reaches operational depth, then the depth of water in the basin is measured over time to observe the ability of the basin to drain. Backhoe trenches (2 meters (7 feet) deep, 1 meter (3 feet) wide) are dug perpendicular or parallel to the basin sidewall to determine lateral spreading. The advantage of this method is that it provides a large-scale determination of infiltration rate and hydraulic conductivity.

Mid-depth and Deep Hydrogeologic Characterization: Borehole exploration is used to ensure that the hydrogeology of the deeper strata (below 3 meters) to depths of about 35-85 meters (115-280 feet), or to water level, is conducive to recharge operations and to estimate hydraulic parameters of deeper layers. This exploration will:

- Determine underground stratigraphy and lithiological formations and
- Identify presence of low-permeability layers that could result in perching and impede recharge to deeper aquifer levels.

On average, one to two test boreholes should be drilled on sites with expected relatively uniform lithology in accordance with the standards set out below. Boreholes are drilled using one of these drilling methods: air rotary drilling, cable tool drilling, or mud rotary drilling [5]. If clay layers are either minimal or extensive, further borehole exploration is not needed. For boreholes less than 85 meters (280 feet) deep, sampling of drilling cuttings will be taken at 1.5 meters (5 feet) depth intervals or at every change in formation material [6]. Samples would be evaluated and described in a driller's sampling log.

Boring logs include the location, depths, geotechnical data and sample description for each material identified in the borehole (Figure 1). Description and identification of soils and classification of soils are in accordance with ASTM standards or any other appropriate geologic standards. Borehole location should be based on the groundwater gradient in the area.

Three boreholes should be drilled-one in the center of the potential recharge basin site, one up-gradient and one down-gradient of the recharge basin. The exact location of boreholes should be determined based on site location.

The first borehole in the middle of the recharge basin will determine if further exploration should be eliminated because of extensive clay layers.

Geophysical logging can be used to supplement borehole logging to aid in interpreting the borehole logging. Gamma logging can be useful to confirm specific subsurface geologic conditions (permeability) if standard methods are inconclusive.

Water Quality: Sampling both potential source water and groundwater will document baseline concentrations, determine geochemistry of source water and aquifer water; and determine the future impact of the recharge water on the groundwater to avoid any degradation that might result from the GSR project. Sampling results can be used as an indicator of the arrival of the source water to the aquifer, especially if there is different geochemistry between the two.

Fig. 1: Example of borehole geologic logging

Source water samples should be collected on a quarterly basis from surface water source. Groundwater samples should be collected from boreholes and other wells in the area. Water quality of groundwater should be compared to recharge source water. These samples can be analyzed for dissolved solids, total and dissolved inorganic constituents, nutrients, organic and volatile organic compounds, radio nuclides and bacteria.

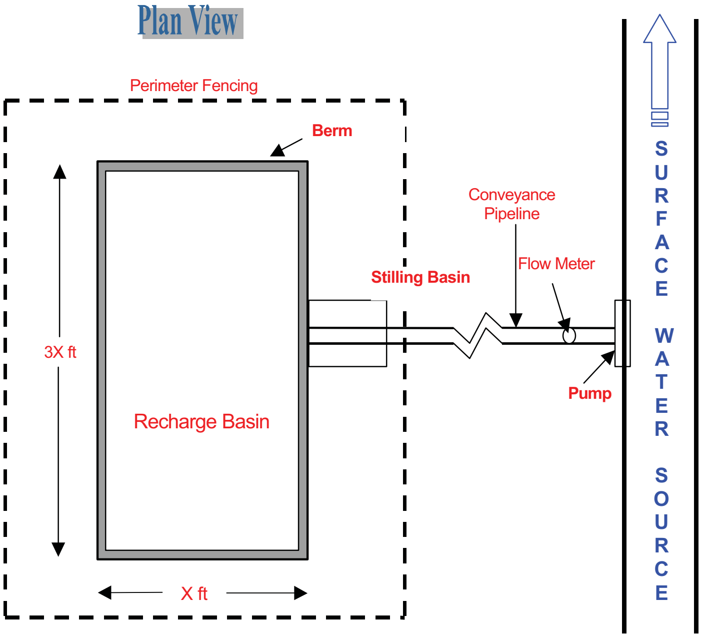

Fig. 2: Schematic Layout of a Typical Recharge Basin

Modeling of Groundwater Level Responses to Recharge Operations: The dynamics and effects of potential recharge operations on groundwater levels at each potential site should be analyzed using simple steady-state reverse drawdown equations or groundwater mounding equations [7]. The complexity of the model assumptions and type of model will depend on the data acquired during the field investigations for each site.

These models will be applied to facilitate quick but reliable analysis of multiple scenarios for recharge operations. The local hydraulic parameters and data collected from each site in previous stages, such as infiltration rate, depth to groundwater table and aquifer parameters will be used to develop these models.

Phase 2: Gsr Facility Design and Construction: GSR facilities are structures that provide for the effective recharge into and recovery of surface water from a local aquifer. Recharge facilities typically include water treatment unit or stilling basins, recharge or infiltration basins and conveyance facilities. Most basins are earthen structures designed to hold water and allow it to infiltrate into the underlying aquifer over a period of time. Therefore, recharge basins do not maintain a permanent pool of water and need a constant input of water supplied through a conveyance facility. Figure 2 provides a generalized schematic of the layout of recharge facilities.

Because recharge basins are susceptible to high failure rates due to clogging by sediments, pretreatment of water is necessary to remove suspended solids before the water enters the basin. Therefore, a water treatment plant or a stilling basin should be established to provide for the removal of suspended solids as part of the recharge facility design. A stilling basin is designed to allow sediment to settle out before the water is put into the spreading basin.

A typical recharge basin (Figure 2) should be graded as flat as possible, having a length-to-width ratio of 3:1, or greater, to provide uniform ponding and infiltration across the basin floor. For public safety and for easier maintenance access, the side slopes of the basin should be 3:1.

A recharge facility requires a constant supply of water that must be conveyed from its source or delivery point. The exact configuration of the conveyance facility required to move water from the source to the recharge facility will depend on the location of the recommended recharge site. If the recharge site is close to the surface water source, water transfer could be by gravity feed from the source to the recharge facility.

If the site is further from the source water, conveyance may require the use of pumps to draw water from the source. The type and number of pumps will be chosen based on the lift between the water surface elevation at the source and the discharge point into the stilling basin. The length of the pipeline or canal to convey the water depends on the location of the recharge facility. A magnetic flow meter should be attached near the discharge point at the recharge basin to measure the inflow.

Water recovery is typically accomplished through wells; however, some GSR systems utilize natural discharge of groundwater to a stream as a virtual means of recovery.

Phase 3: Operation, Maintenance and Monitoring: Operation of the recharge facility will entail management of water into the recharge facility and out of the recovery wells. The operation depends on the quantity and availability of the source water and the infiltration capacity of the facility. On the other hand, recovery can take place on a regular cycle, such as the annual dry season, or it may simply be part of the long-term plan, such as for future development or drought protection.

Maintenance generally consists of routine maintenance of equipment and removal of clogging materials from the recharge facility, which is the most crucial maintenance effort. If sediment accumulates, surface soils will become clogged and the basin will cease to operate as designed. Sediment should be removed by scraping and ripping to rejuvenate infiltration rates only when the surface is dry and “mud-cracked.” Light-weight equipment should be used to minimize soil compaction during maintenance activities

The monitoring element of a project includes recharge basin monitoring of inflow and infiltration, which will govern water management and monitoring of local and regional aquifer to measure changes in groundwater levels, quality and gradients resulting from the GSR operations. Monitoring of groundwater levels locally and regionally is crucial in determining the fate of the recharge water and hence the success of GSR project.

Recharge basin monitoring includes monitoring all elements needed to estimate the water balance of the basin, such as surface water diversion, evaporation, rainfall and water level in the basin. This is very crucial in the operation and management of the facility.

Local shallow aquifer monitoring is performed by utilizing monitoring wells or piezometers. Such monitoring wells and piezometers could be placed in some of the boreholes drilled during the site evaluation process in order to reduce costs. Following well development, pressure transducers and data loggers should be installed in each of the newly installed monitoring wells. For monitoring the regional aquifer and based on the need to determine directions of water movement in the area, shallow wells near the project site should be identified to obtain historic, current and future water level data measurements.

Source water samples should be collected on a monthly basis from the surface water or recycled water source. Groundwater samples should be collected from boreholes before the start of the recharge activities and from piezometers during the operation of the recharge facility. Water quality of groundwater should be compared to recharge source water. Sampling frequency should be at least once every month. These samples should be analyzed for dissolved solids, total and dissolved inorganic constituents, nutrients, organic and volatile organic compounds, radio nuclides and bacteria.

Phase 4: Project Evaluation and Improvement: This task will determine whether the GSR project is effectively meeting the program objectives and will enable project managers to evaluate and improve the performance of the project. In order to achieve that, monitoring data should be regularly collected and reported. Such reporting will enable the project managers to evaluate the performance of the project and to determine what to fix, what type if expansion is needed and how to improve project performance.

Potential for Gsr Projects in South Sacramento County: RBI has developed a phase-based plan for a recharge pilot project in south Sacramento County, California, USA. The South Basin is bounded by the Cosumnes River on the north and west and Dry Creek on the south, which is the boundary with San Joaquin County, as seen in Figure 3.

RBI collected, assembled and analyzed available regional basin data to determine potential initial recharge sites. These data include basin hydrogeology and well logs; regional and local groundwater levels and groundwater contour maps; land use and land parcel availability for recharge projects; basin soil maps; hydrology data, including rainfall and evapotranspiration; surface water supply; water rights and pumping test results; and water quality data for the surface water source and the aquifer

Based on the findings from the data analysis, groundwater is the major supply source for nearly all agricultural, residential and municipal users in southern Sacramento County. Annual precipitation in

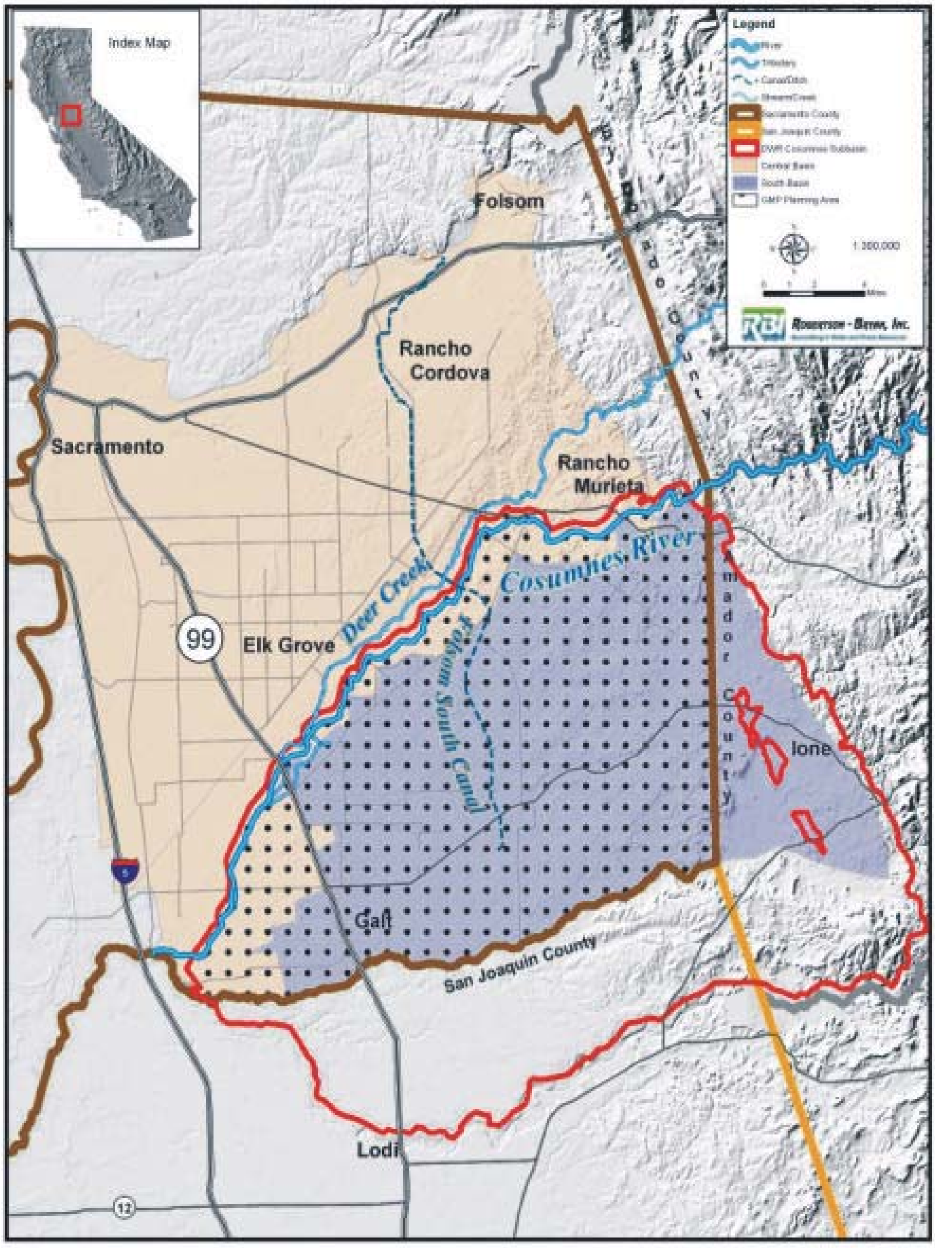

Fig. 3: Area of South Sacramento County Basin

the South Basin ranges from approximately 381 millimeters (15 inches) on the west to about 560 millimeters (22 inches) on the east [8]. Winter storms between November and March account for about 80 percent of the annual precipitation in the basin. Flows on the Cosumnes River are unregulated and result primarily from winter storms and limited seasonal snow melt. The Cosumnes River is the major source of surface flow to the south area and is generally considered to be a major source of groundwater recharge for the South basins. The hydrology and use of the Cosumnes River have changed substantially over time. The river was the major source of water diversions for agriculture in the late 1800s prior to groundwater well technology becoming available and affordable.

In spite of the seasonal recovery of groundwater levels during the non-irrigation season, the groundwater levels in the center of the basin outside the influence of the Cosumnes River have generally declined between 3

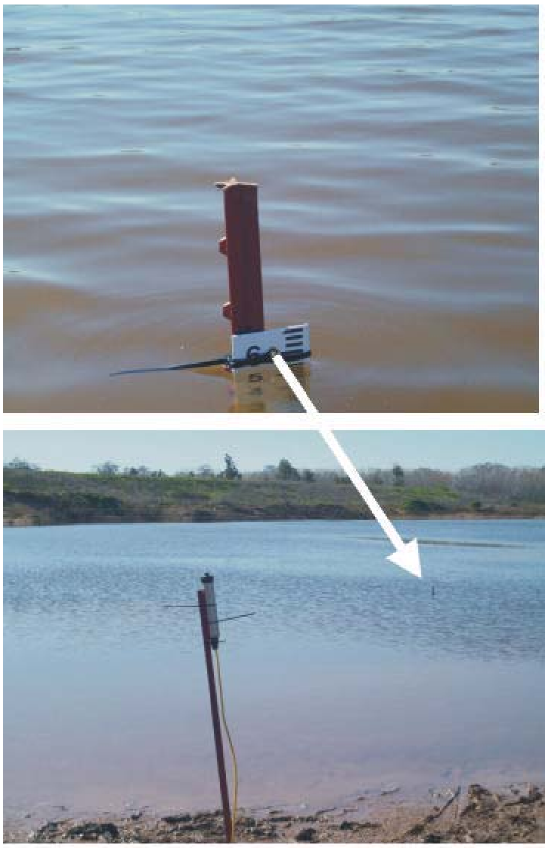

Fig. 4: March 12, 2009

Fig. 5. March 17, 2009

and 15 Meters (10 and 50 feet) over the past 50 years. Recent groundwater contour maps illustrate that the location of the regional cone of depression has shifted toward the center of the basin and increased in size. It is concluded that groundwater levels in the South Basin have generally declined throughout the basin with more severe depressions occurring near the communities of Galt and Elk Grove.

As water demand increases in the area in the future and with the lack of consistent surface water supply, groundwater levels are expected to further decline, leading to adverse economic and ecological impacts. This fact has led local agencies in the area to seriously consider groundwater artificial recharge projects. In addition to that, construction of new water conveyance facilities by Sacramento County and other agencies will provide the necessary means to transfer South County surface water entitlement on the American River. This water entitlement of 15,000 acre-feet per year, which historically has not been utilized due to the lack of conveyance facilities, can be used as a potential source of recharge in the area.

One of the geologic formations that contain groundwater in the South Basin is the Floodplain Formation, which is a younger alluvium layer that includes recent sediments deposited along the channels of active streams and consists of unconsolidated silt, fine-to-medium grained sand and gravel. The maximum thickness of this layer is 35 meters (100 feet), with a specific yield ranging from 6 percent to 12 percent. The sand and gravel zones in this layer are highly permeable and yield significant quantities of water to wells.

Based on hydrologic and hydrogeologic data collected and analyzed, RBI suggested three potential recharge sites within the floodplain formation. In addition, RBI contacted land owners of these sites and they expressed great interest in participating in a pilot GSR project in the area. Those sites are close to existing surface water conveyance routes such as rivers, creeks and canals.

Small Scale Infiltration Test: As a result of a short rise in the Cosumnes River stage in February 2009, water filled one of the potential sites, a mining pit on a property

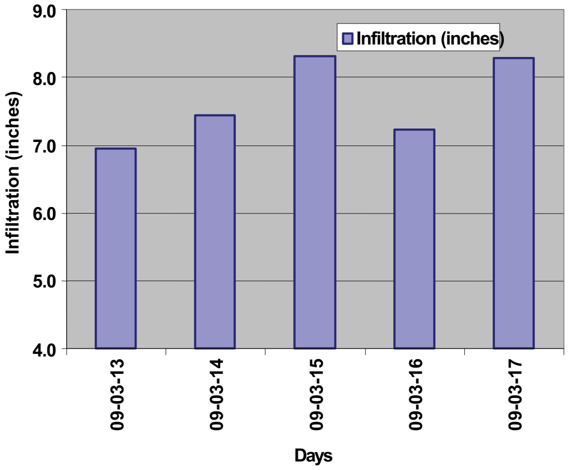

Fig. 6: Observed infiltration rates in recharge site, March 12-17, 2009

adjacent to the Cosumnes River. Two weeks after the event on March 10, RBI staff toured the site and observed water inflow and outflow. Water inflow had virtually stopped and there was no outflow. As a result of the visit, RBI undertook the task of monitoring the water infiltration at the site. The site has an area of approximately 4 hectares (10 acres) and a depth of about 4 meters (13 feet). The topsoil layers had been removed as part of the gravel mining operation, exposing sand strata with high infiltration rates.

RBI staff installed two staff gages on March 12, including a data logger, to record water levels at ½-hour increments (Figure 4). At that time, all inflow had ceased and no outflow was observed. On March 17, RBI staff retrieved the data and gages noting the decline in water levels as seen in Figure 5.

RBI gathered evaporation and rain data from the state Climate Irrigation Management and Information System for the entire period of the test. The findings of this test are:

- The water level dropped 104 centimeters (41 inches) during the five-day measurement period.
- The daily average rate of infiltration, after adjusting for evaporation and rainfall, was 19.3 centimeters (7.6 inches) per day as shown in Figure 6.
- The neighboring pit, which is about 4.6 - 6.1 meters (15-20 feet) deeper, showed no signs of pooled water as a result of lateral flow.

RBI staff concluded that removal of the topsoil layers exposed sand strata that produced relatively high rates of infiltration. Infiltration at his site appears to have been vertical, indicating little if any restriction to long-term success. Because the test started 15 days after the flooding of the site, it allowed infiltration rates to stabilize before the start of the test. This was confirmed by the test results which showed a stable infiltration rate with no erratic changes. RBI recommends small-scale testing of the other sites suggested, including bore holes to better assure the fate of the infiltrated water.

CONCLUSIONS

This study outlines the procedures of implementing specific test procedures, operational measures and a monitoring program. The implementation plan was developed as a generic plan for *recharge basins GSR* projects to serve needs of diverse agencies and wide range of stakeholders and can be slightly adapted and implemented in any location. The plan for the GSR project will allow local stakeholders to determine long-term viability of recharge activities. The multi-phase approach recommended in the study allows agencies and stakeholders to resourcefully fund the project and cost effectively manage the budget for the project, especially under current economic hardship faced by many agencies. RBI has developed a phase-based plan for a recharge pilot project in south Sacramento County, California, USA. Historic contour maps of the area showed a significant drawdown at the center of the basin as a result of increased pumping. The initial phase of this project is underway and preliminary investigations revealed a great potential for the recharge project success in this area.

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