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Rainwater Harvesting for Enhanced Groundwater Recharge Through Capture of Increased Runoff from Site Development

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RAINWATER HARVESTING FOR ENHANCED GROUNDWATER RECHARGE THROUGH CAPTURE OF INCREASED RUNOFF FROM SITE DEVELOPMENT

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In many parts of the western U.S. that rely on groundwater, the sustainability of aquifers is tenuous. Water supply managers have opportunities for rainwater harvesting where community development increases stormwater runoff. Stormwater control systems that increase groundwater recharge can offset the continually increasing water demands experienced in many communities.

This study examined the groundwater recharge experienced on an 85-acre property that was developed in the 1980s with construction of buildings and roadways. All of the onsite storm water is routed to four earthen retention ponds. Water levels have risen in on-site monitor wells, and a water table mound has been created beneath the retention ponds.

A water balance approach was used to quantify each component of the on-site hydrologic system. The site is semi-arid, with average annual precipitation of about 13 inches per year. Storm water runoff calculations showed that 82 percent of on-site precipitation was routed to the retention ponds. Two modeling approaches were used to estimate the recharge rates from the retention ponds: 1) surface infiltration model and 2) groundwater flow model. The results show that routing storm water to retention ponds results in 30 to 50 percent of onsite precipitation becoming recharge to groundwater.

The results show the potential for increased groundwater recharge that could be achieved with wide-scale implementation of policies promoting rainwater harvesting. Policies to consider include: grading and drainage for on-site storm water retention, periodic sediment and vegetation removal from retention ponds, and sufficient depth to groundwater to protect water quality.

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Rainwater Harvesting for Enhanced Groundwater Recharge Through Capture of Increased Runoff from Site Development

Mark E. Miller, P.G.

1. Introduction

In many parts of the western U.S. that rely on groundwater pumping for much or all of their water supply, declining groundwater levels adversely affect well productivity, and the sustainability of aquifers is tenuous. In order to reduce rates of aquifer depletion, water supply managers are increasingly seeking conjunctive use options to make the most of available supplies. Some communities are moving actively to limit growth due to water supply limitations and concerns that development will reduce groundwater recharge. However, development approaches can be implemented that harvest rainwater to increase groundwater recharge, thereby offsetting the continually increasing water demands experienced in many western communities.

This paper describes the methods used to quantify stormwater recharge rates in a case study and discusses approaches to harvest rainwater and increase groundwater recharge, through site development planning and design. The paper discusses some of the benefits and concerns of enhanced recharge using stormwater and offers suggestions for policies to foster enhanced recharge projects.

The rainwater harvesting case study examines the groundwater recharge experienced on a 34-hectare (ha) mine site that was developed in the 1980s with construction of buildings and roadways. All of the on-site stormwater is routed to four earthen retention ponds. Although the original purpose of the retention ponds was to control stormwater on-site, the ponds also function as infiltration basins when they are periodically inundated with stormwater. This study determined recharge rates and estimated the total recharge occurring over 20 years of stormwater routing to the retention ponds.

Planned site development using retention basins for stormwater control offers opportunities to significantly increase recharge as compared to natural recharge. A site development example is provided to show the reduction in overall water consumption that can be achieved using rainwater harvesting for enhanced recharge. Natural recharge is very low in semiarid regions with native vegetation, generally averaging just a few millimeters per year (mm/yr). Land development adds impervious surfaces (roof tops, pavement, etc.), greatly increasing stormwater runoff. Utilizing retention basins for stormwater control can provide significant recharge, allowing communities to improve the sustainability of aquifers and reduce the water consumption impact of new growth.

2. Recharge Performance Case Study

The case study site is located in a semiarid, high-desert environment, where the average annual precipitation is about 330 mm/yr. Previous investigators have estimated that natural recharge rates in the area are less than 1 percent of precipitation, or less than 3 mm/yr. A site map is provided in Figure 1, showing the areas that drain to each of the four retention ponds. The development contains:

- 31 percent impervious rooftops, roadways, and parking
- 57 percent bare ground with little vegetation
- 12 percent stormwater retention ponds

Table 1 provides details of the four watersheds that contribute stormwater to the retention ponds. The site includes a 6-ha rock pile from mining activities, which has a flat and pervious top surface that does not provide runoff to the retention ponds. The area contributing stormwater runoff to the retention ponds is 28 ha.

A network of 16 groundwater monitor wells, installed for environmental monitoring purposes, allowed a unique opportunity to study groundwater recharge rates from the stormwater retention ponds.

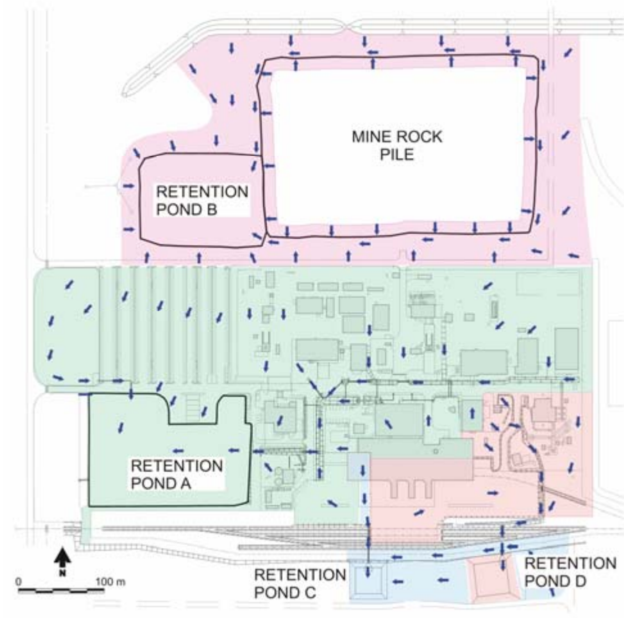

Figure 1. Map of Site Drainage and Retention Ponds

Water levels have risen in the monitor wells, and a water table mound has been created beneath the retention ponds. Knowing the configuration of the observed water table mound allows use of basic hydrogeologic principles to calculate the recharge rate necessary to sustain the mound.

Table 1. Watershed and Retention Pond Details

Watershed	Area (ha)			
	Pervious	Impervious	Pond	Total
Retention Pond A	4.65	8.26	2.35	15.26
Retention Pond B	6.72	0	1.46	8.18
Retention Pond C	1.09	0.16	0.20	1.45
Retention Pond D	0.93	2.06	0.28	3.27
Mine Rock Pile	6.03	0	0	6.03
Total	19.42	10.48	4.29	34.19
Percent	57%	31%	12%	100%

The geological setting is illustrated in Figure 2; formation stratigraphy consists of the following (variable thickness):

- Surficial dune sand over caliche (0 to 3 meters [m] below ground surface[bgs)
- Gatuña Formation sediments (3 to 10 m bgs)
- Santa Rosa Sandstone (10 to 20 m bgs)
- Dewey Lake Redbeds (20 to 170 m bgs)

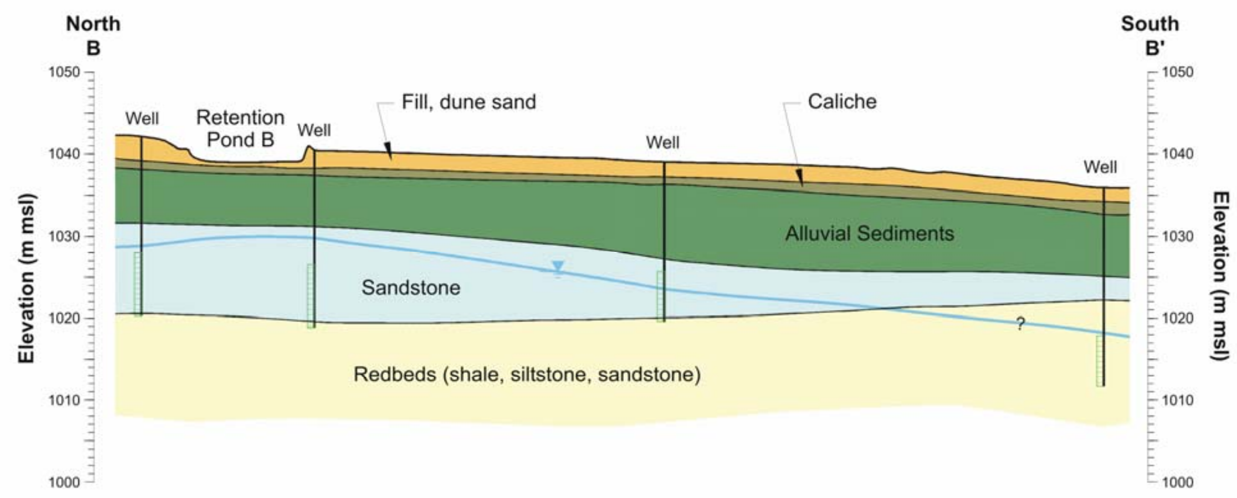

Figure 2. Geologic Profile Showing Perched Groundwater Lens

The regional water table occurs in the Dewey Lake Redbeds, at a depth of approximately 60 m bgs. Drilling in the 1980s, prior to site development, showed that the vadose zone above the regional water table was unsaturated. However, drilling in 1996 found a perched groundwater lens in the Santa Rosa Sandstone with 3 to 10 m of saturated thickness, perched above the low-permeability Dewey Lake Redbeds. The unique site conditions, including an initially unsaturated vadose zone, monitor well network, and expanding perched lens attributable to stormwater recharge, offered an opportunity to examine the increased recharge attributable to site development.

3. Recharge Quantification Methods

A water balance approach was used to quantify each component of the on-site hydrologic system. Stormwater runoff calculations showed that stormwater runoff routed to the retention ponds averages 7.5 hectare meter per year (ha m/yr) (= 75,000 m^3). This runoff amounts to 82 percent of precipitation falling on the 28 ha that drain to the retention ponds, or 68 percent of the precipitation on the entire 34-ha site.

Two modeling approaches were used to estimate the recharge rates from the retention ponds:

- *Surface infiltration model:* UNSAT-H calculated seepage based on soil hydraulic properties and evapotranspiration rates from vegetation in the ponds (Fayer 2000).
- *Groundwater flow model:* MODFLOW-SURFACT calculated recharge from the groundwater mound configuration using aquifer hydraulic properties from monitor well testing (Harbaugh and McDonald 1996; Hydrogeologic 1999).

3.1 Surface Infiltration Model

The UNSAT-H surface infiltration model uses a one-dimensional finite element version of the Richard’s equation to simulate infiltration in variably saturated media as a function of environmental conditions such as climate, soil type, and vegetation. The model accounts for redistribution of moisture in the soil profile and provides a robust consideration of evapotranspiration losses. The model determines seepage exiting the base of a 2-m soil profile set up in the model domain, with downward seepage migrating vertically into the underlying bedrock to become recharge to the perched water lens. The UNSAT-H model was run for a 5-year interval from 1997 through 2001, when detailed climatological records were available as model input.

The UNSAT-H results are presented in Figures 3 and 4. In the UNSAT-H modeling results, infiltration represents the flux into the top surface of the model domain, and seepage represents the flux from the bottom of the model domain contributing recharge. Up to several meters of water in cumulative water depth is discharged to the stormwater ponds in a given year; up to 1.5 m of standing water fills the retention ponds after large storm events. Evapotranspiration losses are relatively small components of the water budget, and most water discharged to the ponds seeps into the deep subsurface, becoming recharge.

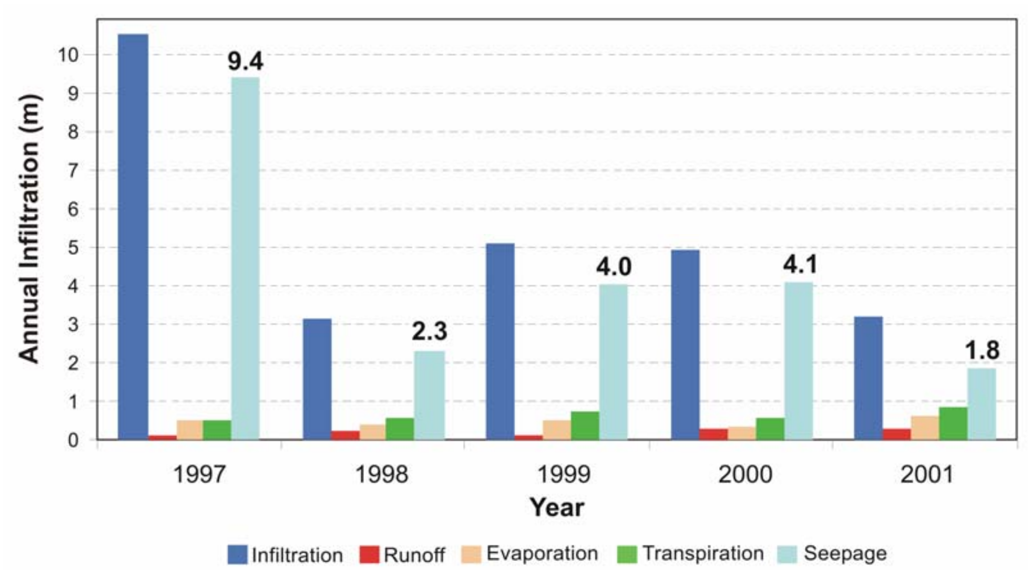

Figure 3. Surface Water Infiltration Results for Retention Pond A

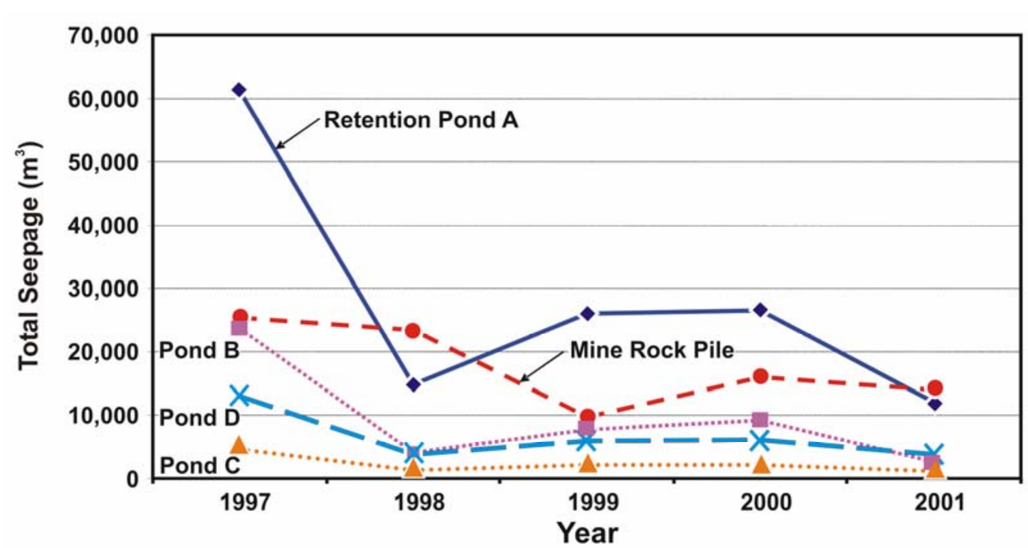

Figure 4. UNSAT-H Predicted Seepage Rates

As shown in Figure 4, recharge rates from individual retention ponds range from 0.1 to 6.2 ha m/yr (1,000 to 62,000 m^3/yr). During the 5-year period of analysis, the combined annual recharge from all four retention ponds is estimated to average 4.7 ha m/yr (47,000 m^3/yr). During the timeframe analyzed, the average annual precipitation was below the long-term average at 229 mm/yr, amounting to an annual average of 7.8 ha m/yr (78,000 m^3/yr) of precipitation falling on-site. The estimated recharge rate is therefore approximately 60 percent of the on-site precipitation, with the remaining 40 percent of on-site precipitation lost to evapotranspiration.

3.2 Groundwater Flow Model

The MODFLOW-SURFACT model was used for transient analysis of variably saturated conditions to simulate recharge to the observed water table mound below the retention ponds and to project long-term expansion of the perched lens. Hydraulic characteristics in the model were based on pumping and slug test results from on-site monitor wells, and boundary conditions were set based on formation characteristics. The modeling considered variable recharge rates needed to simulate the observed water level hydrographs from monitor wells for the period of record available from 1996 to 2002. Recharge rates fluctuated from year to year, based on long-term precipitation records, with seepage partitioned among the various retention ponds. The model was first run in a calibration mode from 1981, when site development began, until water levels were matched in 2002 (Figure 5). The model was then run in a predictive mode to estimate effects of continuing recharge on the expanding perched lens for 100 years until 2102.

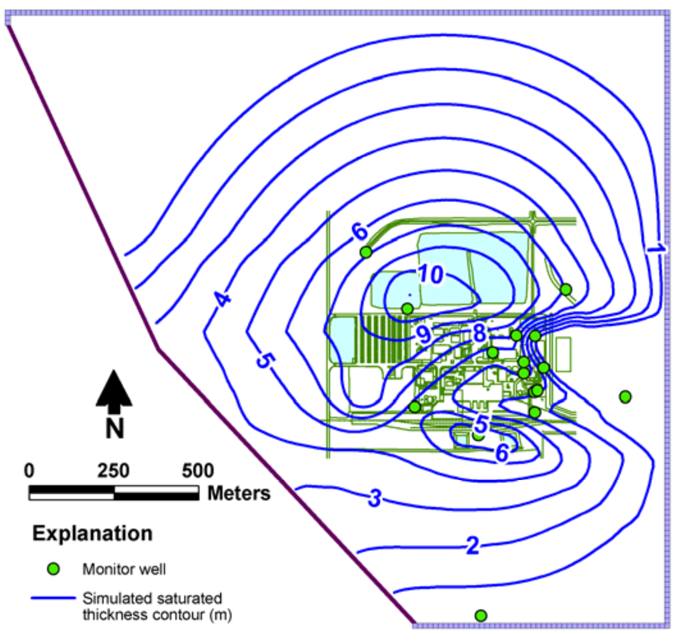

Figure 5 Simulated Perched Lens Saturated Thickness Contours for 2002

The MODFLOW-SURFACT model was able to accurately simulate the observed perched water levels, using transient recharge rates that average 4.3 ha m/yr (43,000 m^3/yr). Over the 22-year calibration period simulated, these recharge rates amount to a total recharge of 95 ha m (950,000 m^3); considering initial moisture in the formation, the perched lens water volume amounts to approximately 120 ha m (1,200,000 m^3), covering an area of approximately 210 ha.

For predictive simulations, the MODFLOW-SURFACT model was expanded to include a 16-square mile area, with an upper perched lens horizon in the Santa Rosa Sandstone and lower regional aquifer horizon in the Dewey Lake Redbeds (Figure 6). Downward leakage from the perched lens contributes recharge to the regional aquifer, with downward fluxes limited by the relatively low permeability of the Dewey Lake. The model accounts for formation hydraulic characteristics and structural features at contacts between the formations. The rate of downward leakage from the upper to lower layer in the model was constrained by the surface recharge rate, which must be sufficient to create the observed perched lens.

Figure 7 shows the model results for the perched groundwater lens in 2002. Figure 8 shows the long-term increase in saturated thickness in the regional aquifer by 2102, resulting from continued stormwater recharge from the retention ponds and downward leakage from the perched lens to the regional aquifer.

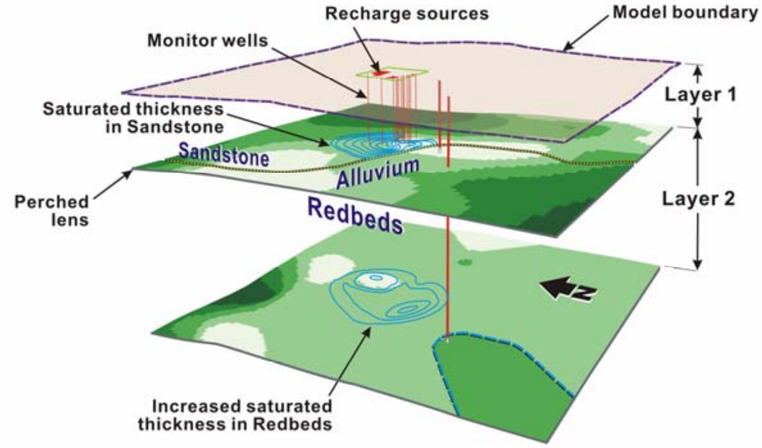

Figure 6. Groundwater Recharge Simulation to Perched and Regional Aquifers

The MODFLOW-SURFACT modeling results show that routing stormwater to retention ponds results in approximately 40 percent of on-site precipitation becoming recharge to groundwater (0.13 ha m/yr of recharge per ha on the developed property). The results from this case study show the potential for increased groundwater recharge that can be achieved by planning site development to manage stormwater with retention basins designed to maximize recharge.

4. Benefits and Concerns of Enhanced Stormwater Recharge

Enhanced recharge of stormwater offers the potential to significantly supplement groundwater supplies through wide-scale implementation of policies for site development design practices that promote groundwater recharge. To capitalize on stormwater recharge, policies must be implemented at (1) the state level to provide incentives for return flow water rights credits, and (2) the local level to require stormwater control systems that maximize recharge rather than routing stormwater off-site.

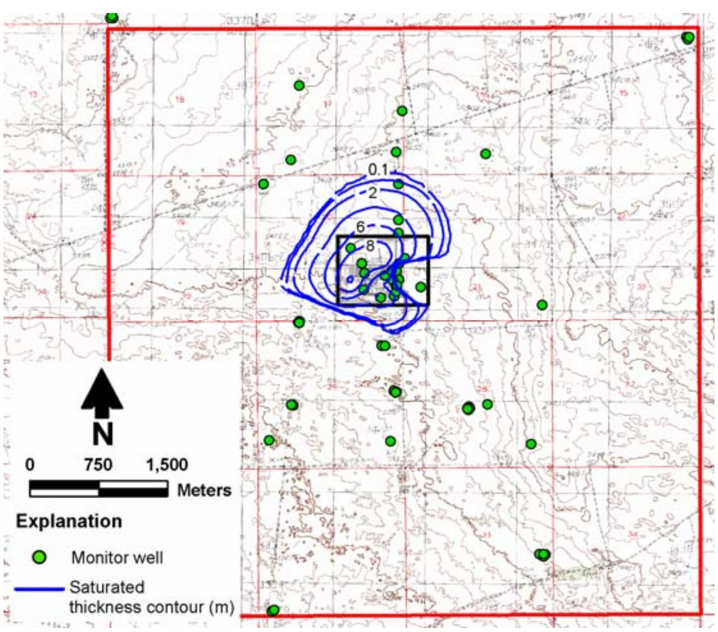

Figure 7. Perched Lens Saturated Thickness in 2002

4.1 Site Development Example

An example of the enhanced recharge approach in site development is offered in the following scenario. Consider a residential subdivision being planned with enhanced recharge objectives that will provide grading and drainage design to route stormwater to retention ponds with rapid infiltration capacity of at least 0.3 meter per day.

The 50-ha development will include the following:

- 40 ha with 15 homes per ha (600 homes)
- 10 ha of roads and common areas
- Household consumption of 500 m^3/yr for a total demand of 30 ha m/yr (300,000 m^3/yr)
- Average annual precipitation of 330 mm/yr for a total of 16 ha m/yr
- Recharge rate of 50 percent of precipitation, providing 8 ha m/yr return flow
- Net consumption from aquifer of 22 ha m/yr, a reduction of 26 percent below the household consumption

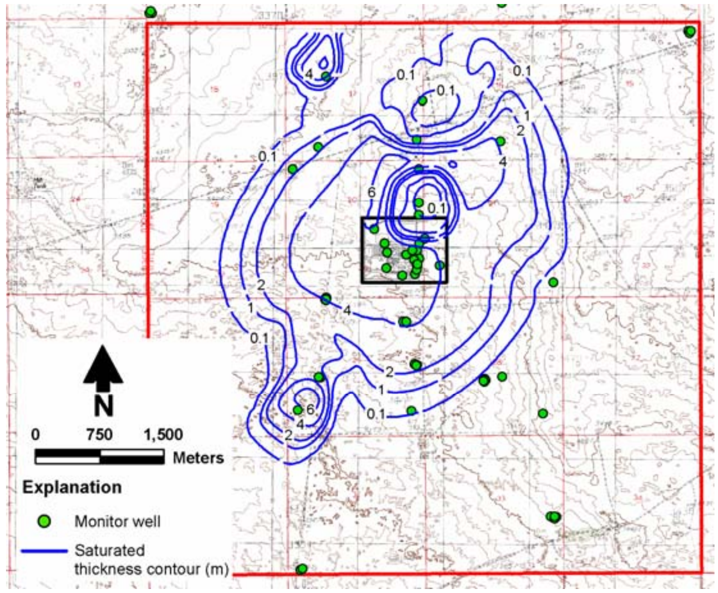

Figure 8. Increase to Regional Aquifer Saturated Thickness in 2102

The recharge rate in this example is consistent with the findings of the case study, and the precipitation is typical of many areas in the western U.S. that are experiencing aquifer depletion. Assuming the water supply is pumped from wells in the same aquifer being recharged, the net impact on the aquifer is substantially reduced.

This example shows that significant groundwater recharge may be realized through designed stormwater retention systems that harvest the increased runoff occurring after development creates large areas of impervious surfaces. The recharge results for a development will depend on construction density, precipitation rates, and the hydrogeologic setting.

4.2 Water Rights Considerations

Harvesting stormwater for enhanced recharge is subject to state water rights laws. Water law may not allow for stormwater capture due to concerns that runoff may be diminished to downstream watercourses and water rights holders. However, most runoff from developed areas is due to construction of impervious surfaces that greatly increase runoff, and capture of this stormwater therefore has little impact on the runoff that occurs under natural conditions. Much of the stormwater captured for recharge from a developed area would be lost to evapotranspiration under natural, vegetated conditions.

Updates to state regulations should be considered that provide for return flow credits for groundwater recharge from designed stormwater containment systems. Mechanisms to quantify the recharge will be needed to establish the amount of return flow credits granted. In this way, recharge systems have value in offsetting the water demands of new and existing development.

Quantifying recharge to obtain return flow credits for rainwater harvesting should account for the total amounts of stormwater, recharge rates considering evaporative losses, and travel time for recharge to reach the aquifer. In the case study described above, travel times for recharge to reach the perched groundwater lens were found to be on the order of months, with precipitation events causing noticeable water table responses. Typical downward migration is in the range of months to years, but within reasonable timeframes to provide substantive benefits to the aquifer.

4.3 Concerns Associated with Enhanced Recharge

Certain concerns exist regarding enhanced recharge of stormwater, most notably (1) suitability of hydrogeologic conditions to benefit the aquifer and (2) possible groundwater quality impacts. Only recharge projects that demonstrate benefits to the aquifer and water quality protection should be pursued. Suitable hydrogeologic conditions for enhanced groundwater recharge include:

- Sufficient permeability of vadose zone geologic materials
- Aquifer water quality that makes recharge an asset
- Reasonable travel time to the aquifer
- Ability to capture the recharged water using wells, or other benefit to the aquifer, including increased water levels or return flow to support surface water systems
- Adequate infiltration rates for ponds to dry periodically to maintain soil permeability and to avoid pests and nuisances

Enhanced stormwater recharge must only use stormwater of adequate quality to prevent adverse impacts to groundwater quality. Several considerations are important to maintain the quality of stormwater and groundwater:

- Appropriate land use is essential, such as residential, rooftops, light industrial, etc. where generally good stormwater quality is typical.
- Soil aquifer treatment (SAT) polishes water quality during transport from the surface to groundwater.
- Depth to groundwater should be sufficient to provide travel times of months to years while water quality improvements occur.
- Best management practices (BMPs) for stormwater quality protection should be implemented.
- Engineered stormwater pretreatment systems are available to reduce contaminant loads.
- Public outreach and education programs should be implemented to avoid contaminant releases.

An increasing number of design alternatives and products are available to implement BMPs and control stormwater on-site, while avoiding contaminant impacts. Stormwater control systems, such as porous pavement and subsurface detention and exfiltration systems, recharge stormwater rather than manage stormwater runoff. These engineered systems are often used where space constraints exist. Where sufficient land is available, stormwater retention ponds can also provide substantial recharge at a relatively low cost.

5. Conclusions and Recommendations

Planning site development projects to promote rainwater harvesting by capturing runoff in stormwater retention ponds can result in approximately half of the on-site precipitation being returned to groundwater recharge. In the case study presented here, two independent calculation methods—one using runoff calculations and infiltration modeling and the other, groundwater flow modeling —provided relatively consistent recharge estimates in the range of 40 to 60 percent of precipitation becoming recharge. The creation of a perched groundwater lens at the case study site conclusively demonstrates the increase in recharge that occurred following site development. The observed recharge was experienced without efforts to maximize recharge rates; therefore, engineered stormwater containment systems may provide even better recharge performance.

Implementing public policies to encourage rainwater harvesting for enhanced groundwater recharge can play a role in moving toward sustainability of groundwater supplies. Equally important, groundwater quality must be protected by implementing stormwater BMPs and limiting recharge projects to locations with suitable hydrogeologic conditions, vadose zone thickness, and travel time to supply wells. Methods are available to quantify recharge rates to provide return-flow water rights credits, if states will foster this approach.

The potential impact of broader use of enhanced stormwater recharge systems should be evaluated at local and regional levels to improve understanding of the benefits that enhanced recharge may provide for aquifer sustainability. In comparison to the many large-scale recharge projects that have been implemented, on-site rainwater harvesting is a small-scale approach that can be implemented widely in numerous stormwater recharge projects. Planning site development to enhance recharge offers promise to achieve significant recharge improvements with widespread application.

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