Optimization of a Managed Aquifer Recharge Network

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REFERENCE: *Proceedings of the 2014 South Carolina Water Resources Conference*, held October 15-16, 2014 at the Columbia Metropolitan Convention Center.

ABSTRACT. Over the last few decades, groundwater resources in many regions have been depleted at a faster rate than the underlying aquifers have been replenished. This imbalance has led water management agencies to consider managed aquifer recharge networks, where infiltration basins are used to replenish the aquifers using previously-uncaptured storm water runoff. In this work, we utilize optimization to evaluate the costs associated with constructing such a network and the ability of the network to meet demands placed on the aquifer. Our objective function incorporates land and construction costs, along with rewards for effective aquifer recharge. We enforce capture of a minimum volume of storm water runoff by penalizing the cost. We present results for two basin networks, one based on results from the literature and another based on a study of the Pajaro Valley region in California. The Pajaro Valley example is used as our realistic test case, and we use the analysis to suggest the viability of a managed aquifer recharge network in a particular sub-watershed associated with the area.

INTRODUCTION

Periods of sustained drought, increased activity in previously undeveloped regions, and overuse of water supplies due to increased demand (from agricultural or domestic water needs) make it difficult for groundwater storage systems to maintain historical levels. A common consequence of overdraft of coastal aquifers is saltwater intrusion into previously uncontaminated fresh water supply wells. This intrusion normally causes the supply well to be removed from service, resulting in increased pumping rates on remaining wells and often necessitating more drilling into the aquifer. In severe cases, local water management agencies reduce the burden on the aquifer by placing restrictions on the amount of water that can be drawn from the aquifer over specified time periods. This is particularly onerous for members of the community whose livelihoods are dependent on adequate water supplies (e.g., agriculture) [Barlow and Reichard, 2007; Werner et al. 2012].

Historical evidence suggests that aquifers can recover if the demand on the resources is more closely balanced with the supply. One of the impediments to increased supply into a groundwater aquifer system is the need for urban developments or agricultural entities to quickly remove water from land after a rain event. The mechanisms for flood control often employ storm water drains, which are effective in removing floodwaters, but often drain to nearby streams and rivers, which then exit the watershed. The water is often not present in the river system long enough to, or the hydrology underlying the system is not conducive to, allow infiltration of the storm water into the groundwater aquifer. [National Research Council, 2008]

In many areas, the creation of a retention basin to trap sediments and contaminants or to manage storm water runoff is part of the permitting process. However, they are not necessarily associated with groundwater recharge. Retention basins are often restricted to the property under development, which may not be the best location for aquifer recharge. Effective recharge of the aquifer depends on many factors, including the underlying geologic properties of the subsurface, the location of an aquifer relative to the basin, the infiltration capacity of the region upon which the basin lies, the ability of the basin to effectively capture and hold surface water runoff, and the quality and origin of the runoff itself [National Research Council, 1995; Kampf and Burges, 2007]. We refer to basins designed specifically for aquifer recharge as infiltration basins.

Studies by the SC Department of Natural Resources, along with media headlines noting extremely low levels in South Carolina rivers and salt-water intrusion in drinking water supplies, highlight the need for management of all conjunctive-use water resources. In this work, we describe a case study of the Pajaro Valley Region in California, home to berry farmers and a severely depleted groundwater aquifer. The need for the berry farmers to maintain their livelihood along with the need to replenish the underlying aquifer has led the water management agency to consider a variety of strategies for water conservation. In particular, in recent work by Russo, et.al., [Russo, et.al, 2014], managed aquifer recharge networks are recommended, along with water use restrictions, as part of a comprehensive basin management strategy for the Pajaro Valley Region. We present this work to highlight the ability of modeling tools to guide decision-making

PROJECT DESCRIPTION

As part of an overall plan for basin management, members of the Pajaro Valley Water Management Agency have limited water use for stakeholders in the region. This includes agricultural stakeholders, who produce the majority of berries consumed in the U.S. As part of a multicomponent solution, our research team has considered farming strategies to minimize water usage and maximize profitability [Chrispell, et.al., 2012, Bokhira, et.al., 2014, Fowler, et.al., 2014] along with analyzing solutions intended to mitigate the imbalances in the current water budget.

Our strategy for mitigating the imbalance includes an analysis of a managed aquifer recharge network. Basic characterization of a network includes local infiltration rates and subsurface hydraulic conductivity values, along with land acquisition costs and costs for constructing the basin and storing water. The infiltration rate and hydraulic conductivity determine the maximum allowable depths for stored water: the basin must meet EPA regulatory guidelines associated with mosquito infestation and must have a minimum time of infiltration to a water table [Travis and Mays, 2008]. These values are used to constrain the area of the basin [Guo, 2001].

The construction of a managed aquifer recharge network has been studied by hydrologists in the Pajaro Valley to reduce salt-water intrusion in near-coastal aquifers [Russo, et.al., 2014]. The authors of the study have identified regions in the valley best suited for construction of a network by considering regional infiltration rates and access to the desired underground aquifers. Our work seeks to supplement the basin study of Russo, et.al. by providing guidance on the size of the basin needed to obtain target infiltration rates at minimal construction costs.

METHODS

We build a recharge basin network where each basin is associated with a sub-watershed region, and sizes of the basins are constrained by either physical (geographical) constraints or drainage capabilities. To model storm events, ensuing runoff, and associated infiltration into the subsurface, we use both an analytical approach based on the rational method and Green-Ampt [Guo 1998, 1999, 2001, Travis and Mays, 2008], as well as a distributed, physics-based watershed model [Julien, et.al., 1995].

We construct a cost associated with the basin that incorporates the monetary value of the land, the cost of constructing the basin, and the ability of the network to meet a target recharge goal. The mathematical formulation of the objective function is

$$\text{Cost} = K(T-Q_0)^2 + LA + C_1S^{C_2}$$

where T is the captured amount of water, Q_0 is a target recharge goal, L is the cost per square meter of land, A is the area of the basin, C_1 is the cost per cubic meter of storing water, C_2 is the cost coefficient, and S is the storage capacity of the basin. The coefficient K is used to balance the recharge target with the other components of the cost function; we found K=40 to be reasonable for the cases we considered, given land costs (per square meter) on the same order of magnitude. The cost function includes an approximate cost of constructing a basin given assumptions on the slope of the side walls [Travis and Mays, 2008] along with a penalty for deviating from target recharge goals. The storage capacity is determined by the area of the basin and the maximum allowable depth of stored water for the basin. We keep the storage capacity (S) and captured runoff (T) as distinct variables, allowing for optimization based on several storm events, each contributing volume to T.

We use optimization methods to minimize the objective function, using the area of the basin as the primary decision variable. We note both S and T in the cost function depend on A. Our objective function is a modification of the framework of Travis and Mays [Travis and Mays, 2008]. In their work, the basin network was constrained to capture all of the storm water runoff. We choose instead to capture a fraction of the runoff and constrain the captured amount only by the total amount of water available.

RESULTS

Our analysis based on a simplification of a basin network highlights the importance of land costs in evaluating the feasibility of the basin. Our baseline study consists of a 9-basin network on an arbitrary watershed. The connectivity of the basin is shown in Figure 1.

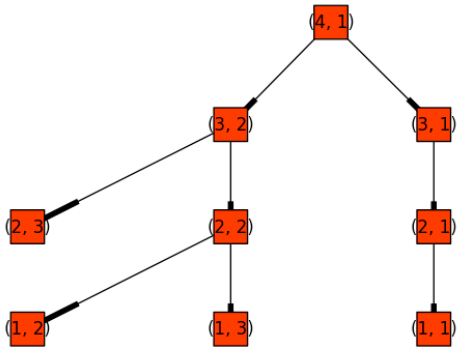

Figure 1: Sample basin network using 4 drainage lines and nine basins. The (4,1) basin is the ultimate basin in the network.

Each basin in the network is associated with a sub-watershed region. The basins in the network may capture the runoff in their sub-watershed, but they may also convey this runoff to their "parent", or the next basin along the drainage line.

The results for minimizing the construction and storage cost of the network configuration given in Figure 1 are provided in Table 1. Note the optimization algorithm completely eliminates one of the basins in the network while allocating somewhat minimal amounts to two other basins.

Basin	Storage (m^3)	Area (m^2)	Cost ($)
(1,1)	392.45	327.04	9815.53
(1,2)	213.18	177.65	5332.29
(1,3)	310.08	258.40	7755.69
(2,1)	14.96	13.90	556.54
(2,2)	389.92	361.07	10836.43
(2,3)	0	0	0
(3,1)	34.73	28.95	1447.97
(3,2)	7.9	6.61	330.63
(4,1)	82.08	68.40	4105.36

Table 1: Optimized basin parameters for capturing one-third of total runoff for sample watershed.

We also considered a more realistic example of a basin network, using a digital elevation map of a region in the Pajaro Valley of California, along with topographical tools that allow us to delineate sub-watershed regions and construct a network along drainage lines. This more realistic basin is shown in Figure 2.

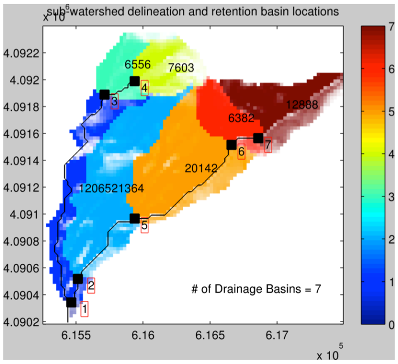

Figure 2: Depiction of the subwatershed regions and basin network in the Pajaro Valley example. The numbers indicate the area of the subwatershed regions.

We use the CASC-2D [Julien, et.al., 1995, Downer, et.al., 2002] software tool to compute run-off volumes for a recorded precipitation event in the region, and we determine land costs from real estate data for the valley. We compute the basin construction cost as before, again incorporating a target recharge amount. The results of this analysis are provided in Table 2.

Basin	Storage (m^3)	Area (m^2)	Cost ($)
1	3139.2	2092.8	172586.98
2	8011.5	5341	352361.41
3	2130.7	1639	81103.57
4	120.8	109.8	4530.72
5	5045.4	3881.1	192042.48
6	49.5	49.5	2041.72
7	443.4	403.1	9976.32

Table 2: Optimized basin parameters for capturing target recharge amount for realistic case.

DISCUSSION

The results highlight the ability of a basin network to effectively capture and propagate water into the subsurface. Given a target recharge amount, ideally tied to the water budget imbalance over the region, an appropriate cost function can be constructed that balances the cost of building the network with the water capture goal. The cost function is necessarily sensitive to land prices in the region, along with the underlying infiltration and conductivity values. The infiltration and conductivity values drive the maximum depth of water allowed to be stored in a basin; smaller depths require more land area to maximize the storage capacity of the basin.

We believe analyses like those presented will aid water management and natural resources agencies in feasibility studies for such networks. Future plans include modifications of the cost function, use of different optimization algorithms to explore competing goals, and incorporation of additional physics-based simulations to guide the management decisions.

ACKNOWLEDGEMENTS

This work was funded, in part, through two NSF funded research institutes: the American Institute of Mathematics and the Statistical and Applied Mathematical Sciences Institute.

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