Percolation Decay Model for Optimization of Surface Water Recharge Basins

Adam M.P. Canfield*, Grisel G. Rodriguez**, Donald W. Phipps, Jr.***
*The Orange County Water District; 4060 E. La Palma Avenue, Anaheim, CA 92807
acanfield@ocwd.com
**The Orange County Water District; 18700 Ward Street, Fountain Valley, CA 92708
grodriguez@ocwd.com
***The Orange County Water District; 18700 Ward Street, Fountain Valley, CA 92708
dphipps@ocwd.com

Abstract

Managed Aquifer Recharge (MAR) operations, such as those at the Orange County Water District (OCWD), are challenged to maintain sustainable high percolation rates in surface water recharge basins. At OCWD, water diverted from the Santa Ana River (SAR) is subject to several stages of gravity desilting before entering terminal recharge basins. Despite desilting efforts, deposition of fluvial-transported fine-grained suspended solids (convective transport) at the sediment/water interface forms a thin, clay-like layer. This layer of accumulated fine-grained detrital sediment reduces the capacity of the basin to transmit water to the underlying aquifer, and is the primary contributor to percolation decay. Laboratory studies indicate that the majority (> 90%) of this “fouling layer” consists of inorganic solids less than 62.5 microns in apparent diameter (silt- to clay-sized particles). Removal of suspended solids in this size range by gravity settling is ineffective. Hypothesized is that loss of percolation is primarily a function of the accumulation of detritus. A log-decay model describing instantaneous percolation in terms of deposition of detrital sediments at the sediment/water interface using a single “sediment/foulant interaction coefficient” was developed. Integration of this relationship as a function of time yields percolation decay kinetics closely resembling those observed in full-scale recharge basins. The design of the study is to test this hypothesis by employing flow cells packed with sand and loaded with sediment-laden water as analogs of field-scale basins. Investigation of the effects on percolation decay kinetics and on the sediment/foulant interaction coefficient consisted of two parts: first, variations in concentration and particle size distribution of the suspended solids, and second, variations in particle-size distribution of basin sediments. The goal of this study is to validate the current percolation decay model and generalize it to accommodate a broader range of sediment and suspended solids compositions. A broadly applicable percolation decay model will be of value for rapid evaluation of potential basin performance optimization strategies and provide a tool for cost/benefit analyses for pre-treatment/desilting of recharge waters.

Keywords: Basin Fouling; Decay Kinetics; Percolation Decay; Recharge; Suspended Solids

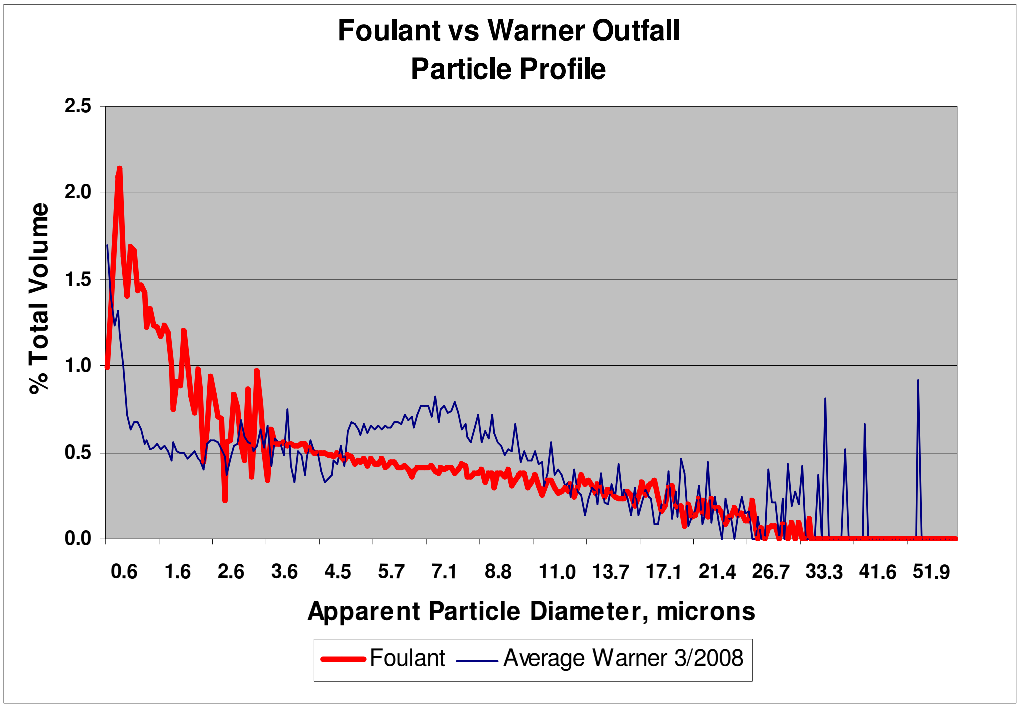
Introduction

In an average year, the OCWD diverts 247 million m^3 (200,000 acre-feet, af) of SAR water for recharge into the Orange County groundwater basin. OCWD recharge facilities include over two-dozen surface recharge basins covering 6.1 km^2 (1,510 acres). SAR base flow, which is comprised primarily of tertiary-treated effluent, contains approximately 25 to 400 mg/L of organic and inorganic total suspended solids (TSS). During percolation, a fraction of these suspended solids in SAR water act as foulants, accumulating in OCWD recharge basins and causing rapid decay of percolation rates. Hypothesized was that loss of percolation rate over time is related to the mass of foulants accumulated at or near the sediment/water interface. A relatively simple log-decay kinetic approach could describe this relationship. This hypothesis was tested using both laboratory analogs of recharge basins (flow cells) and field data obtained during recharge basin operations. Manipulation of the inputs to this model determines the relative contribution of the principal input (detrital sediments) variables as related to percolation decay. The primary motivation for this experimentation is to suggest means to improve recharge basin operations based on predicted basin performance versus costs associated with reducing the suspended load. Variables introduced to the laboratory flow cell include variation of cell media (varied grain-size distribution), varied TSS concentrations, and variations of the sediment-laden water passing the cells.

Methods

Fouling Material Used for Study

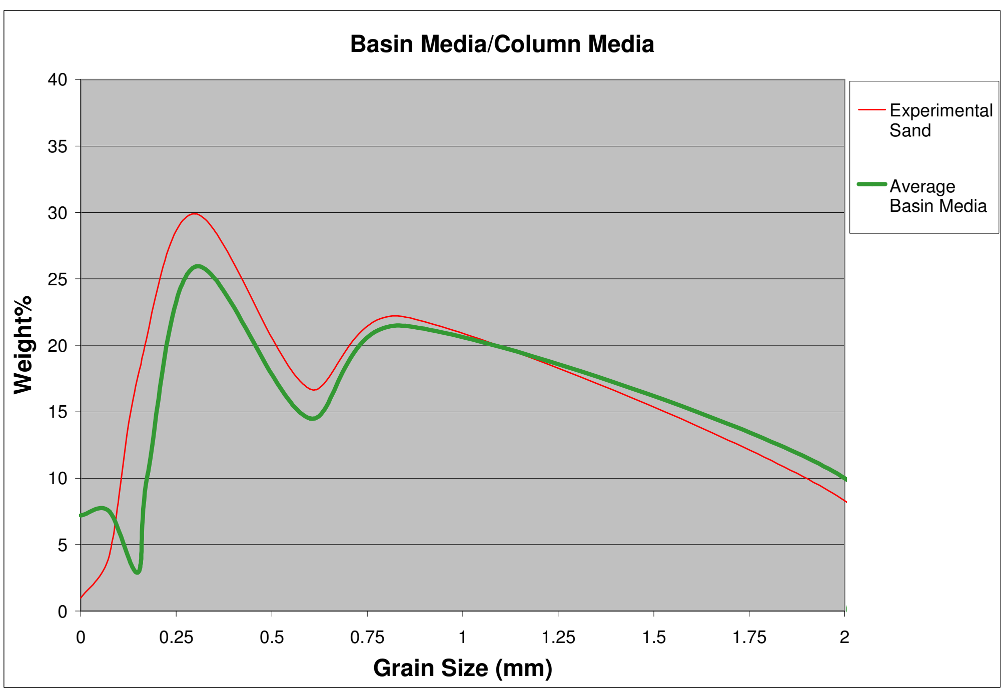
Fouling material used for the study was derived from solids recovered from the bottom of Kraemer Basin, a ~0.12 km^2 (~30-acre) terminal recharge basin operated by OCWD in Anaheim, CA. When Kraemer Basin is drained, foulant that had accumulated at the sediment/water interface during percolation desiccates and forms “chips” on the basin bottom one to several millimeters thick. These chips were manually harvested from the basin bottom. Foulants recovered in this fashion could be stored in the desiccated “chip” state indefinitely. Chips are disaggregated and are passed through a standing column of water and discharged when only the desired particle sizes remain in suspension. The remaining suspension is analyzed for TSS, dry ash weight, and grain-size distribution using a Beckmann Coulter Multisizer 4. Refinement of settling times, based on Stoke’s Law for terminal fall velocity of particles in a low-viscosity media, has allowed for generation of sediment-laden water possessing similar grain-size distribution to water that feeds the basins. Water samples collected from Warner Basin possess a highly skewed fine-grained trend, which appears to contain the primary foulant input. Below is a graph displaying the grain-size distribution comparison between laboratory generated foulant and Warner Basin Outfall water (water that supplies Kraemer Basin).



Comparison of lab-generated foulant and Warner Outfall water

Basin Media Used for Study

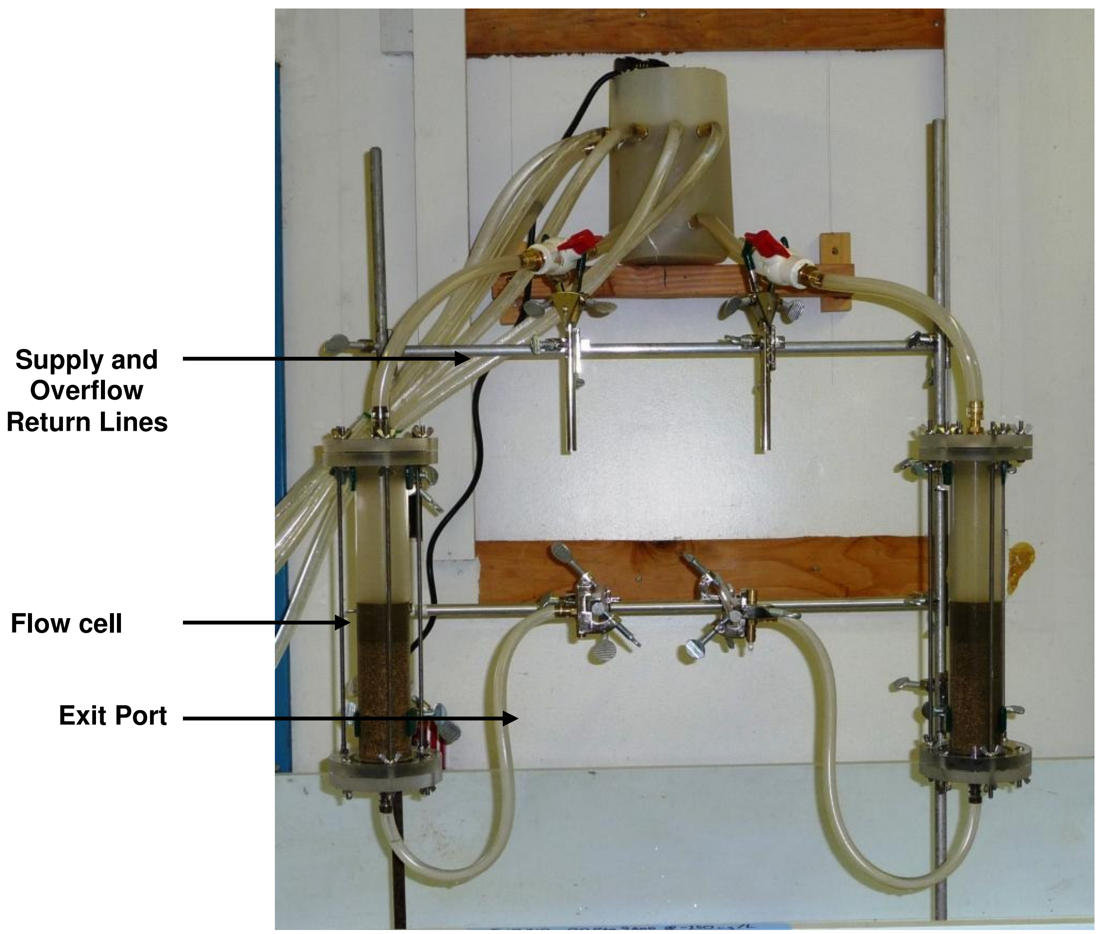
Column media used for conducting flow cell experiments was collected from OCWD basins and sieved between #20 mesh and #100 mesh sieve pans to eliminate any possible heterogeneities. Below is the graph of average basin (5 different basins) media compared with "native" experimental sand.



Comparison of flow cell sand and native basin media

Flow Cell Experiments

Each experiment employed two Soil Measurement Systems, LLC flow cells acting as bench-scale analogs to representative OCWD basins. All experiments were conducted using 170 ml of "native" basin media packed in 1.5" ID acrylic flow cells creating an approximate six-inch column of sand. Flow cells were filled with River Bank Filtered (RBF) water, and allowed to equilibrate for ~18 hours to ensure complete saturation. Once equilibration to remove any residual air is complete, the columns were held static. Prepared foulant was mixed with RBF water to the desired TSS concentration. Suspensions were stored in supply barrels under constant agitation to prevent settling of particles. Suspension is then loaded under a constant head into flow cells from reservoirs secured above the cells at a hydraulic gradient of three. Initial percolation rates were typically in the range of ~80 ml/min to ~120 ml/min. Once sediment-laden water was added to the columns, flow measurements using a stopwatch and timer were recorded at exit ports at experiment-dependant time intervals. Typical time intervals were initially ~3 to 5 minutes apart, and ~1 hour as rapid decay decreased. At each data point, a water sample was collected for TSS, dry ash weight and particle distribution (Coulter Multisizer method on at least one sample per experiment). Columns were permitted to decay to ~10% of the initial percolation rate. Below is a typical flow cell experiment set up.



Typical flow cell experiment set up being loaded with foulant-containing RBF water

Fitting a Mathematical Model to Sediment Column Data

The total foulant deposited at the sediment/water interface was estimated as a function of time by the product of the foulant concentration and the total volume of water percolated through the column. A log-decay expression was fitted to these data using method of Marquardt nonlinear regression (Statgraphics, Centurion XV, Statpoint Incorporated, Herndon, VA).

RESULTS AND DISCUSSION

Modeling Sediment Column Percolation Decay

The results of non-linear regression analysis showed that the relationship between accumulated foulant and percolation could be described by the simple log-decay expression:

$$Q=Q_o e^{-(rL)}$$

Where:
Q_o= the initial percolation rate
L = the total foulant/unit area deposited at the sediment/water interface
Q =percolation observed at L foulant loading.

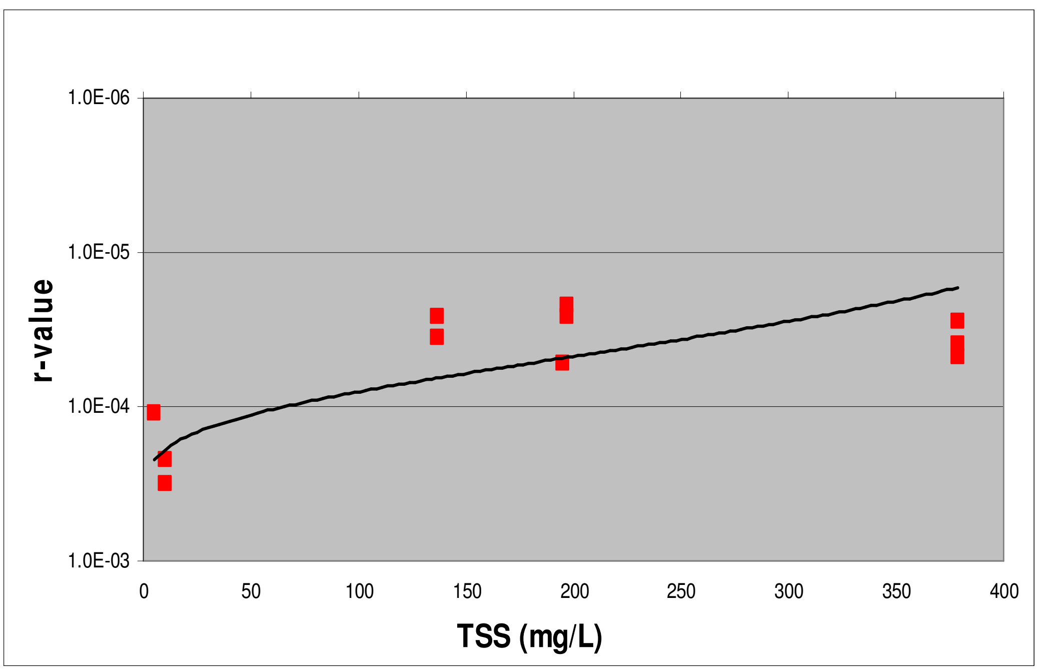
The value of r represents a sediment/foulant interaction coefficient presumed to be unique to the nature of the basin media and the foulant. Percolation decay was modeled by integration of this expression over time using an incremental approach with a spreadsheet calculator (Excel, Microsoft Corp., Redmond, WA). During this integration, foulant deposited during a particular time increment (dL/dt) was determined using the previous time increment percolation rate and the suspended solids concentration derived during the increment (keeping dt small compared to the overall time elapsed prevented serious overestimation of dL). The accumulated solids for the increment dt was totalized with all previous increments to determine the total solids load, and a new percolation rate determined using the relationship defining percolation and total solids loading. This operation was iterated until the end of the desired time was reached.
In a majority of cases, the adjusted R^2 indicated this simple approach was capable of describing greater than 90 percent of the observed data variability.

Foulant accumulation was an excellent predictor of percolation decay. Though this sort of empirical modeling approach precludes by itself establishment of a mechanism, it seems probable from the differences in mean particle size of the foulant materials and of the basin media that a mechanism by which foulant enters and fills voids between sediment particles is indicated Further research examining the ability of foulant particles of differing size and composition to reduce percolation in sediments of defined particle sizes may shed more light on this hypothesis.

Relationship between Foulant Composition, Loading Rate and the Sediment/Foulant Interaction Coefficient

Effect of foulant concentration on the sediment/foulant interaction coefficient

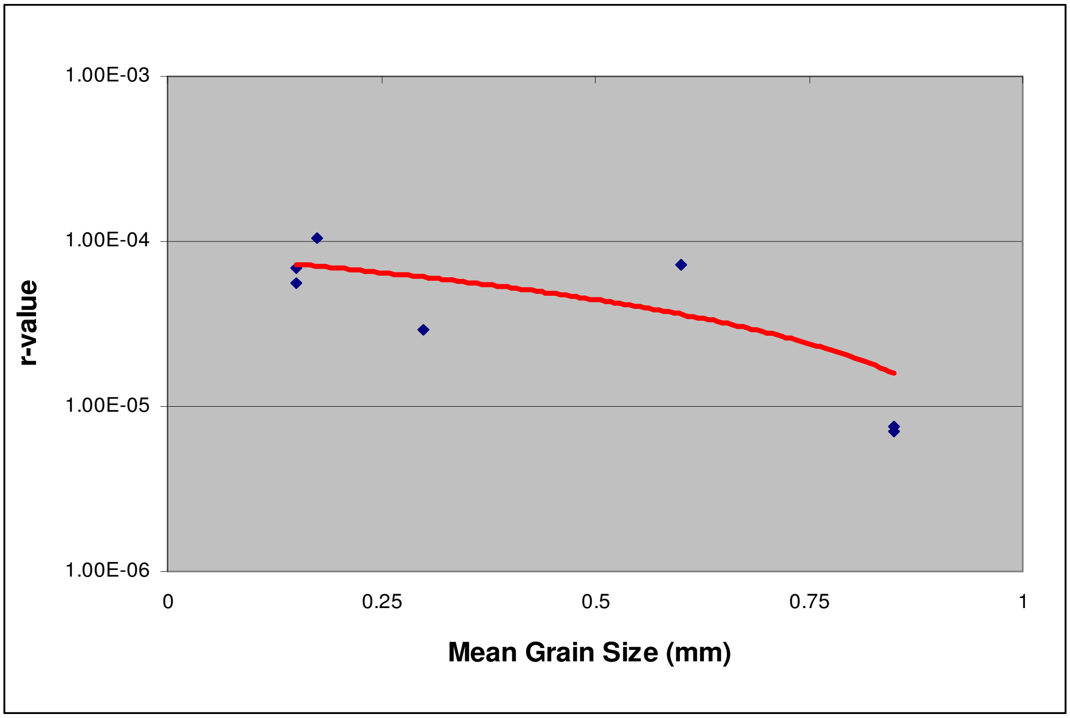
The sediment/foulant interaction coefficient likely represents a composite of many specific interactions between foulant matter and basin media; therefore, it is improbable that it would be a universal constant. However, it was anticipated that for a given basin media and foulant, there would be a range of foulant concentrations over which the coefficient would be nearly a constant. In this range, variations in the foulant concentration would not affect the relationship between percolation and the total mass of foulant accumulated at the sediment/water interface (L). In order to investigate this, percolation fouling kinetics were determined using W-SAR water containing TSS concentrations of 3.8 mg/L to 379 mg/L. Experiments were conducted using “native” sand for multiple experiments with varying TSS concentrations. Little variation was observed in experiments using concentration of 137 mg/L, 197.3 mg/L, 194.5 mg/L, and 379 mg/L. Relatively stable r-values (1e-5 +/- 5e-6) were observed when relatively high TSS concentrations were utilized. At very low TSS concentrations, 3.8 mg/L, 7.0 mg/L, 10.9 mg/L, r-values increase by approximately one order of magnitude (1e-4 +/- 5e-5).



Sediment/foulant interaction coefficient (r-value) plotted versus TSS Loading in Column Experiments

Effects of Flow cell Media Variation on Sediment/foulant interaction coefficient

Experiments were conducted with flow cell media varied about different mean grain sizes. Average native OCWD basin sand contains approximately 25% to 30% medium sand (0.25 mm to 0.50 mm diameter). Experimental sands were blended using grain-size distributions proportional to native materials centered about 0.85 mm, 0.6 mm, 0.175 mm, and 0.15 mm. Each experimental sand yielded different r-values. Increasing the mean grain size tended to decreasing r-value (improved basin performance).



Sediment/foulant interaction coefficient (r-value) plotted versus mean grain size

Sediment/foulant interaction coefficient of Flow Cell Experiments versus Upper Five Coves Basin

Upper Five Coves (UFC) Basin is an approximate 30-acre OCWD recharge basin. UFC was cleaned of all foulant materials, filled with SAR water, and held static for a period of four weeks. UFC basin percolation was allowed to decay to approximately 10% of the initial percolation rate. The wetted area and TSS were recorded and run through the decay model. The resulting r-value was 5.4e-5 compared to the average flow cell r-value of approximately 4.6e-5 (+/- 1.5e-5).

CONCLUSIONS

Foulant accumulation at the sediment/water interface appears to be the predominant mechanism responsible for percolation decay in recharge basins operated by OCWD. The kinetics of percolation decay may be adequately modeled by integration with time of a log decay function requiring three input parameters: initial percolation rate, foulant concentration and a sediment/foulant interaction coefficient that may be obtained by laboratory determination or from historic field performance data. This percolation model may be easily implemented using a spreadsheet, and optimization routines readily performed. Finally, data generated from the model may be easily integrated into cost benefit models, making it possible to predict the most cost-effective cleaning strategies, best pre-treatment strategies, etc., to maximize basin water production and minimize basin operating costs. Widespread successful application of the model will be dependent on several factors. Although the mass loading of suspended solids into OCWD's recharge facilities is reasonably well documented, what fraction of this material contributes to basin fouling and the nature and stability of fouling material is virtually unknown. The degree to which local particle production in recharge basins (primary biological productivity) alters foulant composition seasonally also remains to be determined. The relationship between foulant mean particle size and fouling capability is only poorly understood. Calculation of the sediment/foulant coefficient with foulants of defined mean particle size is needed to elucidate this relationship. Moreover, the relationship between sediment particle size and depth of foulant penetration must be quantified in order to determine the extent to which bottom-cleaning strategies need to be altered to operate groomed basins sustainably, and to balance increased bottom-cleaning costs with improvements in water production. Once these data are obtained and the model is better honed, it should be a highly useful tool for designing and optimizing surface water recharge facilities.

REFERENCES

Hutchinson, A. 2007. Challenges in optimizing a large-scale managed aquifer recharge operation in an urbanized area.

Phipps, D. et al 2006 Development of a Percolation Decay Model to Guide Future Optimization of Surface Water Recharge Basins.