

# Development of a Percolation Decay Model to Guide Future Optimization of Surface Water Recharge Basins

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## Abstract

Reductions in percolation over time due to foulant accumulation are often a significant problem with surface water recharge basins. The ability to predict the impact of foulant accumulation on basin percolation facilitates evaluation of the potential effectiveness of cleaning strategies or water pretreatment schemes in improving percolation efficiency. In this study, both laboratory and field data were used to develop a relatively simple mathematical model capable of describing basin percolation kinetics. This model suggests that initial percolation rate, foulant loading and the interaction between foulant and sediment at or near the sediment/water interface can describe the decay of percolation over time. Simulating performance of a recharge basin indicates that the interaction of foulant with sediment and reduction of overall foulant loading is perhaps the most effective method of improving recharge basin efficiency.

**Keywords:** Fouling; Model; Percolation Reduction; Recharge; Suspended Solids

## INTRODUCTION

In an average year, the Orange County Water District (OCWD) diverts 247 million m<sup>3</sup> (200,000 acre-feet, af) of Santa Ana River (SAR) water for recharge into the Orange County groundwater basin. OCWD's recharge facilities include over two-dozen surface recharge basins covering a total of 6.1 km<sup>2</sup> (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's recharge basins and causing percolation rates to rapidly decay.

It was hypothesized that the time-dependent loss of percolation rate could be related to the mass of foulants accumulated at or near the sediment/water interface using a relatively simple log-decay kinetic approach. This hypothesis was tested using both laboratory analogs of recharge basins (sediment columns) and actual field data obtained during recharge basin operations. Manipulation of the inputs to this model was used to determine the relative contribution of the principal input variables to percolation decay, and to suggest means to improve recharge basin operations.

## METHODS

### Fouling materials used for study

#### *Material Recovered from the Bottom of a District Recharge Basin*

Fouling material used for the study was derived from solids recovered from the bottom of Kraemer Basin, a ~0.12 km<sup>2</sup> (~30-acre) terminal recharge basin operated by OCWD in Anaheim, CA. This basin can receive either SAR water or imported Colorado River water from the Metropolitan Water District (MWD), which has relatively low TSS concentrations (typically <2 mg/L). When Kraemer Basin was drained and dried, foulant that had accumulated at the sediment/water interface during percolation dehydrated and formed "chips" on the basin bottom that were from one to several millimeters thick. These chips were manually harvested from the basin bottom. Foulants recovered in this fashion could be stored in the dehydrated "chip" state indefinitely.

#### *Material recovered from the Basin Cleaning Vehicle (BCV)*

Additional fouling material for the study was recovered from the waste stream of an *in situ* underwater dredge designed by OCWD to remove foulants from operational recharge basins (the Basin Cleaning Vehicle, BCV; Hutchinson, 2007, submitted).

### *Water used for column studies*

Source water used for experiments was derived from a shallow extraction well near the SAR. This well-derived SAR (W-SAR) water was chemically identical to river water except that the suspended solids content was extremely low and contributed negligibly to sediment fouling.

### *Preparation of fouling material for experimental studies*

Fouling material for experimentation was prepared by first disaggregating the large chunks using a Waring blender and suspending in W-SAR at ~50 mg/L (w/v). This suspension was allowed to settle two minutes to remove any clumped material and large particles, and then decanted into a stock container and the TSS determined. This stock was further diluted in 76L (20 gallons) of W-SAR water in a 208L (55-gallon) barrel to make up test loads of 21, 51, 55, 92 and 377 mg/L TSS. The suspension was allowed to mix in the barrel overnight before use, and the TSS concentration was checked for stability prior to experimentation.

### *Comparison of Particle Size Distribution of Experimental Foulant Material to SAR Suspended Solids*

The particle size distribution of test foulant derived from Kraemer Basin chips was compared to SAR water suspended solids using a Coulter Multisizer II particle size analyzer (Beckman Coulter, Hialeah, FL) equipped with 20 $\mu$ m and 100  $\mu$ m counting orifices. Overlapping the counting ranges of these orifices allowed determination of the volume of suspended particles in water samples that ranged from 0.5 $\mu$ m to 57.2 $\mu$ m apparent diameters. The particle size distribution in this range of Kraemer Basin chips processed as described above compared favorably with that of particles derived from SAR water (data not shown).

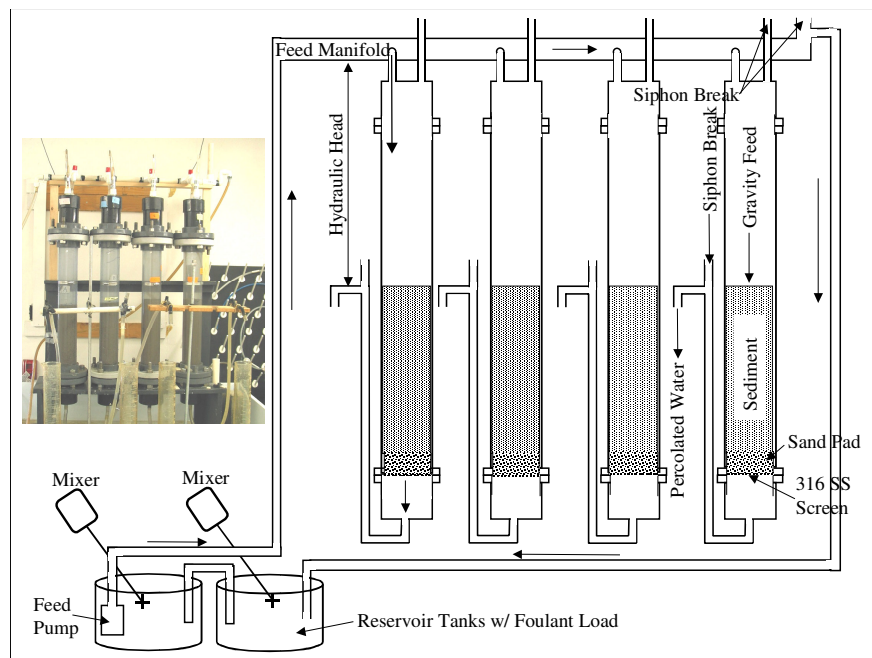
### **Collection and Preparation of Sediment used for the study**

Sediment used for the column experiments was native sandy sediment obtained from the bottom and sidewalls of Anaheim Lake, another terminal deep recharge basin operated by OCWD, when it was dried for cleaning. Sediment obtained in this fashion contained mainly sand particles with sizes ranging from 2.4 mm (8 mesh) to 75 $\mu$ m (200 mesh), with an average size of ~600 $\mu$ m (~30 mesh). This sediment was dried, homogenized and stored in plastic buckets. The sediment was put through a 6.4 mm (#4 mesh) sieve to remove pebbles and other debris before use.

### **Sediment column experiments**

#### *Design of the sediment column apparatus*

Figure 1 shows the column apparatus used in laboratory experiments.



**Figure 1** Laboratory sediment column apparatus.

Four columns 82 cm (32 inches) long by 7.5 cm (2.96 inches) internal diameter (I.D.) (surface area =  $4.42 \times 10^{-4} \text{ m}^2$ ;  $0.0478 \text{ ft}^2$ ) were fabricated from 7.62 cm (3-inch) clear PVC pipe stock and fitted at the ends with bolted-on PVC flanges for easy filling access. A 316 stainless steel screen placed in the lower flange and covered with 1cm (0.39-inch) pad of 1.2mm (16 mesh) sand captured the solid contents of the column during experiments. Each column was connected to a 2.54 cm (1-inch) feed manifold via a 1.3 cm (0.5-inch) diameter 90-degree right angle pipe emerging horizontally from the manifold and penetrating the upper flange of the column. This configuration tended to ensure that suspended solids were transported to the sediment in the columns nearly entirely by advection. A second vertical tube connected to the flange and rising above the manifold acted as a siphon break and allowed equilibration of internal pressure with the manifold, so that the height of the manifold above the column could be used to determine the head pressure and each of the four columns could operate at different flow rates without affecting the pressure of water in the manifold. A flexible tube attached to the lower flange allowed water to drain from the column; this tube was fitted with a siphon break at its distal end. By manipulating the difference in height between the between the feed manifold and the siphon break on the drain tube, the pressure difference across the column could be regulated. This configuration provided a nearly constant head of 0.78 m (1.6 feet) of water.

A recirculation feed pump was submerged in 76L (20 gallons) of W-SAR water in one of two 208L (55-gallon) water reservoir tanks equipped with propeller agitators and connected to the feed manifold with flexible tubing. A siphon break and riser at the distal end of the feed manifold prevented gravity-induced siphoning of water from the manifold, and ensured that fluid levels and pressures were maintained at nearly constant levels in the manifold at the water circulation velocity employed during experiments.

#### *Sediment column experimental protocol*

All experiments were performed in duplicate. Approximately  $1,700 \text{ cm}^3$  ( $0.06 \text{ ft}^3$ ) of sediment was poured into each test column, resulting in a sediment depth of 30.5 cm (1 foot). The sediment was slightly dampened to prevent fractionation of the fine matter during pouring. In order to remove voids, the sediment was compacted by a piston fitting the internal bore of the column and impacted twice with a 1 kg (2.2-pound) weight dropped from a distance of 50 cm (19.7 inches).

Packed sediment was hydrated by first introducing W-SAR water in an up-flow mode through the bottom of the column with a peristaltic pump so as to exclude air from the sediment. Once the sediment was completely hydrated, the drain tube was connected and then the siphon break was set level with the sediment/water interface. The column was connected to the manifold and hence operated in a down-flow mode by gravity.

The rate of water flow through the sediment columns was determined volumetrically using a graduated cylinder and a stopwatch. Flow was monitored during the initial percolation of W-SAR water until it reached a steady state, which typically required from several hours to more than 24 hours. Once the columns reached a steady percolation rate, experimental foulant material prepared as described above was introduced by quickly transferring the feed pump from the W-SAR water barrel to the barrel containing the propeller agitator stirred suspended foulant material. Volumetric flow measurements were initially made frequently (3 – 10 minute intervals) to better define fouling kinetics; later the time between measurements was extended. Measurements were continued until percolation declined to approximately 10 – 20 percent of its initial value; depending on the foulant loading that took from several hours to 24 hours.

#### *Recovery of sediment columns by removal of the fouling layer*

Following experimentation, the outflow tube was clamped to halt flow through the columns, the flow manifold disconnected and the upper column flange carefully removed. The layer of foulant accumulated at the sediment/water interface was removed using a glass tube with gentle suction to aspirate the upper 5 cm (2 inches) of sediment and foulant. The sediment removed was replaced with a layer of fresh material and the column re-hydrated as described above. Sediment columns treated in this fashion were observed to recover their initial percolation rates and therefore could be used for further experimentation.

#### **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).

#### **Kraemer Basin Field Percolation Data**

Kraemer Basin field data pertaining to the percolation of SAR water was obtained for the periods December 1997 to May 1998, November 2004 to February 2005 and from May 2005 to August 2005. Data for the percolation of MWD imported water was obtained for the period August 2000 to November 2000. Specific average percolation was calculated from daily logs of total inflow, the change observed in basin volume and total basin wetted area.

## 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 very well by the simple log-decay expression:

$$Q=Q_0e^{-rL}$$

Where  $Q_0$ = the initial percolation rate,  $L$  = the total foulant/unit area deposited at the sediment/water interface and  $Q$  = 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 sediment and 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.

Sediment/foulant interaction coefficients resulting from fitting this expression to column data are shown in Table 1. 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.

**Table 1.** Determination of sediment/foulant interaction coefficients ( $r$ ) for laboratory sediment column experiments.

Foulant Type	Avg. Loading (mg/L)	Avg. Adj. $R^2$	Sediment/Foulant Interaction Coefficient ( $r$ )			95% CL Diff.?
			Average (n=2) $M^2/mg$ ( $ft^2/mg$ )	S.D.	p-Value (Comparison to To 21 mg/L Load)	
BCV Waste	400	88.17%	$0.67 \times 10^{-6}$ ( $0.72 \times 10^{-5}$ )	$0.14 \times 10^{-6}$ ( $0.15 \times 10^{-5}$ )	0.0211	Yes
KB Chips	377	99.80%	$21.8 \times 10^{-6}$ ( $23.5 \times 10^{-5}$ )	$1.05 \times 10^{-6}$ ( $1.13 \times 10^{-5}$ )	0.0177	Yes
KB Chips	92	97.45%	$3.34 \times 10^{-6}$ ( $3.60 \times 10^{-5}$ )	$0.53 \times 10^{-6}$ ( $0.57 \times 10^{-5}$ )	0.4136	No
KB Chips	51	93.68%	$2.60 \times 10^{-6}$ ( $2.80 \times 10^{-5}$ )	$0.13 \times 10^{-6}$ ( $0.14 \times 10^{-5}$ )	0.3501	No
KB Chips	55	97.94%	$1.81 \times 10^{-6}$ ( $1.95 \times 10^{-5}$ )	$0.33 \times 10^{-6}$ ( $0.35 \times 10^{-5}$ )	0.0747	No
KB Chips	21	92.15%	$2.88 \times 10^{-6}$ ( $3.10 \times 10^{-5}$ )	$0.26 \times 10^{-6}$ ( $0.28 \times 10^{-5}$ )	na	na

Foulant accumulation was an excellent predictor of percolation decay. Although 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 sediment 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 composition on the sediment/foulant interaction coefficient*

The sensitivity of the sediment/foulant interaction coefficient to the nature of the fouling material was tested by comparing coefficients derived from sediment columns receiving similar loads of Kraemer Basin fouling material (from chips) and waste material dredged from Miller Basin (a recharge basin adjacent to Kraemer Basin) by OCWD's Basin Cleaning Vehicle (BCV). The sediment/foulant interaction coefficient of BCV waste material was 32 times smaller than that of Kraemer Basin fouling material, indicating it was substantially less effective in reducing percolation (Table 1). Particle analysis indicated a higher proportion of coarser particulates in the BCV waste material (data not shown), which could have reduced its ability to pack into sediment interstices.

### Effect of foulant loading on the sediment/foulant interaction coefficient

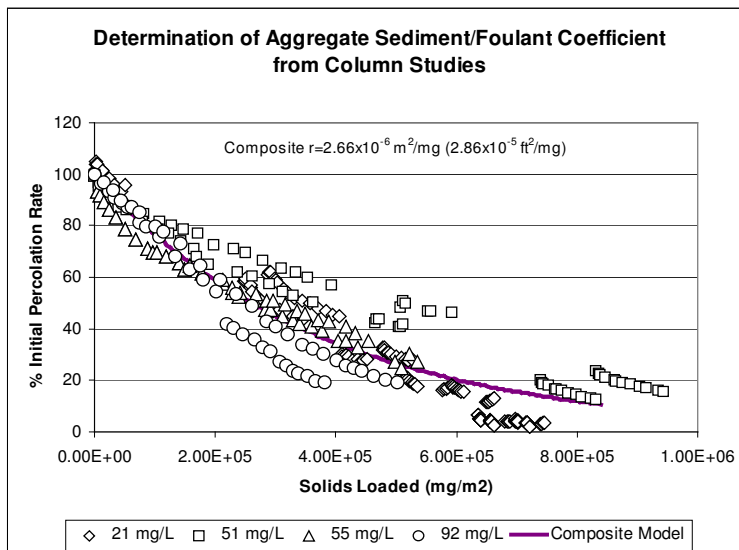
The sediment/foulant interaction coefficient likely represents a composite of many specific interactions between foulant matter and sediment; therefore, it is improbable that it would be a universal constant. However, it was anticipated that for a given sediment and foulant, there would be a range of 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 21, 51, 55, 92 and 377 mg/L of Kraemer basin chip material. For TSS <92 mg/L, the values obtained for the sediment/foulant interaction coefficient were statistically similar by Student's t test ( $p > 0.05$ ). For TSS concentrations less than 92 mg/L, percolation was nearly a constant function of foulant accumulation at the sediment/water interface. This consequence is useful as it allows for compression of the time frame for sediment fouling experiments by employing concentrations of foulant several times greater than that found in actual recharge waters. Thus, fouling that normally takes months can be simulated over a few days, or perhaps hours.

However, for very high TSS concentrations (377 mg/L), the sediment/foulant interaction coefficient was statistically different ( $p = 0.0177$ ) and nearly an order of magnitude greater (Table 1). This may suggest a physically different fouling mechanism may operate at the higher foulant loading rates. In this instance, more rapid introduction of foulants may more rapidly reduce water flow, and decreased hydraulic shear may promote more extensive bridging of the sediment. Alternatively, more rapid generation of the fouling layer may result in increased compression and more rapid water flux reduction through the fouling layer than occurs when deposition is slower.

### Generating an Aggregate Sediment/Foulant Interaction Coefficient

That foulant loading up to 92 mg/L resulted in statistically similar values of the sediment/foulant interaction coefficient justified combining data from all four experiments in that foulant loading range in order to generate a composite coefficient. Figure 2 shows the results of combining all eight experiments (4 [foulants] x 2 replicates) and determining a best-fit log-decay curve using nonlinear regression. This approach, incorporating all the experimental noise in the calculations, gave a value of  $2.66 \times 10^{-6} \text{ m}^2/\text{mg}$  ( $2.86 \times 10^{-5} \text{ ft}^2/\text{mg}$ ) for the interaction coefficient, and explained 90 percent of the variability in the data.



**Figure 2.** Determination of an aggregate sediment/foulant interaction coefficient ( $r$ ) from laboratory sediment column data.

### Testing Ability of the Laboratory Model to Describe Decay Kinetics of a Percolation Basin

The ability of the laboratory model to describe recharge basin behavior was investigated by attempting to describe Kraemer Basin percolation decay using the aggregate sediment/foulant interaction coefficient of  $2.66 \times 10^{-6} \text{ m}^2/\text{mg}$  ( $2.86 \times 10^{-5} \text{ ft}^2/\text{mg}$ ) derived from the column studies. Although the foulant loading of the sediment columns was known, comparable data were not available for the Kraemer Basin field measurements. In order to construct models for Kraemer Basin percolation, the foulant load value was varied in order to obtain a best fit between predicted basin performance and the observed field data.

### Percolation of SAR Water

A general model for the percolation decay kinetics of SAR water by Kraemer Basin was obtained by first modeling the kinetics of each individual percolation event observed, and then averaging the  $Q_0$  and foulant load to produce an aggregated value. Results of this analysis are shown in Figure 3. The model was able to describe the overall kinetics of percolation decay quite well, suggesting general similarity between the behavior of the laboratory sediment columns and the basin. The average foulant load predicted by this model was 8.20 mg/L. This value was somewhat lower than the 25 mg/L TSS that has been observed for SAR water; however, it is possible that foulant material recovered from Kraemer Basin represents only a fraction of the total TSS load observed in SAR water.

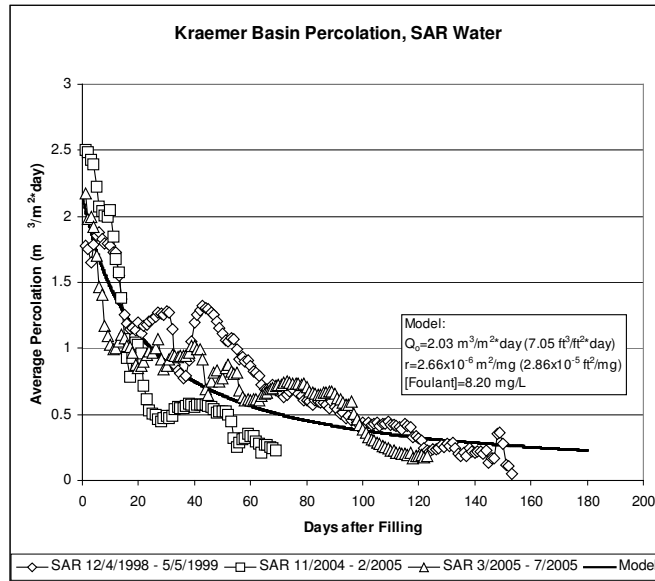


Figure 3. Modeling Kraemer Basin percolation kinetics with SAR water.

### Percolation of Import Water

A similar approach to fitting percolation kinetics of import water in Kraemer Basin is shown in Figure 4.

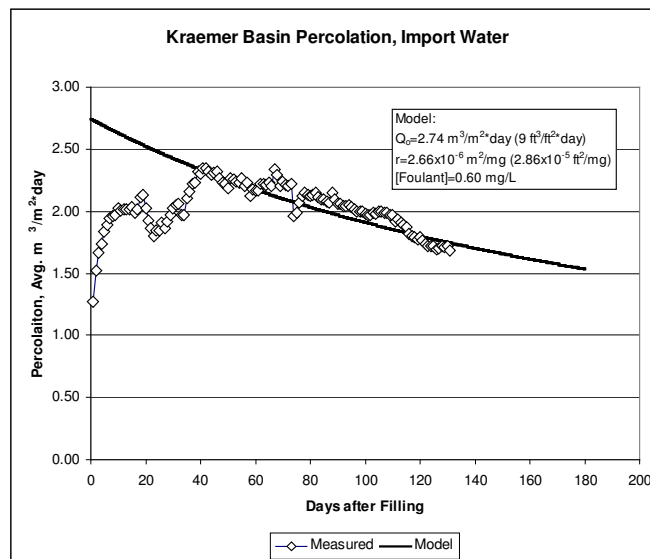


Figure 4. Modeling Kraemer Basin percolation kinetics with imported MWD water.

Again the sediment/foulant interaction coefficient defined by laboratory experiments was used to construct a model involving integration with time of total accumulated solids, relating this to percolation via the log-decay relationship. Although there was no general guarantee that the foulants in SAR water and import water were similar, this approach

allowed a point of departure for predictions. In this case, field data did not show evidence of percolation decay until after approximately the first 45 days of basin operation. It is unclear why percolation was slow to start (perhaps an artifact of how the basin filled; this would be expected if the bottom percolated less efficiently than the side walls), but for modeling purposes only data showing percolation decay was used. Curve fitting was performed manually; values for  $Q_0$  and foulant concentration were varied until a best fit was obtained for the data in the region of 45-130 days of basin operation.

A best-fit model was obtained using a  $Q_0$  of 2.74 m<sup>3</sup>/m<sup>2</sup>\*day (9 ft<sup>3</sup>/ft<sup>2</sup>\*day) at a foulant load of 0.60 mg/L. This value of  $Q_0$  is within a reasonable range for OCWD recharge basins, and import water TSS concentrations are typically less than 2 mg/L. Once again, the TSS concentrations in the field might somewhat overestimate the actual foulant load. It is interesting to note, though, that the models suggest a 14-fold difference in predicted foulant load between SAR water and import water, and that is close to the difference in TSS concentrations typically observed comparing SAR base flow water to import water.

### Effects of Varying Model Inputs on Water Production by a Simulated Recharge Basin

A model was constructed simulating percolation of a 0.12 km<sup>2</sup> (30 acre) recharge basin based on field parameters observed for Kraemer Basin recharging SAR water:  $Q_0=2.03$  m<sup>3</sup>/m<sup>2</sup>\*day (7 ft<sup>3</sup>/ft<sup>2</sup>\*day); [TSS] effective as foulant = 8 mg/L, and the laboratory sediment/foulant interaction coefficient  $r=2.66 \times 10^{-6}$  m<sup>2</sup>/mg (2.86x10<sup>-5</sup> ft<sup>2</sup>/mg). These input parameters were then varied and the effect on percolation analyzed in terms of integrated water production over 180 days (Table 2). The simulated basin produced 12.7 million m<sup>3</sup> (10,269 af) in 180 days, which is reasonable for operation of an OCWD recharge facility such as Kraemer Basin.

**Table 2.** Water production by a simulated 0.12 km<sup>2</sup> (30 acre) recharge basin @ 180 days assuming  $Q_0=2.03$  m<sup>3</sup>/m<sup>2</sup>\*day (7 ft<sup>3</sup>/ft<sup>2</sup>\*day),  $r=2.66 \times 10^{-6}$  m<sup>2</sup>/mg (2.86x10<sup>-5</sup> ft<sup>2</sup>/mg) and [TSS] =8 mg/L. Nominal input values are italicized.

1) Constant r, [TSS]		2) Constant $Q_0$ , [TSS]		3) Constant $Q_0$ , r	
$Q_0$ , m <sup>3</sup> /m <sup>2</sup> *day (ft <sup>3</sup> /ft <sup>2</sup> *day)	Million m <sup>3</sup> (AF)	R, m <sup>2</sup> /mg (ft <sup>2</sup> /mg)	Million m <sup>3</sup> (AF)	[TSS], mg/L	Million m <sup>3</sup> (AF)
1.52 (5.0)	11.0 (8,902)	<i>2.66x10<sup>-6</sup></i> (2.86x10 <sup>-5</sup> )	<i>12.7</i> (10,264)	15	8.5 (6,898)
<i>2.13</i> (7.0)	<i>12.7</i> (10,264)	<i>1.39x10<sup>-6</sup></i> (1.5x10 <sup>-5</sup> )	18.1 (14,701)	8	<i>12.7</i> (10,264)
3.05 (10)	14.5 (11,762)	<i>0.65x10<sup>-6</sup></i> (0.70x10 <sup>-5</sup> )	25.6 (20,780)	4	18.6 (15,063)
4.57 (15)	16.7 (13,518)	<i>0.46x10<sup>-6</sup></i> (0.50x10 <sup>-5</sup> )	29.0 (23,494)	1	32.1 (26,061)
6.10 (20)	18.2 (14,788)	<i>0.19x10<sup>-6</sup></i> (0.20x10 <sup>-5</sup> )	36.9 (29,911)	0	46.6 (37,800)

#### Effect of Varying Initial Percolation Rate ( $Q_0$ )

The effect of varying the initial percolation rate ( $Q_0$ ) and holding r and TSS constant on total water production over 180 days by the simulated basin is shown Table 2 (1). Total water production was directly proportional to initial percolation rate, indicating that basin performance is limited by this parameter. However, increasing  $Q_0$  only produces modest gains in water production since increasing the initial percolation rate simultaneously increases the rate of foulant transport. In this example, a 50 percent increase in total water production requires a nearly 3-fold increase initial percolation rate. Increasing percolation rate of a recharge basin this much is unlikely, as percolation is ultimately limited by the hydraulic conductivity of the larger volume of sediment or aquifer underlying the recharge basin.

#### Effect of Varying the Sediment/Foulant Interaction Coefficient (r)

The effect of varying the sediment/foulant interaction coefficient (r) and holding  $Q_0$  and TSS constant on total water production over 180 days by the simulated basin is shown in Table 2(2). Decreasing r increases water production. Unlike with  $Q_0$ , factors responsible for the sediment/foulant interaction coefficient may be manipulated. One of these is the mean sediment grain size at the sediment/water interface. Laboratory investigations by OCWD (data not shown) indicate that increasing mean sediment grain size to 1.2mm (16 mesh) decreases the sediment/foulant interaction coefficient to as low as 0.46 x 10<sup>-6</sup> m<sup>2</sup>/mg (0.5 x 10<sup>-5</sup> ft<sup>2</sup>/mg), which in this case would increase water production from 12.7 million m<sup>3</sup> (10,264 af) to 28.9 million m<sup>3</sup> (23,494 af), a 2.3-fold improvement in percolation efficiency. In the field, altering the mean sediment grain size at the sediment/water interface could be achieved by application of a relative thin layer of groomed material on top of basin sediments. Cleaning this material could be performed *in situ*

using a submerged sand-washing dredge such as OCWD's BCV, which is capable of separating foulant material from sand while the basin is in operation.

#### *Effect of Varying the Foulant Concentration*

The effect of varying foulant concentration (TSS concentration) and holding  $Q_0$  and  $r$  constant on total water production for the simulated basin operated for 180 days is shown in Table 2(3). For this model,  $Q_0$  is set at  $2.03 \text{ m}^3/\text{m}^2\text{-day}$  ( $7.05 \text{ ft}^3/\text{ft}^2\text{-day}$ ) and the sediment/foulant interaction coefficient is  $2.66 \times 10^{-6} \text{ m}^2/\text{mg}$  ( $2.86 \times 10^{-3} \text{ ft}^2/\text{mg}$ ). Decreasing the foulant concentration decreases the foulant accumulation on the sediment (L) with time, and this has a profound effect on water production. Reducing foulant concentration from  $8 \text{ mg/L}$  down to  $1 \text{ mg/L}$  (the range of foulant concentration in import water) increases basin total water percolation over a 180-day period by nearly 20 million  $\text{m}^3$  ( $>16,000 \text{ af}$ ). Even a modest reduction in foulant concentration has significant impact on water production. Reducing foulant concentration (TSS reduction) may be the most direct method by which recharge may be improved. However, it must be considered that the foulant particles are predominantly small ( $<10\mu\text{m}$ , and many less than  $1\text{-}2\mu\text{m}$ ), and if kept in suspension by slight water currents or Brownian motion, may be difficult to remove by gravity settling alone. Use of chemical or mechanical flocculation methods may improve removal. Media filtration may be useful for small recharge operations, but processing on the order of  $10,000 \text{ m}^3/\text{hour}$  ( $100 \text{ CFS}$ ) would require a sizable filtration plant. Furthermore, not all of the foulant material reaching a basin bottom may originate in the influent water; primary productivity (algal growth) may account for a fraction of this material, especially in summer months. The degree to which biomass accumulation in the recharge basin water influences total particle deposition during percolation is currently not well understood.

#### **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 particle structure is needed to elucidate this relationship. More research is also needed to quantify the relationship between sediment particle size and the sediment/foulant interaction coefficient, which must be understood if grooming the sediment/water interface of a basin to maximize water production is to be attempted. 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 against 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.

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