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Maximizing Infiltration Rates by Removing Suspended Solids: Results of Demonstration Testing of Riverbed Filtration in Orange County, California †

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Abstract: Clogging due to the accumulation of suspended solids is a major constraint that limits the capacity of Orange County Water District's (OCWD) surface water recharge system. In order to decrease clogging and increase system capacity, OCWD is testing the ability of riverbed filtration to reduce suspended solids concentrations and improve recharge rates. Riverbed filtration is achieved through a shallow subsurface collector system placed approximately one meter below the surface. Filtered water from the collector system is conveyed by gravity to the receiving recharge basin. Initial results show that riverbed filtration is highly effective in removing suspended solids in the recharge water, which in turn also greatly increases the recharge capacity of the receiving basin. Some other water quality benefits are also achieved. Data collected thus far indicate that it will be cost-effective to use this approach at a larger scale to capture and recharge increased quantities of storm flow obtained from the Santa Ana River.

Keywords: recharge basin; riverbed filtration; clogging; pretreatment

1. Introduction

The Orange County Water District (OCWD) is a special governmental water agency that was created by the state of California in 1933 to manage the surface water and groundwater resources in northern and central Orange County. OCWD programs include aquifer replenishment or recharge, seawater intrusion control, water quality protection and improvement, water recycling, and storm water conservation [1]. OCWD covers an area of approximately 900 km^2 (350 mi^2) and serves a population of 2.4 million (Figure 1). The Mediterranean-type climate in Orange County is generally mild, with annual rainfall of approximately 350 mm (14 in), and average monthly temperatures ranging from 14 to 24 °C (58–75 °F). Most of the rainfall occurs in the months of December through March.

The Orange County groundwater basin formed in a synclinal, northwest-trending trough that deepens as it continues beyond the Orange-Los Angeles county line. The Newport-Inglewood fault zone, San Joaquin Hills, Coyote Hills, and Santa Ana Mountains form the uplifted margins of the syncline. The total thickness of sedimentary rocks in the basin surpasses 6000 m (20,000 ft), of which only the upper 600 to 1200 m (2000–4000 ft) contain fresh water.

Pleistocene or younger aquifers within the basin form a complex series of interconnected sand and gravel deposits. In coastal and central portions of the basin, these deposits are extensively separated by lower-permeability clay and silt deposits or aquitards. In the inland areas, the clay and silt deposits become thinner and more discontinuous, allowing larger quantities of groundwater to flow more easily between shallow and deeper aquifers [1]. This is particularly true where the Santa Ana River exits the Santa Ana Canyon in east Anaheim. The fluvial deposits in this area are highly permeable with hydraulic conductivities as high as 100 m/day (300 ft/day). As a result, OCWD has concentrated its surface water recharge facilities in this area as shown on Figure 1.

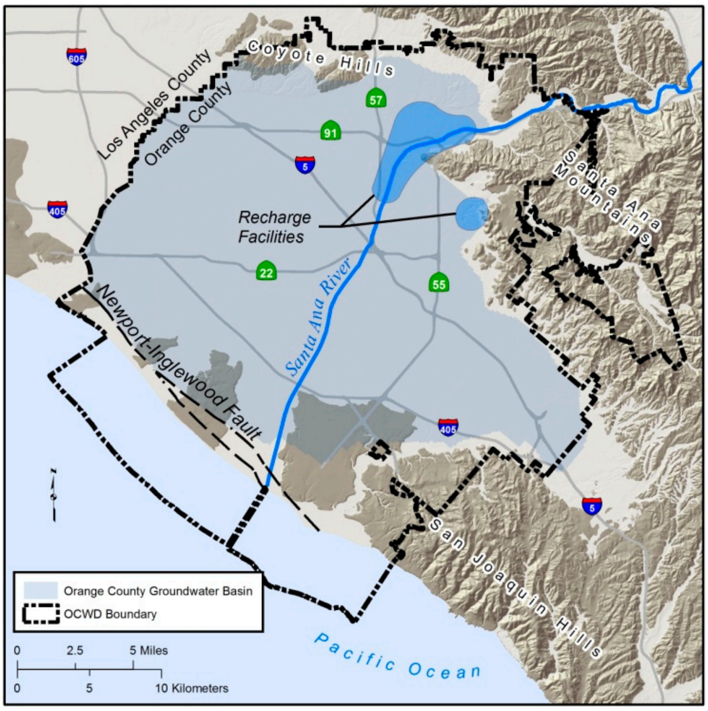

Figure 1. The Orange County Water District recharges the basin with Santa Ana River water, recycled water, and imported water at 400 ha (1000 acre) of infiltration ponds.

The primary source of recharge water to the Orange County groundwater basin is the Santa Ana River, the longest river in southern California. Santa Ana River flows are generally comprised of treated wastewater discharged from upstream sewage treatment plants and seasonal storm flows. On average, the total amount of river flow that OCWD is able to capture and recharge in its recharge system is approximately 185 million·m^3 (150,000 acre-ft) each year. During periods of heavy rainfall, high volumes of storm flow in the Santa Ana River may greatly exceed OCWD's recharge capacity and discharge to the Pacific Ocean. OCWD also recharges approximately 123 million·m^3 (100,000 acre-ft) per year of advanced treated (Reverse-Osmosis and Advanced Oxidation) recycled wastewater from the Groundwater Replenishment System (GWRS) and purchases imported water as an additional source of recharge water. Lastly, the groundwater basin receives an average of 74 million·m^3 (60,000 acre-ft) per year of natural recharge from precipitation and infiltration of irrigation water [1].

Land in Orange County is expensive. OCWD's most recent purchase of land in 2014 for a surface recharge facility cost $4M USD per ha ($1.6M USD/acre). Given the high cost of land and lack of available land in what is a highly urbanized area, it is imperative that OCWD maximize the capacity of the existing recharge system. As is the case with most recharge facilities worldwide, one of the primary constraints to maximizing recharge capacity is clogging [2,3].

Clogging of OCWD's recharge facilities is caused primarily by suspended sediments in Santa Ana River water and to a lesser extent, by biological growth resulting from organic carbon and nutrients in the recharge water [3,4]. Recharge rates achieved when using water with little to no suspended sediment, such as imported water from the Metropolitan Water District of Southern California (MWD) and highly treated recycled water from OCWD's GWRS facility, are many times greater than what is achieved with Santa Ana River water.

In an effort to maximize OCWD's capacity to recharge Santa Ana River water, particularly storm water, which tends to have higher suspended sediment concentrations, OCWD embarked on a multi-phased Recharge Water Sediment Removal Feasibility Study [4]. Phase I of the study identified a number of sediment removal technologies for testing. Phase II of the study included large-scale testing of five different treatment technologies, including:

- Flocculation-Sedimentation
- Dissolved Air Floatation
- Ballasted Sedimentation
- Cloth Filtration (with and without chemical pre-treatment)
- Riverbed Filtration

Phase II results showed that cloth filtration without chemical pretreatment and riverbed filtration were successful in removing sediments and providing increased recharge rates. One of the unexpected outcomes was that any treatment method that used chemical additions, such as flocculants and polymers, while able to produce low turbidity water, resulted in elevated rates of clogging. It is suspected clogging was caused by residual flocculants or polymers remaining in the treated water interacting with the clays and silts present in the sediments.

Phase III of the study is to test cloth filtration and riverbed filtration at the field scale over several years. A key objective of this phase is to assess the performance of these systems to see if it is economical to expand them to treat larger volumes of water. Test results obtained thus far show that cloth filtration, although capable of reducing suspended solids concentrations, can only do so efficiently when total suspended solids (TSS) concentrations range from 5 to 30 mg/L [5–7]. Given this limited range of effectiveness, it is not foreseen that this method can be deployed at a larger scale or at other locations within OCWD's recharge system. The remainder of this paper is focused on presenting the results obtained thus far from the riverbed filtration system (RFS).

The objective of riverbed filtration is to use native river bottom sediments to filter out suspended organic and inorganic solids (e.g., clay and silt particles, algal cells, and microorganisms) and then collect the filtered water in a sub-surface collection gallery. The filtered water is then conveyed to a recharge facility. Success is measured by the increase in the recharge capacity of the receiving basin using filtered water as opposed to unfiltered Santa Ana River water. In addition to examining the overall recharge benefit and water quality improvements, this study also examines design factors that could affect system efficiency with an eye towards expanding this system into the larger Santa Ana River channel.

2. Materials and Methods

The riverbed filtration system (RFS) was installed in a portion of OCWD's recharge system called the Off-River channel. The Off-River channel receives water that flows out of Weir Pond 4 over a sharp-crested weir (see Figure 2). Water depths in the Off-River channel are typically from 15 to 30 cm (0.5–1 ft) and flow velocities range from 0.15 to 0.4 m/s (0.5–1.3 ft/s). Because the upper portion of the Off-River channel sits between the Santa Ana River and Warner Basin (a large recharge basin), groundwater levels tend to be high, causing some reaches the Off-River channel to become a gaining stream. As a result, the upper portion of the Off-River channel is not useful for groundwater recharge. A key consideration for RFS placement was to re-purpose an underperforming portion of the Off-River channel recharge facility and use it to filter sediment laden water and increase recharge rates in a downstream recharge basin.

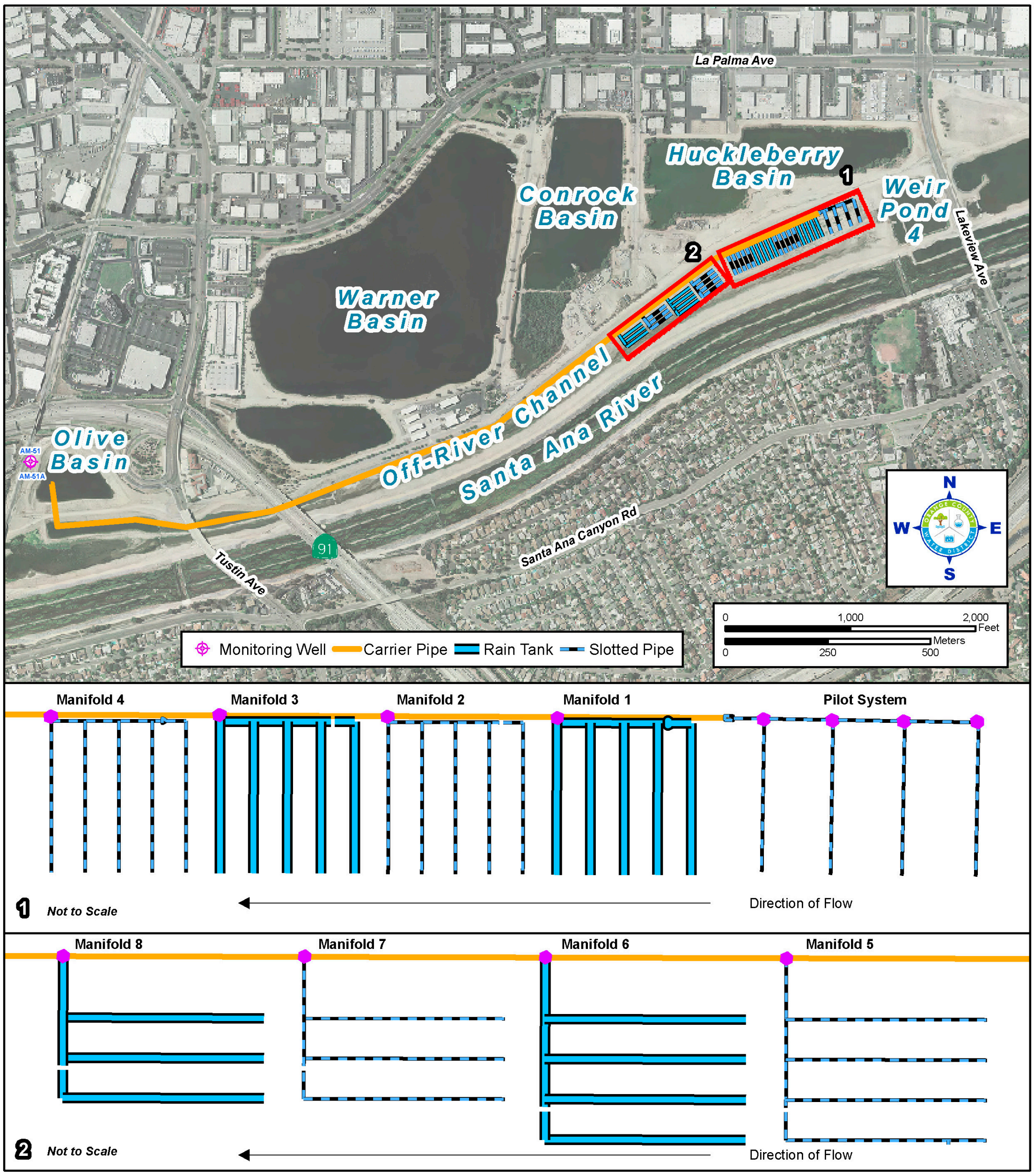

Figure 2. Location and Layout of the Riverbed Filtration System (RFS).

The RFS was constructed with two types of collectors: Slotted PVC Pipe and Flo-Tanks. All the collectors were placed a minimum of 0.9 m (3 ft) below the ground surface and ranged in length from 55 to 61 m (180–200 ft). The total RFS footprint covers 4 ha (10 ac). Table 1 presents key construction details. The PVC pipes are 20 cm (8 in) in diameter and buried in a gravel mixture with a minimum of 2.5 cm (1 in) below and on the sides of the pipe with a minimum of 20 cm (8 in) above the pipe. Native material was then placed on top of the gravel to the ground surface. The pipes were slotted with three rows of 2.54 mm (0.1 in) slots designed to have an overall open area of greater than 10%. The gravel mixture was comprised of material with the following sieve specifications: 100% passing 51 mm (2 in); 90%–100% passing 38 mm (1.5 in); 20%–55% passing 25 mm (1 in); 0%–15% passing 19 mm (0.75 in); and 0%–3% passing 0.074 mm (0.0029 in). The Atlantis Flo-Tank® (Atlantis Corporation, Sydney, Australia) modules were placed end to end and wrapped in geotextile fabric. Once buried, native material was placed around and above the tanks to the ground surface. Each Flo-Tank module is 45 cm (17.7 in) high, 41 cm (16 in) wide, and 69 cm (27 in) long.

Table 1. Riverbed Filtration System (RFS) Construction Details.

Section	Material Type	Length of Collection System	Orientation Relative to Flow in Off-River Channel
Pilot System	Slotted PVC Pipes	220 m (720 ft)	Perpendicular
Manifold 1	Flo-Tanks	220 m (720 ft)	Perpendicular
Manifold 2	Slotted PVC Pipes	220 m (720 ft)	Perpendicular
Manifold 3	Flo-Tanks	220 m (720 ft)	Perpendicular
Manifold 4	Slotted PVC Pipes	220 m (720 ft)	Perpendicular
Manifold 5	Slotted PVC Pipes	244 m (800 ft)	Parallel
Manifold 6	Flo-Tanks	244 m (800 ft)	Parallel
Manifold 7	Slotted PVC Pipes	183 m (600 ft)	Parallel
Manifold 8	Flo-Tanks	183 m (600 ft)	Parallel
Total Slotted PVC Pipes		1087 m (3566 ft)	
Total Flo-Tanks		867 m (2845 ft)	

To quantitatively compare the performance of the two drainage collection types, alternating sets of laterals were constructed as shown on Figure 2. Except for the pilot system laterals, each set of laterals, or sections, are connected to a 36 cm (14 in) diameter trunk line which in-turn feeds a High-density polyethylene (HDPE) carrier pipe that conveys filtered product water to Olive Basin. To accommodate increasing flow from the RFS, the carrier pipe increases in diameter in the downstream direction from 51 cm (20 in) to 91 cm (36 in). Flow from each section is controlled by a gate valve, allowing each set of laterals to be turned on and off to test various section combinations. As shown in Figure 2, the uppermost sections were constructed perpendicular to the direction of surface water flow while the lower sections are oriented parallel to the direction of surface water flow. This was done to assess potential differences in performance obtained by varying the direction of surface water flow. Flow of filtered product water arriving at Olive Basin is measured by a SonTek-IQ Pipe acoustic Doppler flow meter.

The receiving recharge basin, Olive Basin, is a former sand and gravel borrow pit that was purchased by OCWD in 1972. When full, the basin has a wetted area of 2.4 ha (5.8 ac) and a maximum depth of 13 m (40 ft). Historically, surface water from the Santa Ana River was diverted to the basin for recharge. For the study, only filtered product water is supplied to the basin and a comparison of historical performance using unfiltered surface water and RFS product water will provide a measure of the increased recharge obtained using RFS product water. Two groundwater monitoring wells were installed adjacent to Olive Basin, AM-51 and AM-51A. Well AM-51 is screened in the deeper principal aquifer. Well AM-51A is shallow and only receives water when Olive Basin is in operation, thus groundwater in this well is water recently recharged in Olive Basin.

In addition to testing the hydraulic performance of the RFS, a detailed water quality testing program was put into place. As summarized in Table 2, water quality data of interest fall into two categories, (1) Parameters that could impact system performance (i.e., clogging); and (2) Parameters that could impact water quality for potable uses.

Although the reduction of suspended solids and a concomitant increase of recharge rates in the receiving basin are the primary goals of the study, the ability of the RFS to affect parameters related to water quality is also a matter of interest and possibly of regulatory concern. Monitoring parameters related to water quality will show whether the RFS can sufficiently improve the water quality to allow other potential uses, such as direct potable use.

Water quality samples for the RFS influent were obtained from water flowing over the sharp-crested weir in Weir Pond 4 (see Figure 2). RFS product water samples were obtained directly out of the carrier pipe prior to discharge to Olive Basin. Periodically, product water was obtained directly from Olive Basin. Starting in March 2015, auto-samplers were deployed to collect TSS samples to provide a weekly average of TSS concentrations in both the source water at Weir Pond 4 (WP4) and RFS product water.

Table 2. Water Quality Parameters of Interest *.

Impact	Mechanism	Monitored Parameters
System Performance	Clogging due to Solids Accumulation	• Total Suspended Solids • *Particle size distribution*
System Performance	Clogging due to Chemical Precipitation	• *Major cations/anions, TDS, and pH*
System Performance	Clogging due to Biological Activity	• *Principal inorganic nutrients (nitrogen, phosphorus and sulfur)* • Total organic carbon (TOC),dissolved organic carbon (DOC), assimilable organic carbon (AOC)
Potable Use Parameters	N/A	• Indicator bacteria • *Arsenic and other metals* • *Organic halides (TOX)* • Constituents of Emerging Concern (CECs)

Note that italicized monitored parameters are not presented in this paper.

TSS was measured using standard method #2540D [8]. CECs were analyzed at OCWD's Advanced Water Quality Assurance Laboratory following EPA QC protocol using an automated extraction method (Auto-Trace) and isotopic dilution. The analyses were performed using a Liquid chromatography-Mass spectrometry-Mass sprectrometry (LC-MS-MS). All other parameters, other than AOC, were also analyzed at OCWD's Advanced Water Quality Assurance Laboratory using the same methods used for testing potable drinking water supplies.

Assimilable organic carbon (AOC) was monitored as an additional water quality parameter to Total Organic Carbon (TOC). AOC is the fraction of TOC (typically 0.1%–1%) that is most readily utilized by bacteria for regrowth and for metabolic activity. Generally, AOC is the fraction of TOC that heterotrophic bacteria use to increase their biomass. AOC concentrations can serve as an indicator of the nutrient level and a measurement of the potential for microbial regrowth. The AOC concentrations for this study were determined by using a rapid bioluminescence assay that measures the assimilation of organic compounds by a specific organism, *Vibro harveyi* harboring a luminescence gene that responds to organic compounds. The gene is induced, even at low concentrations and produces light in the presence of variety of organic compounds (AOC). The intensity of luminescence increases with the concentration of the organic compounds in water and is measured with a luminometer (Turner Biosystem, Sunnyvale, CA, USA) [9].

3. Results

Construction of the RFS was completed in late 2013 at a cost of $1.9M USD. Of this total, approximately $950,000 USD was for the carrier pipeline. Once put into service, it was discovered that the flowmeter was not operational. As a result, hydraulic performance for 2014 cannot be evaluated. A flowmeter manufactured by SonTek (San Diego, CA, USA) was installed in February 2015 and a hydraulic testing program was developed to measure the performance of various sections of the RFS. Due to drought conditions in Orange County since 2011, it has not been possible to sustain steady flow to the RFS for extended periods of time. As a result, it may take several more years of testing to measure the capacity of all the various RFS configurations.

Testing conducted to date shows the RFS is capable of producing a maximum flow of 44,000 m^3/day (18 cfs), which is greater than the design rate of 37,000 m^3/day (15 cfs). This maximum flow was generated with all slotted PVC pipe and Flo-Tank sections open and was sustained for weeks at a time. Due to supply variability, the duration of the test cycles is highly variable, ranging from a few days to several months. As shown in Table 3, the total flow generally increases with the number of sections open; however, the efficiency, based on the average flow per section, is not consistent with the number of sections open. One key finding is that the efficiency declines when all of the sections are open. Based on the area of recharge created by the number of sections open, the unit infiltration rate ranges from 0.6 to 1.5 m/day (2–5 ft/day). By comparison, the unit infiltration rate of the Santa Ana River, which is adjacent to the Off-River channel, ranges from 0.03 to 0.2 m/day (0.1–0.7 ft/day). The higher unit infiltration rates achieved over the RFS indicate that it is inducing a higher infiltration rate than would occur naturally.

Table 3. Summary of Hydraulic Testing to Date.

Section [1]	Open (Shaded)										
Pilot System (Pipe)		■		■		■			■	■	■
Manifold 1 (FT)		■		■		■				■	■
Manifold 2 (Pipe)		■		■		■	■		■	■	■
Manifold 3 (FT)	■		■	■	■	■	■	■	■	■	■
Manifold 4 (Pipe)					■	■	■		■	■	■
Manifold 5 (Pipe)			■		■		■	■	■	■	■
Manifold 6 (FT)								■			■
Manifold 7 (Pipe)			■		■		■	■	■		■
Manifold 8 (FT)								■			■
No. of Test Cycles	1	1	1	2	1	1	1	1	1	1	3
Flow (1000 m^3/day)	7.3	17.1	21.5	24.1	25.2	29.4	22.0	26.4	39.1	39.1	41.9
No. Open Sections	1	3	3	4	4	5	5	5	6	6	9
Avg Flow/Section (1000 m^3/day)	7.3	5.7	7.2	6.0	6.3	5.9	4.4	5.3	6.5	6.5	4.7

Notes: [1] Pipe = Slotted PVC Pipe; FT = Flo-Tanks.

Note that the testing conducted thus far is relatively limited given the large number of potential section combinations. In addition, potential temperature impacts on performance have not been accounted for. Further testing is needed to help to understand system performance and implications for the design of an expanded system in the Santa Ana River.

Flows shown in Table 3 do not include any significant contribution of shallow groundwater, based on the fact that flow from the RFS with all sections open but no surface flow in the Off-River channel ranged from zero to 1700 m^3/day (0–0.7 cfs).

Figure 3 shows how the water levels in Olive Basin and flows from the RFS into Olive Basin varied in 2015 and 2016. Water flow and water depth were highly variable due to variabilities in the supply of water and RFS system testing (i.e., laterals being turned on and off).

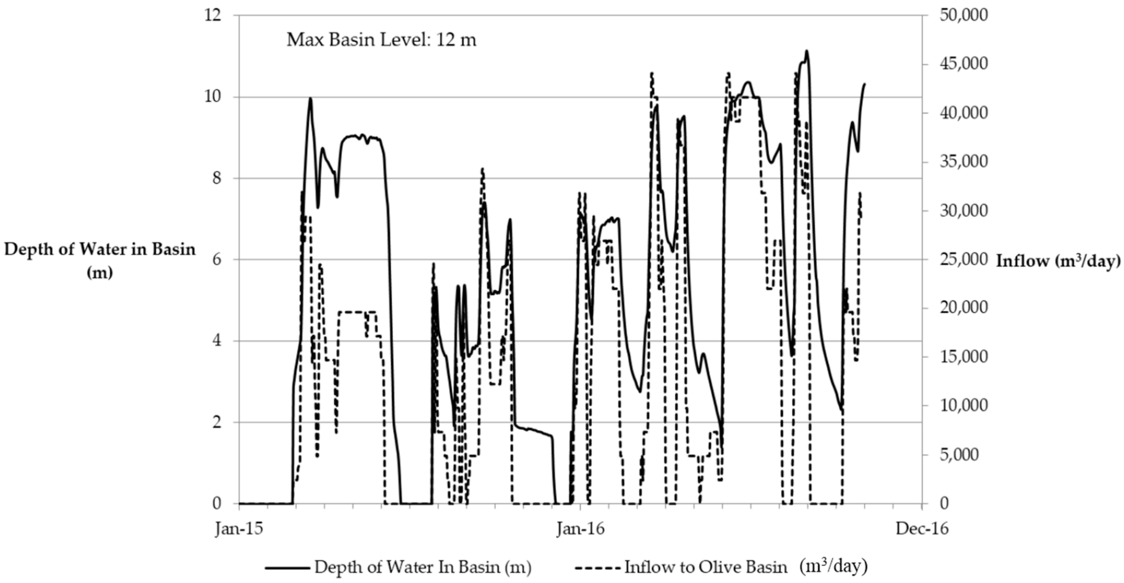

Figure 3. Depth of Water and Flow into Olive Basin.

Figure 4 shows how the average percolation rate obtained with unfiltered Santa Ana River water compares with the percolation rate obtained with the third and longest operational cycle, Cycle 3, which extended from December 2015 to October 2016. Typically, basins become clogged over time and must be drained, dried and then scraped with heavy equipment to remove and disturb any clogging layer. Historically, Olive Basin was cleaned every three to six months when using unfiltered Santa Ana River water. As shown on Figure 4, the basin was not cleaned during the nearly year-long Cycle 3 and yet showed sustained high percolation rates that only recently may be showing signs of decline.

This shows that the high quality of the water produced by the RFS has greatly increased the recharge capacity of Olive Basin and reduced operating costs by avoiding the need to clean the basin two to four times per year.

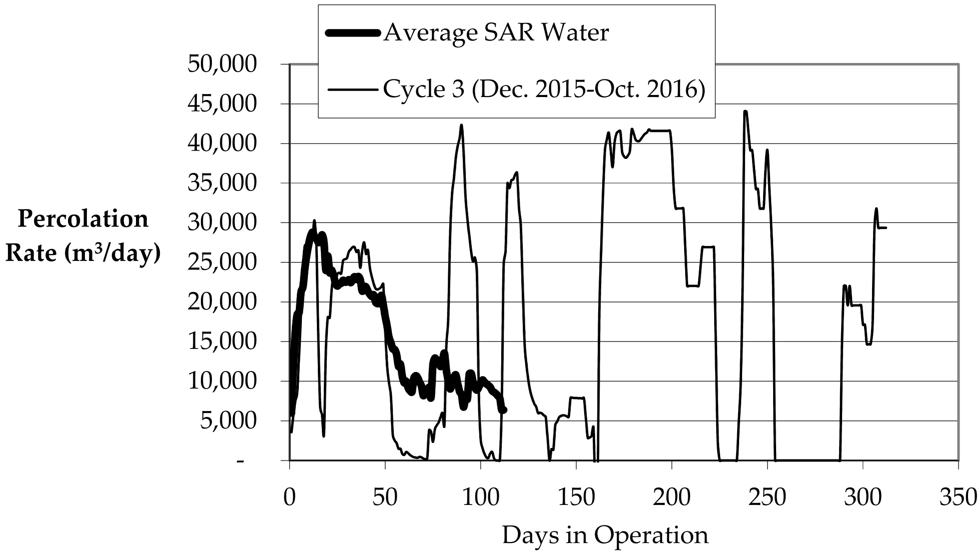

Figure 4. Olive Basin Percolation Rate with Water from Unfiltered Santa Ana River (SAR) and Riverbed Filtration System.

Water quality testing shows that the RFS is very effective in removing suspended solids. Samples collected to date indicate the RFS removes from 70% to 99% of the suspended solids in the source water with an average removal of 97%. Figure 5 shows the range of source water and RFS product water TSS concentrations from December 2014 to October 2016. Table 4 summarizes changes in selected water quality constituents, including TSS.

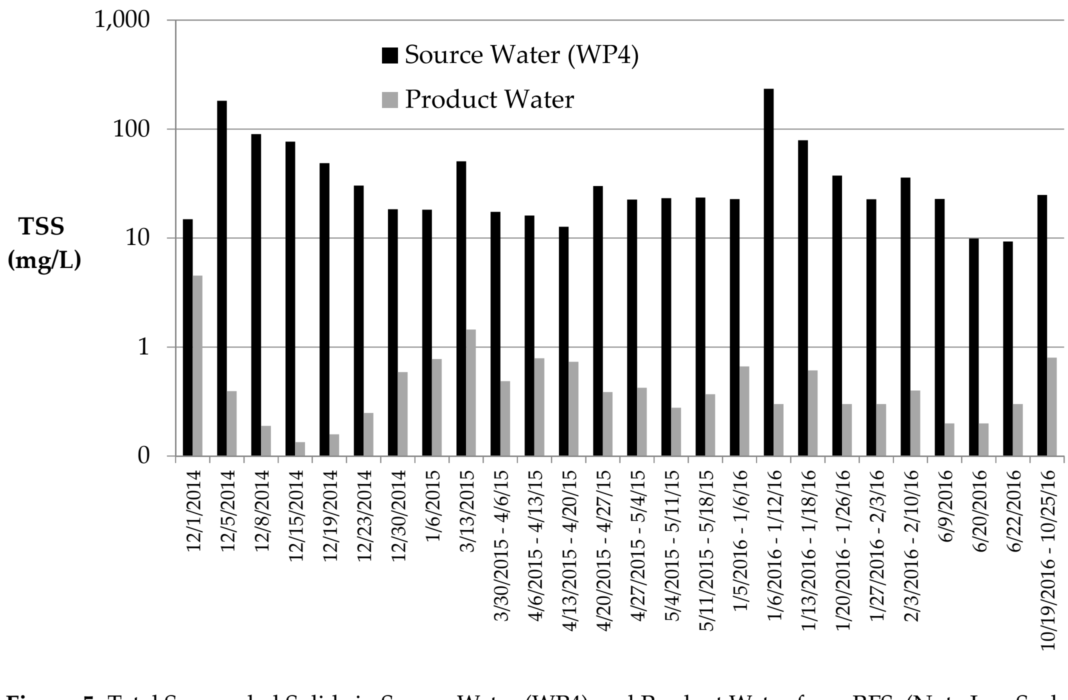

Figure 5. Total Suspended Solids in Source Water (WP4) and Product Water from RFS. (Note Log Scale, samples with a date range are weekly averages).

Table 4. Changes in Selected Water Quality Constituents.

	Source Water (WP4)	Filtered Product Water	Change
Parameter	Total Suspended Solids (mg/L) (n = 26)		
Maximum	234	4.5	
Minimum	9	0.13	
Median	23.2	0.39	
Average	45.1	0.62	97% reduction
Parameter	Total Coliform (cfu/100 mL) (n = 8)		
Maximum	24,000	700	
Minimum	400	40	
Median	2800	100	
Average (*)	6290	235	96% reduction
Parameter	Total Organic Carbon (mg/L) (n = 4)		
Maximum	109	6.0	
Minimum	6.2	3.5	
Median	9.8	4.8	
Average	9.3	4.8	49% reduction
Parameter	Dissolved Organic Carbon (mg/L) (n = 4)		
Maximum	9.9	5.6	
Minimum	7.0	3.5	
Median	8.1	4.1	
Average	8.2	4.3	47% reduction
Parameter	Assimilable Organic Carbon (μg/L) (n = 5)		
Maximum	139.9	242.1	
Minimum	15.0	7.15	
Median	114.0	114.3	
Average	92.0	112.8	18% increase

Notes: * Insufficient number of samples to calculate geometric mean.

TOC and dissolved organic carbon (DOC) concentrations were reduced by over 40%, which is consistent with removals seen in monitoring wells adjacent to OCWD recharge basins.

The removal of Constituents of Emerging Concern (CECs) by the riverbed filtration system was monitored during two sampling events in 2016 via collection of grab samples of the source water and filtered product water (Figure 6). Of the 29 compounds that were surveyed in the source water, 18 were detected, typically at similar concentrations between the two sampling events. These compounds are likely derived from upstream treated wastewater effluent discharges to the river. Figure 6 also shows data for monitoring well AM-51A, a shallow well located adjacent to Olive Basin which only has water when Olive Basin is in operation (see Figure 2). Groundwater data indicate that there was additional removal for several compounds through aquifer treatment. Of the 18 CECs detected in the source water, the average removal was significant (greater than 80%) for six compounds, moderate (between 20% and 80%) for six compounds, and low or negligible (less than 20%) for the remaining six compounds (Figure 7), demonstrating that removal is dependent on compound properties, i.e., biodegradable and sorbing compounds will be removed more extensively over short travel times. Sucralose is considered a conservative tracer for wastewater impact because it is not significantly biodegraded nor sorbed in the subsurface [10], and indeed, it showed a relatively high concentration compared to other wastewater-derived organic compounds.

The observed average increase (~20%) in the AOC concentration between the source water and filtered product water in this study could be a result of specific redox conditions whereby complex organics are converted into simpler assimilable organics detected by the rapid AOC assay; of the five sampling events, on three days, the AOC concentration was approximately constant or slightly lower while on the remaining two days it increased. Additional AOC testing over a continuous monitoring period would be needed to establish trends.

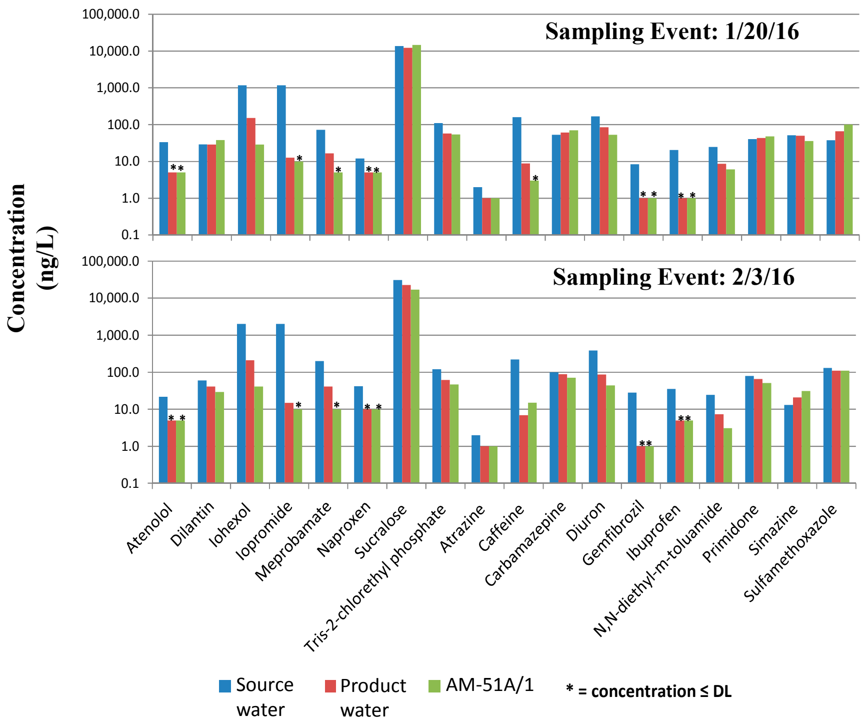

Figure 6. CECs Detected in Source Water, RFS Product Water and in Groundwater (AM-51A) Downgradient of Olive Basin for January and February 2016 Sampling Event. (Note: For compounds detected in source water but not in product water, the detection limit value is shown and denoted with *. Additional compounds were analyzed but were below the detection limit in the source water.)

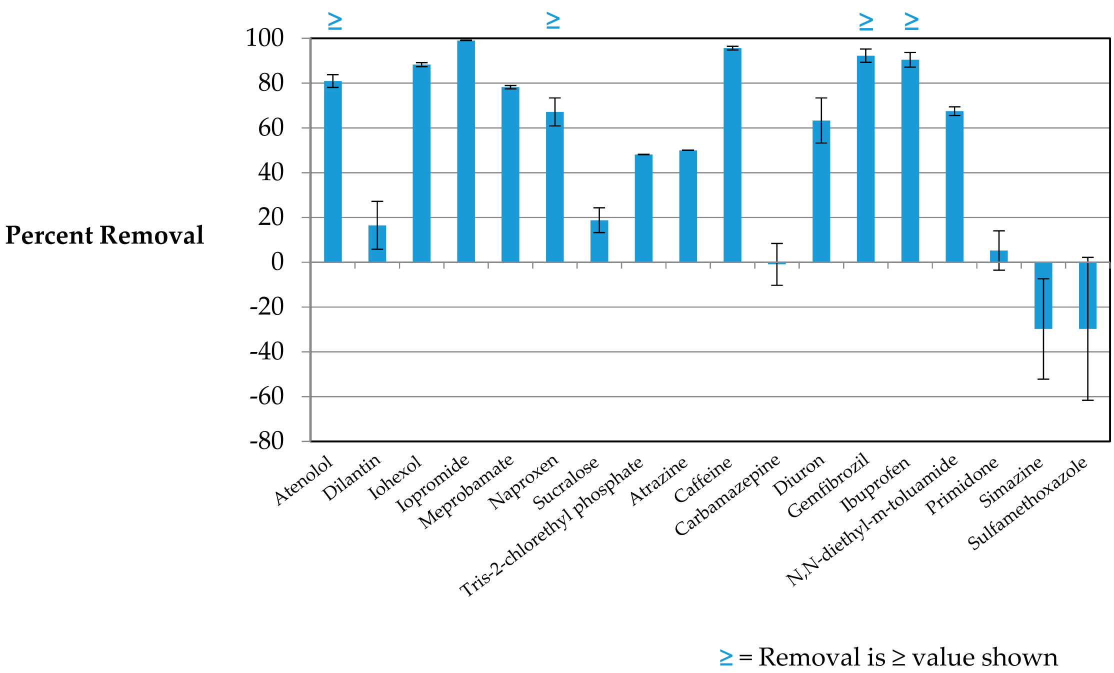

Figure 7. Removal of CECs in RFS (Comparing Source and Product Water). Values are the mean of two sampling events from the previous figure. Error bars represent one standard deviation. In cases where the product water concentration was non-detectable, removal is calculated using the method reporting limit (hence removal is $\geq$ value shown).

4. Discussion

Based on data collected thus far, the RFS is effective in reducing TSS concentrations, which is significant given that suspended solids are the primary clogging agent. As a result, the RFS is capable of reducing clogging and significantly increasing the recharge capacity of Olive Basin. The RFS improves overall water quality in a manner consistent with soil aquifer treatment (SAT) despite the short 0.6 to 0.9 m (2–3 ft) distance between the channel surface and the sub-surface collection system. Reductions in organic carbon may be due to filtration and sorption to carbon in the sediments; however, additional data are being collected to assess how much change is caused by biological processes. Removal of CECs, which represent a portion of the organic carbon, is likely due to a combination of sorption and biodegradation, depending on the individual compound.

Flow rate data indicate that the RFS is capable of filtering at least 11,000 m^3/day of water per ha of channel area. The relative efficiency of the RFS is highest with fewer than all nine sections open, which suggests the collection system density is in excess of what is needed and that the limiting factor is the permeability of the near surface sediments. Nevertheless, the unit percolation rate within the RFS footprint is several times greater than what is seen in the adjacent Santa Ana River. The excess RFS capacity could allow for cycling of the sections to reduce clogging rates, or for lower cost future designs with reduced drain system density. Additional testing is required to assess the relative efficiency of the slotted PVC pipes and Flo-tanks, impact of surface flow rates and surface water depths on collection rates, the impact of collection system orientation relative to the direction of surface water flow, and the potential impact of surface clogging in the Off-River channel. Additional testing is also needed to provide information on the increased recharge obtained in Olive Basin using filtered water compared to unfiltered Santa Ana River water. A nearly one-year-long test cycle has shown some promising results, but more testing is needed to both assess the gains in recharge obtained in Olive Basin as well as potential clogging of the RFS. The long-term test results will be central in evaluating the feasibility of using riverbed filtration in other areas, including the main Santa Ana River channel and other parts of the Off-River channel.

5. RFS Expansion Potential

Upstream of the main diversion point off the Santa Ana River is approximately 40 ha (100 acres) of engineered Santa Ana River channel that could potentially be used to install a large RFS. Figure 8 shows the potential location of a large system in the Santa Ana River channel. It is unlikely the system could be further extended upstream due to naturally occurring habitat present in the upper reaches of the river channel. Within the reach shown on Figure 8, the channel is approximately 91 m (300 ft) wide.

Based on RFS testing in the Off-River channel, a range of unit percolation rates were applied to a potential area in the Santa Ana River channel to develop an estimate of the capacity of the system to capture and divert water from the river channel. Table 5 shows how the potential system capacity varies with varying unit percolation rates.

Table 5. Unit Percolation Rates and Estimated System Capacity.

For 40 ha RFS	Low	Medium	High
Unit Percolation Rate (m/day)	0.61	1.1	1.5
Potential System Capacity (1000 m^3/day)	240	440	610

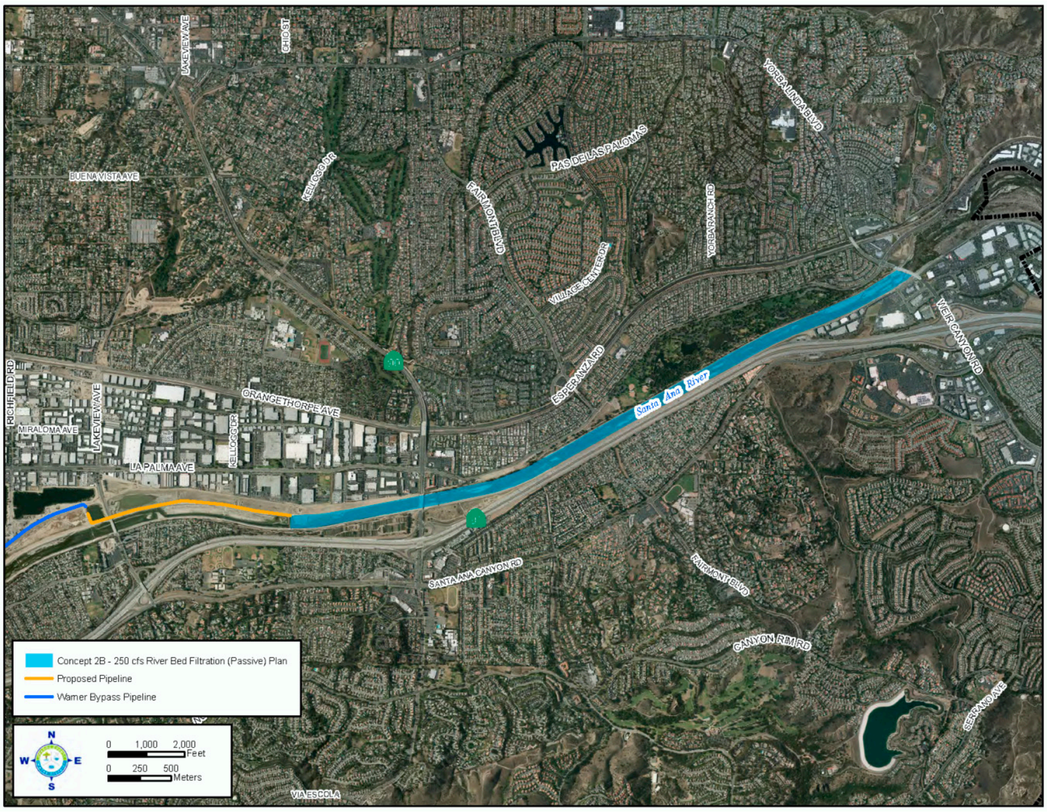

Figure 8. Potential Location of Riverbed Filtration System (RFS) in Santa Ana River Channel.

Assuming a medium system capacity (0.44M·m^3/day), the collection pipeline to convey water to the recharge basins by gravity would require a telescoping pipeline that expands in the downstream direction from a diameter of 20 cm (8 in) to 229 cm (90 in). The estimated capital cost to construct this gravity system is approximately $90M USD [2]. The annualized capital cost assuming an interest rate of 5% and project life of 50 years, is approximately $4.6M USD. Estimated annual operations and maintenance costs are $500,000 USD, resulting in a total annualized cost of $5.1M USD. The operations and maintenance costs assume that heavy equipment operations will be needed to continuously maintain the river channel, particularly between storm events. It is likely that actual operations and maintenance costs will be lower. The estimated additional recharge of water that would otherwise be lost to the ocean due to producing higher quality water, which results in reduced clogging of the receiving basins, is estimated to be 8.6M·m^3/year (7000 acre-feet/year). As a result, the estimated annualized cost per unit of recharge is $593 USD/1000 m^3 ($730 USD/acre-foot). This cost is comparable to the current cost of untreated imported water. Since the cost of untreated imported water is expected to increase in the future, the cost of the additional recharge produced by the RFS will likely become more cost-effective in the future.

One of the risks associated with placing an RFS in the Santa Ana River is the potential for scour, which could damage the RFS. Additional work needs to be done to assess the potential for scour; however, the presence of Prado Dam upstream controlling flows in the Santa Ana River and several grade stabilizers in the reach considered for the larger system will mitigate potential scour. In addition, the system would be designed so that the laterals could be easily replaced if needed in the event they are damaged by major storm events.

6. Conclusions

Initial data show that riverbed filtration is highly effective, removing suspended solids in the recharge water, which in turn also greatly increases the recharge capacity of the receiving basin.

Some other water quality benefits are also achieved. Data collected thus far indicate that it will be cost-effective to use this approach at a larger scale to capture and recharge increased quantities of storm flow obtained from the Santa Ana River.

The RFS approach has the potential to provide a relatively benign method of diverting filtered surface water from river channels with minimal impacts to aquatic and riparian wildlife once the system is constructed. Finally, the RFS allows the suspended sediment load to remain in the river channel, which not only reduces costs associated with removing sediment from recharge basins, but retains the natural balance of sediment transfer in the river channel, which benefits riparian and marine habitats.

In closing, the RFS approach represents a partnership with nature where natural and engineered processes intersect to produce a result that is beneficial for man and for the environment.

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Abbreviations

The following abbreviations are used in this manuscript:

ac	acres
AOC	Assimilable Organic Carbon
CEC	Constituents of Emerging Concern
cfs	Cubic feet per second
cm	Centimeters
DOC	Dissolved Organic Carbon
EPA	US Environmental Protection Agency
ft	Feet
ft/s	Feet per second
ha	Hectares
GWRS	Groundwater Replenishment System
in	Inches
km^2	Square kilometers
LC	liquid chromatograph
m	Meters
mm	Millimeters
MS	Mass spectrometry
m/s	Meters per second
m^3/day	Cubic meters per day
mi^2	Square miles
mg/L	Milligrams per liter
MWD	Metropolitan Water District of Southern California
OCWD	Orange County Water District
QC	Quality control
RFS	Riverbed filtration system
SAR	Santa Ana River
SAT	Soil aquifer treatment
Study	Recharge Water Sediment Removal Feasibility Study
TOC	Total Organic Carbon
TSS	Total Suspended Solids
USD	United States Dollar

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