The Orange County Water District Riverbed Filtration Pilot Project: Water Quality and Recharge Improvements Using Induced Riverbed Filtration

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Abstract

In an effort to reduce suspended solids and organic carbon loading and to increase long-term groundwater recharge rates at Orange County Water District's spreading basins, a pilot project was conducted to evaluate riverbed filtration as a technology to treat river water prior to groundwater recharge. A shallow under-channel lateral drain system was constructed within a channel adjacent to the Santa Ana River to induce and capture infiltration. Water pumped from the drain system was analyzed for a variety of water quality parameters and then recharged into percolation columns to evaluate recharge rates compared to raw Santa Ana River water (without treatment). At the pilot project drain system, phreatic surface and temperature were continuously monitored at thirteen points. River water inflow and outflow and drain system pumping rates were also monitored.

The pilot test was divided into two periods: Period 1 had shallow overflow (3- to 8-cm) within the river channel; Period 2 achieved deeper surface water depths (8- to 30-cm). Lateral drain system pumping during both test periods were incrementally increased to establish the maximum pumping capacity of the drain system for each test period. Monitoring data indicate that riverbed filtration effectively removed essentially all suspended solids and reduced turbidity with the bulk of water captured by the under-channel drain system from induced infiltration. The phreatic surface and subsurface water movement within the drain system area was shown to be very sensitive to changes in surface water flow rates and depth, and drain system pumping rates. In addition, surface clogging was observed. The pilot project results indicate that riverbed filtration is a viable technology for treating surface water prior to recharge operations, however, additional testing and optimization is needed.

Keywords

Recharge, Filtration, Infiltration, Percolation, Water Quality, Total Suspended Solids

INTRODUCTION

The Orange County Water District (OCWD) located in southern California, USA is responsible for managing the local groundwater basin that supplies water to more than 20 cities and water agencies, serving more than 2.3 million people. OCWD primarily recharges the groundwater basin by applying water from the Santa Ana River (SAR) to over 600 hectares of surface spreading basin recharge facilities. SAR flows are primarily comprised of tertiary-treated effluent during the dry season and storm water during the winter rainy season. The concentration of organic and inorganic total suspended solids (TSS) in the SAR can typically range from 5 to greater than 400 mg/L and can be extremely high during storm flow conditions. The suspended solids in SAR water accumulate in the recharge basins, causing the formation of a foulant layer and rapid declines in recharge basin percolation (Phipps et al, 2007, Hutchinson, 2007). For example, Phipps et al. (2007) report foulant layer induced percolation losses of approximately an order of magnitude over the first 60 days of recharge basin operation.

Riverbank filtration as a technology to improve water quality is well documented through numerous case studies (e.g. Ray et al., 2003; Hubbs, 2006). Riverbank filtration is a passive treatment system whereby river water is captured by shallow wells adjacent to the river. River water infiltrates through the underlying sediments within the river channel and suspended organic and inorganic solids (e.g. clay and silt particles, algae cells, and microorganisms) are removed from the water prior to well capture. OCWD desired to evaluate whether pre-treatment of SAR water by percolating it through riverbed sediments could improve recharge basin percolation rates. OCWD operates a channel adjacent to the main SAR channel, which is called the Off-River Channel, for routing and recharging SAR flows. Maximum off-river channel flow rates are less than 650 cubic meters per minute (m^3/min), which result in generally shallow water depths across the riverbed. A pilot study was designed to use the off-river channel to investigate “riverbed filtration” as a treatment technology to reduce solids and organic carbon concentrations in SAR water prior to groundwater recharge operations.

METHODS

A lateral drain system designed to capture 17 m^3/m of filtered water was installed approximately 1.5 m beneath the SAR off-river channel. The phreatic surface is typically within 0.5 meters of the ground surface when water is flowing in the off-river channel. Figure 1 shows a plan view of the lateral drain system, which consists of eight slotted pipes spaced approximately 24 m apart and extending 58 m across the channel to a main line along the river bank, which drained to a water collection vault containing submersible pumps. Each slotted pipe segment had a gate valve at its junction with the main line to allow lateral drains to be isolated. The slotted pipe was backfilled with approximately 0.5 m of washed pea gravel followed by native riverbed soil material to the surface. Additional details on development and optimization of the lateral drain system design are provided in Keller et al. (2010).

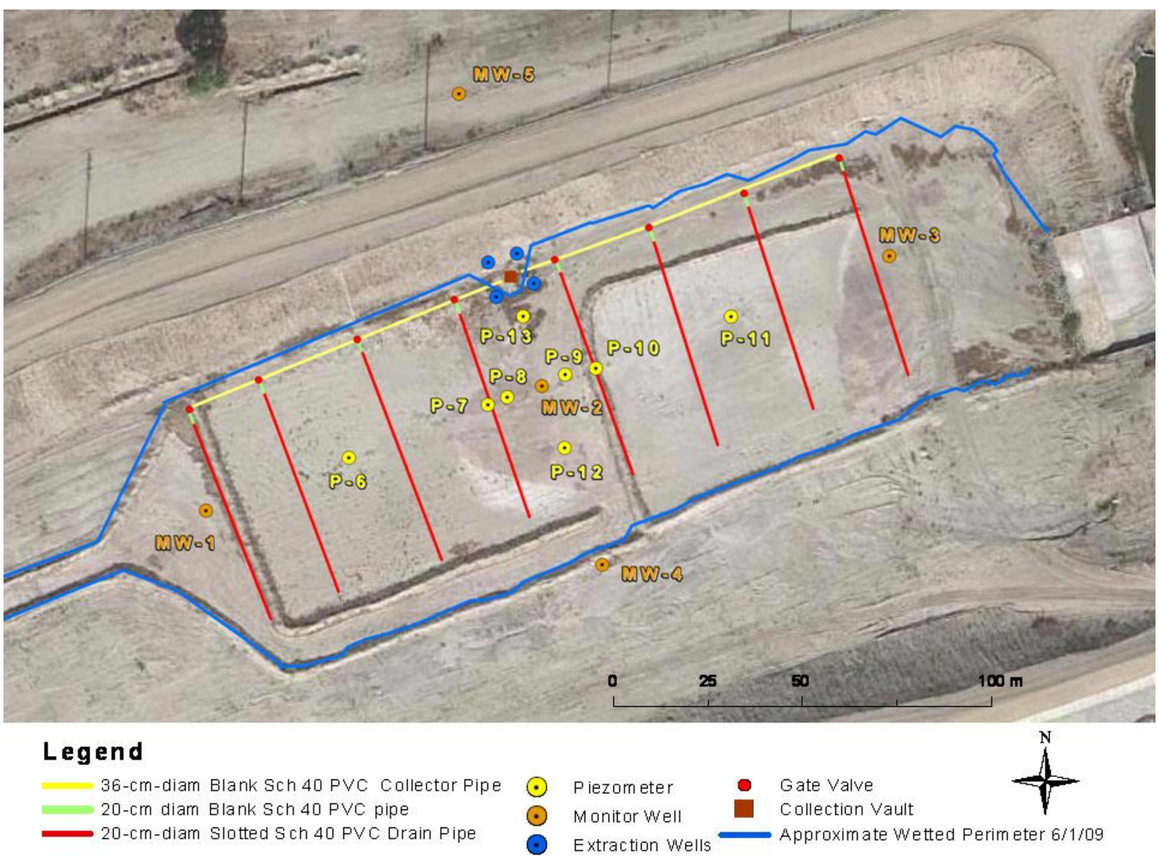


Figure1. Under-channel lateral drain pilot project layout and monitor instrument design.

The pilot study monitoring system consisted of monitoring: inflow and outflow into the drain system area via stream gaging; phreatic level via 5 monitor wells and 8 piezometer points, and; a flowmeter to determine the pumping rates from the under-channel lateral drain system. Locations of piezometers and monitoring wells (i.e. phreatic level monitoring points) are provided in Figure 1. To estimate infiltration and water flux via temperature profiling of heat transport (Constantz, 2008), the piezometers and MW-1 were instrumented with subsurface temperature sensors at 0.3, 1.8, and 3 m below ground surface (bgs). Monitoring wells MW-2 through MW-5 were each instrumented with a single temperature sensor at 3 m bgs.

The pilot test was divided into two periods: Period 1 had shallow overflow (3 cm to 8 cm) within the river channel; Period 2 achieved deeper surface water depths (8 cm to 30 cm) due to the installation of berms within the channel. Lateral drain system pumping during both test periods were incrementally increased to establish the maximum pumping capacity of the drain system for each test period. The maximum sustainable pumping rate was identified as the rate that could be sustained without draining the collection vault or significantly dropping the phreatic surface.

Bi-weekly samples of raw source water and effluent from the riverbed filtration system were collected and analyzed during the first five weeks of Test Period 1 for turbidity, Total Suspended Solids (TSS) and other water quality parameters. Additionally, percolation column testing was performed using raw source water and riverbed filtration system effluent to evaluate percolation decay as an indicator of the effectiveness of the water treatment. The percolation columns were packed with washed sand from an OCWD recharge basin. All columns were saturated from the bottom with riverbed filtered water to avoid air entrapment. Raw water or riverbed treated effluent was then added to the column at constant head conditions and changes in the volume of water passing through the column monitored. The initial percolation rate was measured as the volume of water passing through the column during the first two minutes of the experiment.

RESULTS AND DISCUSSION

Water Quality Improvement: Turbidity, TSS, and Percolation Decay

Table 1. Raw and riverbed filtered water quality

Water Quality Parameter	Influent Value Range	Average Percent Removal
Turbidity	8 - 80 NTU	96%
TSS	7 - 37 mg/L	> 99%
Chlorophyll A	52 - 68 mg/m^3	> 99%
Total Organic Carbon (TOC)	6 mg/L	47%
Total Kjeldahl Nitrogen (TKN)	0.8 - 0.9 mg/L	> 99%
Iron	0.7 - 0.8 mg/L	80%
Manganese	0.06 mg/L	> 99%

Table 1 presents the results of biweekly water quality testing from the first 5 weeks of Test Period 1. Relative to the raw water, the riverbed filtration system significantly reduced the TSS and turbidity by an average of 93 and 86 percent, respectively. Other water quality parameters such as TOC, TKN and iron and manganese showed decreases of 50% or greater. Water quality delivered by the passive riverbed filtration system was significantly better than other active treatment technologies evaluated (data not presented), such as cloth filter, flocculation-sedimentation, dissolved air flotation and ballasted sedimentation (HDR, 2009).

Column percolation decay results using raw water, riverbed filtration water, and conventional filter cloth treated water are presented in Figure 2. Raw water percolation rates decreased to 50 percent of the initial percolation within approximately seven hours. Riverbed filtered water sustained column percolation rates for an extended period of time, decreasing to 50 percent of the initial percolation at approximately 58 hours. However, the percolation rate did not steadily decrease over time and instead variably increased and decreased through-out the column study (Figure 2). Of note, air entrapment occurred in the riverbed filtration column with an initial reduction in percolation rates. However, percolation rates partially recovered once the air was no longer entrapped.

The pilot test water quality and percolation column results indicate that under the study conditions, riverbed filtration significantly reduced turbidity, TSS and other water quality parameters and improved percolation rates. In addition improvements in water quality were superior to other conventional active treatment technologies evaluated.

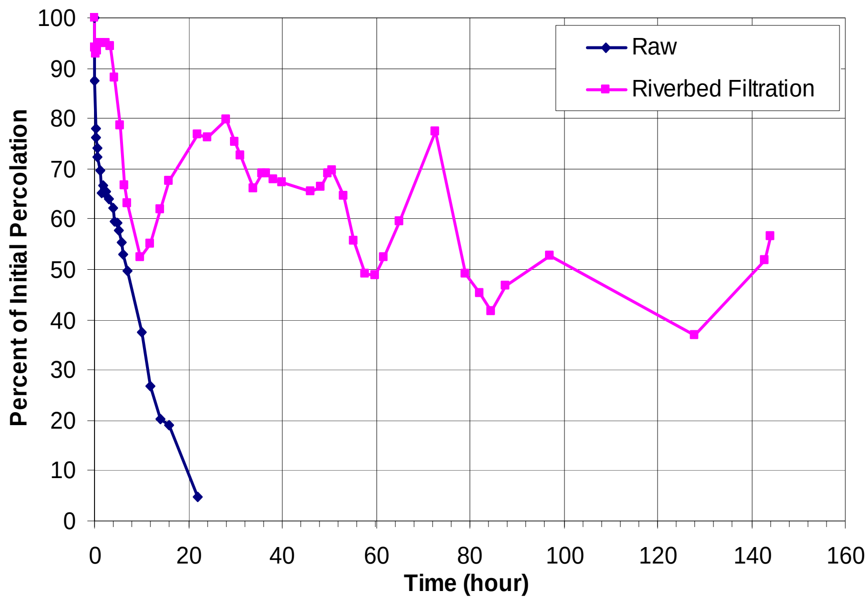
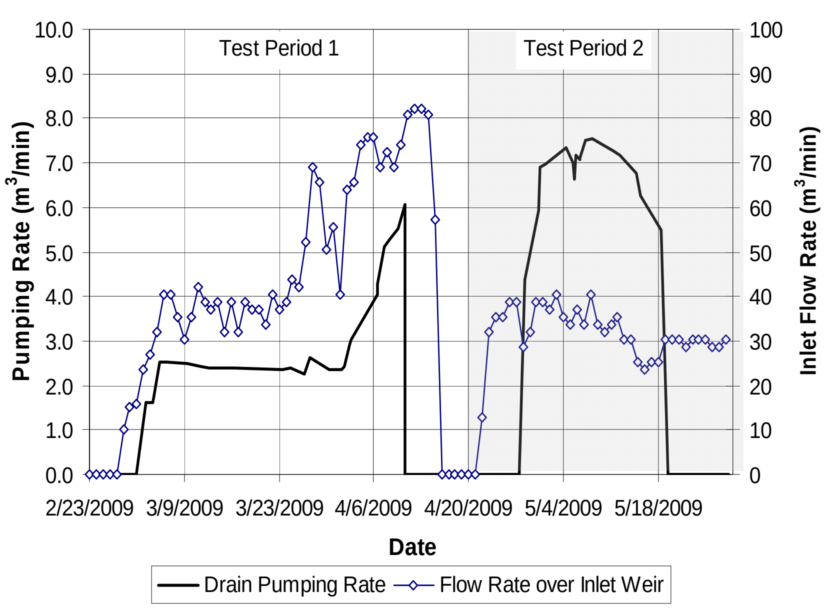


Figure 2. Raw water and filtered water percolation decay.

Hydraulic Performance

Flow and Phreatic Surface Monitoring

Figure 3 presents the drainfield system average daily inlet surface flow rates and pumping rates during the two test periods. During Test Period 1, initial pumping was limited to about 2.5 m^3/min. To increase the depth of water in the channel, surface water inlet flow rates were increased from approximately 40 m^3/min to 80 m^3 /min after which a maximum pumping rate of 6 m^3/min was achieved (Figure 3). However, above 5 m^3 /min pumping rates were not sustainable.



Prior to Test Period 2, berms were constructed to raise the surface water depth over the off-river channel surface. Subsequently, maximum pumping rates of 7.5 m^3/min were achieved during Test Period 2 at channel inlet rates of approximately 40 m^3/min. The achievable maximum pumping rate in both test periods was very sensitive to the flow rate (surface water depth).

Figure 3. Pilot study daily average inlet surface flow and pumping rates.

The response of the phreatic surface to the test period surface flow and pumping activities is shown in Figures 4 and 5 for east-west and north-south monitoring transects through the drainfield system, respectively. The diversion of water over the under-channel drain system is clearly shown in both figures by an increase in phreatic level surface on 3/1/2009. Prior to the start of Test Period 1 pumping, the phreatic surface reached the ground surface only at P-6, indicating an unsaturated zone existed between the surface and most of the under-channel drain system.

Initial pumping in Test Period 1 slightly decreased the phreatic surface east of P-6 (3/26/09, Figure 4). Pumping rates and inlet flow rates were then increased as discussed above. The phreatic levels stabilized at a pumping rate of 4.1 m^3/min and began to decrease at pumping rates greater than 5.1 m^3/min, reaching their deepest Test Period 1 (TP 1) depth at the final pumping rate of 6.1 m^3/min (Figure 4). Slight gradients existed from east to west under non-pumping conditions and, during pumping, a depressed phreatic surface forms between MW-2 and P-11 that reversed the gradient between the east and west sides of the collection vault (Figure 4).

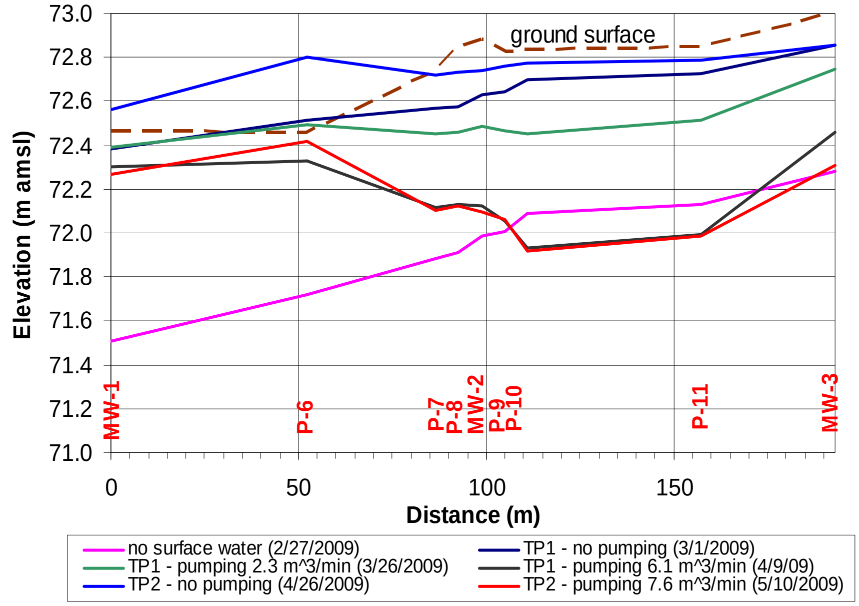


Figure 4. East-west phreatic surface transect data (TP = Test Period)

The Test Period 1 data indicated that the east side of the under-channel drain system is less productive than the west side. In addition, the N-S phreatic level transect shows a steep hydraulic gradient between MW-2 and MW-5 existed during all times of Test Period 1 (Figure 5), indicating that subsurface water flow also occurs to the north away from the under-channel lateral drain system.

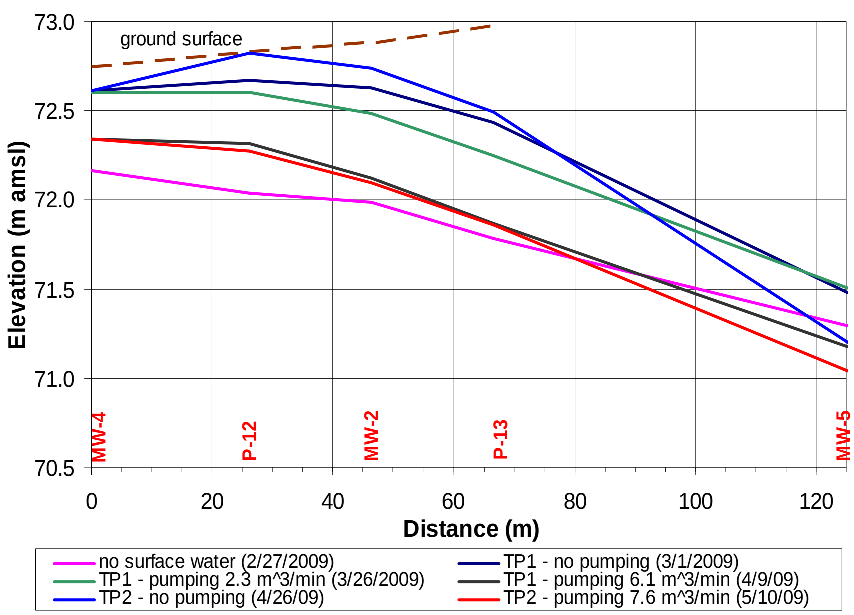


Figure 5. North-south phreatic surface transects data (TP = Test Period).

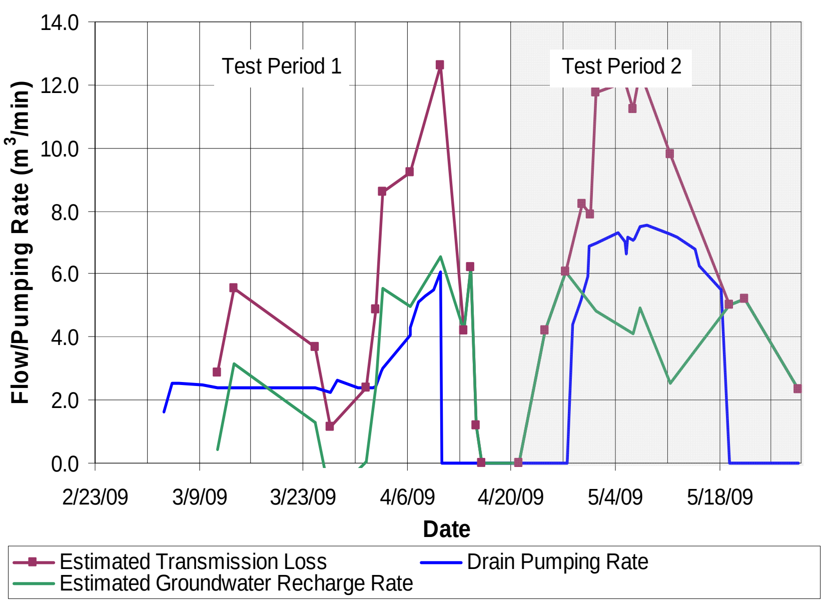
At the end of Test Period 1, the pumps were shut off and the phreatic surface rebounded quickly. West of the collection vault the phreatic surface returned to conditions similar to the start of Test Period 1 pumping. Of note, the construction of berms prior to Test Period 2 and resultant increase in the surface water depth resulted in increased phreatic surface levels at MW-1 and P-6 (4/26/2009 in Figures 4 and 5).

Increases in phreatic surface elevation prior to Test Period 2 were most notable from MW-2 west towards MW-1. East of P-7 remained unsaturated, however the thickness of the unsaturated zone decreased compared to Test Period 1 (Figure 4). During Test Period 2, pumping was again increased daily to identify the maximum pumping capacity of the system. The pumping rate stabilized at above 7.0 m^3/min (Figure 3), at which point the phreatic surfaces began to decrease, until the E-W and N-S transect data closely resembled the phreatic surface elevations observed during maximum pumping rates (6.1 m^3/min) in Test Period 1 (Figures 4 and 5). As in Test Period 1, after pumping was ceased the phreatic surface levels showed less recovery in the eastern monitoring points (data not shown).

The phreatic surface was very responsive to surface water flow (depths) above the drain system. Phreatic surface levels were observed to decrease sharply in response to periods during testing when flows over the inlet weir significantly decreased for a few hours of the day. Finally, it should be noted that the sustainable maximum pumping decreased towards the end of Test Period 2 (Figure 3) due most likely to a combination of reduced surface water flow rates (depth) and possibly clogging of the channel surface.

Estimated Channel Transmission Loss and Groundwater Recharge Rates

The difference between the volume of surface water flowing into the under-channel lateral drain system and the volume of surface water flowing out of the system is defined as transmission loss. Transmission losses were estimated as the difference in measured surface water flow rates over the inlet weir and the stream gage measured outlet (Figure 1). All estimated transmission losses were assumed to have infiltrated into the subsurface within the lateral drain system area. The volume of water going to groundwater recharge is, therefore, the difference between the estimated transmission loss and the volume of water pumped from the under-channel system. Figure 6 shows the estimated transmission loss (difference in flow), pumping rates and calculated groundwater recharge during the pilot study. As pumping rates increased, transmission losses increased, indicating that the under-channel drain system induces percolation. Although the estimated error in the transmission loss calculation is high, the general trends are consistent with the pumping rates. At pumping rates of 7.6 m^3/min during Test Period 2, estimated groundwater recharge volumes began to decline, indicating that the maximum infiltration rates possible under existing conditions (i.e. surface hydraulic conductivities, hydraulic head on the off-river channel sediments) had been attained.



Excluding data prior to 4/1/2009 due to large measurement errors, groundwater recharge rates averaged 4.3 m^3/min during non–pumping periods. During pumping periods, groundwater recharge averaged 4.1 m^3/min. The similarity between estimated recharge rates with and without pumping indicates that the bulk of water pumped from the under-channel lateral system was from induced percolation.

Figure 6. Pilot study estimated transmission loss, groundwater recharge, and pumping rate.

Percolation / Water Flux Estimates from Temperature Data

Near surface percolation and downward water flux estimates at nine different monitoring locations were calculated using down-hole temperature data as a heat tracer. A thorough description of the heat tracer method to estimate subsurface water flux can be found in Constantz (2008).

The average estimated downward flux rate for the maximum and no pumping periods are presented in Table 1. Due to low measured temperature response at most 3 m bgs depth sensors, flux estimates were not made for the 1.8 m to 3 m bgs depth interval. However, temperature response at 3 m bgs was observed at all monitoring locations except MW-5, which is out of the channel, indicating that some water was percolating past the collection laterals and recharging into the local aquifer. Conversely, estimated flux rates over the 0- to 0.3 m bgs interval were greater than estimates between the 0.3- to 1.8-m bgs interval during all time periods. Differences in flux rates between these depths likely reflect lateral flow caused by the steep hydraulic gradients to the north and a decrease in downward flux rates from below the lateral drains (located at 1 to 1.5-m bgs) during pumping,

Table 2. Average estimated fluxes (m/day) using heat tracer data at each monitoring point.

Monitoring Well / Piezometer	0 to 0.3 m bgs			0.3 to 1.8 m bgs		
	Test Period 1, Max Pumping	**Test Period 2, No Pumping**	**Test Period 2, Max Pumping**	**Test Period 1, Max Pumping**	**Test Period 2, No Pumping**	**Test Period 2, Max Pumping**
Average West (MW1,P6,P7,P8)	0.49	0.56	0.84	0.36	0.24	0.89
Average East (P9,P10,P11)	0.46	0.35	0.68	0.26	0.22	0.66
Average All	0.46	0.49	0.86	0.28	0.22	0.68

The average estimated downward water fluxes displayed variability at different locations within the under-channel lateral system. Estimated water fluxes during Test Period 2 maximum pumping rates were approximately double those observed during Test Period 1 maximum pumping rates, and the average estimated flux rates at the monitoring locations west of the collection vault were higher than monitoring locations east of the vault. The spatial variability in estimated flux may represent local differences in hydraulic conductivity and the hydraulic head (surface water depth) at that location. At 0 m to 0.3 m bgs the slight increase in estimated flux during Test Period 2 no pumping compared to Test Period 1 maximum pumping rates most likely reflects the increased surface water depth after the berm addition. The increase in estimated downward flux rates during Test Period 2 maximum pumping period also confirms that the under-channel lateral system induces increased percolation in response to increased pumping rates.

CONCLUSIONS

The riverbed filtered water quality results and percolation column results indicate that riverbed filtration significantly reduces turbidity, TSS and other water quality parameters and improves percolation performance in addition to outperforming conventional active treatment technologies.

The sustainable maximum pumping capacities were highly affected by surface water depths in the channel. Additionally the maximum pumping capacities achieved during the different test periods equated to 30 percent and 44 percent, respectively, of the design collection rate (Keller et al., 2010). The discrepancy between the design collection rate and maximum pumping rates achieved during the pilot study was due to primarily to the field conditions not matching assumptions used in the pilot system design. Most notably, the pilot system design assumed saturation below the off-river channel surface due to underlying geologic conditions. Unsaturated conditions below most of the drainfield and the steep hydraulic gradient to the north reduced the available hydraulic head to induce flow into the under-channel drain system.

The phreatic level data also confirm that the under-channel drain system performance is sensitive to both spatial and temporal variability in surface water depth, such that decreases or increases in surface water flow and hydraulic head substantially decreased or increased the phreatic surface. As evidenced by the higher phreatic levels in the western portion and induced hydraulic gradients to the east portion of the drain system, performance may also be affected by variability in channel sediment permeability and reduced hydraulic conductivity as the underlying sediments become unsaturated. In the future surface and subsurface treatments (i.e. ripping/scarifying or removal of surface sediment) may be evaluated to determine whether these treatments can improve channel sediment hydraulic conductivities.

The temperature data also confirmed that the under-channel drain system induces percolation during pumping operations and that most of the water collected by the under-channel drain system is from induced percolation. Estimated transmission losses, groundwater recharge, and downward water flux rates from temperature data were significantly greater during Test Period 2 than those estimated during Test Period 1. The increase in estimated flux rates during Test Period 2 correlate to increased surface water depth and increased drain pumping.

Results from the pilot study indicate that riverbed filtration is a viable and superior method to other commercially available active treatment technologies to improve water quality and increase downstream recharge basin percolation rates. Ongoing testing is needed to determine the optimum conditions for surface water flow rates/depths and the under-channel drain system performance. In addition, long-term maintenance of channel sediment clogging and operational treatments will need to be assessed. Finally, results from this pilot study can be used to guide future design of other OCWD riverbed filtration systems.

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