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Soil aquifer treatment to meet reclaimed water requirements

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Abstract

To increase the opportunities and reduce the cost of indirect potable reuse, soil aquifer treatment (SAT) was evaluated at the City of Los Angeles' Donald C. Tillman Water Reclamation Plant (DCTWRP) in a 2.5-year pilot study. Six soil columns were operated between February 2016 and November 2018 treating DCTWRP effluent. The goal was to reduce the dissolved organic carbon (DOC) in the effluent to lower concentrations in order to increase the allowable volumes for reclamation. An integrated part of the study was to evaluate the biodegradability of organics in different waters using biodegradable (BDOC) analyses. BDOC has been used in similar research in the past, and in this research, BDOC was an accurate predictor of column performance in removing organic carbon. The total organic carbon in tertiary DCTWRP effluent was reduced from 7 to 10 mg/L to 0.9 to 2.5 mg/L through a process train beginning with ozonation of the tertiary effluent, followed by biological activated carbon, and finally to the soil column effluents. Additional short-term treatments including reverse osmosis, additional ozonation, and low-pressure UV were also evaluated. The soil columns removed N-nitrosodimethylamine to detection limits. Finally, results from SAT and BDOC were used to develop a kinetic model to predict biodegradation of organic matter of wastewater origin through a soil aquifer system. © 2019 Water Environment Federation

Practitioner points

- Soil aquifer treatment is often used in indirect potable reuse projects to protect aquifers.
- Soil aquifer treatment was simulated in six pilot columns for 2.5 years.
- Columns were fed tertiary effluent from a nutrient-removal type-activated sludge plant.
- Effluent TOC was reduced from 10 mg/L to 0.9 to 2.5 mg/L, and nitrosodimethylamine (NDMA) was also removed.
- Biodegradable organic carbon analyses accurately predicted soil column performance in removing organic carbon.

Key words

biodegradable dissolved organic carbon; indirect potable reuse; ozonation; reclamation; soil aquifer treatment

Introduction

Over the past seven years, with the exception of 2018, California has experienced its driest years on record. Water imports are becoming more costly, and the groundwater reservoirs are over exploited (Metropolitan Water District, 2018). The City of Los Angeles is increasing its local water sources and decreasing in water imports by means of water reuse through groundwater recharge. The City's largest water reclamation plant, Hyperion, treats approximately 1,060,000 m^3/day with 166,000 m^3/day being provided to the West Basin Municipal Water District for reclamation, with the rest being discharged into Santa Monica Bay. The City has three other water reclamation plants, Terminal Island, Glendale, and the Donald C. Tillman. The Terminal Island plant has a full Advanced Water Purification Facility (AWPF) composed of microfiltration, reverse osmosis (RO), and low-pressure ultraviolet (LPUV) light disinfection. The Glendale plant produces tertiary-treated water in accordance with Title 22 regulations (California Water Quality Control Boards, 2019) which is used for nearby non-potable water needs and augmentation of the Los Angeles River during dry periods. The Donald C. Tillman plant (DCTWRP) in Van Nuys also produces tertiary-treated water which is used to recharge Lake Balboa, Wildlife Lake, and the Japanese Garden Lake, as well as augmenting flows in the Los Angeles River.

This project is in response to Mayor's Executive Directive #5 signed on October 14th, 2014, to reduce Los Angeles Department of Water Power (LADWP)'s purchases of imported water by 50% by 2024. As a part of increasing the City's local water supply, the City is planning to build an AWPF at DCTWRP for surface spreading at Hanson spreading grounds for indirect potable reuse. Since 2009, two pilot studies, Phase I and Phase II, have been performed at DCTWRP to evaluate different treatment strategies for the future full-scale AWPF. Pilot Phase I focused on a full advanced treatment (FAT) train, which includes 0.2-micron filtration, reverse osmosis followed by an advanced oxidation process. The goal of pilot Phase II was to study the effectiveness of alternative but less expensive, less energy-consuming, and less waste-producing treatment trains based on ozonation, biological activated carbon (BAC), and different ultraviolet (UV) treatments, and to compare these alternatives side by side with FAT. The FAT process produces water that meets the regulations for both surface spreading of the product and direct injection into the groundwater reservoirs. Ozonation followed by BAC produces water that is suitable for surface spreading only, with volume limits on the amount of reclaimed water than can be added, which is based on total organic carbon (TOC). Much greater volume of reclaimed water treated by FAT is possible because of its low TOC (<0.4 mg/L).

Ozonation followed by BAC has the advantage of not producing brine and transforms contaminants of emerging concern (CEC), which will otherwise concentrate in the FAT brine, which must be treated at the City's Hyperion water reclamation plant (LASAN & the Advanced Water Purification Pilot Study Report, 2018; Sundaram, Emerick, & Shumaker, 2014). Soil aquifer treatment (SAT) was evaluated using six soil columns for further reducing the TOC of effluents. The BAC effluent with additional ozone or LPUV and diluted BAC effluent with RO permeate treated further with LPUV were evaluated as columns feed. The main purpose of dilution of the feed with RO permeate was to reduce the TOC ahead of SAT to determine whether it affected removal efficiency.

Further treatment of tertiary effluents to reduce TOC has been evaluated previously. Khan, Babcock, Suffet, and Stenstrom (1998), Khan, Babcock, Viriyavejakul, Suffet, and Stenstrom (1998) developed a mythology to measure biodegradable dissolved organic carbon (BDOC) and used it to quantify small changes in dissolved organic carbon (DOC) typically observed in SAT treatment, which are too small to be quantified using biochemical oxygen demand (BOD). The oxygen consumed per mg of DOC removed is in the range of 1–3 mg O_2/mg DOC and is below the detection limit and precision of the BOD test (Khan, King, Babcock, & Stenstrom, 1999). Drewes and Fox (1999, 2000) and Fox, Narayanaswamy, Genz, and Drewes (2001) have evaluated soil aquifer treatment for meeting the low TOC requirements for reclaimed water. Their work is part of a larger monograph by AWWARF (2001) which describes SAT for sustainable water reuse. Amy and Drewes (2007) and Cha, Chi, Kim, and Kim (2004) have also proposed SAT for sustainable treatment.

The goal of this paper was to describe the progress of SAT in meeting the needs of TOC concentration requirements for indirect potable reuse, which after blending in the aquifer must be less than 0.5 mg/L, if the contribution of reclaimed water is more than 20% of the total volume.

Six pilot soil columns were fed DCTWRP tertiary effluent with varying pretreatments and hydraulic retention times (HRT) over a period of two years and 9 months. The results, described in this paper, will be used to select a full scale a pre-SAT treatment train to maximize TOC removal. DOC and BDOC analyses were used to compare treatment alternatives. SAT removals of other CECs were also evaluated and were generally less than method detection limits (MDLs), but are only briefly summarized; however, the full report with all data is available (City of Los Angeles, 2018).

Materials and Methods

Treatment trains

All the pilot treatment trains used effluent from the DCTWRP after cloth media final filters (Aqua Aerobic Systems, Loves Park, IL) but before disinfection. The plant has two identical phases and is currently operating only one phase using 9 parallel aeration trains and 22 secondary clarifiers. The process is designed to remove nitrogen using an anaerobic, anoxic, oxic process with mixed-liquor recycle, followed by cloth media filters (10 microns), and chloramine disinfection. The process is basically a modified Ludzack-Ettinger process proceeded with a short residence time anaerobic selector. The plant generally removes total inorganic nitrogen to less than 10 mg/L and effluent TOC to <12 mg/L.

Figure 1a shows some of the treatment trains used to prepare feeds to the soil columns. Figure 2 shows a special train to prepare diluted feed water with RO permeate for soil columns. For this pilot study, Hydranautics-ESPA2-4040 membrane elements were selected. All of the treatment trains started with ozonation of DCTWRP tertiary effluent. The ozonated tertiary effluent was further treated by BAC. Addition of 4 mg/L of ozone to BAC effluent and addition of 1,300 mJ/cm^2 of LPUV to BAC effluent or blends of BAC effluent with RO permeate were used to prepare the feeds of the soil columns. Table 1 summarizes operation of the columns with timeline of using different feeds.

Figure 1b shows other treatment trains that were evaluated as part of the pilot study; however, further discussion of these treatment trains is outside of the scope of this paper but all information is available (City of Los Angeles, 2018).

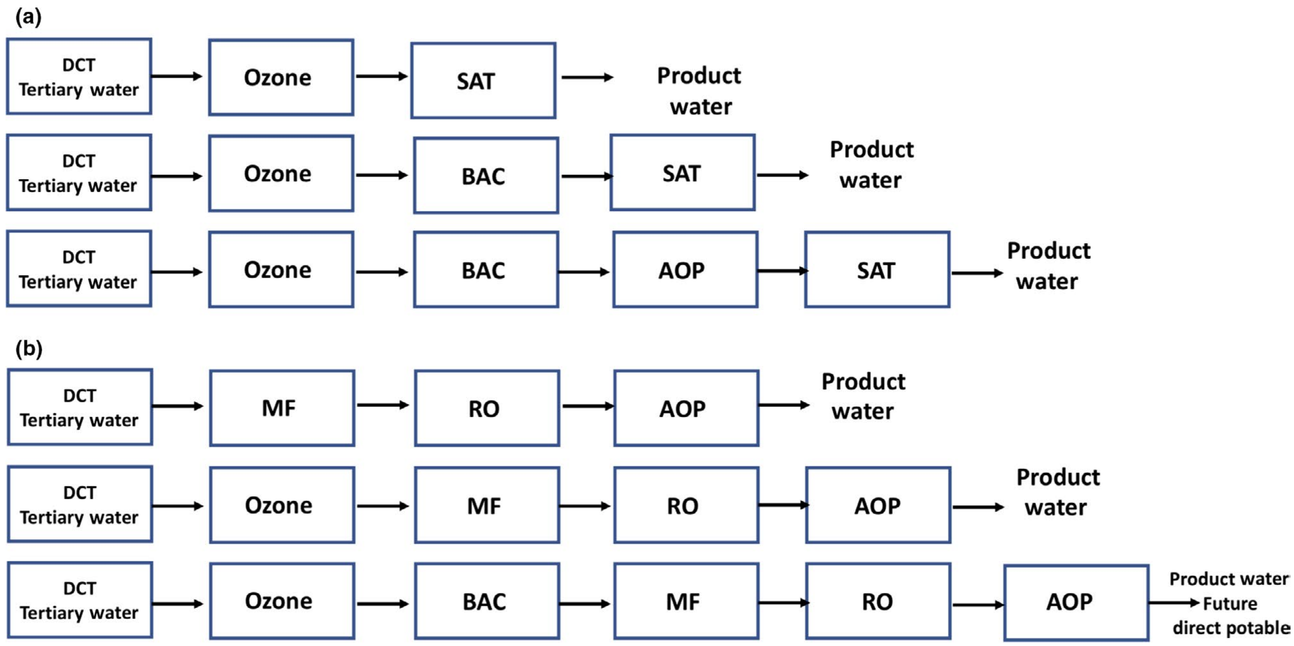


Figure 1. (a) Pilot treatment trains used to prepare soil column feeds (b) Other treatment train studies as part of the pilot.

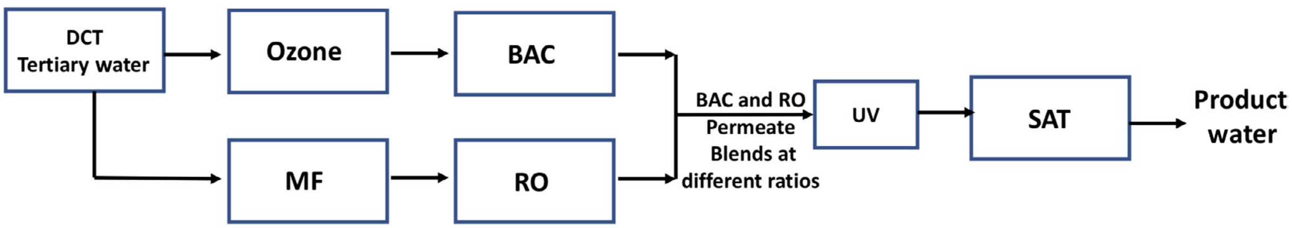


Figure 2. Treatment train including dilution with reverse osmosis product water.

Table 1. Summary of Soil Columns Operation condition

Date	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
2/16/16-3/24/16	DCT filter effluent	DCT filter effluent	DCT filter effluent	DCT filter effluent	DCT filter effluent	DCT filter effluent
3/24/16-4/27/16	Ozonated filter effluent					
4/27/16-8/25/16			BAC effluent		BAC effluent + 4 mg/L ozone	
8/25/16-Present	[66% RO permeate + 37% BAC effluent] + 1,300 mJ/cm^2 LPUV at 30 days HRT	[50% RO permeate + 50% BAC effluent] + 1,300 mJ/cm^2 LPUV at 30 days HRT	[50% RO permeate + 50% BAC effluent] + 1,300 mJ/cm^2 LPUV at 180 days HRT	[33% RO permeate + 67% BAC effluent] + 1,300 mJ/cm^2 LPUV at 30 days HRT	BAC effluent +1,300 mJ/cm^2 LPUV	

Soil aquifer treatment

In order to determine the TOC reduction that should occur as the reclaimed water percolates through the saturated zone to ground water wells, soil aquifer treatment was simulated in soil columns. Six saturated soil columns were placed in upflow operation in February 2016 and have been operated and monitored continuously. Each column is 3.6 m tall and constructed of 0.35 m diameter clear polyvinyl chloride (PVC) pipe. Each column includes an under drain screen to prevent soil loss and clogging of the openings at the bottom of the column. Columns were covered since the beginning of the test with black polyethylene to prevent light penetration and resulting algae growth. Columns were housed indoor at DCTWRP in an air-conditioned building (20°C). Five gallon drinking water plastic bottles were used for feed containers. These feed containers were stored in refrigerators at 4°C. Flow connections were made with opaque, ozone-resistant neoprene tubing. In order to minimize biological growth, the tubing was periodically autoclaved during cleaning cycles.

The columns were filled by representative soil samples collected near the Hanson Spreading Grounds (HSG) in the San Fernando Valley Groundwater Basin (San Fernando Basin) in Los Angeles County, California, from Vulcan Material Company (Sun Valley, California) which has an active mining ground within the vicinity of HSG. Washed plaster sand was collected and screened with a 2-mm sieve to remove large materials prior to loading the columns. The purpose of this process was to eliminate the "Wall Effect" or the distortion in flow caused by materials, which are large relative to the diameter of the test column. This process maximizes plug flow conditions, creating a homogeneous soil column fill material and preventing wall effects.

Feed water was pumped into each column at the bottom using a model ISM4408 Reglo Independent Channel Control Peristaltic Pump (IDEX Health and Science, Oak Harbor, WA). Upflow operation achieved accurate control over flow rates to obtain one-month and 180-day HRTs in the columns.

Prior to filling the columns with soil, they were partially filled with DCTWRP tertiary effluent. When adding the media to the columns, the soil was compacted by using a rubber mallet by tapping the outside of the column near the soil surface. This process was used to limit stratification by creating a more homogeneous composition of soil throughout the column, as well as minimizing entrapped air pockets. All columns were filled with 3 m of aquifer material, allowing 0.6 m of freeboard in each column.

The porosity of the media was 36% void volume, and void volume was used to calculate the actual media volume. The inflow rates were selected to produce the desired retention times. The HRT of each column was verified using a bromide tracer, by introducing 500 ml of 1,200 molar KBr to the columns in the feed line and collecting samples continuously afterward for measuring Br concentration. Results of this tracer test are provided as Appendix S1. The inflow to each column was readjusted based on the results of the tracer test and to obtain the desired HRT which ranged from 1.64 to 2.75 ml/min for the soil columns with HRT of 30 days and 380 µl/min for the soil column with HRT of 180 days. The effluent flow rate to each column was maintained at desired value and checked every week, to maintain a consistent HRT.

Operation of the columns

Six columns were in operation since February 23, 2016. Feeds were prepared on a weekly basis. During the first 21 days of operation, the HRT was set to 5 days. The columns were initially operated at short HRT to flush out any unrepresentative constituents introduced during soil collection and column loading as well as to accelerate acclimation.

After nearly 3 weeks of operation at 5-day HRT, the HRT was increased to 30 days corresponding to the expected HRT for future operation. The purpose of the acclimation period was to enable the development of a stable biofilm consortium well-adapted to the conditions in the soil columns and the nutrients in the feed water. The columns were later fed different influents as the other treatment processes came online in the pilot study.

Table 1 shows the change in conditions and influents over the transition to stable operation and the evolution of column acclimation. Columns were assumed to be acclimated when they reached a stable TOC removal rate, approximately 4 months after the start of the operation. A tracer test was performed to verify the HRTs of each column. The initial HRTs and the HRTs calculated from the tracer test were different by 4–10 days, and inflow rates were adjusted to produce a 30-day HRT. Results of the tracer test and related calculations are included in Appendix S1. After 180 days of operation, the influents to columns 1–4 were changed to a blend of RO permeate, which had a TOC of 0.3 mg/L on average, and BAC effluent in order to meet the goals of the research. The HRT of column 3 was increased to 180 days to evaluate the impact of higher HRTs on TOC removal.

Throughout the test period, soil column feed waters and effluents were sampled and analyzed weekly for the following constituents, with the analytical method in parenthesis: ammonia (EPA 350.1), nitrate (EPA 300), nitrite (EPA 300), organic nitrogen (EPA 351.2), TOC (SM 5310C), and UV absorbance at 254 nm (UVA-254). After the acclimation period for the soil columns, the DOC and TOC of the column feed waters and effluents were measured and compared over a 3.5-month period and found to be virtually equal and DOC monitoring was stopped. UV transmittance (UVT), which can be correlated with DOC, was calculated from UVA-254 measurements in effluent samples using Equation (1) (Hach, 2019).

$$\mathrm{UVT} = \left(10^{-(\mathrm{UVA254})}\right) \times 100 \tag{1}$$

To collect effluent water samples, 4-L glass bottles were set up in a 4°C refrigerator. A neoprene tube was used to transfer effluent from the discharge valve on top of each column to the glass bottle inside the refrigerator. Samples were collected as 20- to 24-hr composites. Effluent samples were transferred directly from the 4-L bottles to sample bottles and sent to the

City's Environmental Monitoring Division Laboratory for analysis.

BDOC procedure

BDOC is a measure of degradable DOC and was used to evaluate the column performance. BDOC is a method of measuring the reactivity of waters with low organic carbon contents. The oxygen demand exerted by the DOC of the column effluents should range from 1 to 3 mg O_2/DOC and is well below the detection limits and precision of the BOD test. Currently, there is no standard method for measuring BDOC but several procedures have been developed and published. BDOC methods used earlier to characterize drinking and reclaimed water (Khan, Babcock, Suffet, et al., 1998; Khan, Babcock, Viriyavejakul, et al., 1998; Khan et al., 1999) demonstrated that BDOC can be used to assess the performance of a water reclamation plant using dual membrane treatment (Madireddi et al., 1997) and also to show the differences in TOC removal in activated sludge processes as a function of solids retention time (Babcock, King, Khan, & Stenstrom, 2001). An alternative procedure used mainly in potable water studies is assimilable organic carbon (van der Kooij, Visser, & Hijnen, 1982) and is also used to monitor low levels of organic carbon, but uses a specific species of bacteria which may not be able to acclimate to all types of wastewaters (Frias, Ribas, & Lucena, 1995). Therefore, a BDOC test using naturally present, indigenous organisms was selected. A method conforming to these requirements was used by Cha et al. (2004) for soil aquifer treatment and based on previous work by Drewes and Fox (1999). Figure 3 shows the procedure.

A total of 82 BDOC reactors were prepared. Each reactor used a 1-L Mason Jar. The same sand that was used in the columns was also used in the reactors. To prepare the sand, it was first hand sieved through Tyler sieves #8 and #40. The sand that passed through the #8 sieve, but was retained on the #40 sieve was collected. One hundred twenty grams of sand was dried, weighted and put in each jar, and rinsed with deionized (DI) water until the water came out completely clear. Then, the sand was washed by filling each reactor with 300 ml of a saline solution (mixture of 0.15 M sodium chloride and 1 mM magnesium chloride) and drained carefully three times. The purpose of washing the sand with saline solution was to remove the background DOC without disturbing biomass in the soil. At that point, reactors were ready for acclimation.

To acclimate the reactors, 300 ml of each test water was put into the reactor and mixed with the soil. The dissolved oxygen (DO) and DOC were measured and then left in the reactors for seven days. On the seventh day, the DO and DOC were measured on the supernatant. The DO was measured to insure that the reactors remained aerobic during the entire week. The decline in DO over one week was typically less than 1 mg/L. The supernatant was drained, and the reactors were refilled with 300 ml of fresh water. BDOC was calculated using Equation (2):

$$\mathrm{BDOC}_{\#\ \mathrm{days}} = \mathrm{DOC}_{\mathrm{initial}} - \mathrm{DOC}_{\mathrm{final}}. \quad (2)$$

Percent BDOC reduction was defined according to Equation (3):

$$\text{Percent BDOC}_{\#\ \mathrm{days}}\ \text{reduction} = (\mathrm{DOC}_{\mathrm{initial}} - \mathrm{DOC}_{\mathrm{final}})/\mathrm{DOC}_{\mathrm{initial}} \times 100. \quad (3)$$

The reactors were maintained on the 7-day cycles, until the BDOC percent reductions were stabilized for at least 2 weeks. At that point, the reactors were assumed to be acclimated. All the reactors were acclimated after nearly 12 weeks. After acclimation, all but six reactors were switched to 28 days of water retention; six reactors were used for kinetic analysis and remained at 7 days. After switching the reactors to 28 days, they were opened weekly, mixed, and reaerated.

Several types of waters were analyzed for BDOC using these reactors. For some of these waters, BDOC was measured for different retention times, ranging from 7 to 28 days. For each water, at least three reactors were prepared to provide triplicate results. Table 2 summarizes waters tested for BDOC and retention times.

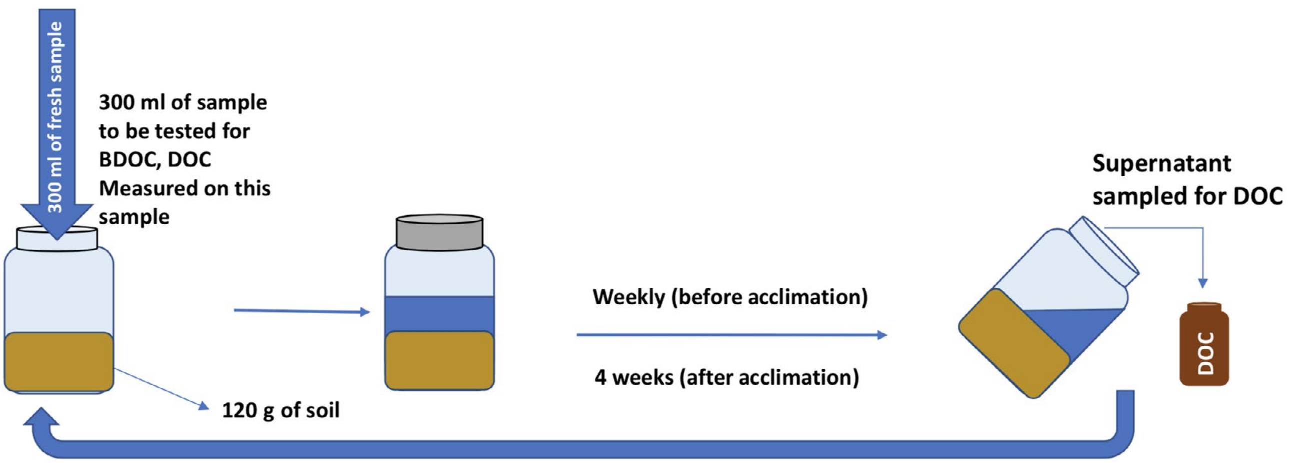


Figure 3. BDOC test procedure.

Table 2. Waters tested for BDOC and retention times

TYPE OF WATER	RETENTION TIME
DCTWRP tertiary effluent	28 days
DCTWRP tertiary effluent/8–12 ppm ozone	28 days
DCTWRP tertiary effluent/8–12 ppm ozone/BAC	28 days
DCTWRP tertiary effluent/8–12 ppm ozone/BAC/2 ppm ozone	28 days
DCTWRP tertiary effluent/8–12 ppm ozone/BAC/4 ppm ozone	28 days
DCTWRP tertiary effluent/8–12 ppm ozone/BAC/6 ppm ozone	28 days
DCTWRP tertiary effluent/8–12 ppm ozone/BAC/1300 mJ/cm^2 low pressure UV (LPUV)	28 days
DCTWRP tertiary effluent/8–12 ppm Ozone/BAC/1,300 mJ/cm^2 medium pressure UV (MPUV)	28 days
DCTWRP tertiary effluent/8–12 ppm ozone/BAC/6 ppm H_2O_2/1,300 mJ/cm^2 low pressure UV (LPUV)	28 days
[33 percent RO permeate + 67 percent BAC effluent]/ 1,300 LPUV mJ/cm^2	28 days and 7 days
[50 percent RO permeate + 50 percent BAC effluent]/ 1,300 LPUV mJ/cm^2	28 days
[66 percent RO permeate + 37 percent BAC effluent]/ 1,300 LPUV mJ/cm^2	28 days and 7 days
Potable water	28 days
Potable water/4 ppm O_3	28 days

Results and Discussion

It is important to note that although the upstream treatment train did not change throughout the operation, process upsets occurred and were unavoidable. All major process upsets, including but not limited to difficulties in controlling ozone doses or BAC downtimes, can be observed in soil column effluent TOC. However, for all columns the overall trend of TOC in the column effluent is a continuous decrease, as shown in Figure 4, which is most likely due to further acclimation and adaptation of microorganisms with the environment over time.

Ozonated versus non-ozonated feed

Figure 5 shows the average percentage reduction in BDOC for the different types of waters. The error bars show standard error of the mean (standard deviation divided by the square root of the number of observations times the t static (1.96) for 95% probability or $p = 0.05$). The means are significantly different if the error bars do not cross. The reductions in BDOC of the tertiary effluent and the ozonated tertiary effluent are different. The BDOC reduction in the BAC effluent is significantly different than that in the ozonated tertiary effluent. These observations suggest that both ozonation and BAC significantly changed the BDOC concentrations. The other treatments of BAC effluent did not result in any significant change in BDOC. Ozonation increased the BDOC percentage of the tertiary effluent from 41% to 56% on average, while BAC reduced it to 44%. Further treatment of the BAC effluent with ozone, LPUV, or hydrogen peroxide/LPUV did not result in any statistically significant improvements. The BDOC concentrations of potable water and ozonated potable water are provided for comparison.

Figure 6 shows DOC of the fresh samples as well as the DOC remaining after 28 days. The error bars show the standard error of the mean at $p = 0.05$, with confidence intervals ranging from 0.2 to 0.4 mg/L. All samples showed significant differences between fresh and 28-day BDOC. Tertiary remaining DOC is significantly different than the other 28-day remaining DOCs. The various other treatments did not reduce the 28-day remaining DOCs beyond the BAC effluent, implying that the amount of ozone used or LPUV applied is either not effective or too low in concentration/intensity to affect improvements.

Los Angeles tap water TOC ranged from 1.6 to 3 mg/L with a BDOC of less than 0.5 mg/L on average, approximately one-half or less than the SAT product water. Potable water ozonated with 4 mg/L ozone (ozone to TOC ratio from 1.3 to 2.5) increased the BDOC by 12% on average, a significant difference. The organics in potable water were assumed to be natural organic matter and are different than organics of wastewater origin. Based on the results, potable water on average has 1.7 mg/L of non-biodegradable organics and ozonation appears to have increased BDOC by 0–0.5 mg/L. Drewes and Fox (2000) also reported the contribution of organics in reclaimed water originating from potable water.

Selected CECs and N-nitrosodimethylamine (NDMA) were measured in column feed and effluent, taking the HRT in the columns into account, on four different occasions. NDMA an averaged 15 ng/L in the influent, but was consistently not detected in the effluents (method detection limit = 2 ng/L). The full monitoring results are beyond the scope of this paper but are presented in the project final report (tables 2–4, page 2–3, City of Los Angeles, 2018).

In the final stages of the pilot studies and while conceptual design for the full-scale project was in progress, the California State Water Quality Control Board Division of Drinking Water (DDW) in July 2018 released new notification levels (NL) for perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic (PFOS) at 14 and 13 µg/L, respectively. PFOA and PFOS were measured (EPA 537) in the column influents and effluents on four different occasions. The average concentration of PFOA and PFOS in the column effluents was 28 and 6 ng/L, respectively. The very low NLs will apply to the full-scale project and were not anticipated in the pilot study. To anticipate treatment changes needed to remove PFOS and PFOA using granular activated carbon, a rapid small scale column testing (Crittenden et al., 1991) experiment using the BAC effluents was performed. No PFOA and PFOS were detected before TOC

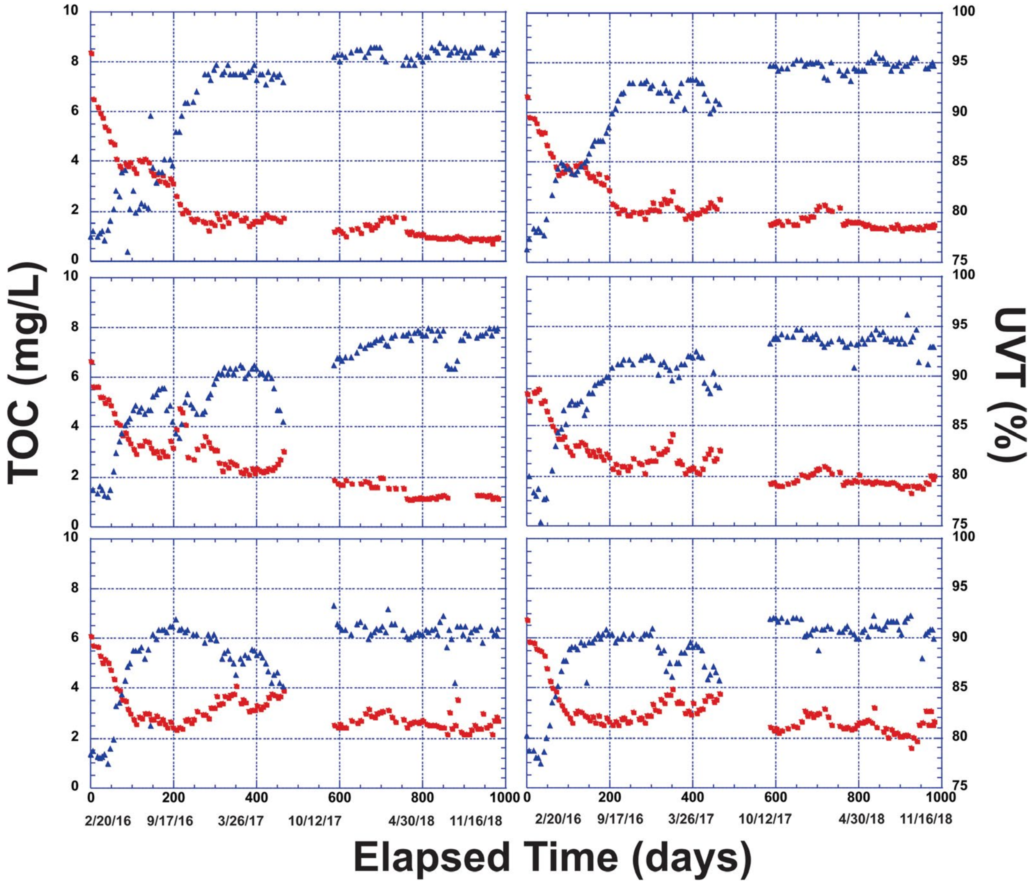


Figure 4. Effluent TOC (red squares) and UVT (blue triangles) from six columns.

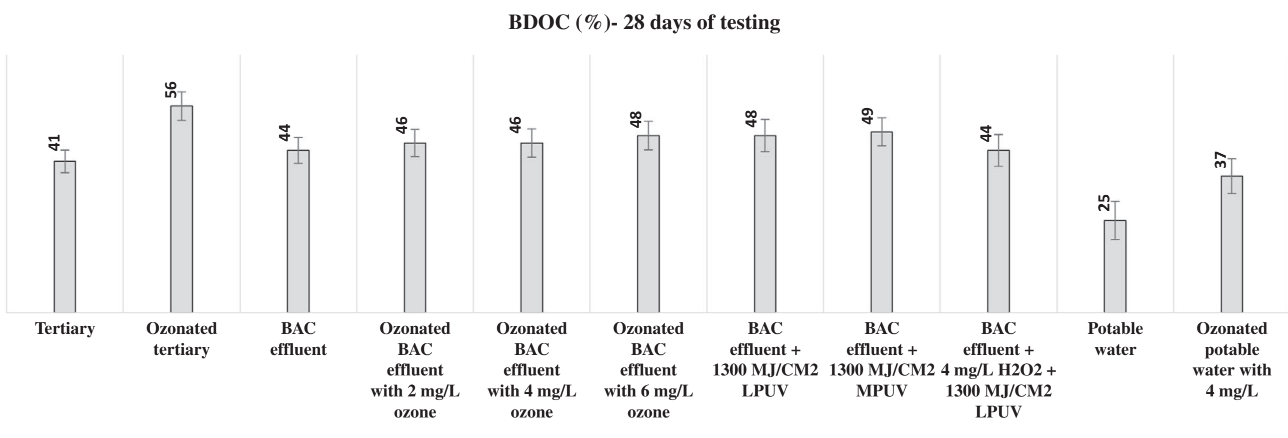


Figure 5. Percent BDOC Reduction in 28 days (mean values and error bars show the standard error of the mean at $p = 0.05$.

breakthrough. The TOC passing through the columns was 40 to 50% biodegradable.

Ozone versus low-pressure UV

In order to determine whether additional oxidation could further increase the BDOC of BAC effluent, 4 mg/L ozone was added to BAC effluent and fed to column 6 beginning in April 2016. BAC effluent irradiated with 1,300 mJ/cm^2 (LPUV) was fed to column 5 from August 2016 until the end of the pilot study. Ozonation or addition of UV oxidizes and can potentially increase the biodegradability of the TOC but in this case the TOC was not reduced significantly. Therefore, TOC of influents to column 5 and column 6 was very similar. Effluent data from these two columns are presented in Figure 4 and in detail in Appendix S1. The two effluents had very similar TOC ranges showing that there is not a considerable improvement in TOC removal between ozonation and LPUV methods. It appears that the high dose of ozone in

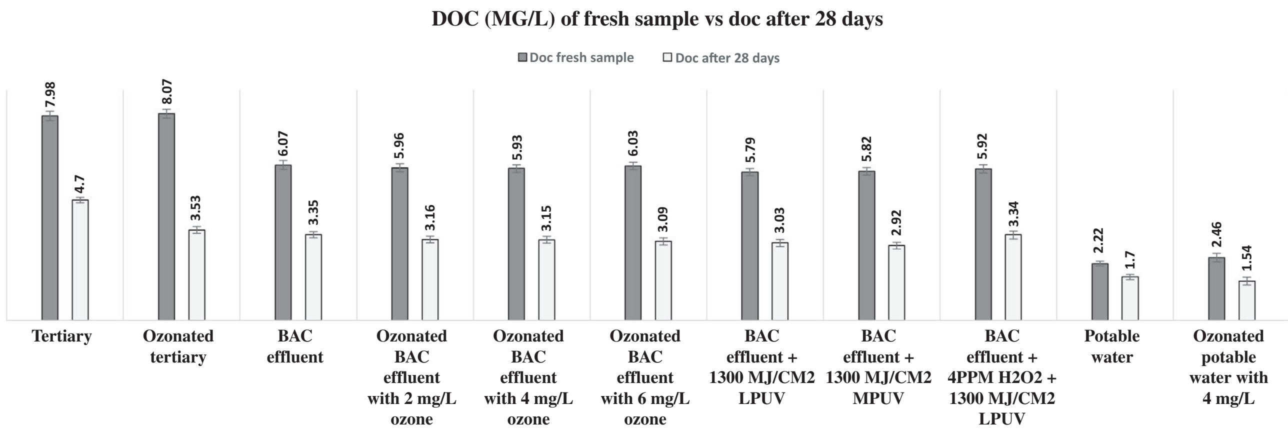


Figure 6. DOC of Fresh sample and DOC after 28 days (mean values and error bars show the standard error of the mean at $p = 0.05$).

the pre-BAC ozonation step (O_3/TOC of 0.7–1.0) effectively converted all the readily reactive TOC. If less ozone had been used in this first step, post-BAC ozonation might have produced more BDOC in BAC effluent. Figure 7 shows a strong correlation of TOC in the effluents of soil columns 5 and 6. BDOC tests show similar results for ozonation post-BAC and LPUV post-BAC with average percent TOC reduction of 55% and 53% for 4 mg/L ozone and 1,300 mJ/cm^2 LPUV, respectively (Figure 6).

Feed dilution with RO permeate

The DDW Groundwater Replenishment Reuse Regulations (GRRRs) were adopted and went into effect on June 18, 2014. The GRRR specifies water quality requirements, including limiting the TOC of wastewater origin. The municipal recycled water contribution (RWC) is

$$\mathrm{RWC} = \frac{\text{Recycled Water Applied}}{\text{Recycled Wate Applied} + \text{Dilution Water}}. \quad (4)$$

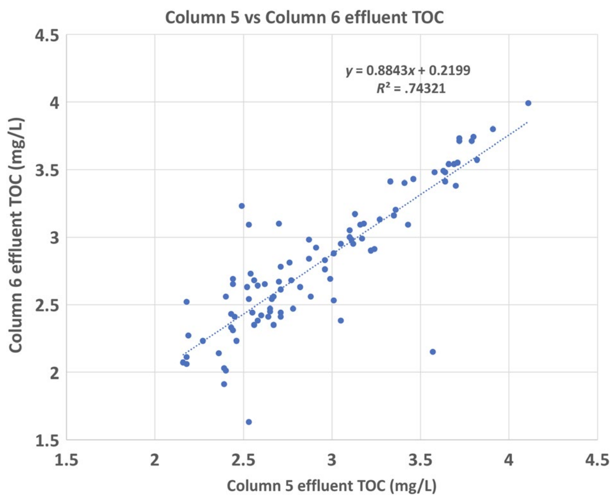


Figure 7. TOC in the effluents of soil columns 5 and 6.

The maximum TOC concentration in the wastewater that can be applied in a surface spreading project is defined as follows:

$$\mathrm{TOC}_{max} = \frac{0.5\ \text{mg/L}}{\mathrm{RWC}}. \quad (5)$$

In effect, this regulatory requirement controls the amount of recycled water that can be applied based on TOC in the recycled water and the amount of dilution water available. One way of reducing TOC is to blend and dilute reclaimed wastewater with RO permeate, which essentially has very little or no TOC (<0.3 mg/L). To evaluate this possibility, blends of BAC effluent and RO permeate from BAC/MF pretreatment were mixed to determine whether blending affects degradability. Additional treatment with LPUV at 1,300 mJ/cm^2 was also performed to reduce the NDMA from the RO permeate, and these blends were used as feed in columns 1, 2, 3, and 4 since August 2016. The HRT in column 3 was increased from 30 days to 180 days at the same time the feed was changed to the 50% blend.

The TOC results in column effluents are presented in Figure 4 and in Appendix S1. The TOC of the effluent in the columns with blends decreased approximately by the ratio of dilution. Dilution of feed water decreased TOC degradation by only 2%–4% (not statistically significant at $p = 0.05$ using the standard error of the mean technique described for Figures 5 and 6). The effluent TOC from columns fed diluted water was consistently lower than those columns without diluted feed.

Impact of HRT

Figure 8 shows the TOC of 50% RO permeate blend (feed for columns 2 and 3) and TOC of effluent from columns 2 and 3. The effluent TOC data are shifted 1 HRT in the graph to account for the column retention time in order to facilitate comparing influents and effluents. The TOC in the effluent of column 3 was higher than effluent of column 2 for the first 34 weeks after increasing the HRT to 180 days. We believe this is due to the wash out of biomass associated with the higher loading rate (lower HRT). After 34 weeks of operation, a new

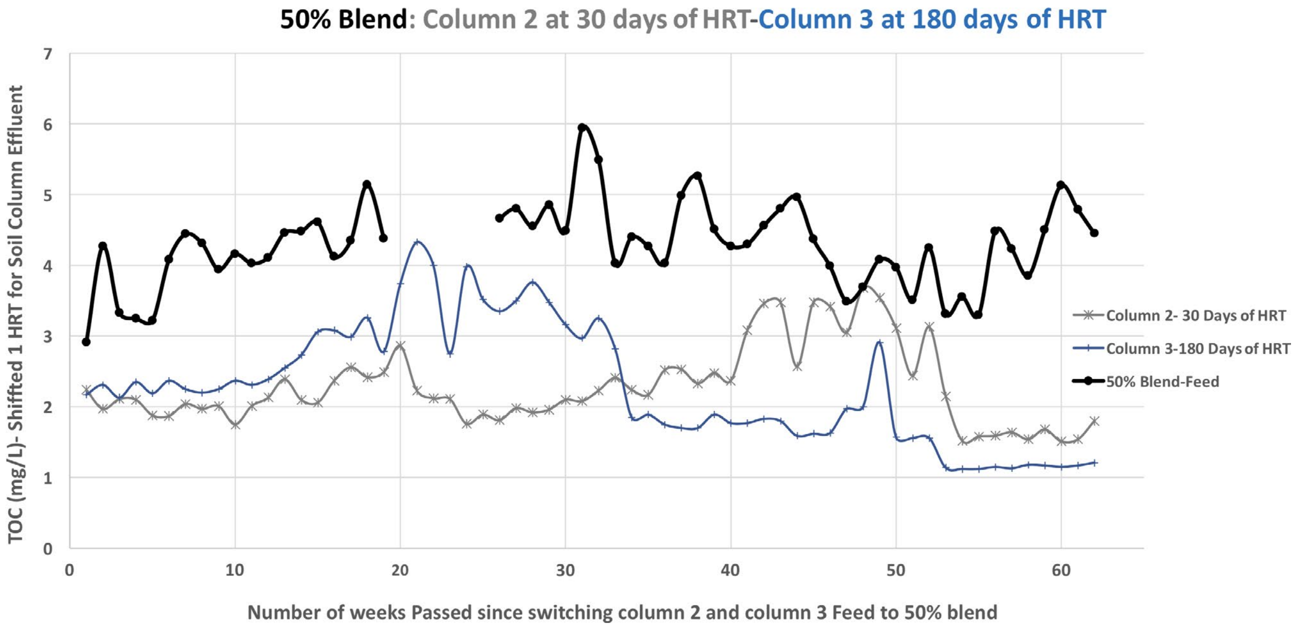
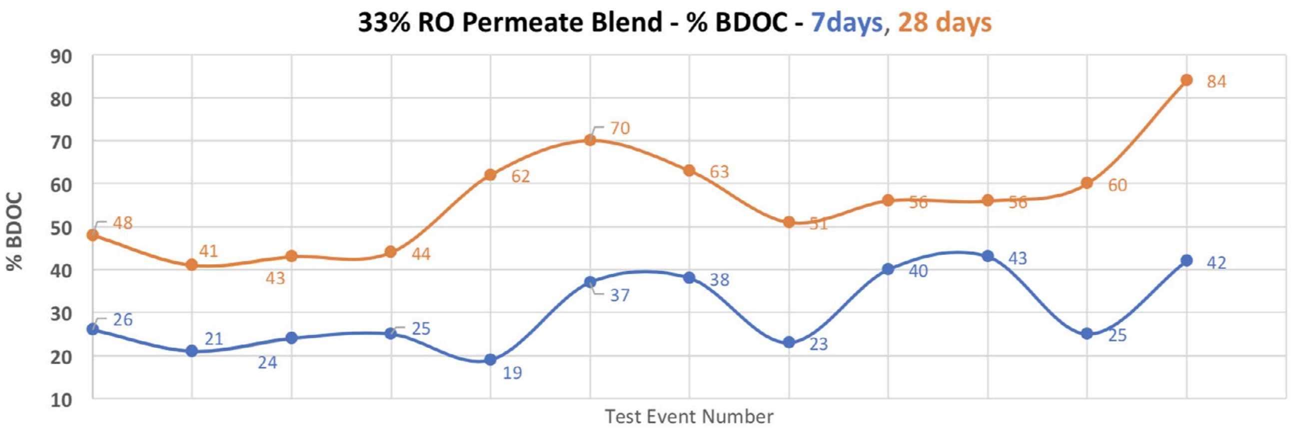


Figure 8. TOC in effluents of columns 2 and 3 after changing feed to blends with RO permeate and increasing HRT of column 3 to 180 days (when the HRT increased to 180 days in column 3, TOC rate to the column decreases that can result in microorganisms die off, hence increased TOC in effluent, until these organisms adjust to the new condition.).



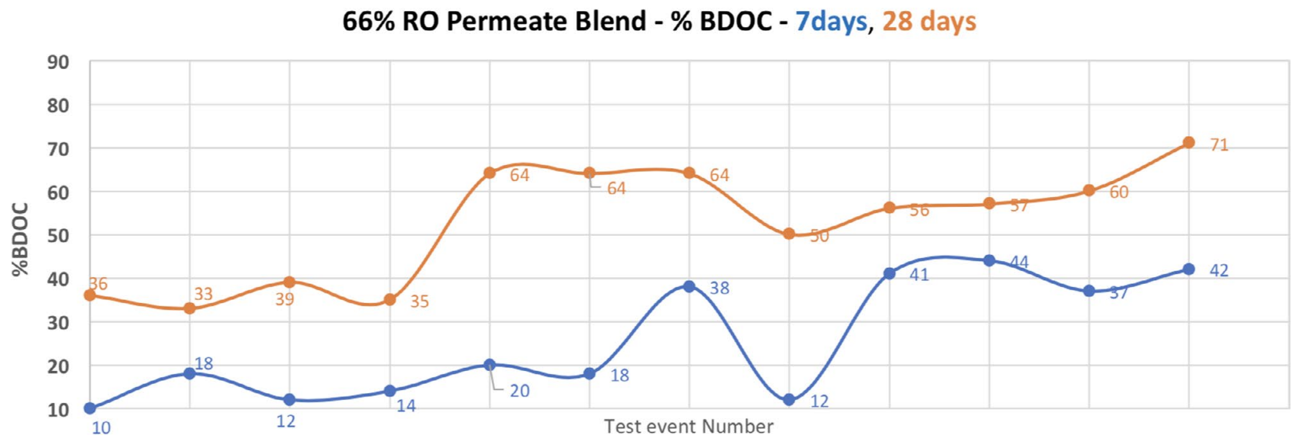


Figure 9. BDOC in percentage for 7 days and 28 days of retention time.

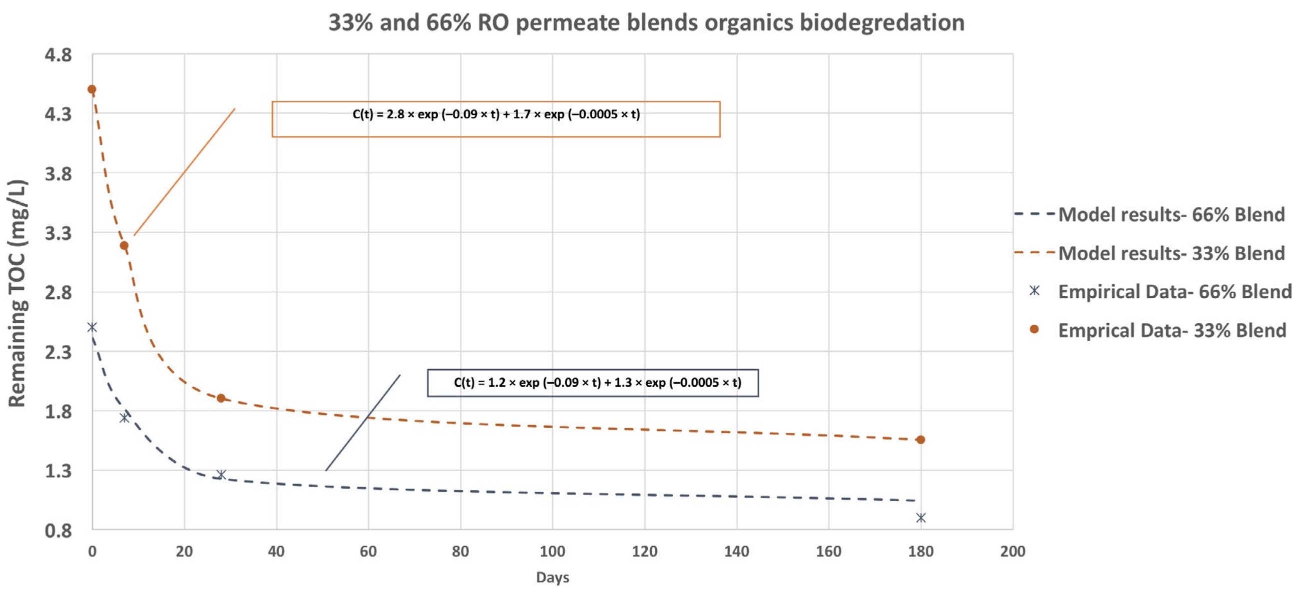


Figure 10. Model fit of remaining TOC.

equilibrium in the 180-day HRT column was established and its effluent TOC decreased and stayed at least 30% less than of the effluent TOC of the 30 day HRT column. Figure 9 shows 7- and 28-day BDOC test results for each of 33% and 66% feed blends. The 7-day BDOC was usually half of the 28-day BDOC, showing that at least 50% of the BDOC exertion is achieved during the first 7 days.

The 7-day and 28-day BDOC results led to the hypothesis that there are two categories of organics in the bulk DOC: slowly and rapidly biodegradables. To verify this hypothesis, two pseudo first-order biodegradation reactions were assumed and results are presented in Figure 10. The 33% blend data were used for calibration using MATLAB's curve fitting application (MathWorks, Natick, MA.). The 66% blend data were used for validation; only the concentrations were fit. Reaction rates used for the 66% blend were the same as those for 33% blend. Microsoft Excel's goal seek function was used to identify the initial concentrations in the equations shown in Figure 10. Similar type of analysis has been done in the past by Fox et al. (2001).

SAT and BDOC correlation

DOC in BDOC reactors supernatant after 28-day retention was compared to TOC in the effluents from columns which had similar feeds. Results are presented in Figure 11. There is a direct correlation between DOC values and TOC in soil column effluents with HRT of 30 days. A linear regression between the two verifies that these two values were very comparable. These results indicate that BDOC testing can closely predict the TOC reduction in soil aquifer treatment systems.

Conclusions

A 2.5-year pilot study was performed at the City of Los Angeles' DCTWRP to evaluate treatment technologies and research procedures to produce low TOC reclaimed water for indirect potable reuse. The goal was to determine the most effective treatment train that produces suitable reclaimed water to be used at the Hanson spreading grounds which recharges one of the main water supplies for the City of Los Angeles. Six pilot columns using soil from the Hanson spreading grounds were fed BAC effluents and operated with variable hydraulic retention times and additional types of treatment. The columns were routinely monitored for a variety of water quality parameters including DOC, BDOC, nitrogen, UVA-254, NDMA, and 34 other CEC.

1. Ozonation and BAC treatment reduced the DCTWRP tertiary effluent DOC from 7 to 10 mg/L to approximately 5 mg/L.
2. In order to explore BDOC as an alternative indicator to TOC, BDOC measurements were made throughout the study. The BDOC results accurately predicted the column effluent TOC within ±5%.
3. The five pilot soil columns operating at 30-day HRT reduced the DOC of the BAC effluents by 48%–50%, to approximately 2.5 mg/L. The 180-day HRT reduced the DOC by 60%, showing that additional biodegradation can be achieved with longer HRT, which was also verified by the BDOC tests. The accurate prediction of the BDOC reactors suggests that column studies are not needed to obtain accurate estimates of the expected biodegradation in soil aquifer treatment. The results of this study can be used to predict soil aquifer treatment performance in removing biodegradable organics through BDOC measurements, which are much less expensive than column studies. Soil columns may be needed to predict removal of other constituents.
4. Influents to the soil columns were diluted with RO permeate during parts of the study but did not affect degradation. Soil column effluent DOCs declined by the expected ratios of the dilution volumes.

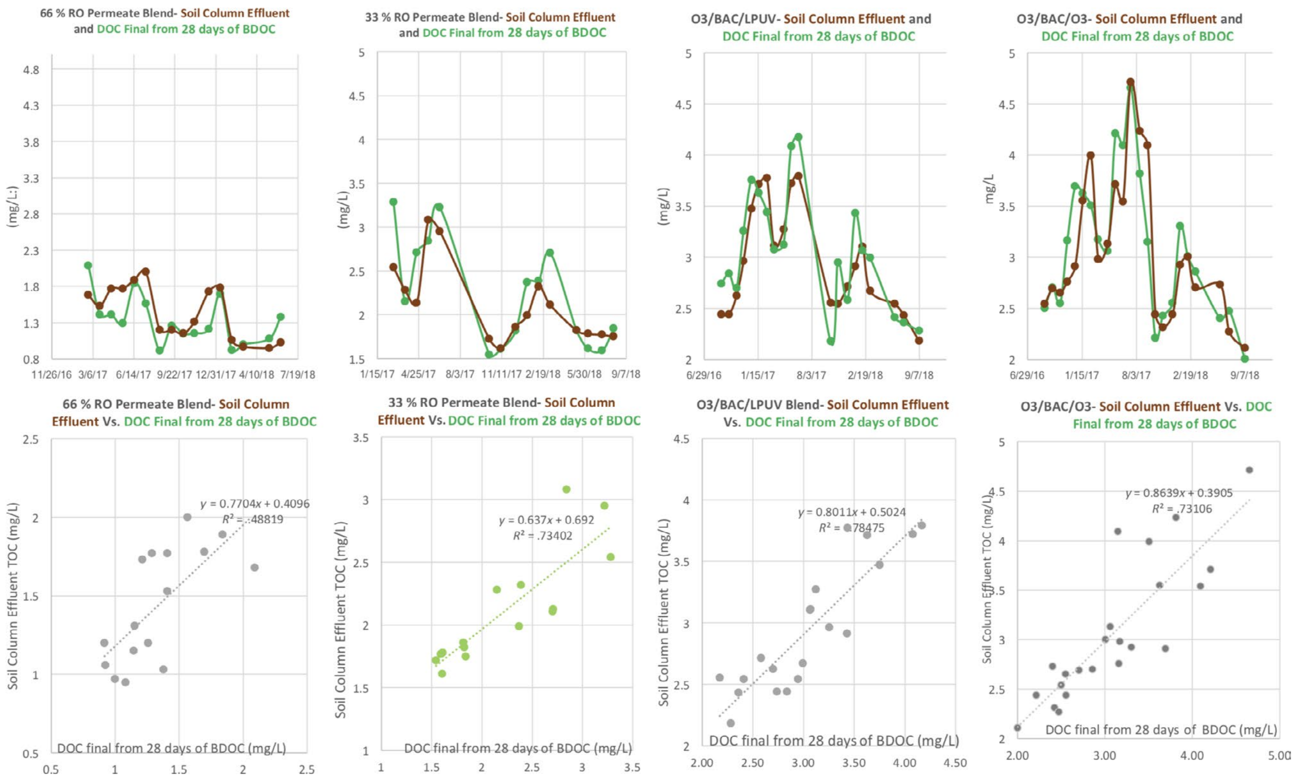


Figure 11. TOC in soil column effluents and DOC in BDOC reactor supernatant after 28 days of retention time.

5. NDMA was measured four times during the study on column feed and effluents. Influent NDMA averaged 15 ng/L. Column effluents were below the MDL (<2 ng/L) showing that NDMA is either biodegraded or adsorbed onto soil. Most of the other 34 CECs including estrogens were reduced to below MDLs.
6. A simple kinetic model was developed that divided the DOC into two parts—a rapidly degrading part and a slowly degrading part. Parameters identified with the 30-day HRT column data were validated with 180-day HRT column data and accurately predicted degradation. The final SAT columns with no RO permeate dilution had effluent TOCs from 1.7 to 2.5 mg/L. Ozonated potable water had a non-biodegradable DOC from 1.0 to 1.5 mg/L. The difference between the two measurements suggests that the wastewater's contribution to the final SAT effluent TOC ranged from 0.7 to 1.4 mg/L.

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