Robert W. Goldsworthy Desalter Foulant Investigation and Performance Assessment

Water Quality Investigation Summary

October 30, 2020

Water Replenishment District of Southern California

TOR E20-001

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Project No:	W9Y29800
Document Title:	Water Quality Investigation Summary
Document No.:	PPS1014201337SCO
Revision:	Final
Date:	October 30, 2020
Client Name:	Water Replenishment District of Southern California
Client No:	TOR E20-001
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File Name:	FinalReport_WQ_Investigation_Final.docx

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Contents

Tables

Figures

Acronyms and Abbreviations

°	degree(s)
°C	degree(s) Celsius
µg/L	microgram(s) per liter
µS/cm	microsiemen(s) per centimeter
ATP	adenosine triphosphate
AWC	American Water Chemicals
bgs	below ground surface
cell/mL	cell(s) per milliliter
CIP	clean-in-place
CU	color unit (s)
CYW	City Yard Well
DO	dissolved oxygen
DOC	dissolved organic carbon
DPW	Delthorne Park Well
EDS	energy dispersive X-ray spectroscopy
EMWD	Eastern Municipal Water District
gfd	gallon (s) per square foot per day
gpd	gallon(s) per day
gpm	gallon(s) per minute
HCO_3	bicarbonate ion
HRSD	Hampton Roads Sanitation District
Jacobs	Jacobs Engineering Group Inc.
LC-OCD	liquid chromatography with online carbon detection
LMW	low molecular weight
LOI	loss of ignition
ME/mL	microbial equivalent(s) per milliliter
mg/L	milligram (s) per liter
MTBE	methyl tert-butyl ether
mV	millivolt (s)
ND	nondetect
NOM	natural organic matter
NTU	Nephelometric Turbidity Unit
ORP	oxidation-reduction potential
PEI	prismatic elemental imaging
RO	reverse osmosis
ROC	reverse osmosis concentrate
ROF	reverse osmosis feed
ROP	reverse osmosis permeate
RWGD	Robert W. Goldsworthy Desalter
SCADA	supervisory control and data acquisition
SEM	scanning electron microscopy
SU	standard unit
TDS	total dissolved solids
UVA	UV absorbance
WRD	Water Replenishment District of Southern California

1. Introduction

The Water Replenishment District of Southern California (WRD) owns the Robert W. Goldsworthy Desalter (RWGD). In 2017, the RWGD was expanded and added two new wells, Delthorne Park Well (DPW) and City Yard Well (CYW). Since the expansion, RWGD has struggled to achieve design production due to reverse osmosis (RO) membrane fouling. Previous investigations (AWC 2017; 2018a, b; 2019) completed for WRD have indicated that the potential source of fouling is humic acids with increased salinity levels present in the DPW. The purpose of this Water Quality Investigation Summary report is to characterize the source and type of RO membrane fouling occurring from the DPW and CYW and the combined influent to the RWGD. This report summarizes the results of the membrane autopsy, well static video survey, flow profiling, and water quality sampling conducted in August and September 2020.

RO membrane performance and water quality data were reviewed to determine representative elements to harvest for the membrane autopsy and at what point to conduct the harvest. RWGD consists of two trains: Train 1 and Train 2 that operate in parallel with equal flow splitting of the reverse osmosis feed water (ROF). Each train operates in two stages in series; the first stage has 42 elements, and the second stage has 24 elements. Based on the duration of operation since the last chemical cleaning, together with train performance characteristics, Train 2, first stage tail element (Position 40), and second stage tail element (Position 22) were chosen to harvest. To accommodate the clean-in-place (CIP) cleaning schedule, elements were harvested on August 25, 2020, and sent to American Water Chemicals (AWC) for autopsy. The results of that autopsy are included in Appendix A and discussed in Section 4 of this report.

To better define the sampling needs, past RO membrane performance, autopsies, and studies were reviewed. The membrane permeability data confirmed City of Torrance operator observations that an immediate reduction in performance occurred when DPW is brought online. Jacobs Engineering Group Inc. (Jacobs) recommended increasing the number of sampling points in DPW's upper screen area to better define the source and characteristic of the foulant.

INTERA/BESST performed a static video survey on DPW on August 18 and at CYW on September 16, 2020, to better characterize each well and confirm screen depths and bottom of well measurements, and to capture visual fouling in the well. Appendix B provides the results of this static video survey in the INTERA/BESST report.

Well flow profiling and water quality analysis are both necessary to provide a comprehensive assessment of the water quality constituents that may be responsible for the RO membrane fouling. Well profiling, which provides the flow characteristics of a well, was performed at DPW on September 14 and at CYW on September 16, 2020 by INTERA/BESST. The results from the flow profiling are included in Appendix B and discussed in Section 2 of this report.

Based on the flow characteristics, the water sampling depths were further refined, and INTERA/BESST performed depth-specific sampling at DPW on September 15 and CYW on September 17, 2020. Jacobs conducted water quality sampling of (1) the RWGD feed water prior to pretreatment chemical addition, (2) in the ROF after chemical addition and cartridge filtration, (3) in the reverse osmosis concentrate (ROC), and (4) in the reverse osmosis permeate (ROP) on September 17, 2020. The flow split from the wells was 54 percent from CYW and 46 percent from DPW during all sampling events. As described in the *Robert W. Goldsworthy Desalter Investigation Plan* (Jacobs 2020), a total of 18 samples were collected, including 6 samples from the CYW, 8 samples from the DPW, and 4 samples from the RWGD. These sample locations were selected to assess water quality differences as a function of well depth, as well as water quality changes resulting from intra- and inter-well blending, RO pretreatment, and treatment. Clinical Laboratories of San Bernardino analyzed each of the samples. Appendix B provides results of the sampling effort.

In addition to basic water chemistry and organic and inorganic analyses that were conducted by Clinical Laboratories, INTERA/BESST and Jacobs conducted several field analyses. INTERA/BESST collected the following measurements:

- pH
- Temperature
- Conductivity
- Dissolved oxygen (DO)
- Oxidation-reduction potential (ORP)

Jacobs used a luminometer to measure adenosine triphosphate (ATP), which is a surrogate for biological activity, to evaluate the potential for biopolymer production at various well depths and through the treatment process. DOC-Labor in Germany conducted liquid chromatography with online carbon detection (LC-OCD) testing on select well and plant samples and on the membrane element foulant to more fully characterize the organics present because organics have been suspected as the primary cause of RO fouling. Appendix C provides the LC-OCD results for the water samples; the LC-OCD results for the membrane foulant (after ultrasonification) are included in AWC's report in Appendix A. All of the water quality results are summarized and discussed in Section 3 of this report.

2. Well and RWGD Operation

The DPW and CYW flow were relatively consistent over the 4-day sampling period. The supervisory control and data acquisition (SCADA) system results for the week of testing are shown on Figure 2-1. A smaller subset of data was calculated from the 15-second SCADA system data between 8:30 a.m. and 3:00 p.m. each day of testing during the active flow profiling and depth-dependent sampling efforts, as shown in Table 2-1.

During the testing period, the relative fluctuations were less than 5 percent for each well. However, as show on Figure 2-1, the daily fluctuations for CYW are greater than for DPW. The City of Torrance reported (Goldsworthy Operations, pers. comm. 2020) that the CYW was rehabilitated in spring 2020, but during the video survey of the well, approximately 10 feet of silt and sand buildup was observed. Operations staff shared that the CYW pump operation tends to fluctuate more than the DPW pump, which may be caused by control programming, system hydraulics, and other factors. Further investigations would be required to determine the cause of CYW fluctuations. Fortunately, the flow rates are within the statistical allowance by INTERA/ BESST for accurate flow profiling and mass balancing for each well.

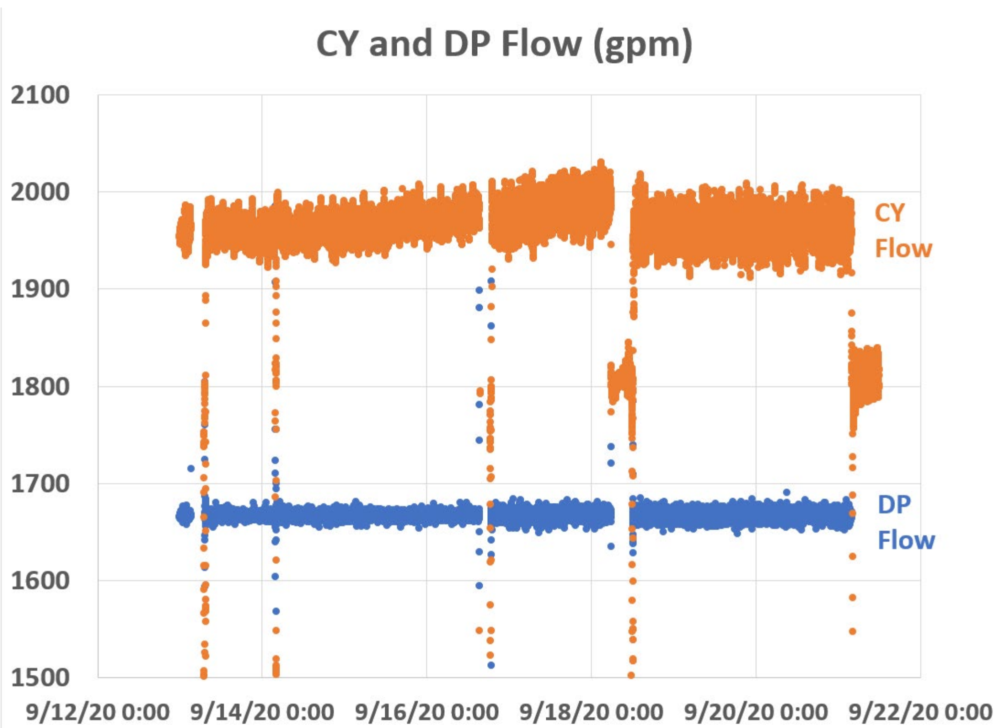


Figure 2-1. SCADA System FlowResults for Week of Testing

Table 2-1. SCADASystem Flow Parameters during Testing

Parameter	DPW Flow (gpm)	CYW Flow (gpm)
Average	1,667	1,978
Maximum	1,680	2,016
Minimum	1,649	1,934
Percent Variation	1.9	4.2

Notes:
gpm = gallon(s) per minute

2.1 Calculating the Flow Profile

As shared in INTERA/BESST's report in Appendix B, the dynamic flow profiling work was conducted using the tracer-pulse method. The flow profile was calculated using the tracer dye travel times as follows:

1) Average flow velocity at each injection depth was calculated by dividing the distance between sequential pairs of injection depths by the difference in travel times.
2) With calculation of the well casing's cross-sectional area, cumulative flow was calculated at each depth interval by multiplying average velocity by the cross-sectional area.
3) The zonal flow contribution from each interval between injection depths was calculated using the difference in cumulative flow measured at each injection depth.
4) Percent flow contribution from each interval between injection depths was calculated by dividing the average wellhead discharge rate (that is, 1,667 gpm for DPW and 1,978 gpm for CYW) by the zonal flow contribution from each interval.
5) Lastly, the average zonal flow per unit screen length was calculated for each interval by dividing each zonal flow contribution by the associated interval length – which provides a relative sense of the transmissivity of each zone.

The flow profile serves as a basis for the dynamic water quality profiles.

2.2 Delthorne Park Well Flow Profile

INTERA/BESST performed flow profiling of DPW on September 14, 2020, and is summarized on Figure 2-2, which shows percent well flow by depth. Approximately 68 percent of the flow (or 375 gpm) is produced from the upper screen, with the remaining 32 percent coming from the lower screen interval. Within the upper screen, the 330-foot to 340-foot- and 360-foot- to 370-foot-below-ground-surface (bgs) screen intervals contribute the largest flows at 19 percent and 15 percent (of total flow), respectively. In the lower screen, the 400-foot- to 420-foot-bgs screen interval contributes the largest flow at 15 percent (of total flow). The screen section from 370 feet to 460 feet bgs, where discoloration was observed on the screen in the video survey, does not seem significantly plugged from the encrustation, as it contributes approximately 28 percent of the total flow. The bottom 65 feet (435 to 500 feet bgs) of the lower screen contributes minimal amount of flow, with only approximately 10 percent of the total flow coming from that section.

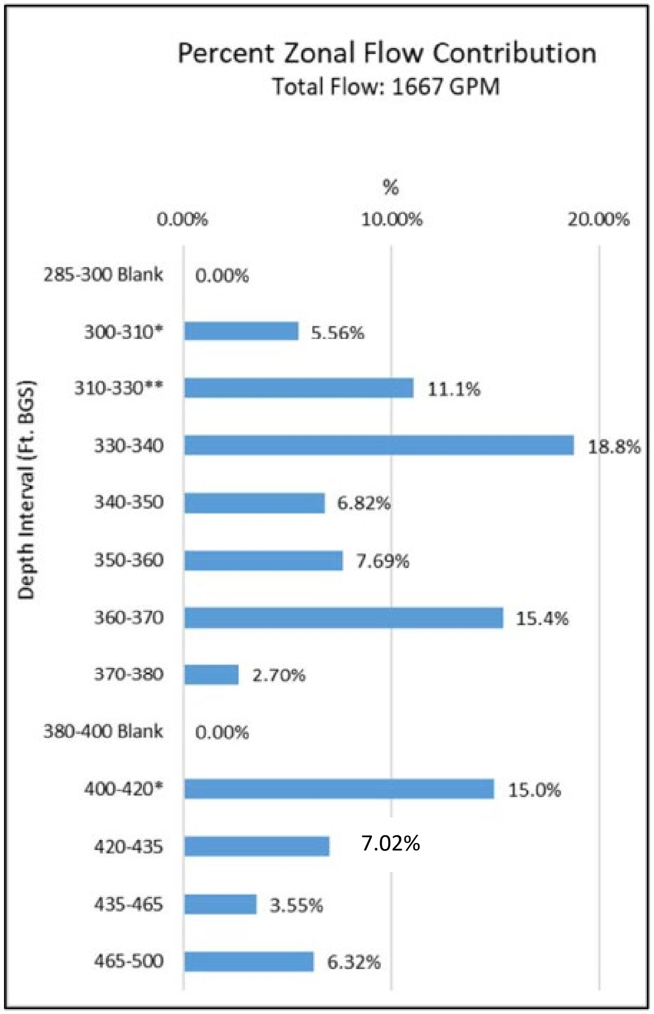
Dye return times were unstable from 285-foot- to 320-foot-bgs depths, indicating turbulent flows at those depths. Therefore, flows from the 300-foot- to 310-foot-bgs and 310-foot- to 330-foot-bgs intervals were estimated.

The DPW flow profile is generally consistent with the spinner log data gathered at the time of construction, as shown in Table 2-2. In both measurements, most of the flow comes from the upper screen area. The percent zonal flow contribution is shown on Figure 2-2. The flow rates used for the mass balancing effort are shown on Figure 2-3 as gpm per interval. The column to the right is grouped to be consistent with the water quality sampling intervals.

Table 2-2. Delthorne Park Well Flow Profiling Data Comparison

Screened Area	Flow at Construction (%)	Flow on September 14, 2020 (%)
Upper Screen Area	78	68
Lower Screen Area	22	32

Notes:
% = percent



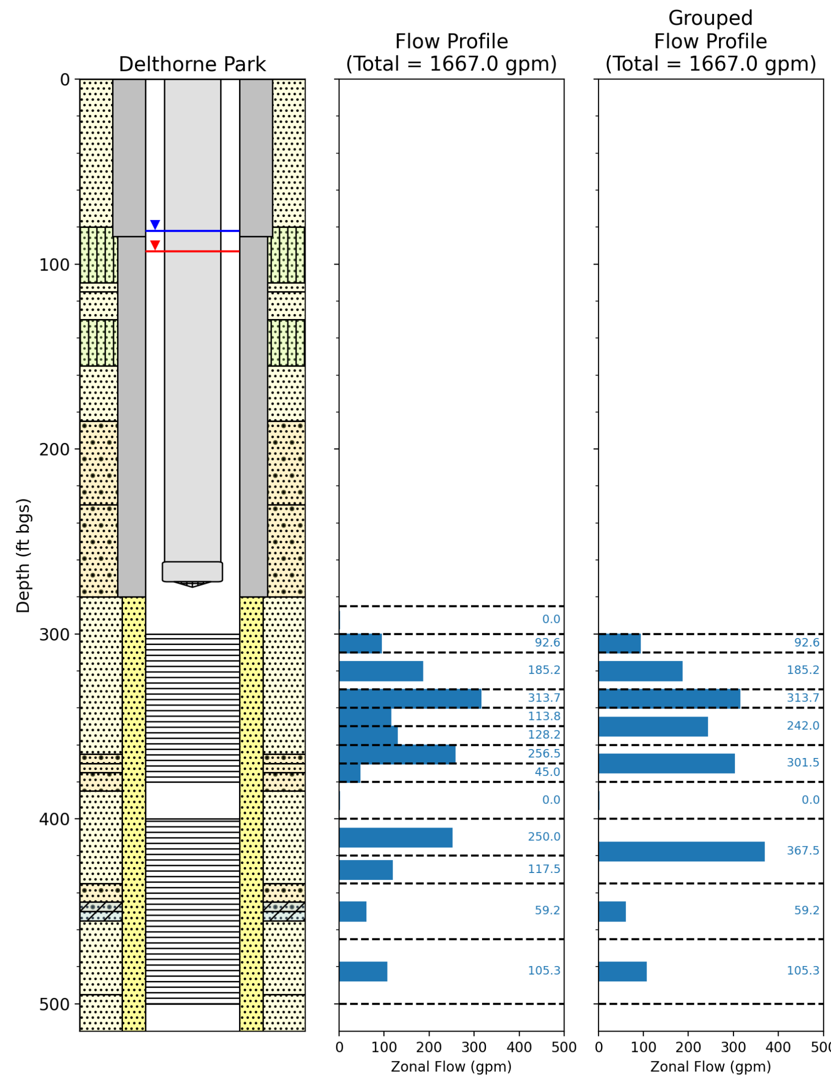


Figure 2-2. Delthorne Park Well – Overall Percent Zonal Flow Contribution

(Also provided in AppendixB, INTERA/BESSTReport, Ocbber 2020)

Figure 2-3. Delthorne Park Well – Dynamic Flow Profile (gpm per depth interval)

(Also provided in AppendixB, INTERA/BESSTReport, Ocbber 2020)

2.3 City Yard Well Flow Profile

INTERA/BESST performed flow profiling of CYW on September 16, 2020 and is summarized in Table 2-3 and on Figure 2-4, which shows percent well flow by depth. These values are based on a total average flow of 1,978 gpm for the day of testing. Most of the flow (79 percent) is produced from the upper screen, with the remaining 21 percent coming from the lower screen interval. Within the upper screen, the top 10 feet (370 feet to 380 feet bgs) produce most of the flow, contributing approximately 53 percent of the total flow. Within the lower screen, the top 10 feet (430 feet to 440 feet bgs) seem to contribute a bulk of the flow, accounting for approximately 14.5 percent of the total flow at the wellhead.

The static video survey of CYW did indicate that the bottom of the well was 549.5 feet bgs, which means approximately 10 feet of silt accumulation at the bottom of the well since the well rehabilitation was completed on March 24, 2020 (Bautista, pers. comm. 2020).

The percentage of flow in the lower screen area, estimated at 21 percent, or 409 gpm, is higher than the spinner log data gathered when the well was constructed, 14 percent of 2,533 gpm, or 355 gpm. The percent zonal flow contribution is shown on Figure 2-4. The flow rates used for the mass balancing effort are shown on Figure 2-5 as flow contributions per interval. The column to the right is grouped to be consistent with the water quality sampling intervals.

Table 2-3. City Yard Well Flow Profiling Data Comparison

Screened Area	Flow at Construction (%)	Flow on September 14, 2020 (%)
Upper Screen Area	86	79
Lower Screen Area	14	21

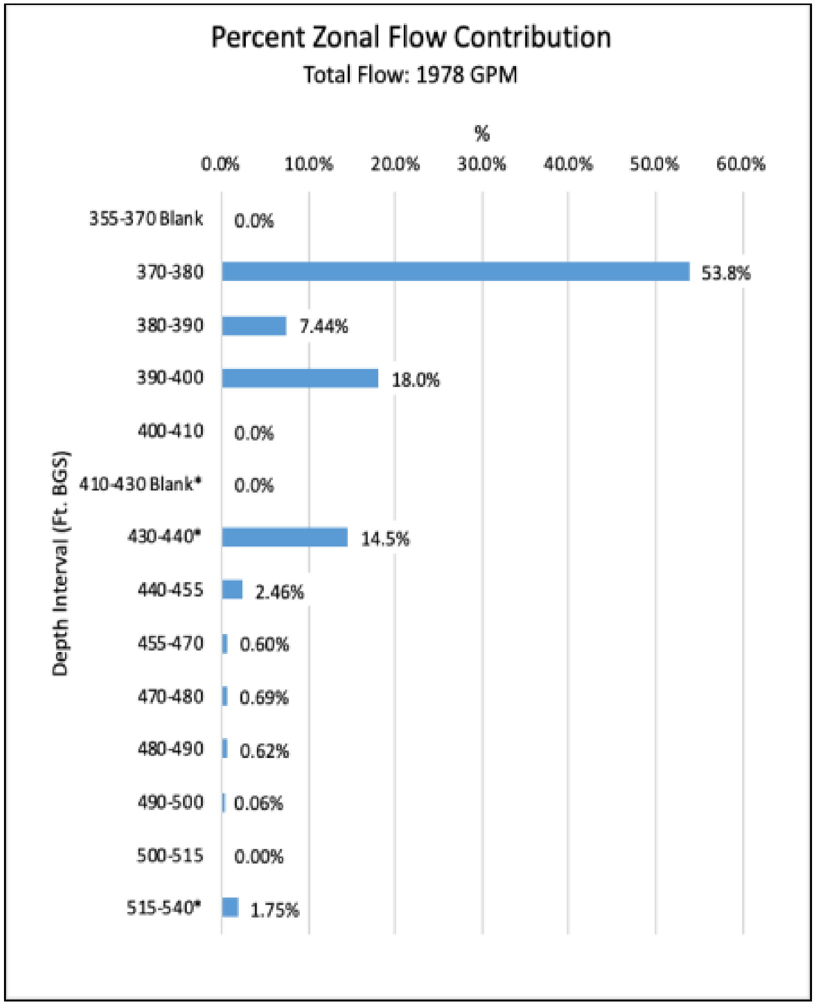


Figure 2-4. City Yard Well – Overall Percent Zonal Flow Contribution

(Also provided in Appendix A, INTERA/BESST Report, October 2020)

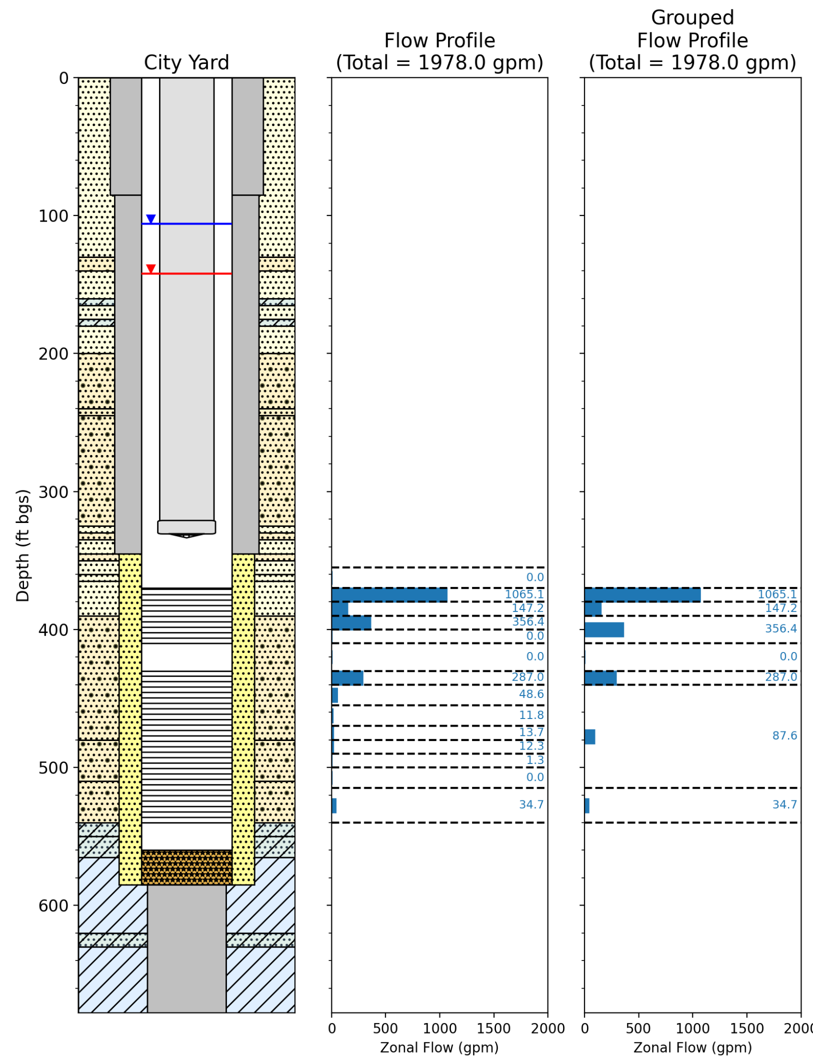


Figure 2-5. City Yard Well – Dynamic Flow Profile (gpm per depth interval)

(Also provided in Appendix A, INTERA/BESST Report, October 2020)

2.4 Reverse Osmosis Membrane Operation

To better evaluate the sampling data, RWGD operation prior to and during the week of sampling was observed. Table 2-4 summarizes the cleaning frequency in the month before and immediately following water quality sampling. Normally, the RO train cleaning protocol alternates between a full CIP conducted with AWC's C-227 membrane cleaning formula and a less intensive CIP with sodium hydroxide (at pH 12), at 4-week intervals. Cleaning of the two trains is normally staggered by 1-3 weeks to allow for constant operation of the plant. Prior to sampling, Train 1 operated for 14 days (following a caustic CIP), while Train 2 operated for 21 days following a full CIP.

Table 2-4. RWGD Membrane Clean-in-Place Schedule

Type of Cleaning	Train 1	Train 2
Average Duration Between CIPs from Jan – Sept 2020	28 days	28 days
Last Full CIP	August 5, 2020	August 25, 2020
Last Caustic CIP	September 1, 2020	None
Time Since Last Cleaning (days)	14 days	21 days
Sampling Effort	September 14-17, 2020	
Caustic CIP	September 18, 2020	September 22, 2020

Permeability and recovery percentage for Trains 1 and 2 during the 3-month period prior to, and 1 month following, water quality sampling is trended on Figures 2-6 and 2-7. As shown, the RWGD is operating at a recovery of 70-75 percent, reduced from the 80 percent design recovery of the facility. Train 2 is operating at a Stage 1 flux of approximately 11.5 gallons per square foot per day (gfd) and Stage 2 flux of approximately 7.5 gfd, reduced from a 12-gfd design flux for both stages.

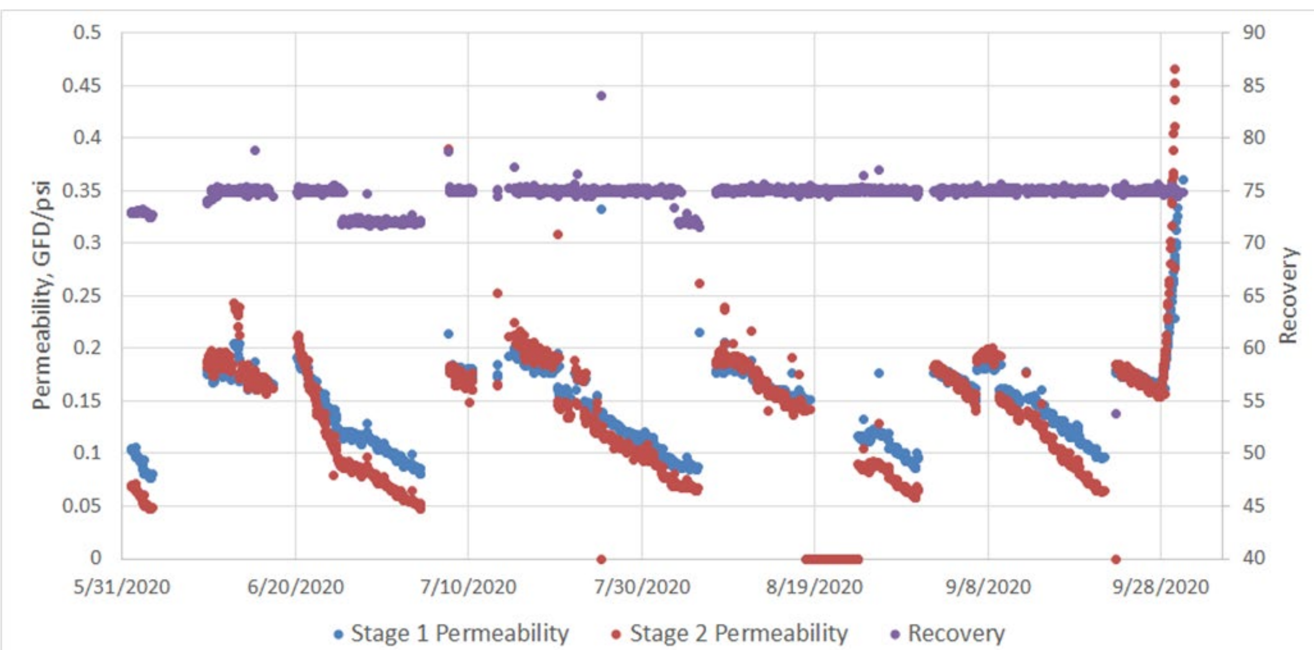


Figure 2-6. Train 1 Reverse Osmosis Performance Data during Sampling Effort Train 1 (June – October 2020)

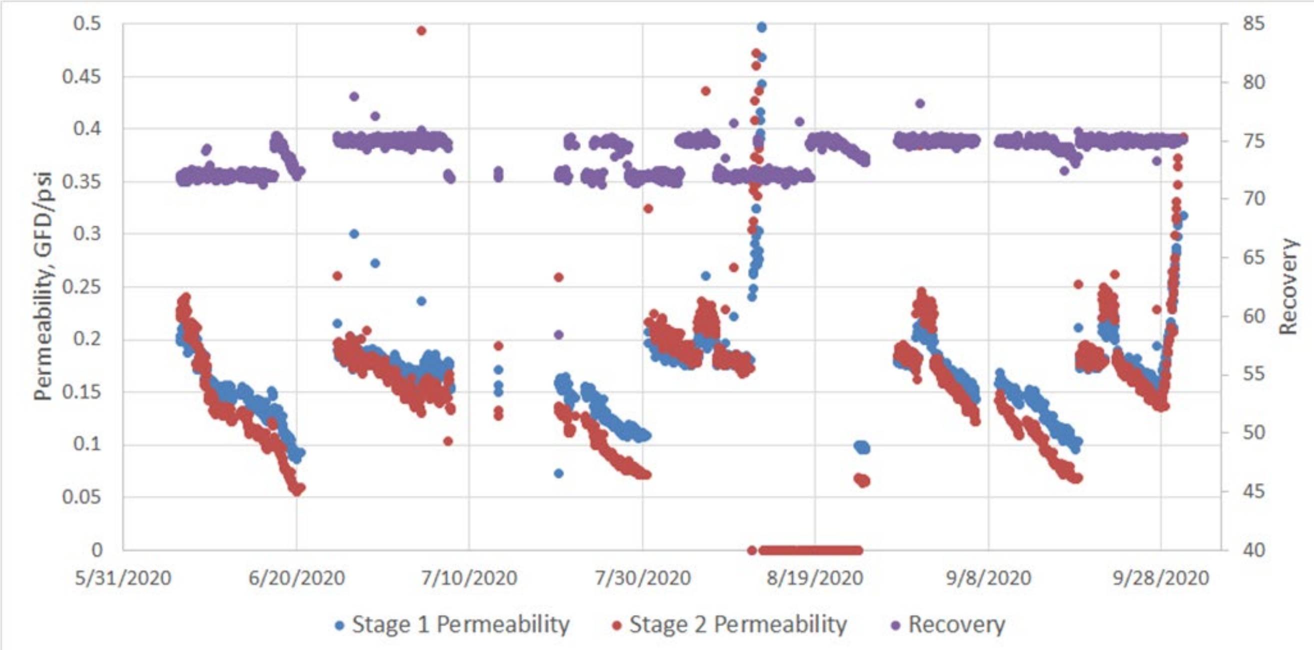


Figure 2-7. Train 2 Reverse Osmosis Performance Data during Sampling Effort Train 2 (June – October 2020)

2.4.1 Reverse Osmosis Operation after Delthorne Park Well Chlorination and when Treating Only Delthorne Park Well Water

Figure 2-8 shows the specific flux of Train 2 after chlorination of DPW and after the CYW was shut off and the RWGD was only treating DPW water. This figure was developed from RO operating data, shared by WRD (Bautista, pers. comm. 2020). The DPW has only been disinfected once since well start-up. Disinfection consisted of adding 500 milligrams per liter (mg/L) of chlorine to the DPW on July 23, 2019 (Goldsworthy Operations, pers. comm. 2020). The single disinfection event did not appear to improve RO performance when DPW was returned to service on August 6, 2019, just as CYW was removed from service, as shown by the steep permeability decline after August 7 when treating only DPW water.

According to the Figure 2-8 data supplied by WRD, this impaired performance was repeated twice in August 2019 when the RO was only treating DPW water, suggesting higher fouling potential associated with the DPW as compared to the CYW. The recovery rates at this time were 75 percent, and the stages were operating in a staggered flux, with Stage 1 approximately 12 gfd and Stage 2 at approximately 7 gfd. The flow split prior to disinfection of the well was approximately 65 percent CYW and 35 percent DPW. Immediately after disinfection, the flow was 100-percent CYW. After August 6, 2019, the flow was 100 percent DPW.

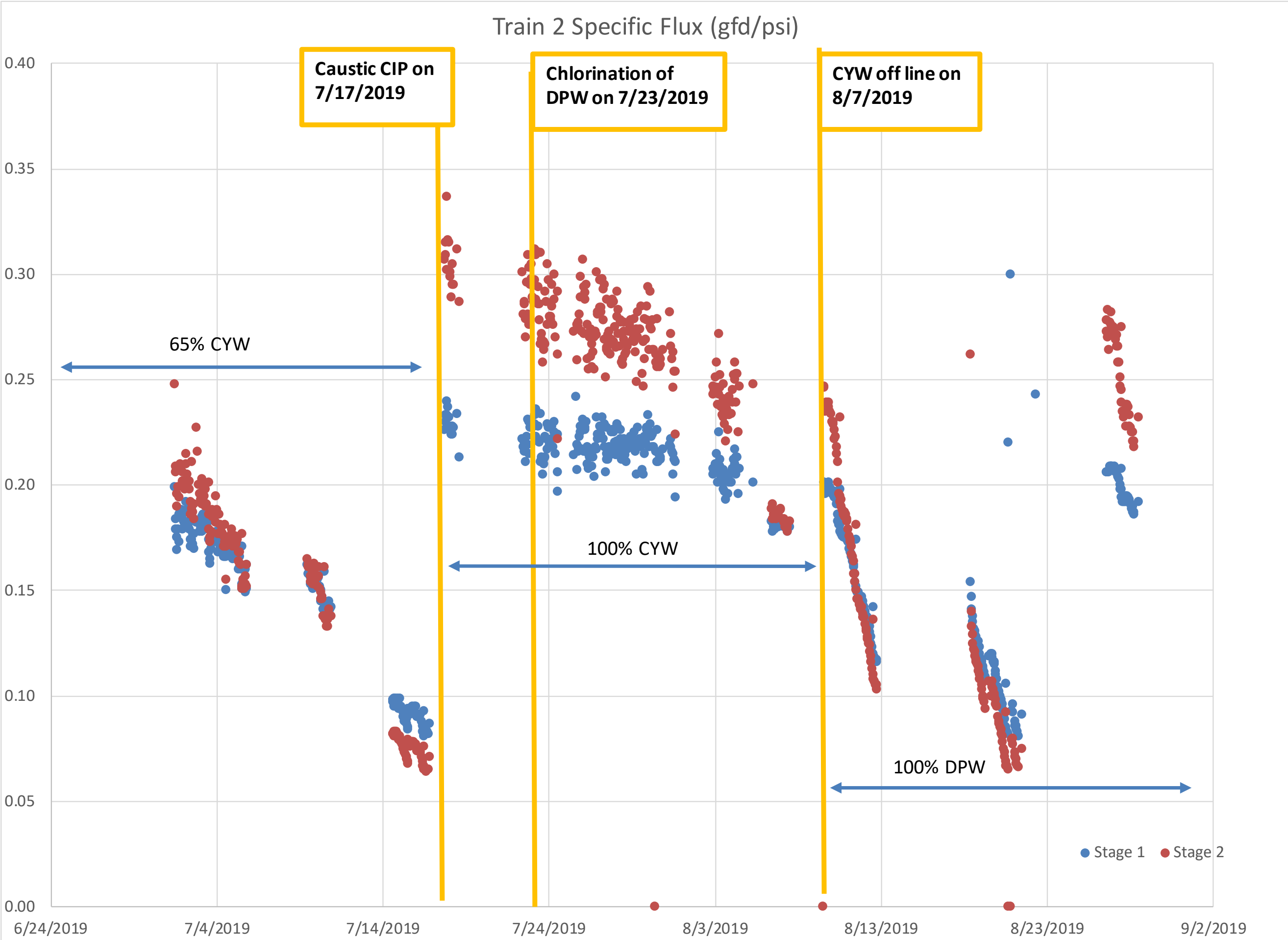


Figure 2-8. Train 2 Reverse Osmosis Performance afterDelthorne Park Well Chlorination and when Treating only Delthorne Park Well Water

2.5 Cartridge Filter Operation

During the week of sampling, the cartridge filters experienced high differential pressure, indicating the need for replacement, which requires plant shutdown. After discussion with City of Torrance operators, WRD staff, and the Jacobs team, it was determined that filter replacement should occur after flow profiling on Wednesday, September 16 and prior to the sampling effort on Thursday, September 17, 2020, to reduce the risk of an unplanned plant shutdown during sampling, while reducing the disruption of the sampling effort.

Cartridge filters from all three housings were replaced, and photos of the filters are shown on Figure 2-9. Fouling was observed on all filters; and a granular, silty substance was observed both on the filters and at the bottom of the housing. The cartridge filter autopsy previously conducted on August 19, 2019, by AWC indicated the deposits on the filter consisted mainly of silts and clays, iron disulfide (pyrite), and calcium carbonate. However, the color of the material deposited on the autopsied cartridge filters on Figure 2-10 differed substantially from that on Figure 2-9. The former was greenish in color, while the latter was dark brown, similar to the color on the RO elements autopsied as part of this study. Although no analyses were performed on the post-sampling filters, the color similarity suggests that organics could also be fouling the cartridge filters.

Samples of the DPW-CYW blend, ROF, ROP, and ROC used for mass balancing of the RWGD were taken on September 17, 2020, after the cartridge filters were replaced.

The silt and sand sample was taken from the bottom of the filter when the cartridges were removed. Dark grit was seen being washed from the bottom of the filter.

Figure 2-9. Cartridge Filters during Replacement on September 16, 2020

Figure 2-10. 2019 Cartridge Filter Autopsy Photo

Photo courtesy of AWC

3. Water Quality Analysis

This section presents the results of the field measurements; water quality analyses (including LC-OCD); and mass balances for the DPW, CYW, and RWGD.

3.1 Calculating Well Water Quality

In the following sections, the laboratory results are summarized for each well and RWGD in tabular form, and figures show the mass balanced concentrations. The intent of mass balancing the analytes based on weighted flow percentage is to estimate an analyte's zonal concentration, which is an estimate of its concentration within the aquifer (prior to entering the well) at a specific depth. The zonal concentrations for each analyte of concern were calculated by subtracting the difference in cumulative flow-weighted concentrations between each sample depth.

For example, the zonal calcium concentration for DPW between 330 and 340 feet bgs is 309 mg/L. This value is calculated by taking the difference in concentrations between the depth sample points, in this case, 480 mg/L at 330 feet bgs and 530 mg/L at 340 feet bgs, as shown in Table 3-1, weighting by the cumulative flow at each point, and dividing by the portion of flow from that interval. This results in the following equation:

*(480 mg/L *1,389 gpm – 530mg/L*1 ,075 gpm)/ (1 ,389 gpm -1,075 gpm) = 309 mg/L*

Table 3-1. Delthorne Park Well – Calcium Mass Balance Example

Well Depth (ft bgs)	Cumulative Flow (gpm)	Measured Calcium (mg/L)
330	1,389	480
340	1,075	530

Notes:

ft = foot (feet)

The theoretical average wellhead concentration was calculated by summing each zonal concentration and dividing by the total discharge rate of the well.The data and results are impacted by non-ideal flow conditions (such as turbulent flow in and around the pump intake) and other field variability in sampling conditions. As such, the analyzed flow and estimated concentration for different depth intervals are susceptible to sampling and mass balance error.

The data were checked, and if a mass balance error was calculated by comparing the theoretical and measured wellhead concentrations, then the concentration was set as half the detection level, as a negative concentration is not possible. The zonal concentrations are based on the specific well blend and flowrates at the time of sampling. With small flowrate variations, the percent contributions of the constituents are expected to be proportional. However, when the wells are operated at flowrates that are significantly different than at the time of sampling, or if the pump inlet depth is modified, then the water quality profiles could change.

3.2 Delthorne Park Well – Depth-specific Water Quality

Groundwater samples were analyzed for the constituents of concern specified in the *Robert W.Goldsworthy Desalter Investigation Plan* (Jacobs, 2020). Laboratory analytical reports for groundwater samples collected from the DPW on September 15, 2020, are included in Appendix B and summarized in Table 3-2. These results are the raw data for the samples collected directly from the well and have not been adjusted for flow contributions from the aquifer at various depths in the well; thus, the results in Table 3-2 only reflect the analyte concentrations within the well and not analyte concentrations within the aquifer. Mass balance calculations have been conducted for true color and inorganics to adjust measured concentrations for flow contributions at various depths; these zonal concentrations represent analyte concentrations within a specific aquifer zone and are described in Sections 3.2.3 and 3.2.4.

Table 3-2. Delthorne Park Well Water Quality Summary

	Raw Data										
				Wellhead	Upper Screen				Blank	Lower Screen	
			Reporting	DPWH	DP1	DP2	DP3	DP4	DP5	DP6	DP7
	Parameter	Unit	Limit	0 ft	310 ft	330 ft	340 ft	360 ft	385 ft	435 ft	465 ft
Field	pH	SU	-	7.7	-	7.57	7.6	7.45	7.37	7.18	7.21
	Temperature	°C	-	22.6	-	25.2	25.5	23.6	27.4	23.3	23.5
	Conductivity	µS/cm	-	4,494	-	6839	7602	9495	10222	17907	19393
	ORP	mV	-	-33.3	-	-42.2	-63.7	-78.8	-49.1	-49.8	-62.5
	DO	mg/L	-	0.07	-	0.11	0.06	0.06	0.26	0.09	0.03
	Turbidity	NTU	-	0.29	-	0.23	0.8	1.33	0.41	0.36	0.45
	ATP	ME/mL	-	5,077	11,206	14,224	12,349	52,690	72,814	23,967	34,578
Lab	pH	SU	-	7.8	7.8	7.9	7.8	7.6	7.7	7.4	7.5
	Conductivity	µS/ cm	2	4,500	4,900	6,800	7,400	9,500	10,000	18,000	20,000
	TDS	mg/L	5	2,800	3,100	4,500	5,000	6,400	7,000	12,000	12,000
	HCO_3	mg/L	5	200	-	-	-	-	-	-	-
Lab – Inorganics	Aluminum	µg/L	50	16	-	-	-	-	-	-	-
	Barium	µg/L	100	62	-	-	-	-	-	-	-
	Calcium	mg/L	20	280	340	480	530	680	770	1,200	1,200
	Chloride	mg/L	4	1,300	1,500	2,200	2,400	3,100	3,400	6,500	7,100
	Fluoride	mg/L	0.1	0.44	-	-	-	-	-	-	-
	Iron	µg/L	100	15	19	29	ND	ND	ND	14	ND
	Potassium	mg/L	10	11	-	-	-	-	-	-	-
	Manganese	µg/L	20	170	200	290	320	420	460	880	790
	Magnesium	mg/L	10	79	-	-	-	-	-	-	-
	Nitrate	mg/L	0.4	ND	-	-	-	-	-	-	-
	Orthophosphate	mg/L	0.02	0.2	-	-	-	-	-	-	-
	Silica	mg/L	0.5	35	-	-	-	-	-	-	-
	Sodium	mg/L	10	510	-	-	-	-	-	-	-
	Sulfate	mg/L	0.5	320	-	-	-	-	-	-	-
	Strontium	µg/L	630	2400	-	-	-	-	-	-	-
Lab – Organics	True Color-Filtered	CU	3	15	7.5	7.5	7.5	7.5	5	ND	ND
	UVA-254	cm^{-1}	0.005	0.04	0.029	0.033	0.036	0.039	0.04	0.03	0.036
	DOC	mg/L	-	2.27	-	-	1.976	-	2.045	-	-
	Hydrophobic DOC	mg/L	-	0.964	-	-	0.647	-	0.764	-	-
	Hydrophilic DOC	mg/L	-	1.308	-	-	1.328	-	1.281	-	-
	MTBE	µg/L	3	ND	-	-	ND	-	ND	ND	-

Notes:

– = not applicable
°C = degree(s) Celsius
µg/L = microgram(s) per liter
µS/cm = microsiemen(s) per centimeter
DOC = dissolved organic carbon
HCO_3 = bicarbonate ion
ME/mL = microbial equivalent(s) per milliliter
MTBE = methyl tert-butyl ether
NTU = Nephelometric Turbidity Unit
SU = standard unit
TDS = total dissolved solids
UVA = UV absorbance

3.2.1 Oxidation-Reduction Potential and Dissolved Oxygen

Analytical results for ORP ranged from -77.8 to -33.3 millivolts (mV), while DO levels ranged from 0.03 to 0.26 mg/L. Both low ORP and DO values indicate anoxic well conditions.

3.2.2 Adenosine Triphosphate

As the primary energy carrier for all forms of life, ATP is measured to indicate the activity level of biological organisms. For this study, ATP was measured to assess bacterial activity in the wells and the RWGD, and the potential for such activity to contribute to RO membrane fouling through the production of biopolymers.

ATP was measured using LuminUltra® test kits, and the results were converted to active cell concentrations. Result ranged from 5,077 to 72,814 cells per milliliter (cell/mL). The greatest concentrations were within the DPW at 52,690 and 72,814 cell/mL at 360 feet and 385 feet bgs, respectively, indicating possible elevated biological activity within this interval. In addition, the lower screened well interval also showed elevated ATP values, correlating with higher biopolymer concentrations. LC-OCD results are discussed in more detail in Section 3.2.5. The elevated ATP and biopolymer levels also correlated with heavy screen buildup and discoloration from the video survey taken from 370 to 460 feet bgs.

3.2.3 True Color

Measured true color levels ranged from nondetect (ND) at the lower screen to 15 color units (CU) in the upper section of the upper screen. The higher color in this 10-foot interval is consistent with well construction data that also showed elevated color in the top portion of the upper screen. When true color is mass balanced based on weighted flow percentage, as shown on Figure 3-1, the zonal color concentration in the uppermost 10 feet of the aquifer is estimated at 142 CU.

Note that because color is an indirect measurement and is not a direct measurement of mass, use of mass balance calculations to estimate the zonal concentration is not entirely correct, but does provide a rough estimate on the likely color contributed by this portion of the aquifer zone. These results indicate that the upper zone of the aquifer, and in particular, the upper 10 feet, is contributing most of the colored organics.

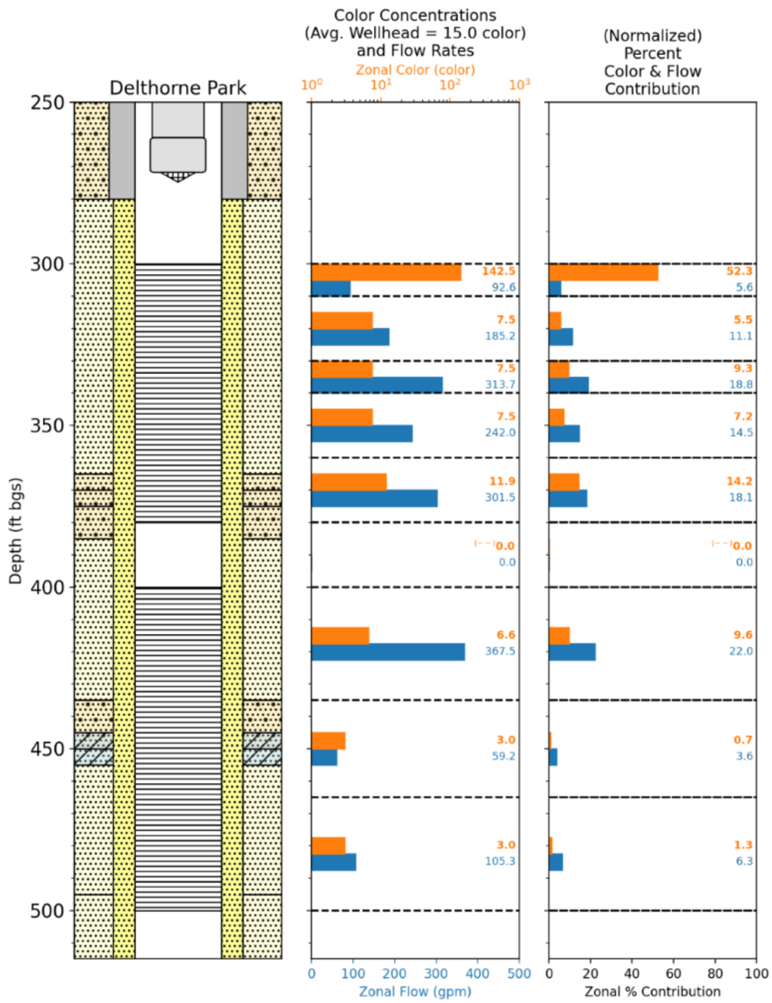


Figure 3-1. Delthorne Park True Color Zonal Concentrations

3.2.4 Inorganics

The inorganics measured in the groundwater samples include the following constituents:

- Calcium
- Chloride
- Fluoride
- Iron
- Manganese
- Magnesium
- Orthophosphate
- Silica
- Sodium
- Sulfate
- Strontium

Analytical results for calcium show increased zonal concentrations with well depth. As shown on Figure 3-2, concentrations of both calcium and chloride levels increase with depth. At 300 to 330 feet bgs, both ions are present at less than 10 mg/L; while at 435 to 500 feet bgs, calcium is 1,200 mg/L, and chloride is as high as

7,100 mg/L. Calcium was found to be part of the RO foulant and may be contributing to membrane fouling, as discussed in Sections 4 and 5 of this report.

Iron was detected at very low concentrations within the well (from ND to 29 µg/L) and only 15 µg/L at the wellhead. Although manganese was elevated at the wellhead (170 µg/L) and very high at the lowest well depth (790 µg/L per Figure 3-3), no evidence of manganese fouling was observed during the RO autopsies, consistent with anoxic conditions of the well.

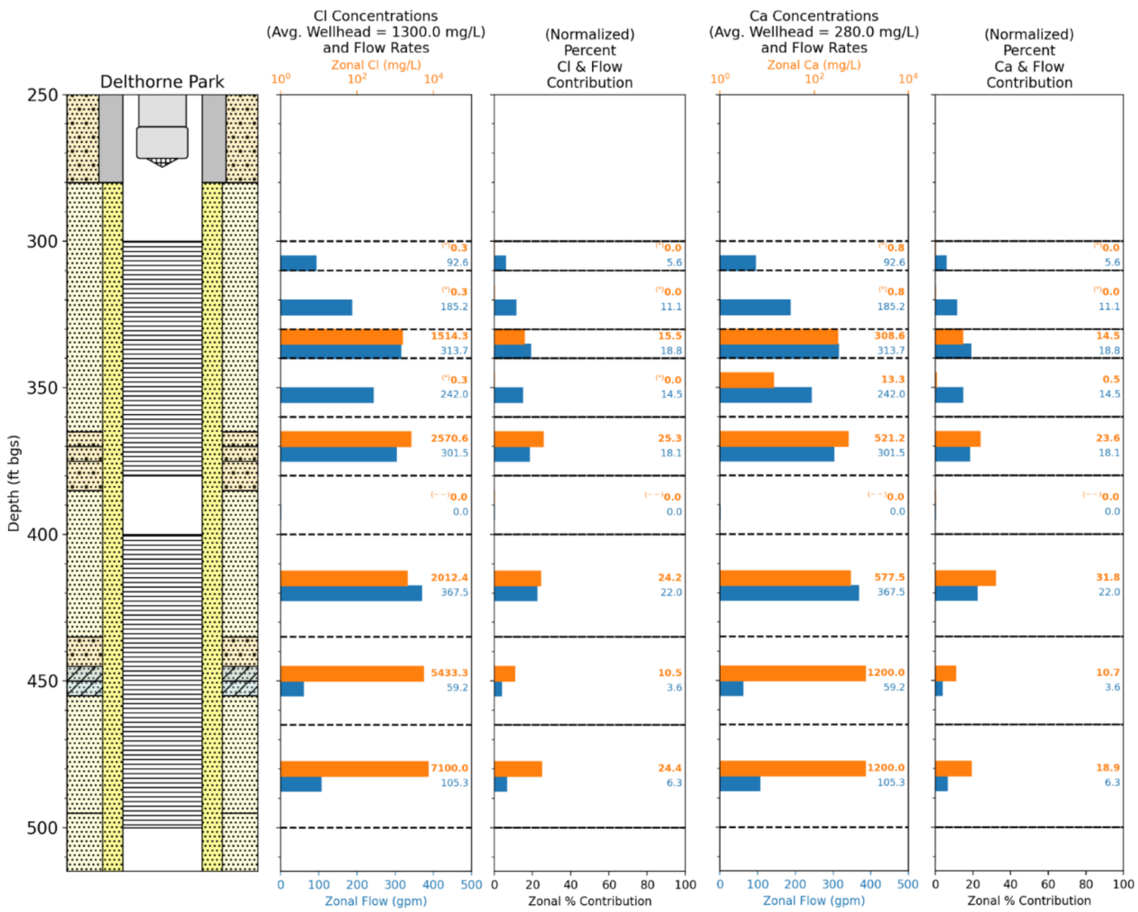


Figure 3-2. Delthorne Park Chloride and Calcium Zonal Concentrations

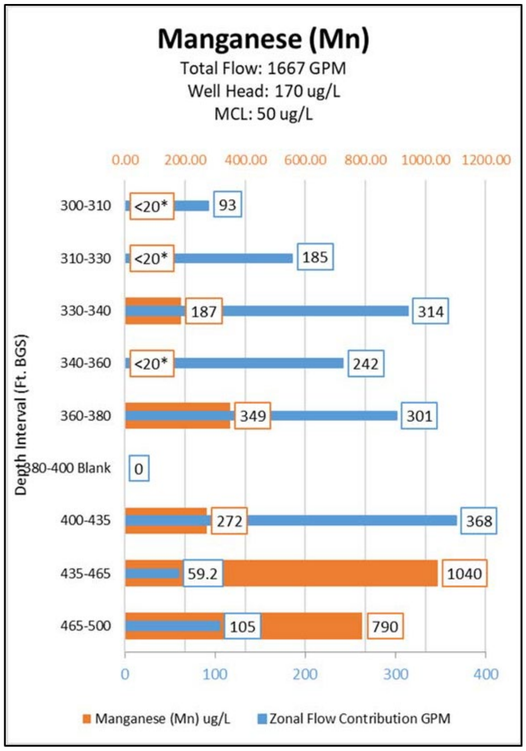


Figure 3-3. Delthorne Park Manganese Zonal Concentrations

3.2.5 Organics

Methyl Tert -Butyl Ether

MTBE was not detected in any of the samples collected in the DPW.

Dissolved Organic Carbon

Three samples from the DPW were evaluated using LC-OCD. Those results are presented in Appendix C and summarized in Table 3-3. LC-OCD distinguishes between hydrophobic DOC and hydrophilic DOC, both of which can be classified as natural organic matter (NOM). The hydrophilic NOM is further separated into subfractions, including:

- Biopolymers
- Humic substances
- Building blocks
- Low molecular weight (LMW) acids
- LMW neutrals

Total DOC was elevated throughout the well, with zonal concentrations ranging from 1.9 to 2.6 mg/L (Figure 3-4). The hydrophilic and hydrophobic DOC comprise approximately 60 percent and 40 percent of the total DOC, respectively (Table 3-3). Humic substances are the dominant hydrophilic NOM fraction, comprising approximately one-third of hydrophilic DOC. Biopolymers, which are typically associated with membrane fouling, were present at surprisingly low levels, ranging from 1 to 18 µg/L, representing less than 1 percent of the total hydrophilic DOC. LMW neutrals were the other major NOM fraction.

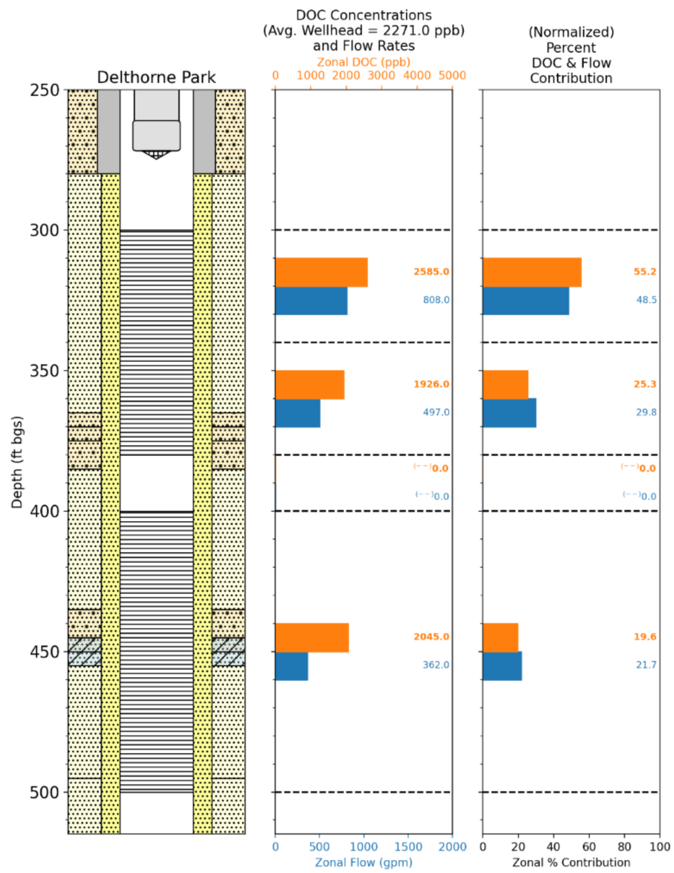


Figure 3-3. Delthorne Park Dissolved Organic Carbon Zonal Concentrations

Table 3-3. Delthorne Park Liquid Chromatography with Online Carbon Detection Results

Parameter	DPWH: 0ft		DP3: Upper Screen; 340ft		DP5; Blank; 385 ft	
	µg/L	% of total	µg/L	% of total	µg/L	% of total
DOC	2,271	100	1,976	100	2,045	100
Hydrophobic DOC	964	42	647	33	764	37
Hydrophilic DOC	1,308	58	1,328	67	1,281	63
Hydrophilic DOC Components						
Biopolymers	1	0	9	1	18	1
Humic Substances	729	32	675	34	617	30
Building Blocks	215	10	210	11	199	10
LMW Acids	1	0	1	0	1	0
LMW Neutrals	363	16	434	22	447	22

3.3 City Yard Well – Depth-Specific Water Quality

Groundwater samples were analyzed for the constituents of concern specified in the *Robert W. Goldsworthy Desalter Investigation Plan* (Jacobs 2020). Appendix B provides the laboratory analytical reports for groundwater samples collected from CYW on September 17, 2020. Table 3-4 summarizes the analytical results for CYW.

Table 3-4. City Yard Well Water Quality Results

	Raw Data								
	Parameter	Unit	Reporting Limit	Wellhead	Upper Screen		Blank	Lower Screen	
				CYWH	CY1	CY2	CY3	CY4	CY5
				0 ft	380 ft	390 ft	415 ft	440 ft	515 ft
Field	pH	SU	-	7.52	7.4	7.4	7.21	7.19	7.34
	Temperature	°C	-	22.8	27.5	24.7	26.7	25.2	23.6
	Conductivity	µs/cm	-	4,457	8,128	7,944	13,044	14,736	17,838
	ORP	mV	-	-57.3	-107.5	-140	-143.9	-161	-175.8
	DO	mg/L	-	0.16	0.08	0.09	0.04	0.03	0.04
	Turbidity	NTU	-	0.26	1.25	0.64	0.64	0.84	0.49
	ATP	ME/mL	-	3,236	-	-	-	-	-
Lab	pH	SU	-	7.6	7.7	7.8	7.4	7.4	7.4
	Conductivity	µs/cm	2	4,400	8,200	8,100	13,000	15,000	18,000
	TDS	mg/L	5	2,600	4,600	4,700	7,600	9,500	13,000
	HCO_3	mg/L	5	210	-	-	-	-	-
Lab - Inorganics	Aluminum	µg/L	50	ND	-	-	-	-	-
	Barium	µg/L	100	88	-	-	-	-	-
	Calcium	mg/L	10	290	590	620	1100	1200	1400
	Chloride	mg/L	4	1,300	2,600	2,600	4,500	5,300	6,500
	Fluoride	mg/L	0.1	0.48	-	-	-	-	-
	Iron	µg/L	100	ND	ND	ND	ND	ND	ND
	Potassium	mg/L	10	15	-	-	-	-	-
	Manganese	µg/L	20	180	360	370	580	650	770
	Magnesium	mg/L	10	89	-	-	-	-	-
	Nitrate	mg/L	0.4	ND	-	-	-	-	-
	Orthophosphate	mg/L	0.02	0.11	-	-	-	-	-
	Silica	mg/L	0.5	26	-	-	-	-	-
	Sodium	mg/L	10	460	-	-	-	-	-
	Sulfate	mg/L	0.5	330	-	-	-	-	-
	Strontium	µg/L	1,300	2,600	-	-	-	-	-
Lab - Organics	True Color-Filtered	CU	3	ND	ND	ND	ND	ND	ND
	UVA-254	cm^{-1}	0.005	0.018	0.025	0.03	0.026	0.019	0.025
	DOC	mg/L	-	1.466	-	-	0.76	-	-
	Hydrophobic DOC	mg/L	-	0.345	-	-	0.001	-	-
	Hydrophilic DOC	mg/L	-	1.121	-	-	0.76	-	-
	MTBE	µg/L	3	5.7	0.33	ND	ND	ND	ND

3.3.1 Oxidation-Reduction Potential and Dissolved Oxygen

ORP ranged from -175.8 to -57.3 mV, and DO ranged from 0.03 to 0.16 mg/L. Both ORP and DO values were less than measured at the DPW, indicating that the CYW is more anoxic than the DPW.

3.3.2 Adenosine Triphosphate

The ATP result for the CYW wellhead was measured at 3,236 cell/mL, indicating lower biological activity than in the DPW.

3.3.3 True Color

No color was observed in the CYW.

3.3.4 Inorganics

Calcium zonal concentrations increased with aquifer depth from 33 mg/L in the top portion of the upper screen to a maximum concentration of 1,400 mg/L in the lower screen, as shown on Figure 3-5. Chloride and TDS follow the same trend. Calcium was observed as part of the RO foulant during the membrane autopsy and may be contributing to membrane fouling, as discussed in Sections 4 and 5 of this report.

Iron was not detected at the wellhead. Although manganese concentrations were high at the wellhead (180 µg/L), and very high at some well depths, as represented by the zonal concentrations (Figure 3-6), current conditions in the wells and the system are anoxic; and manganese remained in solution, as confirmed by the lack of manganese fouling observed during the RO autopsy.

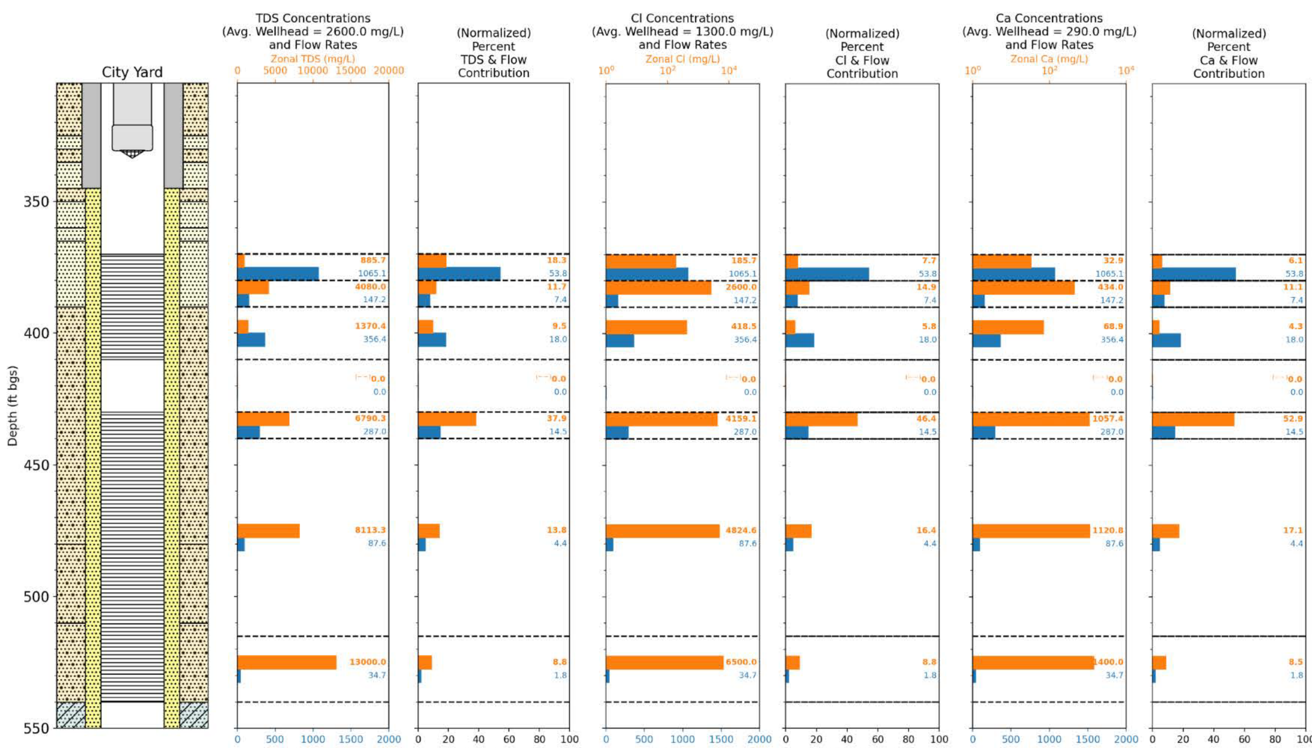


Figure 3-5. City Yard Well Total Dissolved Solids, Chloride, and Calcium Zonal Concentrations

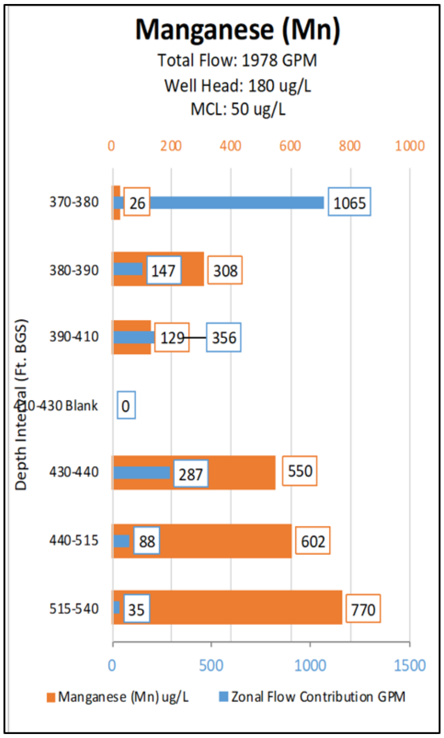


Figure 3-6. City Yard Well ManganeseZonal Concentrations

3.3.5 Organics

Methyl Tert-Butyl Ether

Mass balance calculations estimate a significant concentration of MTBE from 370 feet to 380 feet bgs, but there is no contribution of MTBE at lower well depths (Figure 3-7).

Dissolved Organic Carbon

The DOC concentration at the CYW wellhead was less than at the DPW wellhead but was still significant (1.5 mg/L), with approximately 75 percent being hydrophilic DOC. DOC was less in concentration in the lower portion of the well relative to the wellhead (zonal concentration of 0.76 mg/L at 415 feet bgs), indicating that the upper portion has greater DOC levels. The lower portion sample comprised 100 percent hydrophilic NOM, significantly different than the lower portion DPW sample (approximately 60 percent hydrophilic DOC). Humic substances are the dominant hydrophilic NOM in the CYW, comprising 50 to 60 percent of hydrophilic DOC components, as shown in Table 3-5. The biopolymer concentration was very low, ranging from 2 to 4 µg/L, 0.5 percent or less of the total DOC

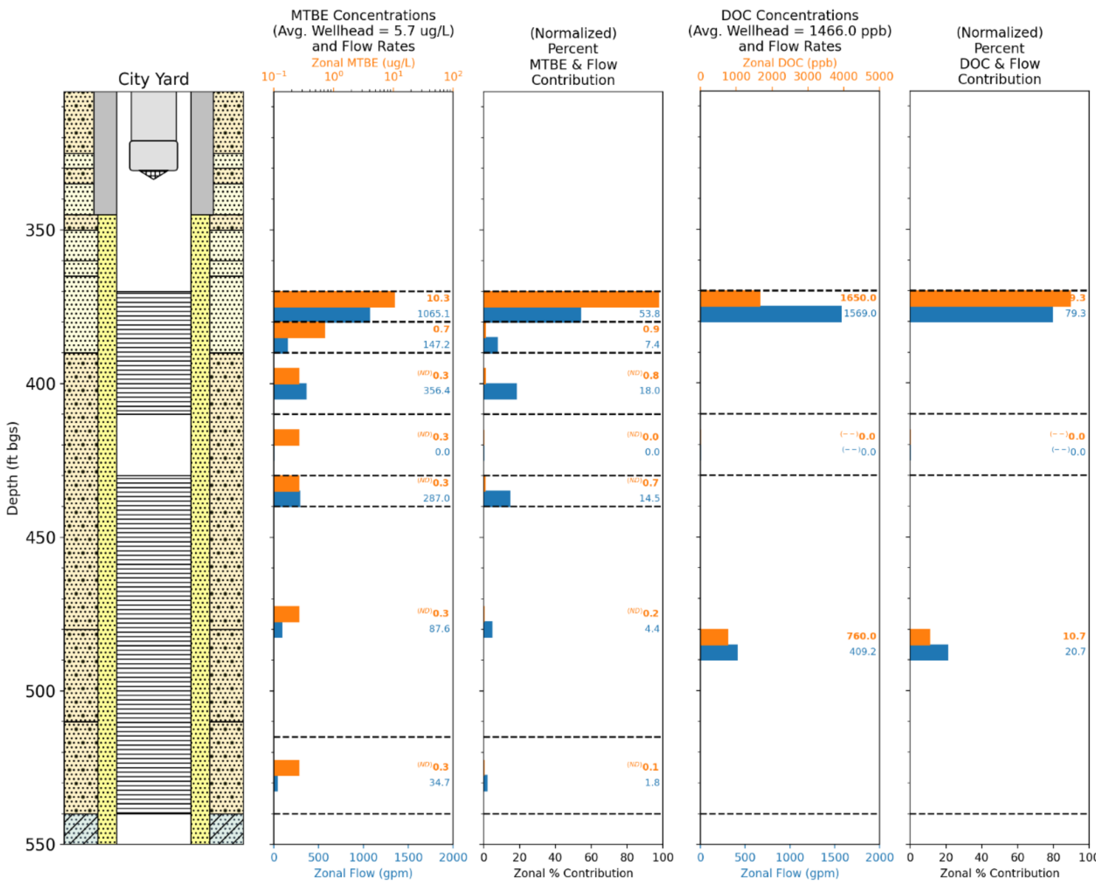


Figure 3-7. City Yard Well Methyl Tert-Butyl Ether and Dissolved Organic Carbon Zonal Concentrations

Table 3-5. City Yard Liquid Chromatography with Online Carbon Detection Results

Parameter	CYW WH: 0 ft		CYW3: Upper Screen; 415 ft	
	µg/L	% of total	µg/L	% of total
DOC	1,466	100	760	100
Hydrophobic DOC	345	24	1	0
Hydrophilic DOC	1,121	76	760	100
Hydrophilic DOC Components				
Biopolymers	2	0.1	4	0.5
Humic Substances	726	50	459	60
Building Blocks	169	12	92	12
LMW Acids	1	0	1	0
LMW Neutrals	224	15	206	27

Notes:

CYW3 = sample point in upper screen at 415 feet bgs

WH = wellhead

3.4 RWGD Water Quality

Appendix B provides the laboratory analytical reports for groundwater samples collected from RWGD on September 17, 2020. Table 3-6 summarizes the analytical results for RWGD.

Table 3-6. RWGD Water Quality Results

	Raw Data						
	Parameter	Unit	Reporting Limit	Blend of CYW and DPW Water	ROF	ROC	ROP
Field	pH	SU	-	7.58	7.58	7.65	5.91
	Temperature	°C	-	22.5	22.6	23.2	22.8
	Conductivity	µs/cm	-	4,472	4,476	15,391	90.3
	ORP	mV	-	-47.1	-67	-39	30.2
	DO	mg/L	-	0.27	0.12	0.11	0.09
	Turbidity	NTU	-	0.28	0.2	0.23	0.13
	ATP	ME/mL	-	6,906	5,501	13,798	5,917
Lab-Basic	pH	SU	-	7.8	7.7	7.7	6.7
	Conductivity	µs/cm	2	4,400	4,500	15,000	90
	TDS	mg/L	5	2,700	2,800	9,100	56
	HCO_3	mg/L	5	200	-	750	6.3
Lab - Inorganics	Aluminum	µg/L	50	21	-	26	ND
	Barium	µg/L	100	75	-	270	ND
	Calcium	mg/L	1	300	310	1100	0.21
	Chloride	mg/L	4	1,300	1,300	4,900	23
	Fluoride	mg/L	0.1	0.48	-	ND	ND
	Iron	µg/L	100	15	ND	42	ND
	Potassium	mg/L	10	12	-	50	0.37
	Manganese	µg/L	20	170	180	610	ND
	Magnesium	mg/L	10	80	-	300	ND
	Nitrate	mg/L	0.4	ND	-	ND	ND
	Orthophosphate	mg/L	0.02	0.17	-	0.62	ND
	Silica	mg/L	0.5	24	-	96	0.3
	Sodium	mg/L	10	510	-	1,800	16
	Sulfate	mg/L	0.5	320	-	1,300	0.31
	Strontium	µg/L	1,300	2,400	-	9,600	ND
Lab - Organics	True Color-Filtered	CU	3	7.5	5	30	ND
	UVA-254	cm^{-1}	0.005	0.046	0.04	0.16	ND
	DOC	mg/L	-	1.505	1.398	5.845	-
	Hydrophobic DOC	mg/L	-	0.264	0.177	1.008	-
	Hydrophilic DOC	mg/L	-	1.241	1.221	4.837	-

3.4.1 Oxidation-Reduction Potential and Dissolved Oxygen

ORP in the DPW-CYW well blend and ROF were measured at -47.1 and -67 mV, respectively. DO at these process locations were 0.27 and 0.12 mg/L, respectively. These values are consistent with the measurements from individual wells, indicating that anoxic conditions were maintained in the ROF.

3.4.2 Adenosine Triphosphate

The ATP for the DPW-CYW well blend was 6,909 cell/mL, and for RO feedwater was 5,501 cell/mL. These are consistent with levels measured in the DPW and CYW, suggesting similar biological activity is present in the ROF.

3.4.3 True Color

The results of laboratory-analyzed true color were 7.5 and 5 CU for the DPW-CYW well blend and ROF, respectively. ROC color was 30 CU, which is higher than anticipated, given a concentrate feed concentration factor of 4 at 75 percent recovery. No color was measured in the RO permeate, indicating the colored NOM fraction is removed by RO.

3.4.4 Inorganics

As expected, calcium, chloride, and manganese concentrations in both the well water blend and ROF were consistent with the measurements from the individual wells. A mass balance calculation around the RO process (using ROF, ROP, and ROC) provided the following recoveries: 86 percent for calcium, 93 percent for chloride, and 83 percent for manganese, suggesting that 14 percent of calcium, 7 percent of chloride, and 17 percent of manganese present in the ROF were retained with the RO trains. The higher percentage of calcium loss is consistent with its presence in the membrane foulant, while the lower percentage of chloride loss is also consistent with its absence in the foulant.

The loss of manganese is surprising, given that it was not detected in the foulant. The loss of manganese may be the result of a non-representative concentration from a single sampling event or laboratory measurement error. Although no iron was detected in the ROF, the ROC contained 42 µg/L, indicating that iron is present in the well water blend but at less than 15 µg/L (method detection limit).

3.4.5 Organics

Dissolved Organic Carbon

As shown in Table 3-7, the DOC level in the ROF was similar to that at CYW wellhead (1.5 mg/L), and less than that at the DPW wellhead (2.27 mg/L). This result is reasonable, given the higher flow contribution from the CYW. The RWGD DOC was composed of approximately 15 percent hydrophobic DOC and 85 percent hydrophilic DOC, with humic substances being the dominant NOM – approximately 50 percent of the total DOC. These distributions are consistent in both wells.

Table 3-7. RWGDLiquid Chromatography with Online Carbon Detection Results

Parameter	CYW-DPW		ROF		ROC	
	µg/L	% of total	µg/L	% of total	µg/L	% of total
DOC	1,505	100	1,398	100	5,845	100
Hydrophobic DOC	264	18	177	13	1,008	17
Hydrophilic DOC	1,241	82	1,221	87	4,837	83
Hydrophilic DOC Components						
Biopolymers	10	0.7	4	0.3	11	0.2
Humic Substances	746	50	743	53	3,050	52
Building Blocks	177	12	175	13	689	12
LMW Acids	1	0	1	0	5	0
LMW Neutrals	307	20	299	21	1,087	19

4. Membrane Autopsy Results

Two RO elements were harvested on August 25, 2020, and sent to AWC for a silver level autopsy:

- Train 2, Stage 1, Tail Element: Position 40 (T2, S1, P40)
- Train 2, Stage 2, Tail Element: Position 22 (T2, S2, P22)

Figure 4-1 shows the condition of the elements prior to shipping. From left to right is the Stage 2 element, a new element, and the Stage 1 element. The membrane autopsy (Appendix A) included a series of tests to characterize the performance of each element and determine the degree and nature of fouling. As listed in Table 4-1, performance testing showed fluxes for Stage 1 and Stage 2 elements at 17 percent and 23 percent less than the nominal specification, respectively. Salt rejection for both elements was also less than specification, while differential pressure was greater. All of these results indicate both elements were moderately fouled.

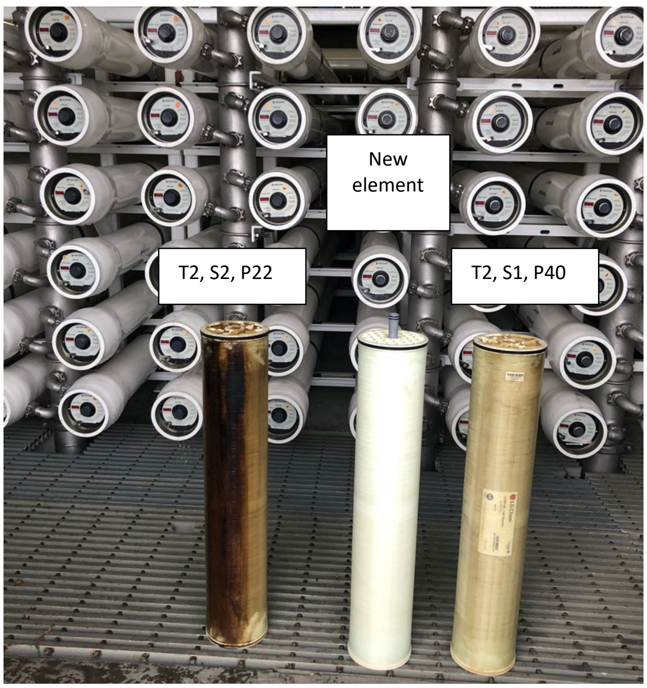


Figure 4-1. Reverse Osmosis Elements Prior to Shipment

Table 4-1. Membrane Initial Performance Test Results

Performance Testing	Manufacturer Nominal Specification	Train 2, Stage 1, Position 40	Train 2, Stage 2, Position 22
Permeate Flow (gpd)	10,500	8,720	8,067
Membrane Flux (gfd)	26.3	21.8	20.2
Salt Rejection (%)	99.6	99.23	99.18
Differential Pressure	3.6	4.9	4.4

Notes:

gpd = gallon(s) per day

After the performance test, each membrane was subjected to a vacuum test to check for the presence of leaks. Both elements passed, indicating no significant breach in integrity from abrasion, delamination, or water hammer.

The fiberglass shell was then removed to inspect the membrane leaves. A dark brown foulant was deposited uniformly on the leaves, as shown on Figure 4-2.

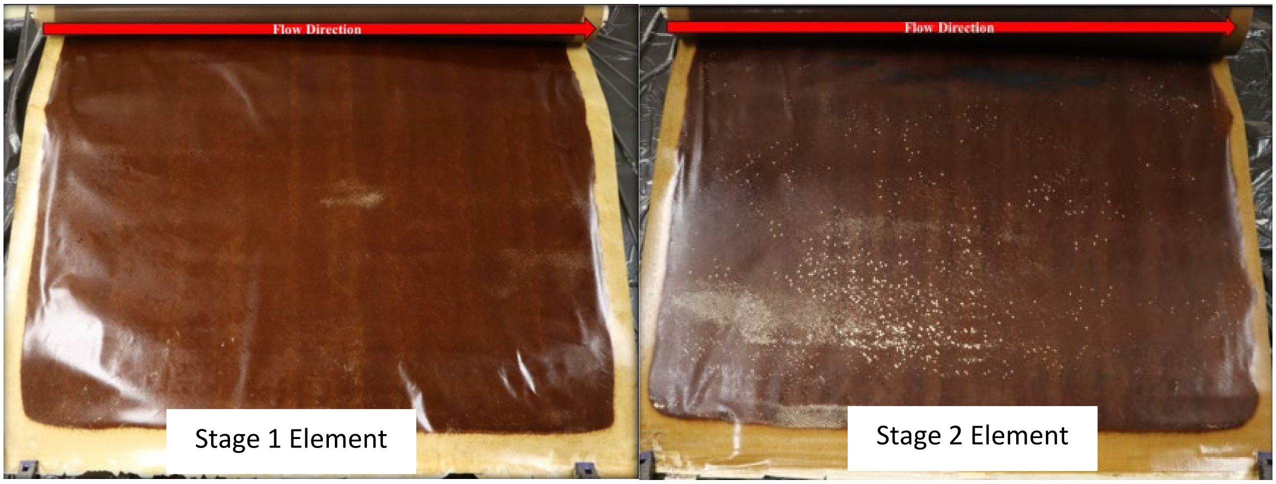


Figure 4-2. Brown Foulant Deposited on All Membrane Leaves for Stage 1 and Stage 2 Elements.

As shown on Figure 4-3, the foulant was scraped and collected to conduct a series of characterization tests, as described in this section. The foulant from both elements had a similar appearance. A portion of the foulant was sent to Germany for LC-OCD testing to compare with LC-OCD results from the water sample testing.

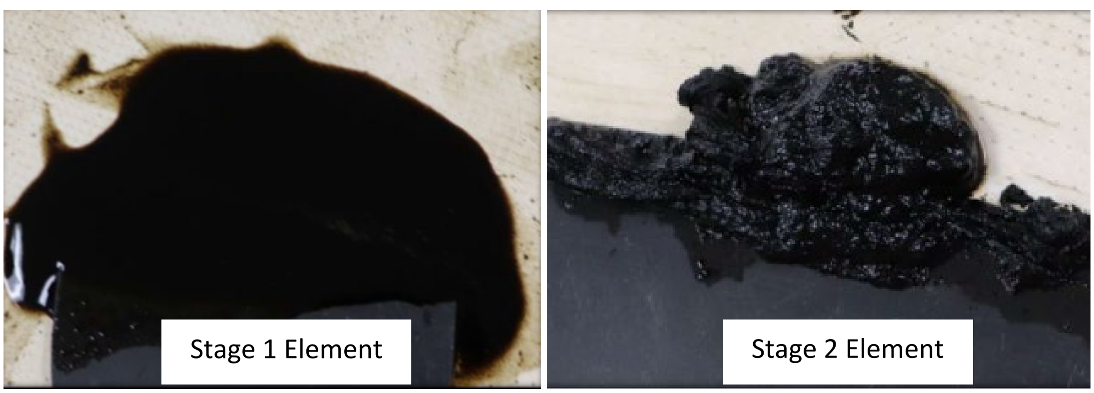


Figure 4-3. Foulant from Stage 1 and Stage 2 Elements

Loss of ignition (LOI) testing was performed to determine the organic and inorganic content of the foulant. As shown in Table 4-2, 85 percent of the foulant was determined to be organic for both elements. This was anticipated based on the results of previous autopsies.

Table 4-2. Loss of Ignition Test Results for Stage 1 and Stage 2

Foulant Scraped from Membrane	Stage 1 Foulant from Membrane	Stage 1 Calculated Without Moisture	Stage 2 Foulant from Membrane	Stage 2 Calculated Without Moisture
Moisture and Volatiles (%)	98.71	-	98.57	-
Organic Content (%)	1.11	86.04	1.22	84.99
Inorganic Content (%)	0.18	13.93	0.22	15.0

The scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) analysis, and prismatic elemental imaging (PEI) tests confirmed the foulant to be organic based (Figure 4-4). Calcium and sodium represented the major inorganic constituents. In the absence of counterions (anions), calcium and sodium are most likely complexed with deprotonated organic acid functional groups on the organic moieties. Sporadic deposits of silts and clays were also identified, although they appear to represent a very minor contributor to the foulant mass.

Spectrum 1

Element	Atom [%]
Oxygen	18.76
Silicon	0.02
Sulfur	0.87
Calcium	0.71
Carbon	77.68
Sodium	1.28
Aluminium	0.09
Chlorine	0.09
Phosphorus	0.09
Magnesium	0.19
Iron	0.14
Titanium	0.09
	100.00

Carbon and Oxygen Ignored

Spectrum 1

Element	Atom [%]
Silicon	0.49
Sulfur	24.62
Calcium	20.34
Sodium	35.54
Aluminium	2.44
Chlorine	2.43
Phosphorus	2.47
Magnesium	5.23
Iron	3.91
Titanium	2.54
	100.00

Spectrum 1

Element	Atom [%]
Oxygen	18.69
Sulfur	0.95
Calcium	0.75
Carbon	77.71
Sodium	0.99
Aluminium	0.14
Magnesium	0.25
Iron	0.14
Titanium	0.09
Chlorine	0.10
Phosphorus	0.09
Silicon	0.12
	100.00

Carbon and Oxygen Ignored

Spectrum 1

Element	Atom [%]
Sulfur	26.40
Calcium	21.13
Sodium	27.06
Aluminium	3.79
Magnesium	6.75
Iron	4.02
Titanium	2.46
Chlorine	2.78
Phosphorus	2.37
Silicon	3.23
	100.00

Figure 4-4. Energy Dispersive X-Ray Spectroscopy Results – Spectrum 1, Stage 1 and Stage 2

Also provided in the AWC reports in Appendix A

4.1 Contact Angle Testing

The contact angle of the fouled membrane surface was reduced from 53 to 33 degrees (°) (Stage 1) and from 47 to 26° (Stage 2) by chemical cleaning, as shown in Table 4-3 and on Figure 4-5. These decreases suggest removal of hydrophobic organic deposits from the membrane surface of both fouled elements.

Table 4-3. Contact Angle Testing

Sample	Left Contact Angle (°)	Right Contact Angle (°)	Mean
Stage 1 – Fouled Membrane	52.98	52.43	52.71
Stage 1 – Cleaned Membrane	33.47	33.09	33.28
Stage 2 – Fouled Membrane	47.44	46.77	47.11
Stage 2 – Cleaned Membrane	26.79	24.82	25.80

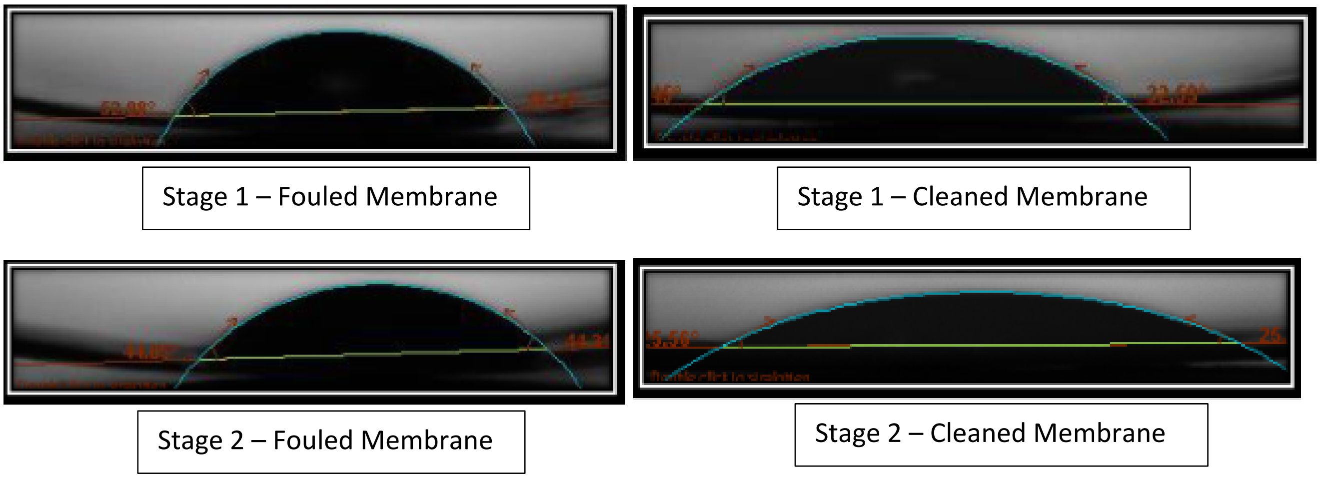


Figure 4-5. Stage 1 and 2 Contact Angle – Fouled and Cleaned Membrane

4.2 Liquid Chromatography with Online Carbon Detection

LC-OCD analysis of the foulant samples was conducted, and the results are summarized in Table 4-4. General observations about the results include the following:

- The portion of hydrophobic organics present in the Stage 2 foulant is greater than present in the CY-DP well blend, RO feed, and RO concentrate.
- The division of hydrophilic components in the Stage 2 foulant is significantly different than that observed in the CY-DP well blend, RO feed, and RO concentrate. In particular, the concentration of biopolymers is much greater in the foulant sample compared to the other three samples, suggesting that although biopolymers are at lesser concentrations in the RO feed, this NOM fraction may be a significant contributor to membrane fouling.
- Unidentified hydrophobic compounds as well as identified hydrophilic fractions (biopolymers, humics, building blocks, and LMW neutrals) all appear to be contributing to membrane fouling, as discussed in Section 5.
- The absence of hydrophobic DOC in the Stage 1 foulant is surprising; however, this foulant sample did contain a greater biopolymers concentration than the RO feed, although less than in the Stage 2 foulant.

Given that LC-OCD analysis is typically performed on water samples and not on solids (such as, harvested membrane foulant), the results presented herein, as well as the observations provided, must be considered in proper context with all of the other analyses performed as part of this investigation.

Table 4-4. Membrane Foulant Liquid Chromatography with Online Carbon Detection Results

Sample	Unit	Hydrophobic DOC	Hydrophilic DOC				
			Biopolymers	Humic Substances	Building Blocks	LMW Neutrals	LMW Acids
2017102FR01216 Stage 1, Tail	% DOC	ND	10.3	37.7	20.4	31.4	0.2
2017102FR01416 Stage 2, Tail	% DOC	24.9	26.1	28.6	11.6	7.6	1.2

5. Discussion

The water quality analysis and membrane autopsy results are consistent with historical water quality data provided by WRD at each well and at the RWGD. Organics present in the well water, partially complexed with select inorganics, are being deposited on the surface of the RO membranes and causing a loss of performance. This section describes the potential types of organic fouling and the role inorganics may play in the fouling.

5.1 Inorganics

Concentrations of key inorganics, including calcium, sodium, iron, and manganese, are summarized in Table 5-1 for samples collected at both well heads, through the treatment process, as well as relative percentages in the membrane foulant. Other inorganics were not tested in the ROF, as they are not expected to change from cartridge filtration and threshold inhibitor addition. Calcium and sodium are present at significant concentrations in both wells, and in the blended well water, and are the two most prevalent inorganics in the RO foulant, suggesting potential complexation of these elements with organics when water is blended within each well and between wells. In addition, the high concentration of these constituents at lower depths in the well may lead to increased complexation and destabilization (bridging) of organics when waters from the different well depths are mixed, especially in the DPW where water in the upper portion of the well is very high in color but very low in inorganics.

Manganese is present at high concentrations in both wells, but because it wasn't observed in the membrane autopsy, it doesn't appear to be a source of RO fouling. In addition, reduced manganese would require a strong oxidant and significant reaction time (typically hours) to form a solid precipitant that would foul the RO membrane, both of which are not present at the RWGD facility. The concentration of iron is very low in the wells but does appear at low percentages in the RO foulant, possibly from particulates small enough to pass the cartridge filters or from complexation with the organics. However, it isn't suspected to be a significant source of RO fouling.

Table 5-1. Comparison of Major Inorganics in Influent Waters and Membrane Foulant

Parameter	Water Quality Analysis (concentration)							Membrane Foulant Analysis (% of total) [a]	
	Unit	DPWWH	CYWWH	DPW-CYW	ROF	ROC	ROP	RO-S1 (Spectrum 1)	RO-S2 (Spectrum 1)
Calcium	mg/L	280	290	300	310	1,100	0.21	20.3%	21.1%
Sodium	mg/L	510	460	510		1,800	16	35.5%	27.1%
Iron	µg/L	15	ND	15	ND	42	ND	3.9%	4.0%
Manganese	µg/L	170	180	170	180	610	ND	ND	ND
Magnesium [b]	-	-	-	-	-	-	-	5.2%	6.8%

[a] Percent of total elements measured after subtracting out carbon and oxygen.

[b] Magnesium was not measured in the water samples.

Notes:

S# = Stage 1 or 2

5.2 Organic Fouling

Organics present in the well water are the major source of the RO membrane fouling, given that organics comprise 85 percent of the foulant (as measured by LOI). The dark color of the foulant also implicates colored organics as the foulant source.

Figure 5-1 shows the distribution of organics at various sample locations as determined by LC-OCD. Examination of this figure and organics results presented in earlier sections reveals the following:

- Like the well water, the RO foulant comprises both hydrophilic and hydrophobic organics, indicating that a wide variety of organic compounds is likely responsible for the RO fouling. The concentration and percentage of hydrophobic substances in the DPW is significantly higher than in the CYW. The CYW contains a higher percentage of hydrophilic substances, but the overall concentration is approximately equivalent. Removal of one specific organic type (for example, humic acids) may not mitigate membrane fouling, given that such selective removal will only address a portion of the hydrophilic NOM fraction. A broader removal of organic compounds will most likely be required.
- Although the biopolymer concentrations are low in both well waters, a significant fraction was measured in the second stage RO foulant, suggesting that these high molecular weight compounds are selectively accumulating on the membrane surface and contributing to the foulant layer. Biopolymers were present at a lower percentage in the Stage 1 foulant but higher than in either of the wells. This suggests that the biopolymer fraction is selectively accumulating in Stage 2 elements, likely due to the higher feed concentration into Stage 2.
- The concentration of organics varies some with depth (Figures 5-3 and 5-4), with higher concentrations of organics in the upper screen area.

Based on mass balance calculations, the high color in the top portion of DPW's upper screen (Section 3.2.3) is consistent with that observed during well construction and may lead to increased fouling, possibly through complexation with the increased concentrations of calcium and sodium present in the lower screen. Mixing of high colored water (and low calcium and sodium) with lower color water (and high calcium and sodium) during pilot testing of two wells screened at different depths for the Irvine Ranch Water District's Colored Water Project in the mid-1990s resulted in rapid fouling of RO membranes, and fouling was not observed when treating either groundwater source alone. As such, mixing of the higher colored, less brackish water from the upper screen with higher salinity water from the lower screen may be causing destabilization of organic matter. However, due to the presence of a variety of other hydrophobic and hydrophilic organic compounds throughout the water column, it is unlikely that the compounds responsible for elevated color are the only organics contributing to membrane fouling.

ATP concentrations measured in the DPW and CYW were compared with ATP levels measured in wells operated by the Eastern Municipal Water District (EMWD) and the Hampton Roads Sanitation District (HRSD) on Figure 5-2. The EMWD wells feed two brackish water desalters that have not experienced organic or biological fouling, except when water from some of the wells was treated for iron and manganese removal through chlorine dosing and filtration. The HRSD wells have experienced heavy biological fouling. The ATP measurements indicate that the DPW has higher bacterial activity than both the CYW and the EMWD wells but lower activity than the HRSD wells, suggesting that the DPW may have biological activity and some degree of biofouling. The DPW levels are also higher than in the EMWD dechlorinated water and the cartridge filter effluent, where the presence of biodegradable organics in these two process streams (resulting from chlorination of the well water) resulted in cartridge filter and RO membrane biofouling once the chlorine residual was quenched. However, the high biological activity in the DPW has not led to significant biopolymer concentrations in the well (less than 18 µg/L), which suggests that the biological activity may not be problematic. Conversely, there is biopolymer accumulation in the Stage 2 (and to a lesser extent, in the Stage 1) foulant, which indicates that biopolymers present in the well water are contributing to membrane fouling but may not be the main fouling component. Regular disinfection of the DPW should be considered to control biological activity in this well.

In summary, the water quality analysis, RO foulant analysis, and membrane autopsy results suggest that the RO fouling observed at RWGD is primarily caused by a wide variety of hydrophobic and hydrophilic organic compounds. The higher concentration of organics and elevated biological activity in the DPW suggests that the organics contributed by the DPW are more problematic than those contributed by the CYW. This is consistent with the greater rate of RO train permeability decline when the DPW is in operation.

However, eliminating the DPW from RWGD's supply may not sufficiently mitigate RO fouling because the organics present in the CYW are still significant. Inorganic and organic complexation appears to be occurring, as observed by the elevated percentage of calcium and sodium present in the RO foulant. Short- and long-term mitigation approaches to address these potential causes of RO fouling will be discussed in the Task 3 – Performance Assessment and Pretreatment Recommendations Report to be submitted under separate cover.

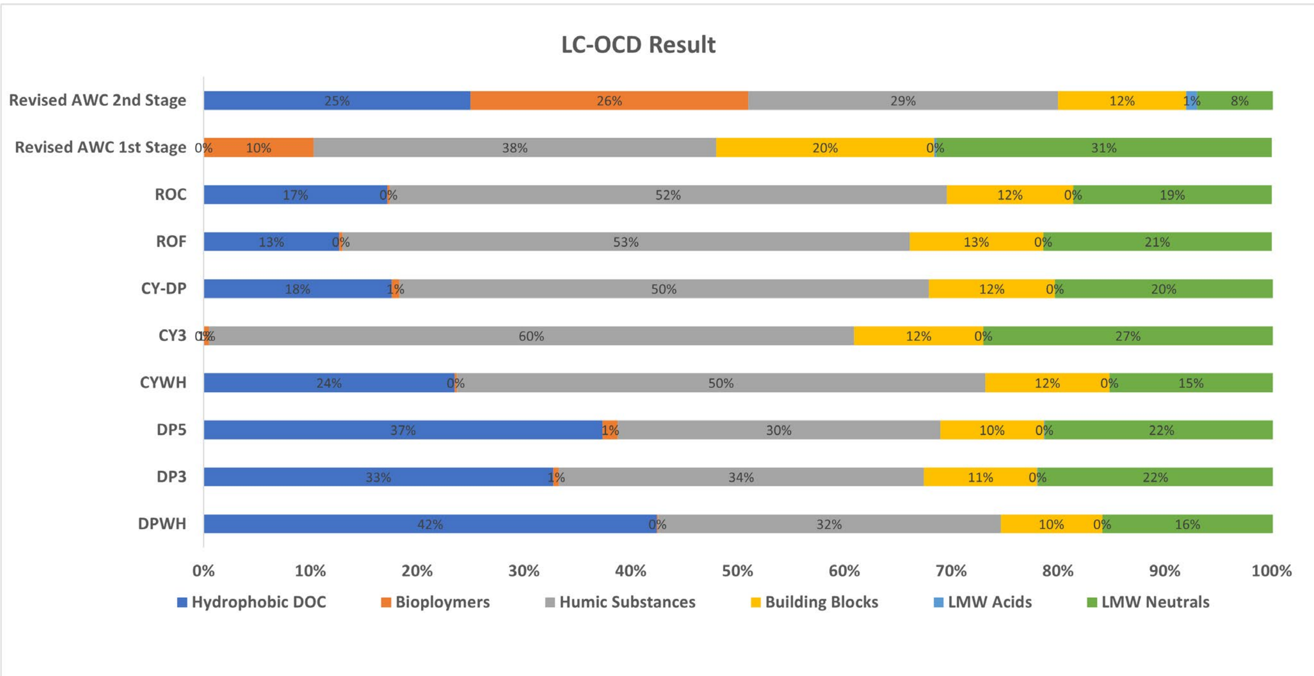


Figure 5-1. Liquid Chromatography with Online Carbon Detection Result Summary

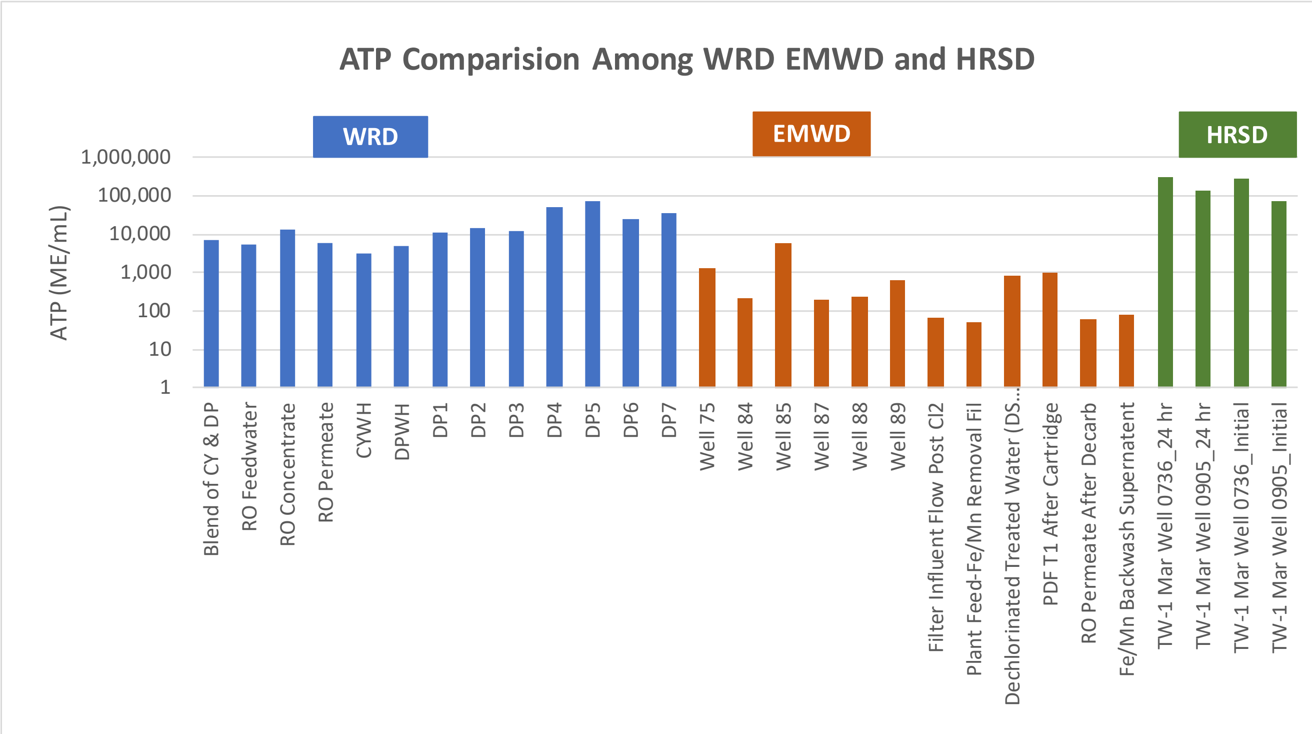


Figure 5-2. Adenosine Triphosphate Comparison to other Municipal Wells

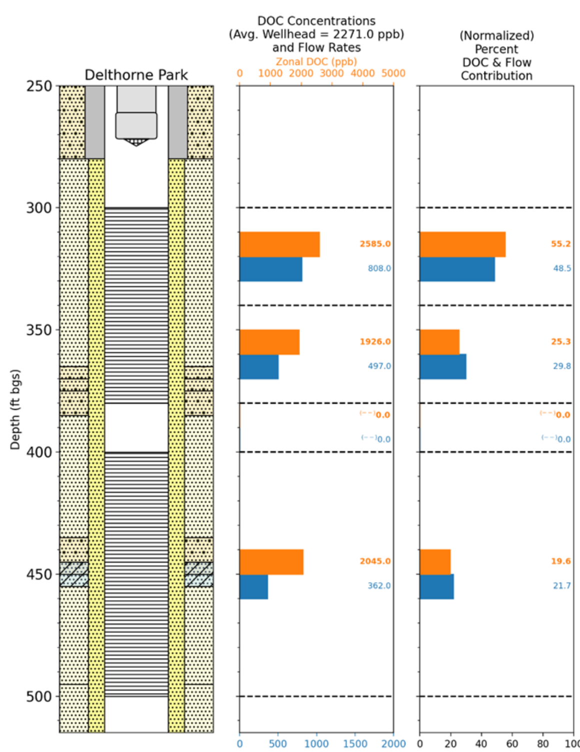


Figure 5-3. Delthorne Park Well Dissolved Organic Carbon Distribution

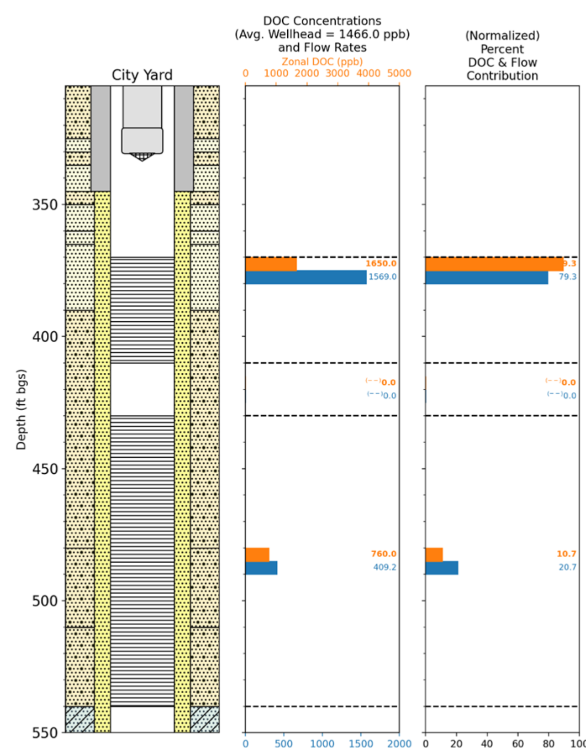


Figure 5-4. City Yard Well Dissolved Organic Carbon Distribution

6. References

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Appendix A
American Water Chemicals Membrane Autopsy Reports

Appendix B
INTERA/BESST Reports

Appendix C
Liquid Chromatography with Online Carbon Detection Results