Attachment C

Imagine the result

City of Boulder

Betasso Water Treatment Facility Filtration Performance Evaluation/Optimization Study

October 6, 2014

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Betasso Water Treatment Facility Filtration Performance Evaluation/Optimization Study

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City of Boulder

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Appendices

A Betasso WTP – Filter Investigation – Filter Media L/d Memo

B Preliminary BWTF Piloting Results

1. Introduction

The City of Boulder (City) contracted with ARCADIS to assist in the evaluation and optimization of filtration performance at the Betasso Water Treatment Facility (BWTF). Filtration performance has been challenging BWTF specifically during spring runoff and high flow events. This project's focus was to further understand the issues and identify potential solutions.

This evaluation/optimization supplements the findings and recommendations from the 2012 Betasso Spring Runoff Optimization study. As a result of this evaluation ARCADIS made several recommendations to improve filter performance during spring runoff challenge periods including:

- Repair basin chlorinators
- Improve flocculation and sedimentation by fixing flocculator drives
- Explore modifying filter L/d ratio
- Evaluate addition of filter aid polymer
- Address filter headloss gauge operability
- Conduct additional investigation on chemical coagulation during 2013 spring runoff

Table 1-1 below presents in more detail the recommendations and actions taken by the City to address.

Table 1-1 2012 Betasso Spring Runoff Recommendations

Recommendations	Actions Taken
1) Repair basin chlorinators	• City repaired basin chlorinators in 2012
2) Improve flocculation/sedimentation performance by fixing flocculators drives	• City repaired flocculator drives in 2012
3) Explore modifying filter L/d ratio	• ARCADIS developed a L/d memo and submitted to the City in May 2014. See Appendix A for Memo. • ARCADIS conducted pilot testing efforts between January and August 2014. See Section 3.0 for pilot testing results
4) Evaluate addition of filter aid polymer	• See Section 3 for pilot testing results
5) Address filter headloss gauge operability	• No actions to date
6) Conduct additional investigation on chemical coagulation during 2013 spring runoff	• 2013 was largely spent getting the pilot moved from the Boulder Reservoir plant to Betasso. Some coagulation testing was conducted in 2012 however it turned out not to be a significant runoff year so the plant did not encounter similar issues as seen during runoff events.

The following sections present in more detail the pilot testing efforts conducted between January and August, 2014 to evaluate different potential L/d ratios (media configurations) and the addition of filter aid polymer to improve filter performance.

2. Pilot Testing Setup

The pilot testing configuration consists of four 4" filter columns. These columns were relocated from the Boulder Reservoir Water Treatment Facility during 2013. ARCADIS supported the installation and commissioning of the pilot system including:

- Wet testing pilot
- Re-plumbing significant portions of the four pilot filter columns system to control leaks
- Installed new valves and rotameters to better control pilot filtration flow rates
- Replaced the tubing that was with the pilot system with all new flexible tubing
- Installed media in the four filters
- Calibration of the pilot filters

Figure 2-1 below presents the pilot testing equipment setup.

Figure 2-1 Pilot Testing Setup

The water supply to the pilot filters was the same as the feed water to the full-scale filters. This is raw water which has been through the coagulation/flocculation process, sedimentation, and pre-chlorination. This pilot was supplied with a side stream from the laboratory, into a break tank, and then through a header system which fed all four filters. Flow into the filters was controlled by the operators using rotameters on the downstream side of the filters.

Table 2-1 below presents a detailed description of the configuration of each of the four columns from April 18, 2014 to June 27, 2014. The media in Filter 1 represents the same configuration as the existing full-scale filters, while the remaining three filter configurations were chosen based on the L/d evaluation findings (Appendix A). Generally speaking, the media arrangements were selected to provide an increase in L/d of about 100 in each consecutive filter.

Table 2-1 Pilot Filter Configuration - 4/18 to 6/27

Parameters	Filter 1	Filter 2	Filter 3	Filter 4
Water Source	From full-scale top of filter water	From full-scale top of filter water	From full-scale top of filter water	From full-scale top of filter water
Media Type	Anthracite/Silica Sand	Anthracite/Silica Sand	Anthracite/Silica Sand	Anthracite/Silica Sand
Media Effective Size (mm)	1.07	1.07	1.07	1.07
Sand Effective Size (mm)	0.54	0.54	0.54	0.54
Filtration Rate (gpm/ft^2)	3	3	3	3
Feed flow (gpm)	0.15	0.15	0.15	0.15
Depth of Media (inches)	18	24	24	24
Depth of Sand (inches)	12	12	14	16
Backwash	No Air	No Air	No Air	No Air
L/d Ratio	992	1134	1229	1322

On June 27, 2014 media in Filter 2 and Filter 4 were modified. At this time in the testing it was seen that 14 inches of sand produced the most favorable UFRV results. As such, Filter 2 was modified to increase the sand by adding an additional 2” of existing BWTF full-scale filter sand, and decrease the anthracite by 6”. The goal of this change was to evaluate the existing media conditions (12” of sand and 18” of anthracite), but with an additional 2” of sand. Additionally, Filter 4 (previously 16” of sand and 24” of anthracite) was modified to contain 14” of angular sand and 18” of anthracite. The City was interested in determining if increasing the angularity of the sand and decreasing the effective size would improve filter performance. Table 2-2 presents a summary of the change in media.

Table 2-2 Pilot Filter Configuration - 6/27 to 8/13

Parameters	Filter 1	Filter 2	Filter 3	Filter 4
Media Type	Anthracite	Anthracite	Anthracite	Anthracite
Sand Type	Silica	Silica	Silica	Silica
Media Effective Size (mm)	1.07	1.07	1.07	1.07
Sand Effective Size (mm)	0.54	0.54	0.54	0.48
Depth of Media (inches)	18	18	24	18
Depth of Sand (inches)	12	14	14	14 (angular sand)
L/d Ratio	992	1086	1229	1168

3. Findings and Results

ARCADIS conducted pilot setup, commissioning/start-up and pilot testing from January 26 through August 13, 2014. The bulleted list below presents a summary of the activities completed during this time period.

- **January 2014**
  - Project kickoff on January 29, 2014
- **February 2014**
  - Integrated pilot system into BWTF
  - Trained CU Boulder student on pilot
  - Re-plumbed significant portions of the system to control leaks due to aging pipe and connections
  - Installed media in all columns
  - Conducted troubleshooting on flow challenges
- **March 2014**
  - Conduct calibration of the pilot including chemical feed systems, pretreatment units, filter columns and water quality monitoring equipment.
  - Evaluated the use of pumping vs. gravity flow
- **April 2014**
  - Pilot testing startup
  - First pilot test started on April 18, 2014
  - Pilot columns being fed by pilot pretreatment unit
  - Three (3) test runs conducted during April 2014
- **May 2014**
  - Pilot testing continued
  - Pilot feed water changed from pretreatment unit to same water being fed to existing full-scale filters (top of filter sample line)
  - Spring runoff testing started
  - Eight (8) test runs conducted during May 2014
- **June 2014**
  - Pilot testing continued
  - Began compilation and review of all data to date
  - Nine (9) test runs conducted during June 2014
- **July 2014**
  - Pilot testing continued
  - Conducted spring runoff update meeting with the City at the Boulder Reservoir Water Treatment Facility (see Appendix B)
  - Ten (10) test runs conducted during July 2014
  - Began polymer testing

- **August 2014**
    - Pilot testing continued
    - Four (4) test runs conducted during August 2014
    - Pilot testing completed on August 13, 2014

Throughout the pilot testing phase, a total of 34 pilot tests runs were completed for each of the four filter configurations. Data was collected for both the pilot and full-scale filters including:

- Filter Run Time
- Turbidity
- Color
- Flow
- Unit Filter Run Volume (UFRV)
- Chemical dosages
- General water quality parameters (chlorine residual, TOC, pH, alkalinity, etc.)

The compilation and comparison of this data is presented in more detail in the following sub-sections.

3.1 BWTF Full-Scale Results

The City provided ARCADIS with filter data dating back to January 2011 for the eight (8) full-scale filters, and ARCADIS focused on spring runoff data which typically runs from May 1 to June 30. This data was compiled and used to develop comparison of the unit filter run volumes (UFRV) UFRV in two ways including:

- All 8 filters year by year (Figure 3-2)
- Each filter for the years 2011 through 2014 (Figure 3-3)

Figure 3-1 below presents a legend for the box-and-whisker plots presented in Figures 3-2 and 3-3.

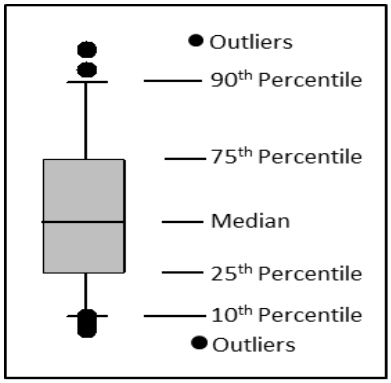

Figure 3-1 Box-and-Whisker Plot Legend

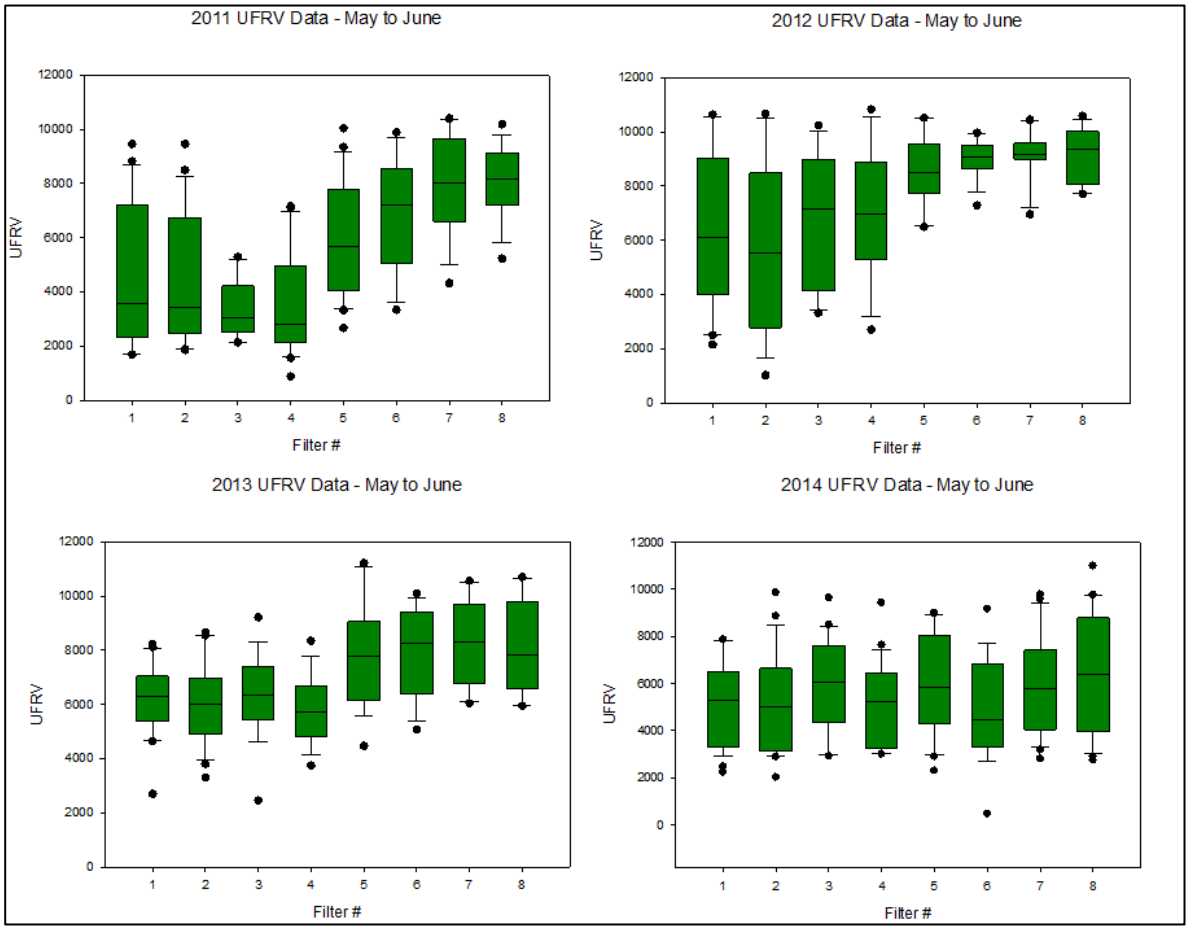

Figure 3-2 Full-Scale UFRV Data by Year

The UFRV data for all eight (8) filters has changed over the past four years of operation. During 2011, filters 1 to 4 produced approximately 50% lower UFRVs as compared to filters 5 to 8. Several studies were conducted during 2012 and it was found that the chlorinators were not functioning properly across filters 1 to 4. After repairing the chlorine feed system in early 2012, it can be seen that the UFRV increased for all filters, although there is still a large variation between filters 1 to 4 and filters 5 to 8. 2013 UFRV data again produced a variation in UFRV values between filters 1 to 4 and filters 5 to 8, although the variability decreased as compared to 2012. Finally, 2014 the UFRVs were similar for all 8 filters, whose medians ranged from 4,500 to 6,000gal/sf.

An interesting comparison from the figure is between 2011 and 2014 because the years presented more typical run off conditions. As discussed above, in 2011 there was a very distinct difference between filters 1-4 and 5-8, which was related to the several different challenges facing the BWTF (See table 1-1). Comparing to 2014, after several different improvements, it can be seen that all filters are performing more consistently when compared to each other, however generally speaking, the 2014 UFRVs are lower than the 2011. In 2011 the UFRVs ranged from 3,500 to 8,000 In 2014, between 4,500 to 6,000 gal/sf. One explanation for the decrease in 2014 is related to water balance in the plant and decisions made for operational purposes. Boulder staff stated that backwashes were often performed prior to breakthrough to cycle through filters and prevent a backup of filters requiring backwashing

Figure 3-3 presents the UFRV values during 2011 to 2014 on a filter by filter basis. Similar trends can be found year to year, as described previously. Several key conclusions from the data include:

- 2011 UFRV values are on average 50% lower for filters 1 to 4
- 2012 UFRV values were on average 10-15% higher for all filters
- For all filters, 2014 UFRV values decreased on average by 1300 gal/sf as compared to 2013 values (greatest decrease = 4,000 gal/sf, lowest decrease = 250 gal/sf)

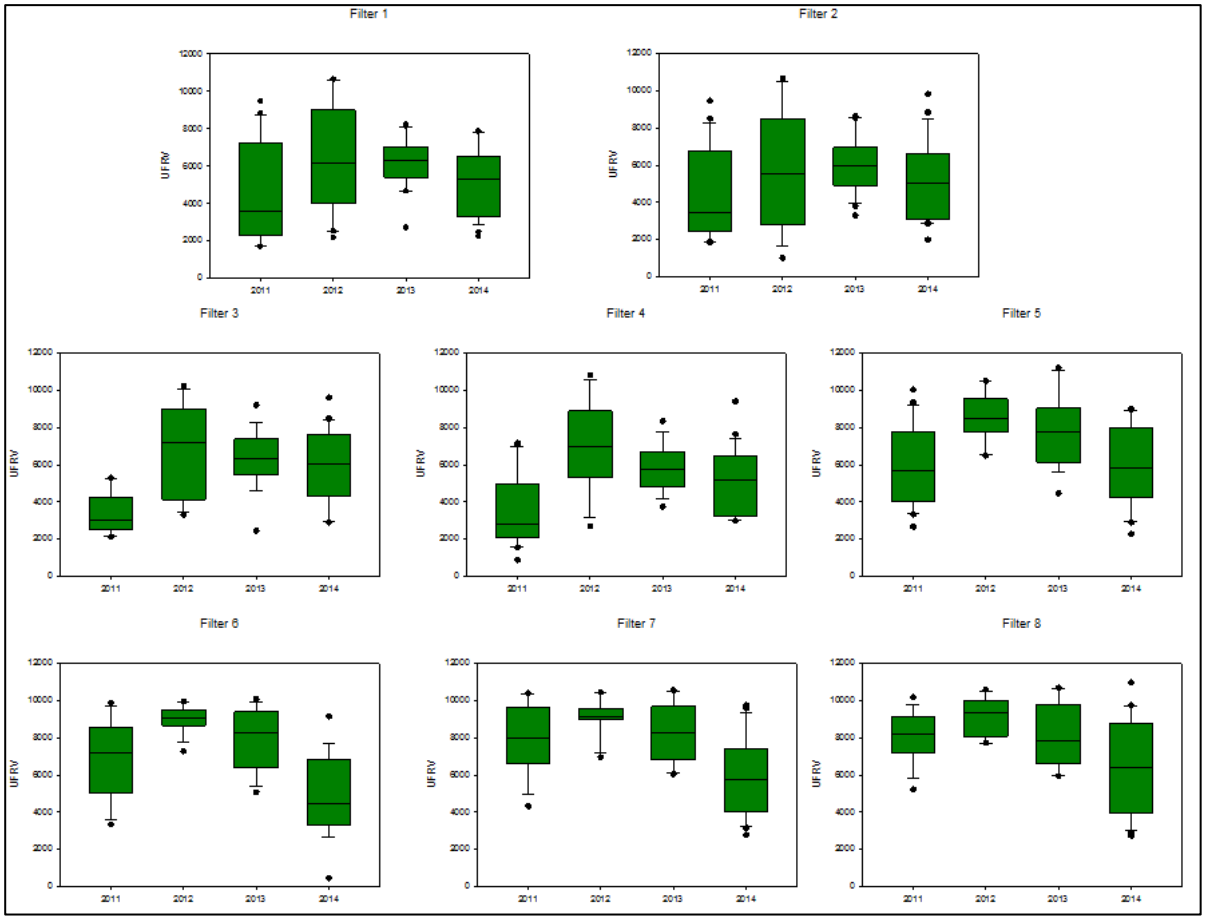

Figure 3-3 Full-Scale UFRV Data by Filter

3.2 Pilot-Scale Results

3.2.1 Source Water Quality

Throughout the course of the pilot study (4/14/2014 to 8/13/2014), 34 test runs were conducted. The source water utilized for these tests was the same water applied to the full-scale filters as described earlier. Figures 3-4 and 3-5 below present several of the key parameters and water quality indicators during the duration of the pilot testing, including:

- BTWF Flow (MGD)
- Alkalinity
- TOC
- Alum and PACl Dosages
- Raw Water Color
- Combined Sedimentation Basin Color
- Combined Sedimentation Basin Turbidity

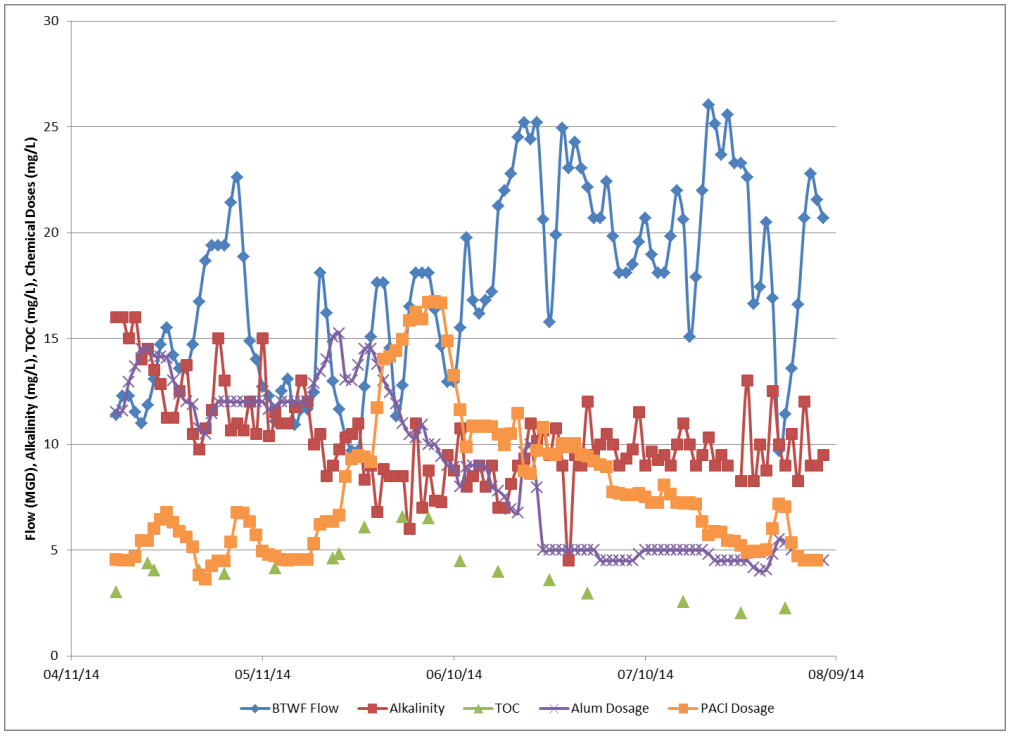

Figure 3-4 Source Water Quality

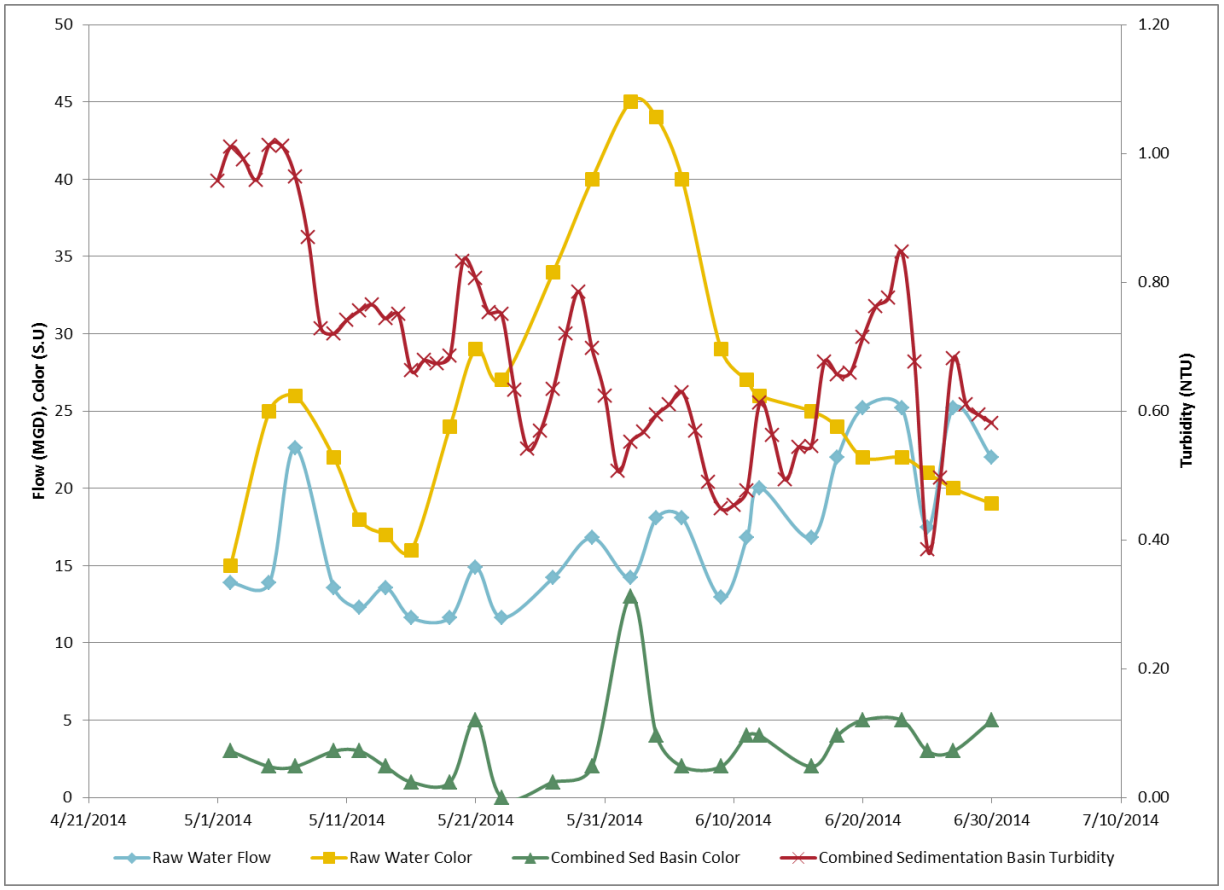

Figure 3-5 Additional Source Water Quality Data

As can be seen above in Figures 3-3 and 3-4, several different water quality trends were captured throughout the 3 months of pilot testing. These include:

- High color periods (mid May to mid June 2014)
- High flow periods (early June to early August 2014)
- Increased TOC during spring runoff
- Increased alkalinity prior to spring runoff
- Increased PACl usage and decreased alum usage during high color periods

This information was used to compare filter performance during two unique challenge periods, high color and high flow.

3.2.2 Pilot Testing UFRV Results

The pilot filter run data was collected and evaluated throughout the pilot testing. Table 3-1 below presents a summary of all 34 test runs, including, UFRV, reason for ending the run, settled water color (i.e. pilot filter feed water), and BTWF average production during the test runs. The purpose of this table is:

1. Present a comparison between the four filters UFRV and two important water quality criteria (flow and color) and
2. Relate this information back to why a specific filter run ended.

The correlation between color and flow will help identify the most challenging conditions for filtration performance. The key for the table is as follows:

- Green
  - Filter run ended due to turbidity breakthrough of above 0.1 NTU
- Purple
  - Filter run ended due to headloss (i.e. loss of flow through filter media)
- Yellow
  - Color between 0 and 5
  - Flow between 10 to 17 MGD
- Orange
  - Color between 5 and 10
  - Flow between 17 to 21 MGD
- Red
  - Color greater than 15
  - Flow greater than 21 MGD
- UFRV
  - Low – 0 to 4,999 gal/sf
  - Medium – 5,000 to 9,999 gal/sf
  - High (Target range) – 10,000 to 14,000 gal/sf

Table 3-1 Filter Pilot Summary

Filter Runs (2014)	Filter 1 UFRV (gal/sf)	Filter 2 UFRV (gal/sf)	Filter 3 UFRV (gal/sf)	Filter 4 UFRV (gal/sf)	Settled Water Color/Feed Water to Pilot Filters (CU)	Average BTWF Production (MGD)
4/18 to 4/21	5,346	7,924	9,201	4,833	2-3	11 - 12

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Filter Runs (2014)	Filter 1 UFRV (gal/sf)	Filter 2 UFRV (gal/sf)	Filter 3 UFRV (gal/sf)	Filter 4 UFRV (gal/sf)	Settled Water Color/Feed Water to Pilot Filters (CU)	Average BTWF Production (MGD)
4/21 to 4/24	2,529	5,108	10,492	12,076	3-4	11 - 15
4/28 to 5/2	2,597	5,982	8,963	8,416	3-6	14 - 19
5/2 to 5/4	5,838	5,023	5,908	7,359	2-3	14
5/5 to 5/7	6,965	6,889	7,619	6,675	2	14 - 23
5/7 to 5/10	11,000	10,130	10,023	11,258	2-3	14 - 23
5/10 to 5/14	9,046	11,649	13,460	11,221	2-3	12 - 14
5/14 to 5/19	11,036	8,678	12,141	12,437	1-2	12 - 14
5/19 to 5/23	9,345	7,906	10,607	10,112	1-5	12 - 15
5/23 to 5/27	9,755	7,179	14,010	5,111	1	12 - 14
5/27 to 5/30	8,120	9,391	10,469	8,438	1-2	14 - 17
5/30 to 6/2	7,100	12,124	7,198	12,102	2-13	14 - 17
6/2 to 6/6	7,962	7,463	11,688	11,615	2-13	14 - 18
6/6 to 6/9	6,527	6,449	8,665	9,378	2	13 - 18
6/9 to 6/12	9,529	11,111	13,088	11,348	2-4	13 - 20
6/16 to 6/18	4,992	6,910	8,072	8,025	2-4	17 - 22
6/18 to 6/20	4,268	6,090	6,522	5,514	4-5	22 - 25
6/20 to 6/23	3,271	5,901	4,438	6,977	5	25
6/23 to 6/27	2,804	2,804	4,235	2,743	3-5	15 - 25
6/27 to 6/30	2,681	4,493	3,532	4,444	3-5	21 - 25
6/30 to 7/2	4,726	6,042	6,852	5,621	--	20 - 23
7/2 to 7/7	10,906	9,433	8,346	10,301	--	18 - 22

Filter Runs (2014)	Filter 1 UFRV (gal/sf)	Filter 2 UFRV (gal/sf)	Filter 3 UFRV (gal/sf)	Filter 4 UFRV (gal/sf)	Settled Water Color/Feed Water to Pilot Filters (CU)	Average BTWF Production (MGD)
7/7 to 7/9	3,556	3,513	2,981	3,467	--	18 - 20
7/9 to 7/13	11,251	11,465	12,950	7,964	--	18 - 21
7/13 to 7/16	5,486	7,228	7,851	3,620	1-2	20 - 22
7/16 to 7/21	2,681	4,493	3,532	--	--	15 - 26
7/21 to 7/23	2,548	6,556	8,230	--	--	24 - 26
7/23 to 7/24	9,122	6,855	6,855	6,140	2-3	23 - 25
7/25 to 7/28	2,933	2,676	3,067	7,942	--	17 - 23
7/28 to 7/29	3,342	2,144	3,849	2,230	2-4	17 - 20
7/29 to 8/1	4,922	11,801	6,440	3,440	--	10 - 17
8/1 to 8/4	6,519	1,374	6,922	1,870	--	14 - 21
8/4 to 8/8	7,760	10,811	11,550	8,377	3-6	21 - 23
8/8 to 8/13	7,359	2,749	9,486	5,199	--	--

Through the evaluation of this data, several important trends were identified:

- Low color/low plant production rate
  - Pilot filters typically terminated due to headloss
  - Average UFRV of 8,800 gal/sf
- Low color/high plant production
  - Pilot filters typically terminated due to turbidity breakthrough (greater than 0.1 NTU)
  - Average UFRV values were 40 – 55% less than that of low color/low production and high color/low production scenarios
- High color/low production
  - Pilot filters typically terminated due to turbidity breakthrough
  - Average UFRV of 9,700 gal/sf
- High color/high production
  - No high color/high flow events were experienced during the pilot testing

The results suggest that the high production is one of the most critical time periods, more so than even the high color events at the beginning of spring runoff (when production is low). It should also be noted that the assumed maximum hydraulic capacity for the BWTF is 50 MGD at a filtration rate of 5 gpm/ft^2. As such, the results presented above will most likely be even more problematic, as the pilot testing was tested at a 3 gpm/ft2 filtration rate, which corresponds to a full-scale capacity of 30 MGD.

Figure 3-6 below presents the UFRV data using a box-and-whisker plot.

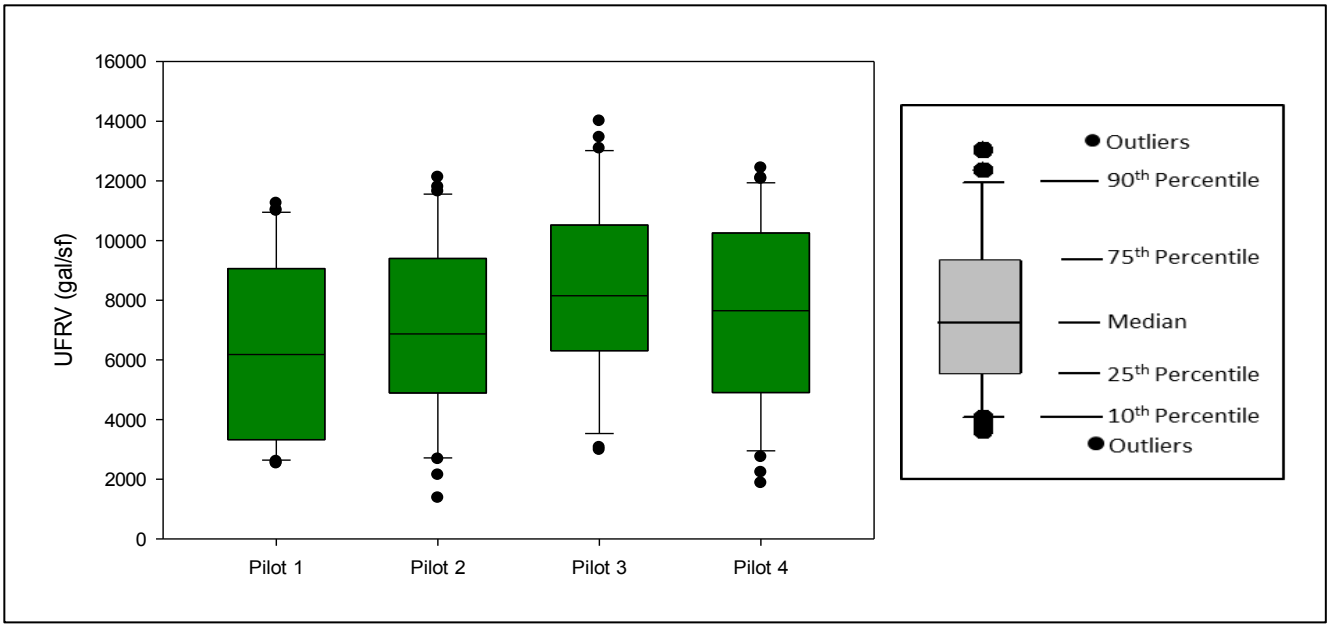

Figure 3-6 Pilot UFRV Box-and-Whiskers Plot (April 14, 2014 to August 13, 2014)

Throughout the 34 pilot runs, filter column 3 (24" anthracite, 14" sand) consistently produced higher UFRV values (on average 5 to 26%) as compared to the other three (3) filters. Table 3-2 and 3-3 below present the general statistics from the complete pilot testing data.

Table 3-2 April 18 to June 27 - UFRV Statistics

Parameter	Filter 1	Filter 2	Filter 3	Filter 4
Anthracite (in)	18	24	24	24
Sand (in)	12	12	14	16
Average UFRV (gal/sf)	7347	7856	9259	8791

Maximum UFRV (gal/sf)	11036	12124	14010	12437
Minimum UFRV (gal/sf)	2804	2804	4235	2743
Standard Deviation (gal/sf)	2592	2534	3150	2898

Table 3-3 June 27 to August 13 - UFRV Statistics

Parameter	Filter 1	Filter 2	Filter 3	Filter 4
Anthracite (in)	18	18	24	18
Sand (in)	12	14	14	14
Average UFRV (gal/sf)	5719	6109	6830	5432
Maximum UFRV (gal/sf)	11251	11801	12950	10301
Minimum UFRV (gal/sf)	2548	1374	2981	1870
Standard Deviation (gal/sf)	2986	3479	3069	2593

As can be seen above in Table 3-2, from April to the end of June 2014, filters 3 and 4 resulted in the highest UFRV values as compared to filters 1 and 2. Comparing filters 2 and 3, it appears the depth of anthracite had little impact on increasing the UFRV of the pilot columns, but that an increase of 2 inches of sand produced approximately 20% better results.

Similarly during June 27 to August 13 2014, the filters with two extra inches of sand resulted in increased UFRV values, with the exception of filter 4. This is potentially due to the fact that the sand had a smaller effective size, which could result in an increase in particulate removal, and a more rapid increase in headloss.

3.2.3 Polymer Testing Results

In addition to evaluating different media configurations and L/d ratios, polymer testing was also conducted over a two-week period. The purpose of the polymer testing was to evaluate if the addition of a filter aid-polymer would improve the filterability of particulates without sacrificing runtime/excessive headloss buildup.

A cationic polymer was tested during the filter aid polymer evaluation at a dose of 0.05 mg/L. This was a brief test to get a sense for the value of conducting additional polymer testing in the future. Typically for cationic polymers the dosage range can be higher than most other polymers (typical doses non-ionic and anionic range between 0.005 to 0.05 mg/L) due to the fact that the materials are water soluble. Table 3-4 below presents the UFRV results of the testing.

Table 3-4 Filter Aid Polymer UFRV Results

Date	Filter 1	Filter 2	Filter 3	Filter 4
7/28 to 7/29	3,342	2,144	3,849	2,230
7/29 to 8/1	4,922	11,801	6,440	3,440
8/1 to 8/4	6,519	1,374	6,922	1,870
8/4 to 8/8	7,760	10,811	11,550	8,377
8/8 to 8/13	7,359	2,749	9,486	5,199

The results of the polymer testing were variable. In two of the 5 filter runs the UFRV values relatively high (> 8,000 gal/sf), while others remained less than 4,000 gal/sf. Referring back to Table 3-1, all the filter runs terminated on headloss during these tests.

One finding from the testing was that a tailored backwashing regime was required to effectively clean the filters. As expected, addition of filter aid polymer resulted in an increased layer of particulate trapped at the top of the filter. This caused increased headloss, and the need to expand the media upwards of 40% during the backwash. This is fairly typical behavior when polymer is added. With a limited data set such as this it is hard to draw hard conclusions. It is recommended that further testing be conducted on polymer types and doses.

3.2.4 Pilot Testing vs. Full-Scale

In addition to evaluating the pilot filter configurations side by side, the piloting results were compared to the BWTF full-scale results throughout the testing period. Figure 3-7 below presents a side-by-side comparison of the average full-scale filter UFRVs and the pilot scale filter UFRVs during testing.

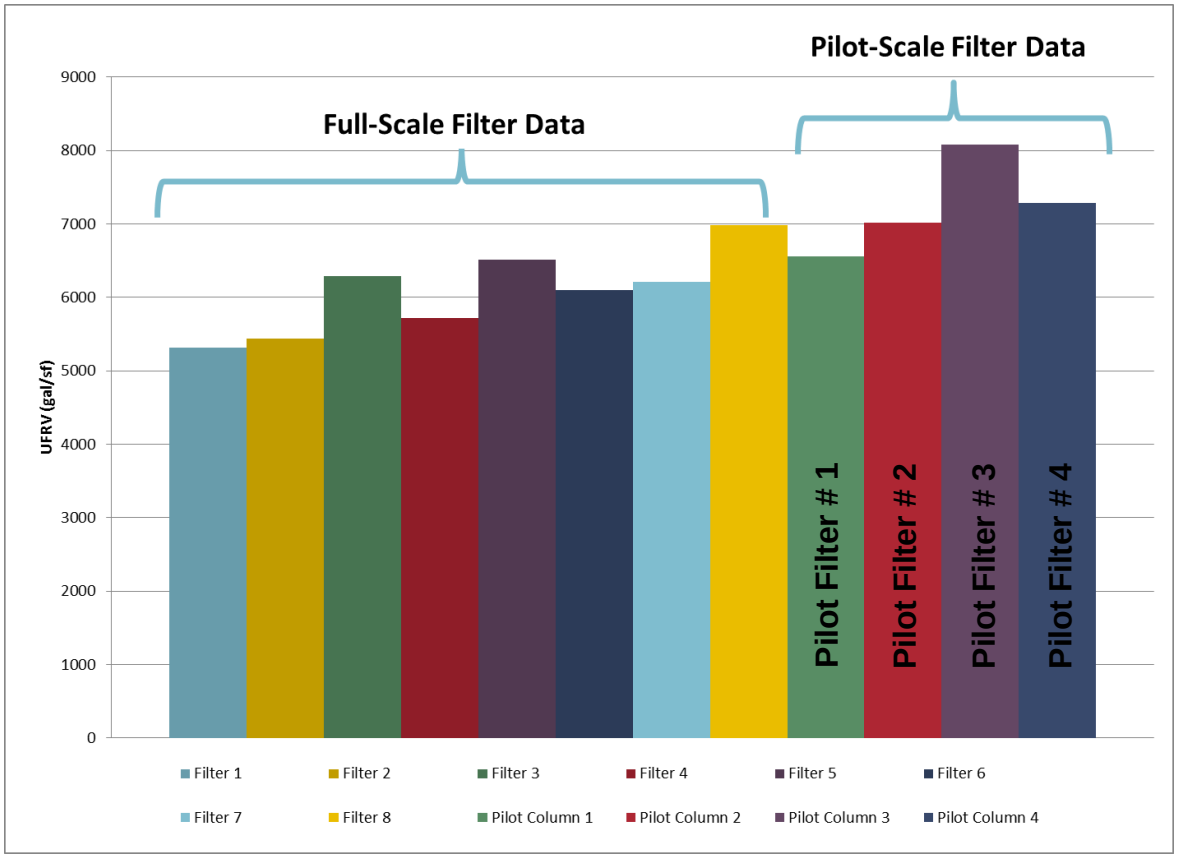

Figure 3-7 Pilot UFRV s. Full-Scale UFRV

As previously discussed, pilot filter 1 had the same configuration as the full-scale filters, 18" of anthracite and 12" of sand. On average, this filter demonstrated similar results as several of the full-scale filters. The average UFRV for pilot filter 1 was approximately 6,500 gal/sf, while the (combined) average of the full-scale BWTF filters was approximately 6,100 gal/sf. This similarity between the control (pilot filter 1) and the full scale filters provided confidence in the results, in particular that the increase in sand provides a benefit to filter performance.

One item to note is that in the pilot filters, a filter run was terminated when the turbidity reached above 0.1 NTU, which corresponds to the AWWA Partnership for Safe Water goal. However, the BWTF filters are often terminated at turbidity levels below 0.1 NTU. This does not however diminish the impact of the testing which clearly demonstrates improved performance with different L/d configurations.

Figure 3-8 below presents an example of the BWTF filter 1 ending turbidities and resulting UFRV. As shown, the majority are taken off line well below 0.1 NTU.

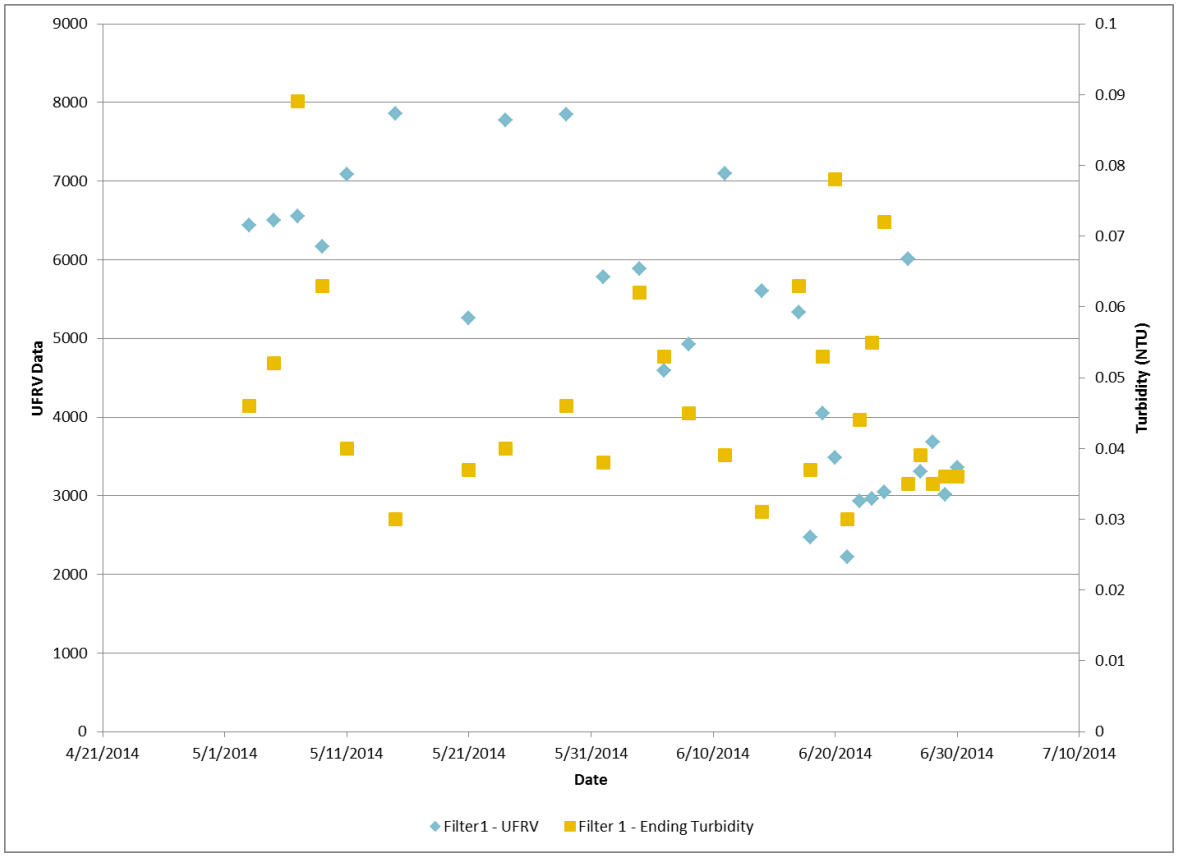

Figure 3-8 BWTF Filter 1 Ending Turbidities

3.3 Conclusions

The conclusions and recommendations from the BWTF Filtration Performance Evaluation/Optimization Study are summarized below in Table 3-5.

Table 3-5 BWTF Pilot Testing Conclusions and Recommendations

Conclusions and Recommendations	Supporting Information (If applicable)
1) Increased sand depths led to increased UFRV values. Recommended that the City consider adding more sand to their filters. Refer to L/d memo in Appendix A for additional information on allowable filter media depths.	• Increasing the depth of sand by 2”-4” inches led to increased filter performance (approximately 20% better)
2) High flow more challenging than high color periods. Recommend additional testing during high flow period. This appears to be more challenging now then the high color period.	• As compared to high color scenarios, the UFRV values on average decreased by 55% during high production scenarios
3) Pilot filter runs most commonly ended due to turbidity breakthrough during high color and a combination of headloss and turbidity during high flow.	• Refer to table 3-1.
4) Full scale filters are taken off line well before turbidity reaches 0.1 NTU. It is recommended that the driver for the early termination of filter runs be identified. This could provide additional plant capacity.	• The Betasso plant is a Partnership facility and as such has a goal of 0.1 NTU
5) Polymer testing produced variable results. It is recommended a more detailed testing regime with polymer and increased sand depth be explored.	• Polymer testing conducted with a cationic filter aid polymer • Improved particulate removal • Increased backwashing was required (40% expansion) to clean filters

Appendix A

Betasso WTP – Filter Investigation – Filter Media L/d Memo

ARCADIS U.S., Inc.
100 Fillmore Street
Suite 200
Denver
Colorado 80206
Tel 303 316 6500
Fax 303 316 6599
www.arcadis-us.com

Mr. Steve Buckbee, P.E.
City of Boulder, Department of Public Works
Utilities Division
1739 Broadway
P.O. Box 791
Boulder, Colorado 80306

Water

Subject:
Betasso WTP – Filter Investigation– Filter Media L/d Memo- Revised

Date:
June 5, 2014

Contact:
Jack Bryck

Phone:
303.316.6535

Email:
Jack.Bryck@arcadis-us.com

Our ref:
05311001.0002

Dear Mr. Buckbee:

Introduction: The ARCADIS August 20, 2012 'Betasso Spring Runoff Report' to the City identified issues with the filter media L/d (ratio of media depth to the media effective size) of Filter 2. The L/d was about 992 based on one City Filter 2 media core taken in 2012, at a minimum should be about 1100 to 1200 and ideally should be 1200 to 1700 to optimize particulate removal. One of the primary issues experienced during spring runoff at the Betasso plant, and the original purpose for spring runoff testing, is short filter runs resulting in part from turbidity breakthrough.

This memorandum identifies the physical characteristics of the filter boxes and the opportunity to modify the L/d within the vertical limitations of the filter boxes. It is recommended that higher L/d ratios greater than 1100 be evaluated as part of 2014 pilot testing program.

Background: The ratio "L/d "is one of the criteria to ensure an appropriate media configuration that will result in good particulate removal. The L/d ratio is calculated as follows:

- L is the media depth in mm
- d = the media effective size in mm

Using sieve analysis data of two core samples collected by the City in the 2009 inspection of Filter 2, an L/d Ratio was estimated to be about 914. While the City media specification in the last media change out in 1994 was for a tri-media (anthracite, sand, garnet), the core samples identified that the sand and garnet layers were blended together. For the L/d calculations the effective size was assumed to be sand.

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June 5 2014

Soon after this evaluation, the media was reportedly supplemented with additional anthracite. The resulting existing L/d for the filter based on one City Filter 2 media core taken in 2012 is estimated to be 992. While the City media specification is a tri-media (anthracite, sand, garnet), the core sample identified that the sand and garnet layers were blended together. For the L/d calculations the effective size was assumed to be sand. Adding media increased the L/d but did not reach the L/d of 1100 to 1200. It is assumed that the filters 1 and 3 to 8 have the same L/d as Filter 2.

Filter Box Dimensions: There are eight (8) Betasso WTP filters. Filters 1 to 4 were constructed in 1962-1966 while the Filters 5 to 8 were constructed in the period 1976-1978. The filters are identical in physical dimensions with the dimensions of the centerline to centerline being 19.5 ft. by 34 ft. and the vertical dimensions as follows:

- Bottom of filter box to top of filter box= 12.0 feet
- Bottom of filter box to top of wash water troughs= 7.0 feet
- Bottom of filter box to bottom of wash water troughs= 5.0 feet

The accompanying Figure 1 illustrates the filter cross-section. This figure is based on the 'Betasso Water Treatment Plant Expansion DMJM-Phillips-Reiste, Inc' drawings February 1976 revised for the filter media change out in 1994. The figure includes a cross section orientation and vertical dimensions of the underdrains/filter media.

At time of design the underdrain was about 10 in. vertical, the gravel support was about 12 in. vertical, the filter sand was 8 in. vertical and the anthracite was 18 in. vertical.

The filter media, however, was changed out in 1994. Table 1 below summarizes media details from information in the City Bid Specifications. It is unknown if the media of the specified characteristics was actually supplied. It was noted, however, that in the analysis of a core sample taken by the City in 2012, the high density sand media and the intermediate sand media layers were indistinguishable. This is assumed to be the media characteristics in 2014.

Table 1 Filter Media Specifications

	Depth	Depth from Top	Effective Size	Uniformity Coefficient	Specific Gravity	Acid Solubility	Other
Silica Gravel	5"	37-42"	3/4" X 3/8"	NA	Avg > 2.5		-
Silica Gravel	4"	33-37"	3/8" X 3/16"	NA	Avg > 2.5		-

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June 5 2014

	Depth	Depth from Top	Effective Size	Uniformity Coefficient	Specific Gravity	Acid Solubility	Other
High Density Support Gravel	3"	30-33"	1 - 2 mm	NA	>= 3.8	<5%	-
High Density Sand	3"	27-30"	0.18 - 0.28 mm	<= 2.2	4	<5%	-
Intermediate Sand	9"	18-27"	0.35 - 0.45 mm	<= 1.45	2.6	<5%	-
Anthracite Coal	18"	0-18"	1.0 - 1.1 mm	<= 1.5	>= 1.55	<5%	Hardness >= 3.5 MOH. Caustic solubility <- 2%...
Total Depth	42”						

From a July 2012 analysis of the media in Filter 2 by the City, the physical characteristics of both the sand media and the anthracite media in Filter 2 are presented in Table 2. The report is attached to this memorandum.

Table 2 July 2012 Media Characteristics of Filter 2

	Effective Size, mm	Uniformity Coefficient
Anthracite	1.07	1.4
Sand	0.54	1.3

The present bed expansion by the Betasso WTP staff is reported to be 20 %. Under the existing media configuration and a 20% bed expansion the expanded bed depth is 36 in. (total filtering media depth is 30 in.). The vertical difference between the bottom of the wash water trough and the expanded media ‘front’ under this situation is estimated to be 1.68 in.

Analysis of Filter L/d: An analysis of the existing L/d based on the media dimensions noted above as well as the depth of the media to achieve the L/d of greater than 1100, assuming the effective size does not change, are summarized in Table 3 below. While the City 1994 media specification was a tri-media (anthracite, sand, garnet), the core sample identified that the sand and garnet layers were

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blended together. For the L/d calculations the effective size was assumed to be sand.

Table 3 Comparison of L/d Values

Configuration	Sand Depth (in)	Anthracite Depth (in)	Total Depth (in)	Combined L/d
Existing	12	18	30	992
Alternative 1	12	24	36	1134
Alternative 2	14	24	38	1228
Alternative 3	16	24	40	1322
Alternative 4	16	28	44	1417

The limiting factor for different alternatives is the proximity of the media 'front' during a backwash bed expansion event to the bottom of the wash water troughs. The greater the media depth the greater the bed expansion. The media 'front' should be below the bottom of the wash water troughs. If not it will increase the upflow velocity and will carry over media. For new filter design the space between the top of the media and the bottom on the underdrains generally allows for 50% bed expansion.

To achieve an L/d greater than 1100, the sand/anthracite depth would have to increase at a minimum from a total of 30 in. to about 36 in. Table 4 provides an estimate of the vertical difference between the bottom of the wash water troughs and the media 'front' on a backwash for 20%, 25% and 30% bed expansion and 36, 38, 40 and 44 in. of filter media.

Discussion: The filter boxes at the Betasso plant are relatively shallow and have limited vertical depth to add deeper media but avoid the media 'backwash front' reaching the top of the wash water troughs on backwash. There are three options:

1. **Retain the existing underdrains-** The underdrains in Filter 1 to 4 were reportedly installed in 1966-1966 and the underdrains for Filter 5 to 8 were installed in 1976-1978. If they are in good physical shape and operate as intended then this option is to retain the underdrains. To achieve an L/d of 1100 the dual media depth would have to increase to a total of 36 inches including 12 in. of sand and 24 in. of anthracite. In this case to meet the criteria that the media 'front' should be below the bottom of the wash water trough only a 25% bed expansion is possible.

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2. **Change out the underdrains**- A second option is to replace the existing underdrain system and gravel support and replace with a low profile underdrain system. Accompanying the memo is an example replacement low profile system (IMS system by Leopold). If the existing underdrains are a found in good condition, a possible approach is a system such as the AWI Phoenix Panel System that would be installed over the clay-tile block underdrains.

   The estimated head loss through the existing underdrain system is not known but for purposes of this memorandum it is assumed that the low profile system headloss is no greater than the headloss of the existing underdrain system.

   The vertical depth of the existing underdrains and the gravel support is estimated to be 22 in. as per the Figure 1 and the low profile under drain system vertical dimension is about 12 in. or a net vertical difference of 10 in. In other words the media depth could be increased from the existing 30 in. to 36 in. yet keep the elevation of the top of the media surface approximately the same. At a bed expansion of 20% on 36 in of media the backwash media 'front' is calculated to be 3.84 in. below the bottom of the wash water trough. At 30% is calculated to be 0.24 in. below the bottom of the wash water trough.

   Figure 2 attached presents a comparison of the existing media configuration/underdrain system to four media configurations and bed expansion alternatives with the low profile underdrain system. The approximate elevations associated with 20%, 25% and 30% bed expansion are highlighted in color. The limiting criteria is that the media 'front' should be below the bottom of the wash water troughs for up to 30% bed expansion. Table 4 below presents a summary of media expansion in reference to the distance to the bottom of the trough.

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June 5 2014

Table 4 Media Expansion Comparison

Configuration	Total Media Depth (in)	L/d	20% Expansion - Distance of Media Front Expansion During Backwash to Bottom of Trough	25% Expansion - Distance of Media Front Expansion During Backwash to Bottom of Trough	30% Expansion - Distance of Media Front Expansion During Backwash to Bottom of Trough
Existing Configuration	30	992	1.68 in.	0.33 in.	(1.02 in.)
New Underdrain Configuration 1	36	1134	3.84 in.	2.04 in.	0.24 in.
New Underdrain Configuration 2	38	1228	1.4 in.	(0.5 in.)	(2.4 in.)
New Underdrain Configuration 3	40	1322	(1.04 in.)	(3.04 in.)	(5.04 in.)
New Underdrain Configuration 4	44	1417	(5.8 in.)	(8 in.)	(10.2 in.)

From Table 4 and in the attached Figure 2, at an expansion of up to 30% the existing underdrain and media configuration, and the possible low profile underdrain system and new configuration 1 meet the criteria that the media 'front' should be below the bottom of the wash water troughs for up to 30% bed expansion.

Configurations 2, 3 and 4 and the low profile underdrain do not meet the criteria that the media 'front' should be below the bottom of the wash water troughs at for up to 30% bed expansion

It is noted that with a low profile underdrain system the L/d ratio is confined to between about 1100 or 36 in. of total media.

3. **Raise the wash water trough**- A possible options is to increase the elevation of the wash water troughs. This will change the hydraulic grade line

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for the filters during a filter backwash. The impact of raising the wash water troughs and the impact on the raising the backwash hydraulic grade line would have to be investigated.

We trust this meets the City's needs. We very much appreciate this opportunity.

Sincerely,

ARCADIS U.S., Inc.

Jack Bryck, P.E., BCEE
Principal in Charge

Copies:
Ms. Laurie Sullivan, P.E., BCEE, ARCADIS
Mr. Jeff Jackson, CWP, ARCADIS

BOWSER-MORNER, INC.

Delivery Address: 4518 Taylorsville Road Dayton, Ohio 45424 Mailing Address: P.O. Box 51 Dayton, Ohio 45401

AASHTO/ISO 17025 Accredited

LABORATORY REPORT

Report To: City of Boulder, CO WTP
Attn: Niall Stewart, PE
1094 Betasso Road
Boulder, CO 80302

Report Date: 07/24/12
Job No.: 158901
Report No.: 708657
No. of Pages: 2

Project/Plant: Filter Media Analysis
Test Method: AWWA B100-01

Date Received: 07/19/12

Sample ID: Anthracite, Filter #2

USA Std.	Nominal, mm	Effective, mm	Percent Passing
#6	3.35	3.35	**100.0**
#7	2.80	2.80	**99.9**
#8	2.36	2.36	**99.7**
#10	2.00	2.002	**94.8**
#12	1.70	1.721	**80.2**
#14	1.40	1.363	**46.1**
#16	1.18	1.183	**20.0**
#18	1.00	0.999	**6.0**
#20	0.850	0.868	**1.6**
#25	0.710	0.721	**0.4**
Effective Size, mm:			**1.07**
Uniformity Coefficient:			**1.4**

If you should have any questions, or if we may be of further service, please contact me at 937-236-8805, extension 329.

Respectfully submitted,
BOWSER-MORNER, INC.

Scott D. Ruhkamp

Scott D. Ruhkamp, Supervisor
Special Projects Section
Construction Materials Laboratory

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708657
1-File
1-stewartn@bouldercolorado.gov

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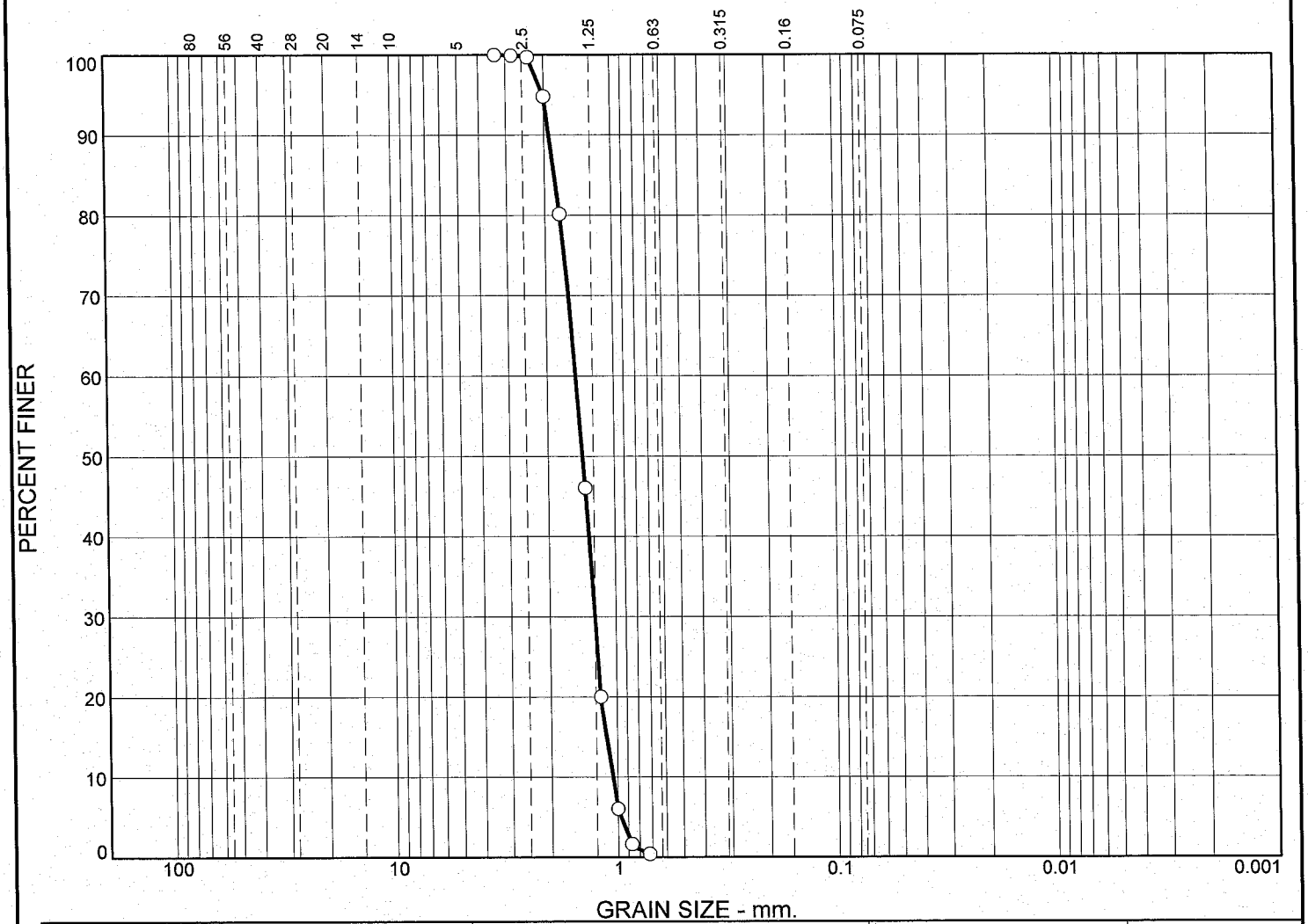
Attachment C

GRAIN SIZE DISTRIBUTION REPORT



	% +3"	% Gravel	% Sand	% Silt	% Clay
○	0.0	0.0			

	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○			1.7953	1.4796	1.3928	1.2545	1.1370	1.0740	0.99	1.38

Material Description	USCS	AASHTO
○ Anthracite, Filter #2		

Project No. 158901 **Client:** City of Boulder, CO WTP

Project: Filter Media Analysis

○ **Location:** Date Received: 7-19-12

Remarks:

BOWSER-MORNER, INC.

Dayton, Ohio

BOWSER-MORNER, INC.

Delivery Address: 4518 Taylorsville Road Dayton, Ohio 45424 Mailing Address: P.O. Box 51 Dayton, Ohio 45401

AASHTO/ISO 17025 Accredited

LABORATORY REPORT

Report To: City of Boulder, CO WTP
Attn: Niall Stewart, PE
1094 Betasso Road
Boulder, CO 80302

Report Date: 07/24/12
Job No.: 158901
Report No.: 708656
No. of Pages: 2

Project/Plant: Filter Media Analysis
Test Method: AWWA B100-01

Date Received: 07/19/12

Sample ID: Sand, Filter #2

USA Std.	Nominal, mm	Effective, mm	Percent Passing
#14	1.40	1.370	**100.0**
#16	1.18	1.213	**98.0**
#18	1.00	1.007	**93.7**
#20	0.850	0.873	**90.2**
#25	0.710	0.705	**66.9**
#30	0.600	0.610	**31.0**
#35	0.500	0.504	**3.6**
#40	0.425	0.409	**0.1**
Effective Size, mm:			**0.54**
Uniformity Coefficient:			**1.3**

If you should have any questions, or if we may be of further service, please contact me at 937-236-8805, extension 329.

Respectfully submitted,
BOWSER-MORNER, INC.

Scott D. Ruhkamp

Scott D. Ruhkamp, Supervisor
Special Projects Section
Construction Materials Laboratory

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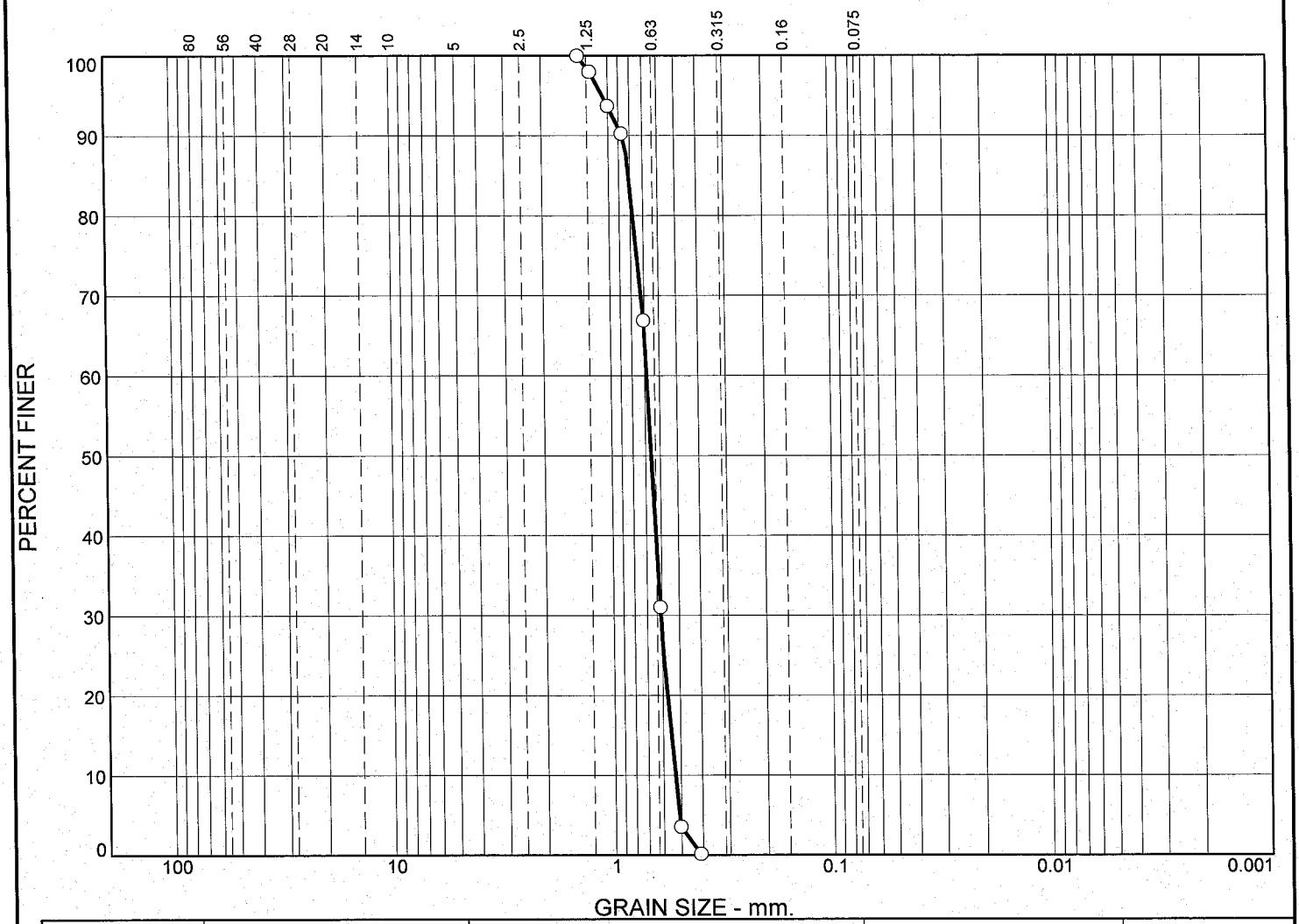


	% +3"	% Gravel	% Sand	% Silt	% Clay
○	0.0	0.0			

	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○			0.8000	0.6839	0.6575	0.6072	0.5606	0.5403	1.00	1.27

Material Description	USCS	AASHTO
○ Sand, Filter #2		

Project No. 158901 **Client:** City of Boulder, CO WTP

Project: Filter Media Analysis

○ **Location:** Date Received: 7-19-12

Remarks:

BOWSER-MORNER, INC.

Dayton, Ohio

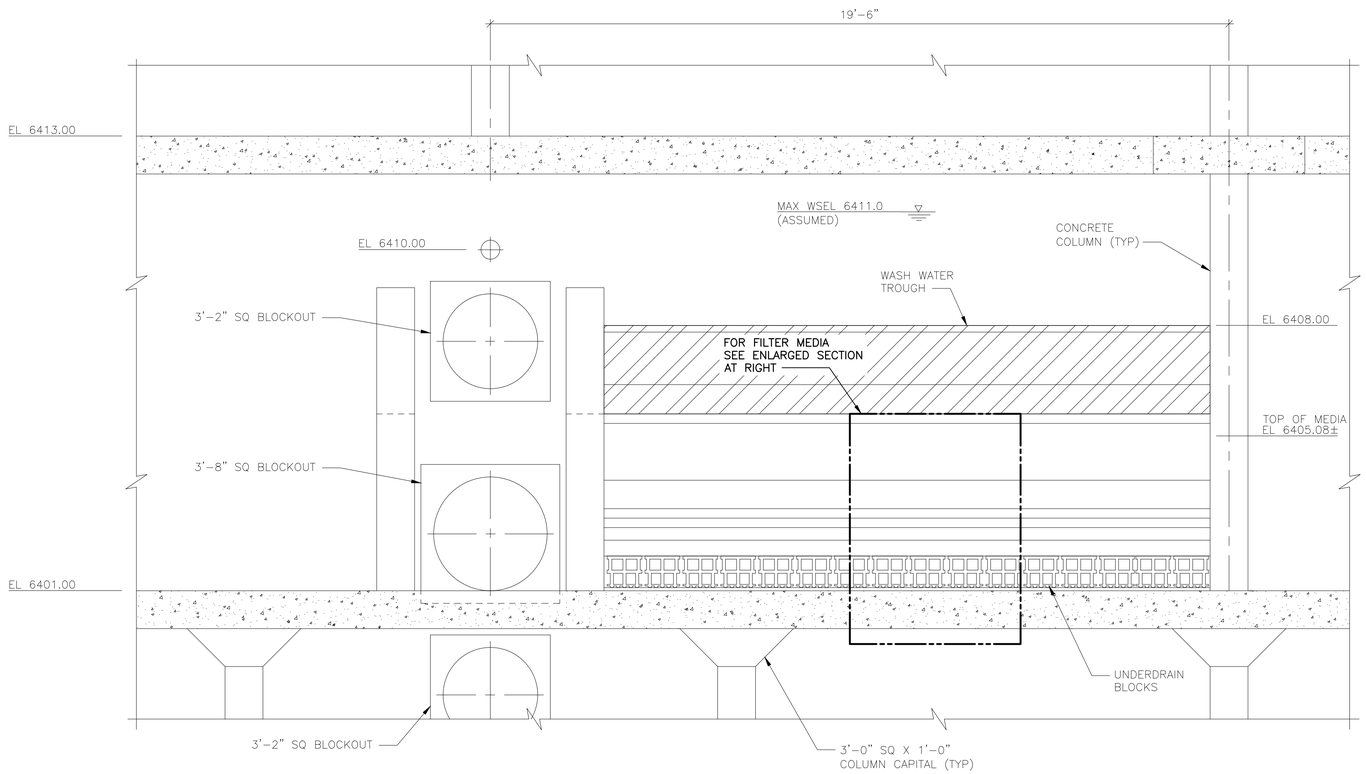
Figure 2 - Comparison of Media Front Expansion/Location During Backwash Operation

Attachment C

30% Expansion
25% Expansion
20% Expansion

Percent Bed Expansion

Configuration	L/d	20% Expansion - Distance to Bottom of Trough	25% Expansion - Distance to Bottom of Trough	30% Expansion - Distance to Bottom of Trough
Existing Configuration	992	1.68"	0.33"	1.02"
New Underdrain Configuration 1	1134	3.84"	2.04"	0.24"
New Underdrain Configuration 2	1228	1.4"	(0.5")	(2.4")
New Underdrain Configuration 3	1322	(1.04")	(3.04")	(5.04")
New Underdrain Configuration 4	1417	(5.8")	(8")	(10.2")



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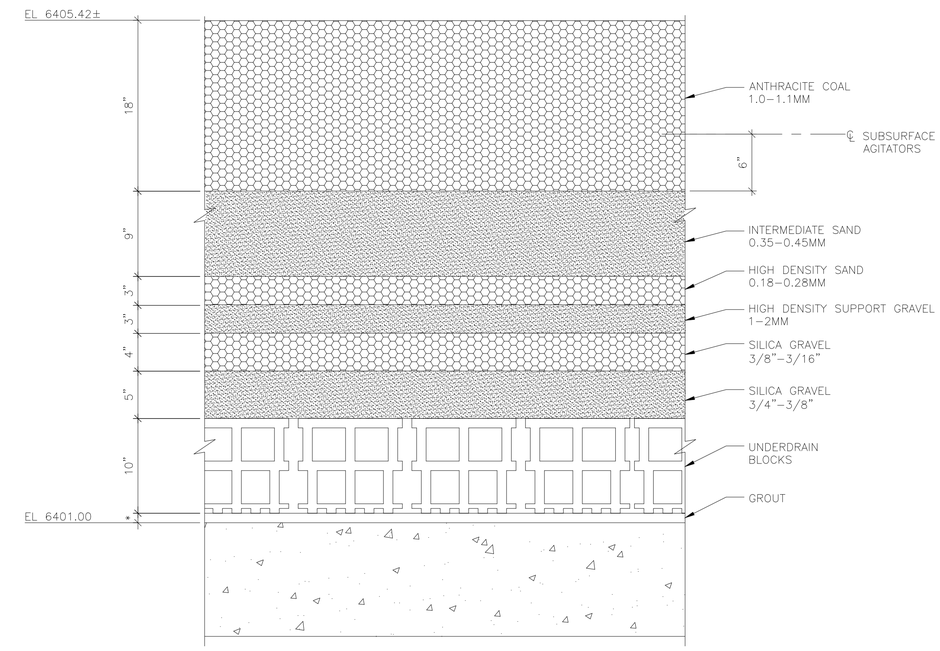

ENLARGED SECTION
SCALE: 1 1/2" = 1'-0"

FIGURE 1

DRAFT

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Infrastructure · Water · Environment · Buildings

REVISIONS			
NO.	BY	DATE	REMARKS

DES .
DWN .
CKD

CITY OF BOULDER, COLORADO
BETASSO WATER TREATMENT PLANT
MEDIA ANALYSIS – 1994

PROCESS
FILTER BUILDING
MEDIA SECTION
SCALE:

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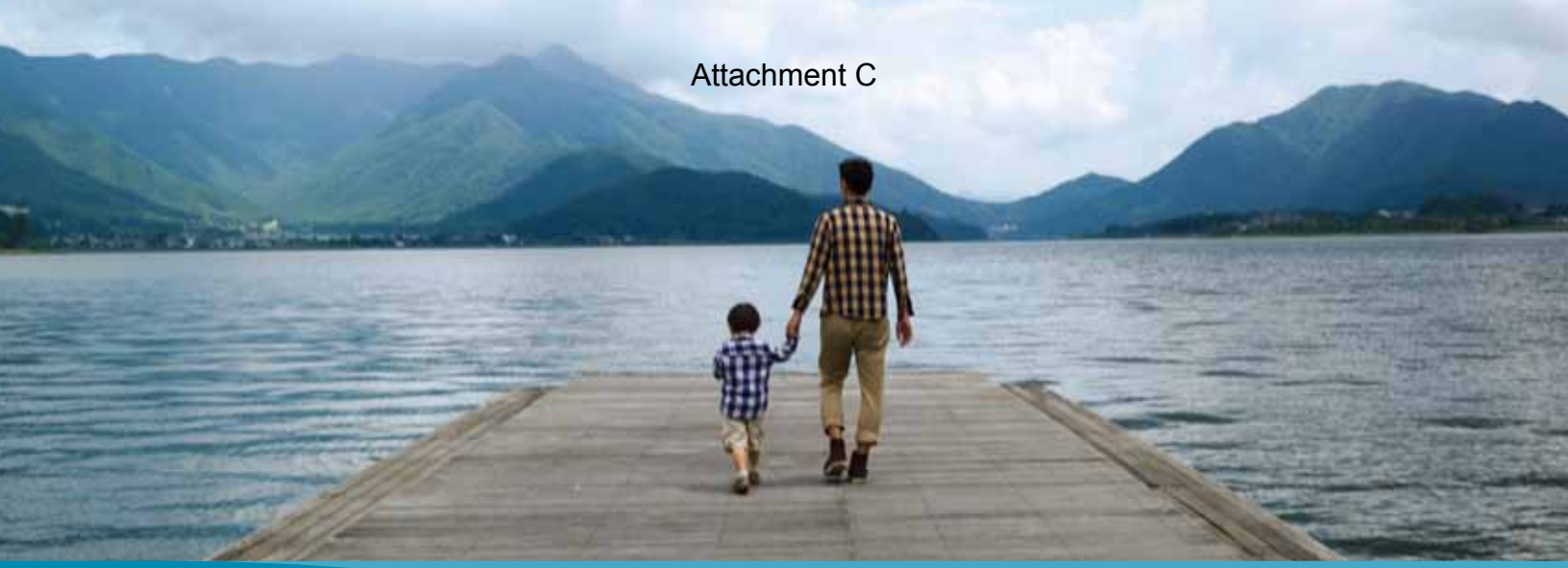
DATE OCTOBER 2013
SHEET 1 OF
CAD REF. NO. MEDIA SEC-1

User: TSperry Spec: PIRNIE STANDARD File: K:\ACAD\PROJ\CITY OF BOULDER\FIGURES\MEDIA SECTION-1.DWG Scale: 1:1 Date: 03/27/2014 Time: 08:50 Layout: MEDIA SEC

Attachment C



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I.M.S® 200 and I.M.S® 1000 media retainers from Leopold – designed to improve the efficiency and reliability of both water and wastewater filtration systems.

Providing a more effective option than using gravel in most applications, these next generation media retainers from the industry leader in water and wastewater filtration systems have been carefully engineered to do their job and help you do yours. As part of the complete Leopold underdrain system, the I.M.S® 200 and I.M.S® 1000 media retainers increase flexibility in media design by eliminating up to 14" (35 cm) of support gravel. And their physically rigid construction reduces flexing of the slots and the chance of clogging or biofouling.

You can choose the right media retainer for your application, but the Leopold tradition of engineering excellence comes standard with both.

You now have two superior solutions for all your water and wastewater treatment applications. Both the I.M.S® 200 and the I.M.S® 1000 are engineered to ensure a highly uniform distribution of air and water during the backwashing process. Thanks to its solid-construction made of high strength thermoplastic and precision engineered injection molded slots, these media retainers eliminate deadspaces and provide longer filter runs reducing overall operating costs.

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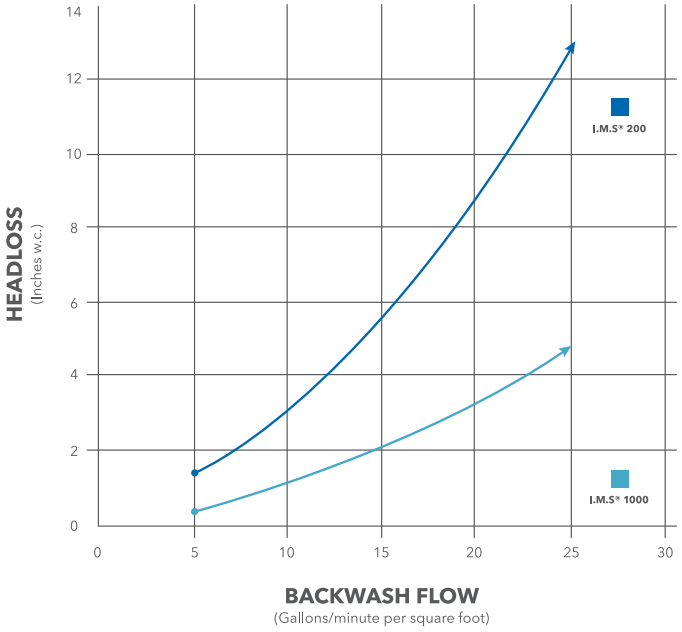
I.M.S® 200 and I.M.S® 1000 PRECISION ENGINEERED MEDIA RETAINERS

Flexibility, affordability, performance, and reliability. What more could you ask for?

Beyond exceptional, worry-free performance, the I.M.S® media retainers deliver a host of other benefits including lower capital expenditures related to its ease of installation and potential for a smaller vertical footprint, reduced operational expenses due to longer filter runs using less water and energy, and the product's performance over an extended period of time. And, the most important benefit being the reliability and support of one of the most trusted names in water treatment. To find out more about how you can get greater performance with lower installation and operating costs, please visit www.fbleopold.com

Headloss during backwash is similar to the gravel it replaces



I.M.S® 200

- Suitable for drinking water plants and desalination plants
- Precision engineered 0.2 mm slots support media down to 450 microns to prevent sand and media penetration and makes it easier to quality control your water treatment system
- Allows for more available media expansion for better backwashing and improves the air and water distribution for cleaner media*
- More driving head results in longer filter runs*
- The patent pending baffles on the bottom of the plate are designed to ensure air doesn't roll to the high end of the cap*
- A narrow water flow path makes it easier to clean during standard backwash operations*
- Eliminates gravel migration or gravel disturbances caused by unforeseen events*
- Reduces installation time resulting in lower installation cost and can be field removed for inspection then reinstalled with standard tools*

I.M.S® 1000

- Suitable for wastewater plants; in GAC contactors, in biologically active filters, and in the construction of filters for denitrification
- Precision engineered 1 mm slots support media down to 1700 microns and make it less prone to fouling than a porous plate (since biological growth will not bridge a gap greater than 0.8 mm)
- Physically rigid design reduces flexing and withstands pressures up to 15 psi*
- Reduces the vertical footprint 11" to 14" (28 cm–35 cm) by eliminating the gravel layer*
- Increases freeboard 11" to 14" (28 cm–35 cm) to allow for media expansion and extended concurrent air/water backwashing*

* Indicates feature of both I.M.S® 200 and I.M.S® 1000

xylem
Let's Solve Water

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Appendix B

Preliminary BWTF Piloting Results

Attachment C

City of Boulder – Betasso Water Treatment Facility

2014 Betasso Water Treatment Performance Evaluation/Optimization Update

Imagine the result

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Findings of 2012 Betasso Spring Runoff plant Optimization Study

- Repair basin chlorine dosage (repaired 2012)
- Improve flocculation and sedimentation by fixing flocculator drive to improve basin performance (repaired 2012)
- Explore modifying filter L/d ratio (currently evaluating)
- Explore filter aid polymers (currently evaluating)
- Address filter headloss gauge operability
- Conduct additional investigation on chemical coagulation during future spring runoff
- Bench-scale testing
- Pilot testing (currently evaluating)

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FULL SCALE RESULTS

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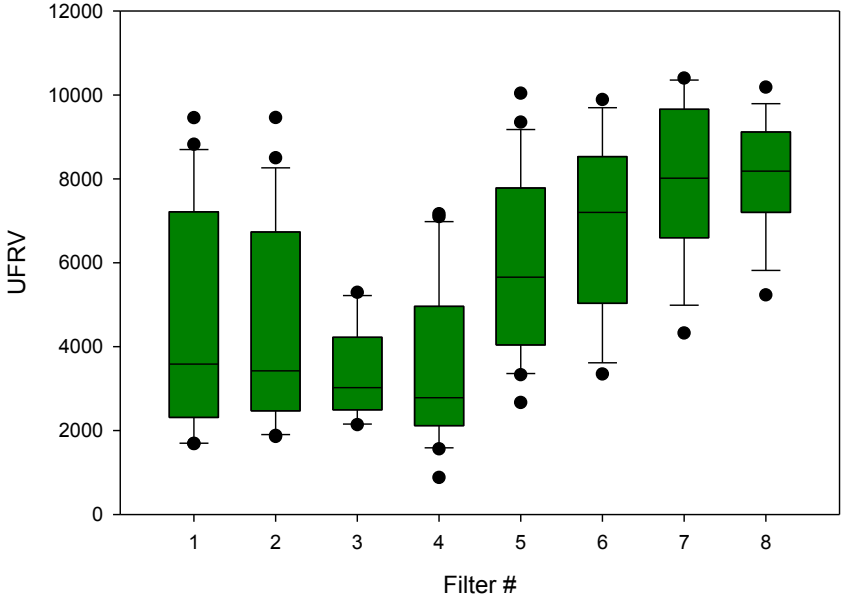
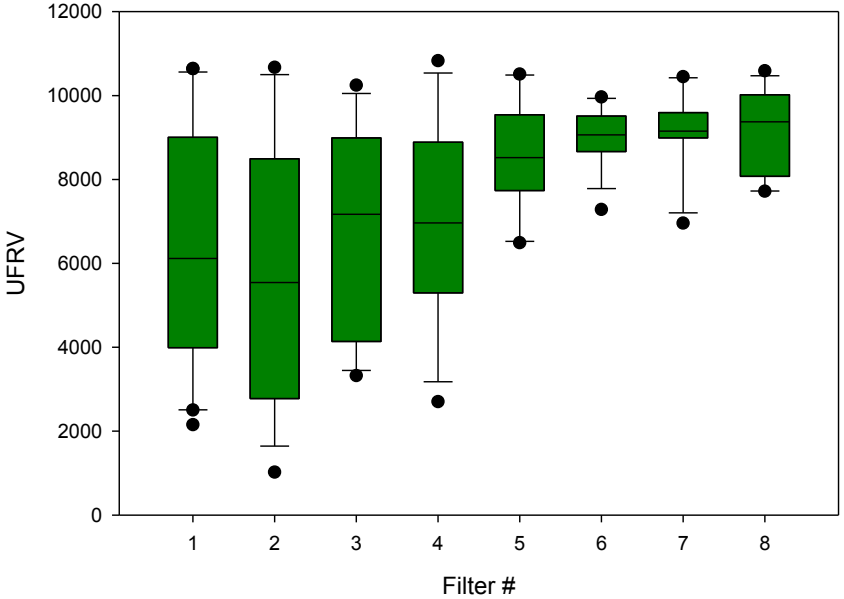
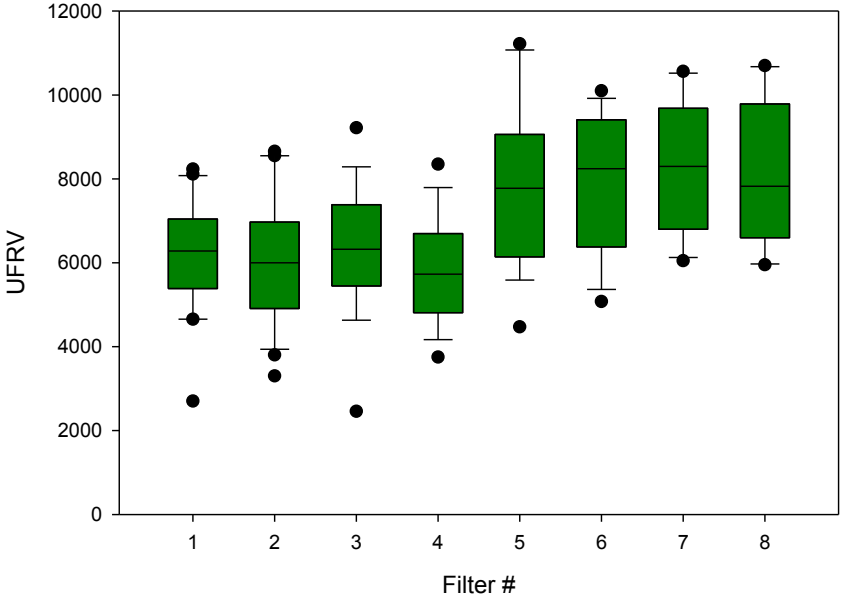
2011 UFRV Data - May to June



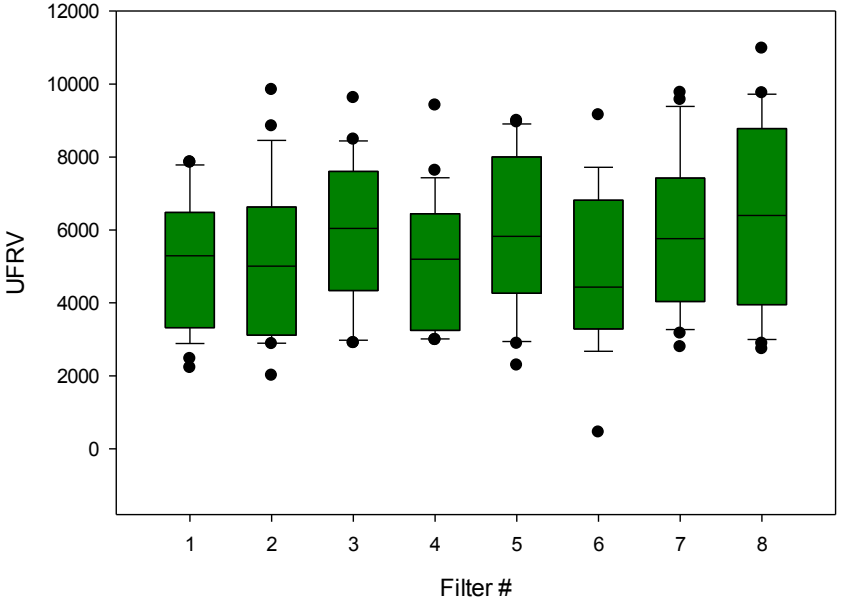
2012 UFRV Data - May to June



2013 UFRV Data - May to June



2014 UFRV Data - May to June

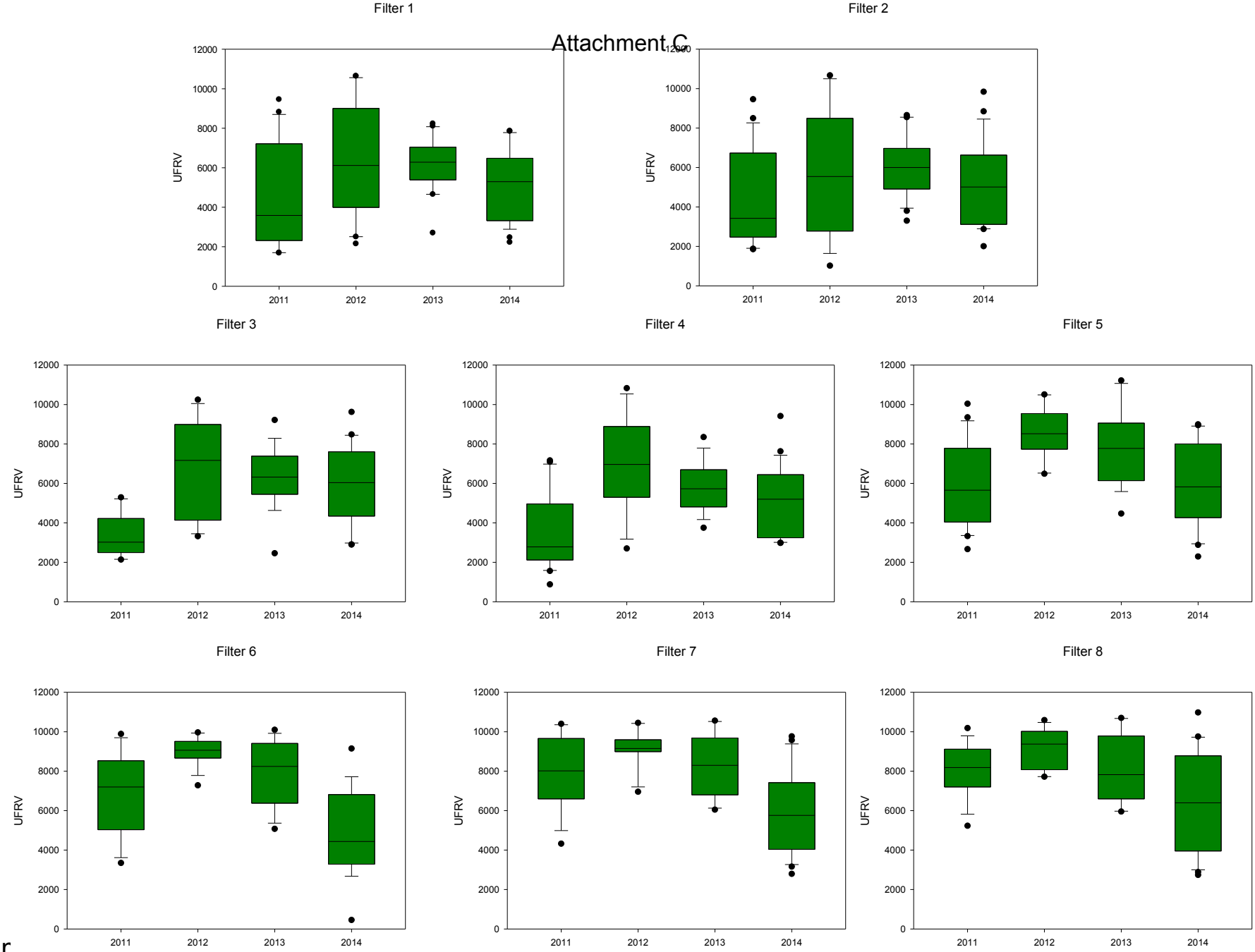


Im

Summary of BWTF Filter UFRVs (May-June)

Average Filter UFRVs				
Filter	**2011**	**2012**	**2013**	**2014**
Filter 1	4547	6324	6185	5043
Filter 2	4495	5670	6053	5207
Filter 3	3301	6730	6347	5969
Filter 4	3523	6939	5763	5195
Filter 5	5958	8659	7814	5990
Filter 6	6906	9045	7943	4951
Filter 7	7885	9119	8291	5801
Filter 8	8101	9217	8076	6435

Attachment C



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2014 PILOT SCALE PRELIMINARY RESULTS

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Pilot Testing Details

- Source Water: Top of Filter (TOF) sample line
- Filter 1 (existing)
  - 12” Sand
  - 18” Anthracite
- Filter 2
  - 12” Sand
  - 24” Anthracite
- Filter 3
  - 14” Sand
  - 24” Anthracite
- Filter 4
  - 16” Sand
  - 24” Anthracite

- 20 test runs completed from 5/1 to 6/30
  - Filters terminated either by headloss or turbidity breakthrough of 0.1 NTU
    - For TB – online turbidity utlized (every 15 min)

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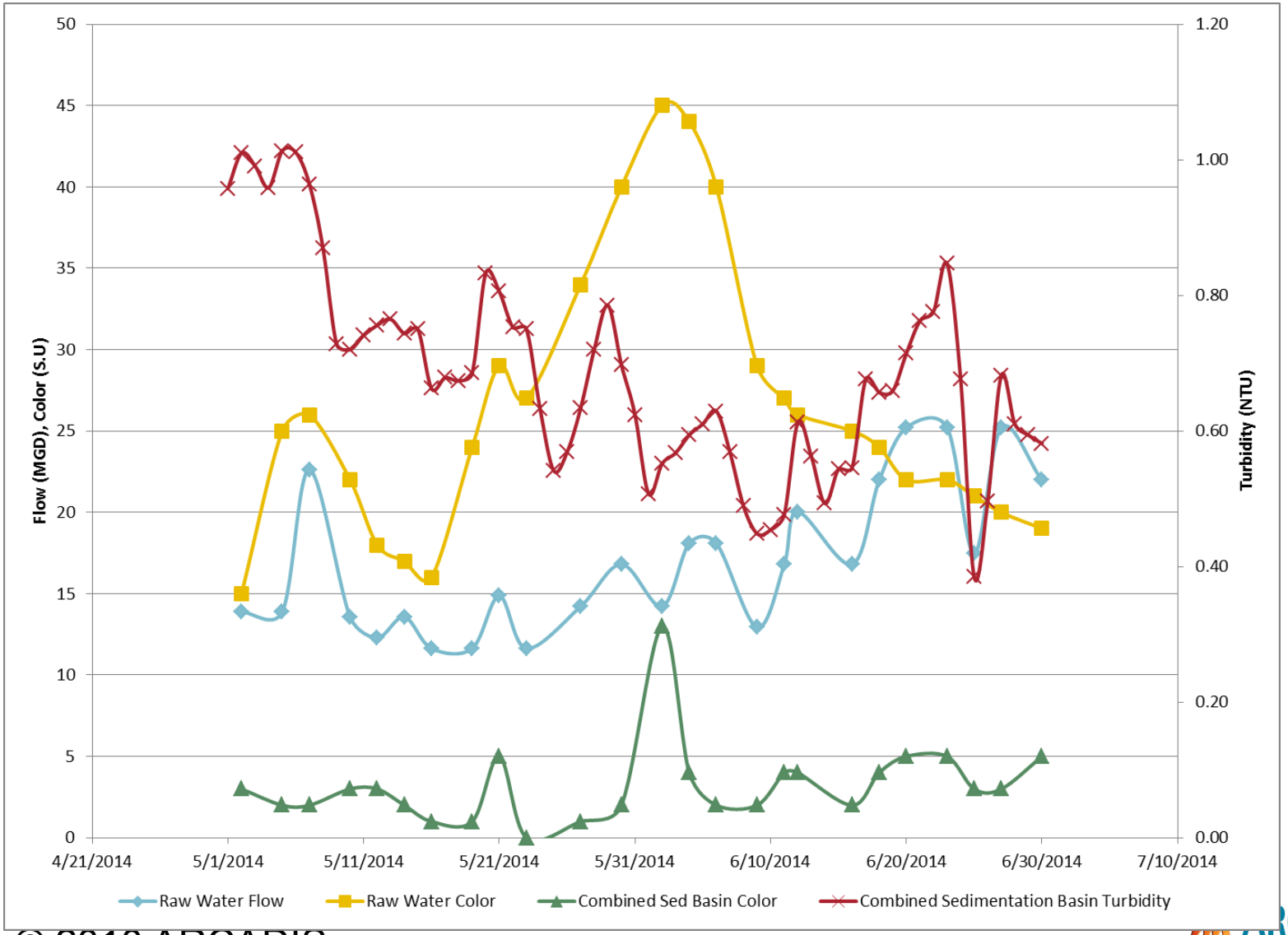
2014 BWTF Source Water Details

Attachment C



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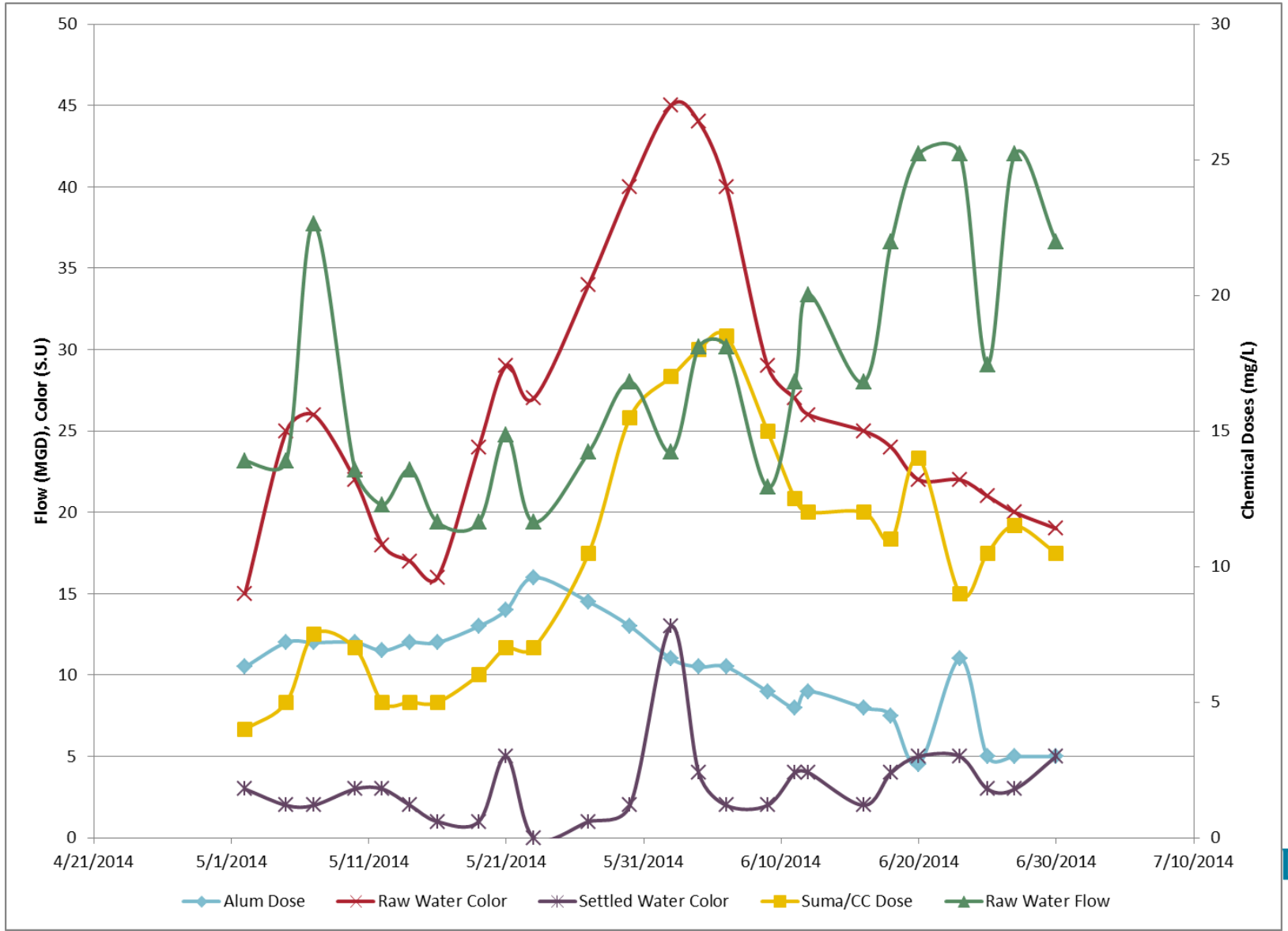
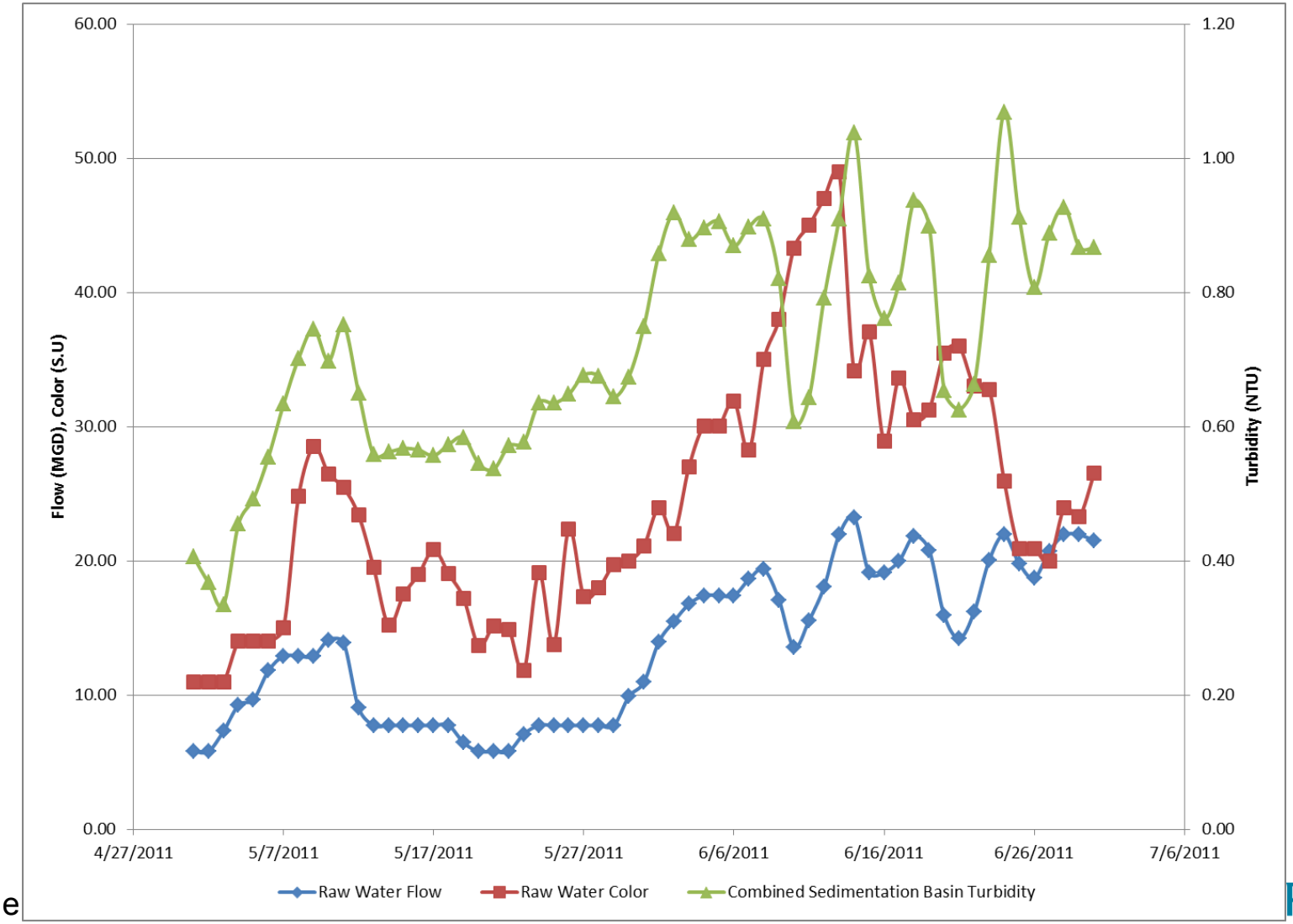
2014 BWTF Source Water Chemical Dosing

Attachment C



2011 BWTF Source Water Details

Attachment C



Imagine

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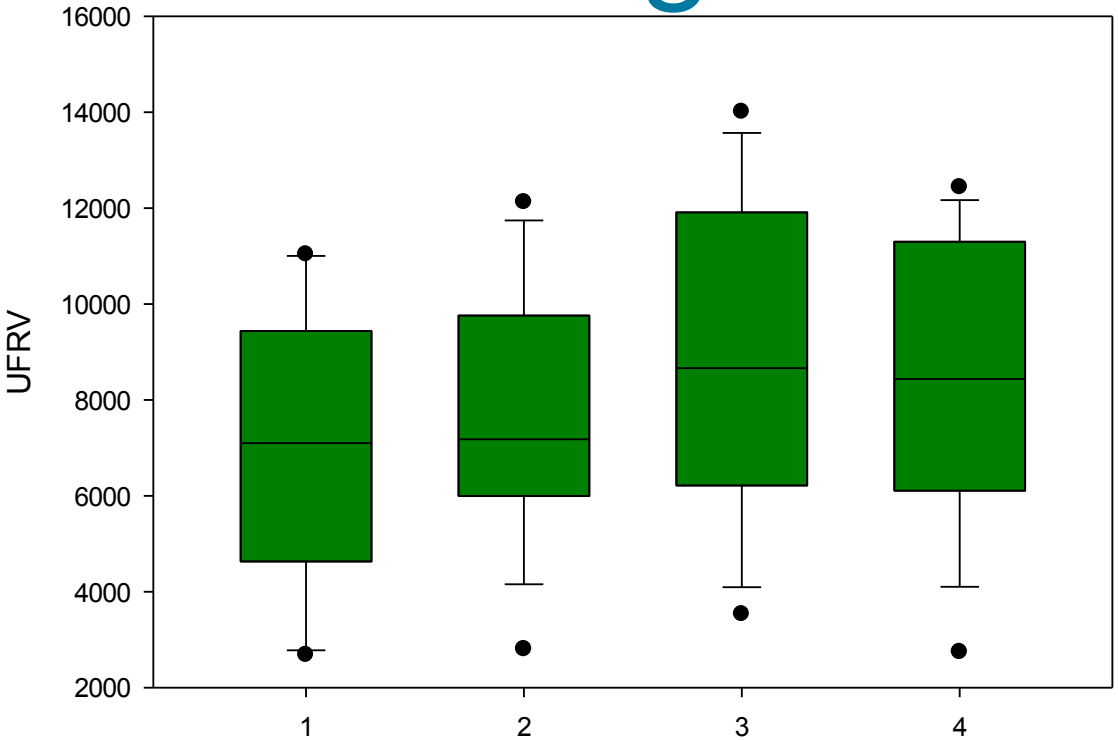
Pilot Testing Results

Attachment C



Statistic	Filter 1	Filter 2	Filter 3	Filter 4
Sand (in)	12	12	14	16
Anth (in)	18	24	24	24
L/d	992	1134	1229	1322
Average	7073	7658	8922	8536
Maximum	11036	12124	14010	12437
Minimum	2681	2586	3352	2998
Std. Dev.	2753	2586	3352	2998

Filter Run	1	2	3	4
5/2 to 5/4	TB	HL	HL	HL
5/5 to 5/7	TB	HL	HL	HL
5/7 to 5/10	TB	HL	HL	HL
5/10 to 5/14	TB	HL	TB	HL
5/14 to 5/19	HL	HL	HL	HL
5/19 to 5/23	HL	HL	TB	HL
5/23 to 5/27	HL	HL	HL	HL
5/27 to 5/30	TB	TB	HL	HL
5/30 to 6/2	TB	TB	TB	TB
6/2 to 6/6	TB	TB	TB	HL
6/6 to 6/9	TB	TB	TB	TB
6/9 to 6/12	TB	TB	TB	TB
6/16 to 6/18	TB	TB	TB	TB
6/18 to 6/20	TB	TB	TB	TB
6/20 to 6/23	TB	TB	TB	TB
6/23 to 6/27	TB	TB	TB	TB
6/27 to 6/30	TB	TB	TB	TB

High Color

High Flow

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Attachment C

Filter Run	Filter 1	Filter 2	Filter 3	Filter 4	Settled Water Color	Raw Flow
5/2 to 5/4	5,838	5,023	5,908	7,359	2-3	14
5/5 to 5/7	6,965	6,889	7,619	6,675	2	14 - 23
5/7 to 5/10	11,000	10,130	10,023	11,258	2-3	14 - 23
5/10 to 5/14	9,046	11,649	13,460	11,221	2-3	12 - 14
5/14 to 5/19	11,036	8,678	12,141	12,437	1-2	12 - 14
5/19 to 5/23	9,345	7,906	10,607	10,112	1-5	12 - 15
5/23 to 5/27	9,755	7,179	14,010	5,111	1	12 - 14
5/27 to 5/30	8,120	9,391	10,469	8,438	1-2	14 - 17
5/30 to 6/2	7,100	12,124	7,198	12,102	2-13	14 - 17
6/2 to 6/6	7,962	7,463	11,688	11,615	2-13	14 - 18
6/6 to 6/9	6,527	6,449	8,665	9,378	2	13 - 18
6/9 to 6/12	9,529	11,111	13,088	11,348	2-4	13 - 20
6/16 to 6/18	4,992	6,910	8,072	8,025	2-4	17 - 22
6/18 to 6/20	4,268	6,090	6,522	5,514	4-5	22 - 25
6/20 to 6/23	3,271	5,901	4,438	6,977	5	25
6/23 to 6/27	2,804	2,804	4,235	2,743	3-5	15 - 25
6/27 to 6/30	2,681	4,493	3,532	4,444	3-5	21 - 25

Turbidity Breakthrough

Headloss

Low
- **Color: 0 to 5**
- **Flow: 13 to 17**

Medium
- **Color: 5 to 10**
- **Flow: 17 to 21**

High
- **Color: 10 to 15**
- **Flow: 21 to 25**

Imagine the result

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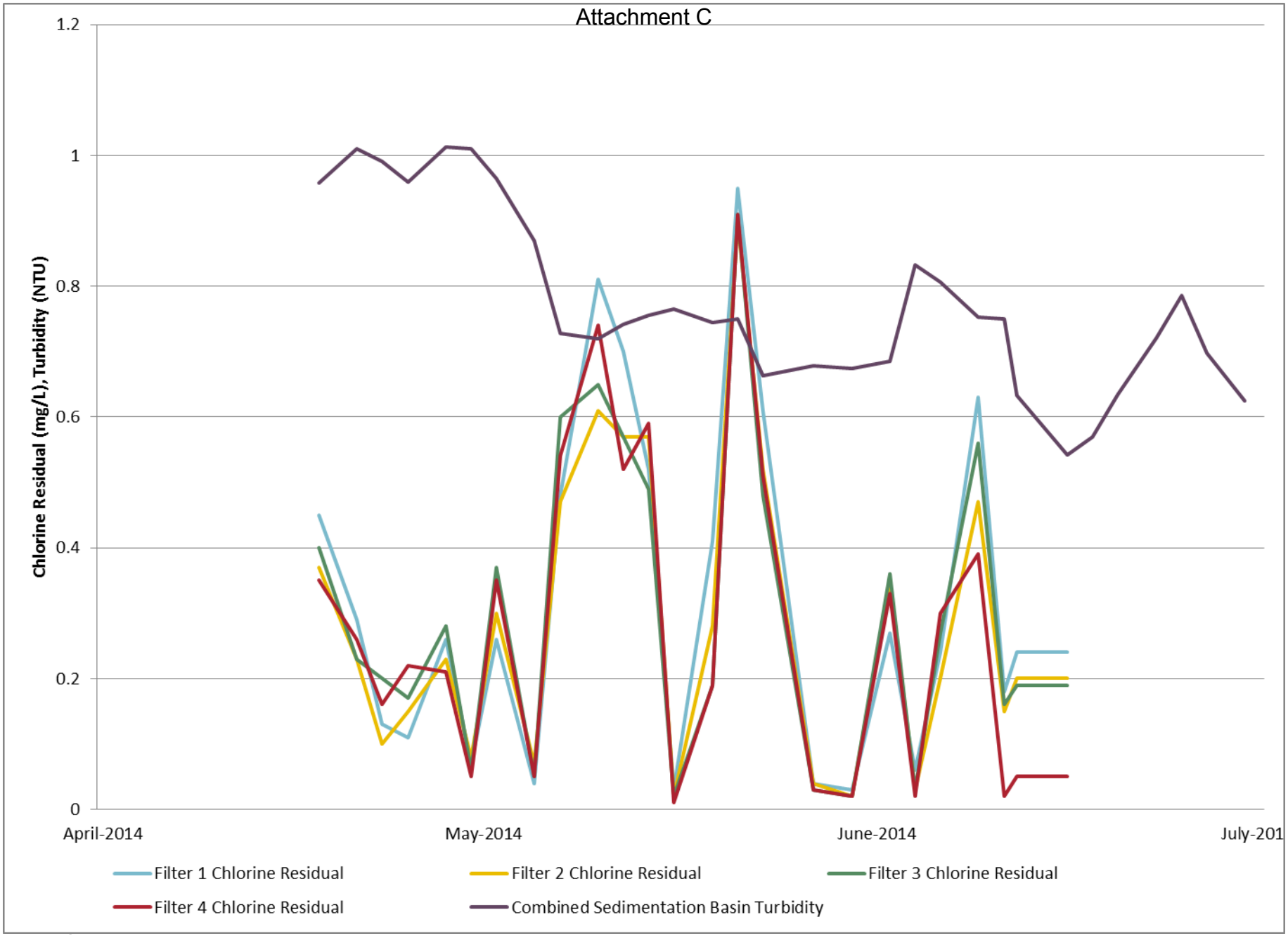
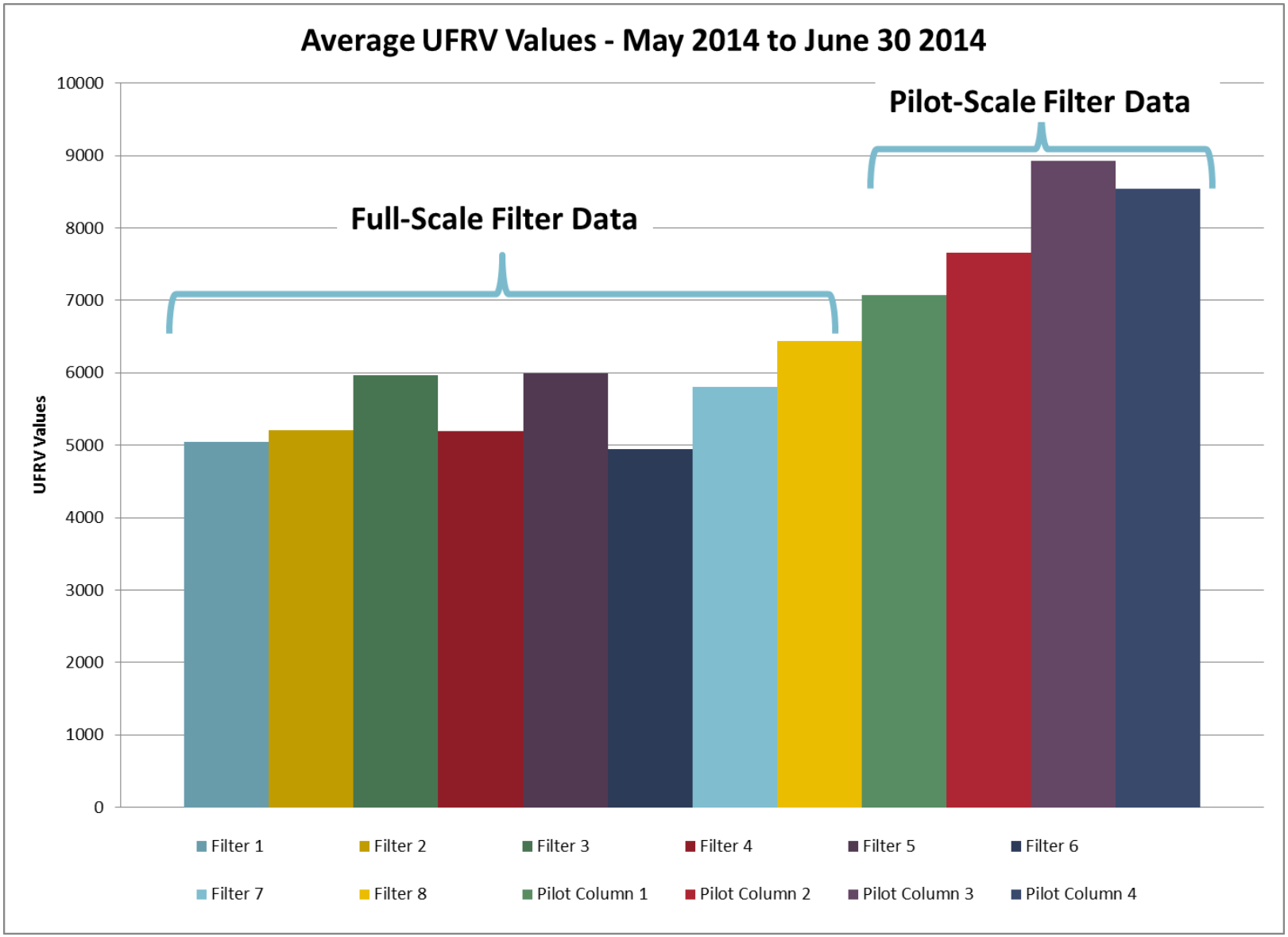

Attachment C
Chlorine Residual (mg/L), Turbidity (NTU)
1.2
1
0.8
0.6
0.4
0.2
0
April-2014
May-2014
June-2014
July-201
Filter 1 Chlorine Residual
Filter 2 Chlorine Residual
Filter 3 Chlorine Residual
Filter 4 Chlorine Residual
Combined Sedimentation Basin Turbidity

Attachment C



Imagine the result

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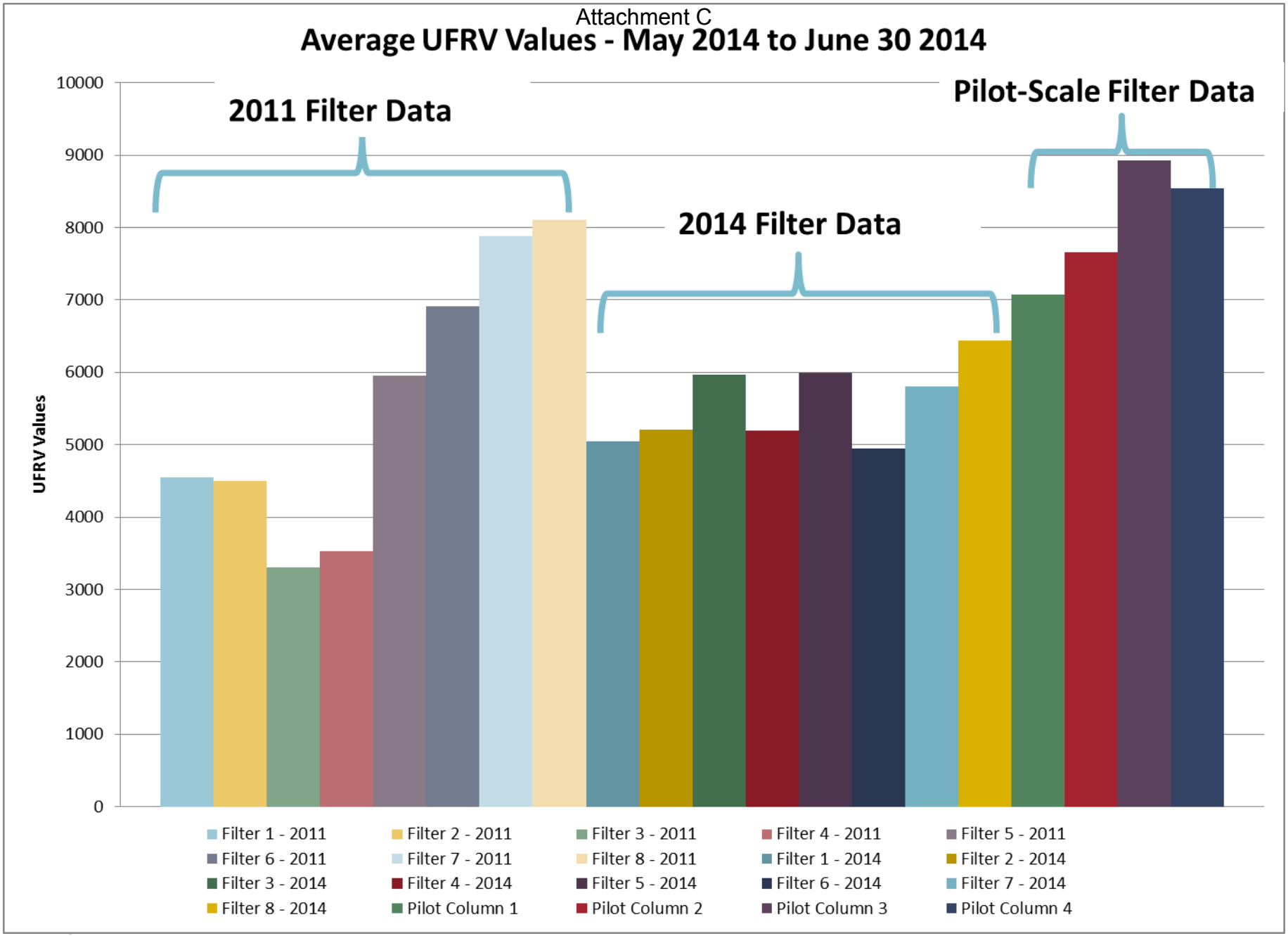
Attachment C



Preliminary Pilot Scale Results

- Increased sand depths increased the UFRV values
  - 12” sand depth columns (1 and 2) performed similar and 14” and 16” (3 and 4) performed 20% better.
- High flow periods challenged pilot more-so than high color periods
- Filter runs most commonly ended due to turbidity breakthrough during June 2014, and a combination of headloss and turbidity breakthrough during May 2014

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