IFC-2018-PWB01

IntelliFlux R & D Group

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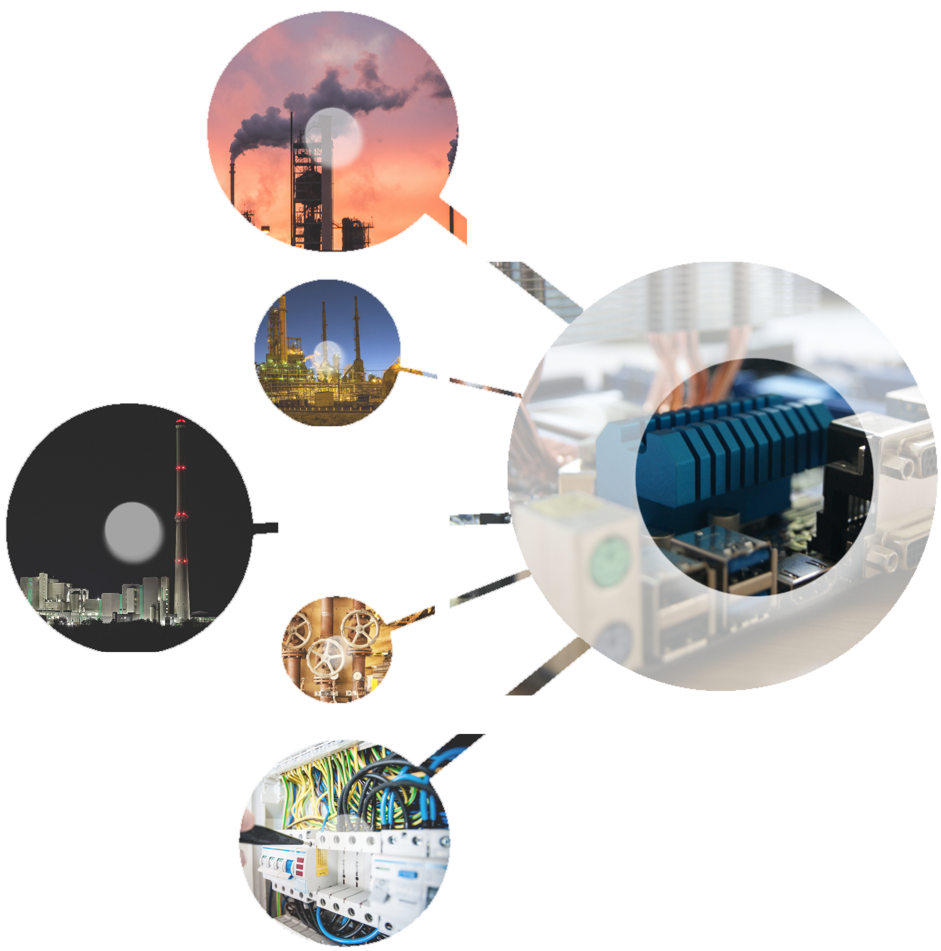
IntelliFlux®

Microfiltration at a Municipal Water Reclamation Facility

APRICOT, Version 1.0.1

November 2018
Revised May 2019



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17322 Murphy Avenue,
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Final Report

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Prepared for Nike

Abstract: IntelliFlux Controls, Inc. conducted a demonstration of its Augmented Process Recommendation & Industrial Control Optimization Toolbox (APRICOT) on a Microfiltration (MF) system located at a municipal sewage tertiary treatment facility in Southern California, USA. The demonstration involved retrofitting one of the MF trains using IntelliFlux, while a second train was operated conventionally. The six-month study demonstrated the benefits of IntelliFlux, which included its ability to respond to influent quality variations and adaptively modulate the cleaning intensity. IntelliFlux was significantly more efficient in responding to influent quality variations compared to conventional operation with operator assistance. The system experienced a 38% savings in operating energy per unit volume of filtrate produced, a 7% increase in net yield of the plant, and a 50% reduction in chemical consumption and waste generation.

Table of Contents

Figures and Tables

Figures

Tables

1 Executive Summary

The IntelliFlux® membrane fouling management and adaptive cleaning system was installed on a 1 million gallons per day (MGD) microfiltration plant at the Southern California Municipal Water Recycling Facility for a performance demonstration. The unique aspect of this study is a side by side comparison of an IntelliFlux operated MF plant with an identical plant that was operated conventionally. This report summarizes the findings of the demonstration.

1.1 Objectives:

The objectives of the demonstration were to:

- Provide a side by side performance comparison of two otherwise identical tertiary treatment MF plants, fed with the same influent drawn from a common head-water source, one operated using IntelliFlux, whereas the other operated conventionally with a static cleaning program.
- Provide a comparison of the specific energy consumption, yield, waste generation, and chemical consumption of the two plants.
- Demonstrate how IntelliFlux autonomously protects the membrane from high intensity fouling due to sudden changes in influent quality or operating conditions.

1.2 Key Observations

During isolated high intensity fouling events, IntelliFlux autonomously increased the frequency and intensity of backwash to prevent extensive membrane fouling and maintain system performance. During normal operation, IntelliFlux reduced backwash intensity and increased backwash interval leading to the following savings compared to conventional operation. The most pertinent benefits demonstrated were:

- A higher net filtrate yield compared to the baseline (7%) as well as the conventionally operated plant (3.5%).

- A 38% savings in energy compared to baseline and 18% energy savings compared to the conventionally operated plant.
- Over 50% chemical savings compared to both baseline operation and to the conventionally operated plant.
- Overall OPEX savings of 18% compared to baseline operation.
- The overall monthly economic benefit of IntelliFlux translated into a pro-rated $/month/MGD value ranging between $2736.50 to $5496.60.
- During the six-month demonstration period, the permeabilities of the two trains of the IntelliFlux operated plant remained constant or slightly increased from the baseline values.

IntelliFlux demonstrated several other benefits, including,

- Alerting operator to component malfunction.
- Continuous remote monitoring and altering operator on critical event triggers.

2 Introduction

A demonstration of the IntelliFlux® membrane fouling management and adaptive cleaning system was conducted on a 1 MGD Microfiltration (MF) system for tertiary wastewater treatment at a Municipal Water recycling facility located in Southern California between March 2018 and August 2018. Two similar MF systems (trains 1801/45 and 1802/46) were deployed at the facility in November 2017 to treat secondary effluent sewage water from the local wastewater treatment plant to produce tertiary treated water. The filtrate is further purified using reverse osmosis at the plant. The reclaimed water is either used as barrier water or utilized for industrial purposes at a nearby refinery. The side-by-side identical MF systems are fed with the same head-water source. The demonstration program consisted of a side-by-side comparison of the two MF systems, with one plant (train 45) monitored and operated using IntelliFlux adaptive cleaning system, and the other (train 46) operated using the conventional approach of static (pre-defined) cleaning. The demonstration process involved three sequential stages:

1. demonstration of the installation and commissioning of IntelliFlux as an additive solution to the existing operating plant,
2. monitoring of the conventional mode operation of train 1801/45 utilizing IntelliFlux (passive mode), to observe the data communication, monitoring, and trend analysis capabilities of the product, including accumulation of performance trends over a four week period to benchmark the baseline performance of the plant, followed by
3. a three month operation of train 1801/45 utilizing the adaptive cleaning regimen specified by IntelliFlux through its machine learning based adaptive flux maintenance software.

Each MF train consists of two racks (designated A and B), each rack having 18 pressure driven outside (PDO) hollow fibre membrane modules operating in an outside-in configuration. Total membrane area per train is 2000 m^2. The system is controlled primarily utilizing programmable logic controller (PLC) using the manufacturer's control program and cleaning logic. Each trailer is connected to the SCADA network of plant, with additional operator monitoring and intervention enabled through the central control room of the treatment plant. A separate third party operator company, operating under contract with municipal water district is delegated the responsibility of maintaining the MF systems.

The membranes were conventionally cleaned using two types of automated cleaning settings:

1. High Frequency or flux maintenance (FM) cleans, which primarily consisted of timed filtrate backwash in conjunction with air scouring, and
2. Low frequency cleans of enhanced flux management (EFM), which consisted of chemically (bleach and caustic) enhanced cleaning through re-circulation of the appropriate cleaning reagent on the feed side of the membranes once a day.

The FM (backwash) interval was 20 minutes with a fixed backwash flow rate of 160 gpm, and a backwash duration of 1 minute. The EFM process involved re-circulation of a 600 gallon batch of the cleaning solution (with predetermined concentration of caustic and bleach) for 120 minutes. A third mode of cleaning, namely clean in place (CIP) was implemented manually, at operator discretion, which was mostly triggered when the performance (permeability) of the membrane decreased below a pre-defined threshold. A typical CIP involved sequential re-circulation of caustic and bleach solutions and optionally proprietary cleaning reagents, with a CIP sequence requiring six to eight hours.

The process flow diagram (PFD), operational logistics and directives, the process and information diagram (P&ID), as well as the PLC control program and input/output (I/O) list were reviewed and analyzed by the technical team of IntelliFlux Controls to ensure that retrofitting the plant with IntelliFlux automation system should provide a measurable performance improvement compared to the baseline operation. These preliminary calculations were used to provide projections of key performance indicators (KPIs) and benchmarks used to assess the performance of IntelliFlux vis-à-vis the conventionally operated plant. As the plants were new (installed in late 2017), we did not have access to long-term operational history of the plant with the influent at the site. However, during the first four weeks of operation in a passive (monitoring mode), operational data was collected and used to create the benchmarks.

The IntelliFlux retrofit consisted of installing an industrial grade edge control device next to the PLC of the MF system. The installation and commissioning were conducted between February and March 3, 2018, the monitoring mode operation was conducted between March 10 – April 10, 2018, and the full time IntelliFlux controlled operation was conducted between April 16 – August 22.

This report analyzes the IntelliFlux performance information gathered during the demonstration and compares this against the baseline performance of conventional membrane cleaning. Attention is given to the performance metrics that can be observed instantaneously, daily, and over prolonged usage.

3 Objectives and Key Performance Indicators

3.1 Objectives

The objectives of the demonstration were to:

- Compare the performance of IntelliFlux adaptive cleaning against conventional cleaning, to be assessed in real-time by the simultaneous operation of an identical trailer cleaned conventionally utilizing the same influent water,
- Assess how IntelliFlux benefits sustainable membrane operation, including lowering chemical and energy consumption, increasing production, and improving the decision automation framework for the operator, providing better economics of operation (lowering OpEx).
- Demonstrate how IntelliFlux automatically protects the membrane from potential high-intensity fouling events due to sudden changes in influent quality or operating conditions.

The unique aspect of this demonstration was the ability to compare the performance of two otherwise identical trailers with the same influent water, one operated using IntelliFlux, whereas the other operated conventionally. This side-by-side comparison provides a real-time demonstration of the potential advantages of IntelliFlux governed fouling intervention over conventional mode of static time based cleaning.

3.2 Key Performance Indicators (KPIs)

The key performance indicators agreed during the commissioning of the demonstration were:

KPI 1: Average increase in overall system recovery (yield): 1-5 % over the baseline plant

KPI 2: Average energy savings: 5-20 % over the baseline plant

KPI 3: Average operating expense (OpEx) savings of 5-20 % over the baseline plant.

Analysis of the plant performance was achieved by monitoring the temperature-normalized permeability (normalized to 20 °C), transmembrane pressure, water production, and specific energy consumption (SEC). Water production was characterized as the gross water production, *i.e.*, filtrate flow rate, as well as the net water production, which is the net water produced after accounting for the amount of water consumed during membrane cleaning. Specific energy consumption (SEC) denotes the energy consumed during the filtration process (which includes the filtration energy as well as the energy consumption for cleaning) normalized by the volume of net water produced. Energy consumption is calculated as the amount of energy required by the feed pumps during normal filtration as well as the energy consumed by cleaning.

These various KPI metrics were calculated using the following equations:

$$E_{filtration} = \frac{Q_{feed} P_{feed} t_{filt}}{36 \eta_{filt}} \quad (1)$$

$$E_{total} = E_{filtration} + E_{cleaning} \quad (2)$$

$$SEC = \frac{E_{total}}{V_{net}} = \frac{E_{total}}{V_{gross} - V_{net}} \quad (3)$$

$$Yield = 100 \frac{V_{net}}{V_{gross}} \quad (4)$$

where $E_{filtration}$ is the energy consumption of the feed pump [kWh], Q_{feed} is the feed flow rate (or the filtrate flow rate when membrane recovery is assumed 100%) [m^3/h], P_{feed} is the feed pressure [bar], t_{filt} is the time of operation in filtration mode [hours], η is the pump efficiency (assumed to be 85%), $E_{cleaning}$ is the amount of energy consumed for cleaning (backwash pump and/or air blower) over time t_{filt} [kWh], V_{net} is the net volume produced over time t_{filt} [m^3], V_{gross} is the gross volume of water produced over time t_{filt} [m^3], $V_{consumed}$ is the total volume of water consumed by all the cleaning procedures executed over time t_{filt} [m^3], and Net Yield is the percentage ratio of the net amount of water production from the plant to the gross production from filtration [%]. Note that these equations describe the theoretical work and energy consumed by the filtration pumps and not all supplemental energy draws, such as from valves, panels, air compressors, *etc.* The intended use of the SEC is not for full plant accuracy to predict expected energy bills, but as a tool to compare relative changes in energy consumption by the filtration system.

4 Project Timeline

The overall demonstration project timeline and milestones are shown in Figure 1.

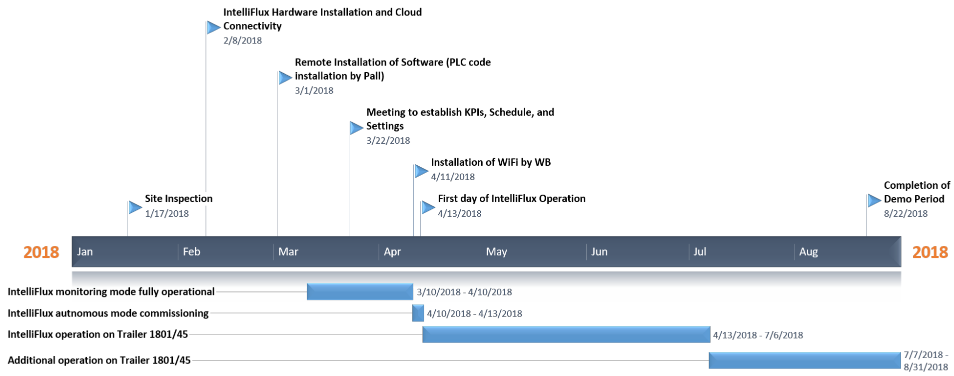

Figure 1. Project timeline for the demonstration of IntelliFlux operation on the Microfiltration train.

5 Baseline System Specifications and Cleaning Settings

The specifications of the target treatment system are as outlined in Table 1.

Table 1. System specifications.

General Specifications	
Plant throughput (influent rate)	1 MGD (Approx.)
Influent type	Treated secondary municipal wastewater
Industry (e.g. Oil & Gas, mining)	Municipal (tertiary treatment)
Installation type (permanent/mobile)	Semi-mobile
System Type	Pressure Driven Outside-in Hollow Fibre
Number of Trains	2 (45 and 46)
Racks per Train	2 (A and B)
Modules per Rack	18
Membrane area per Rack (ft^2)	2000
Treatment Objectives	
Annual operational hours	Year-round operation - observe variations seasonally and daily
Utilities (heat, steam, water, air, electricity)	Energy consumption greatest cost followed by chemical consumption
Operators/ remote operation	Operated by third party operating company

The microfiltration membranes are normally cleaned (Default Cleaning Schema) using three classes of procedures: 1) Flux maintenance (FM), 2) enhanced flux maintenance (EFM), and 3) clean-in-place (CIP). The FM clean is normally executed by time and/or volume of water processed and includes simultaneous filtrate back-washing and air scrubbing. The FM clean can be enhanced by a feed-side flush with feed or filtrate water that can be circulated and drained. The default FM procedure operates for 60 seconds with a backwash flowrate of 320 gpm and is typically activated every 9000 gallons or approximately 20 minutes.

The EFM clean is normally executed by volume of water processed and comprises exposing the fouled membrane to a chemical cleaning solution with time required for both soaking and optional re-circulation. A pre-programmed sequence exposes the membrane to potentially three different chemicals: 1) acid, 2) caustic, and 3) chlorine. The default EFM procedure uses a blend of 0.7% caustic and 855 ppm chlorine (no acid) that recirculates around the membrane for 120 minutes at 95 ° F . The default EFM is executed once a day. The CIP procedure is typically managed manually and, therefore, IntelliFlux only provided recommendations regarding when to perform a CIP and did not perform any CIP procedures itself.

6 IntelliFlux Operational Protocol and Installation Programming

The IntelliFlux control software provides a machine learning and artificial intelligence-guided control philosophy that optimizes membrane maintenance and cleaning in response to influent water quality fluctuations and fouling. The technology deploys only what is necessary to clean the membrane under the given operating and environmental conditions. The IntelliFlux hardware includes an edge control device that connects to the existing PLC running a standard operational and cleaning program. The edge control device contains the SCADA-level IntelliFlux software, which assumes control of the PLC cleaning set-points. Data is recorded and stored locally and output to the IntelliFlux cloud server for visualization and analysis via a dual-encrypted VPN tunnel.

6.1 Control Set-points and Ranges

IntelliFlux only assumes control over select set-points within existing membrane cleaning protocols. These set-points were developed in consultation with Client , and in doing so, IntelliFlux did not integrate any new programming sequences nor any overwrites of any existing PLC permissives or failsafes. After collaboration with both the membrane manufacturer and operator, IntelliFlux developed the restricted control zones for the cleaning operations over the cleaning set-points within associated boundaries as shown in Tables 2 and 3. Note that remaining PLC variables and set-points not controlled by IntelliFlux remain unchanged and accessible to the field operator.

Through control over the IntelliFlux cleaning set-points, a series of predefined cleans was created by the IntelliFlux Controls engineers and made available to the edge control device/software solution through an Ethernet connection to the PLC. Each clean executed by IntelliFlux was given an intensity number representing a cleaning mode, which utilized optimized set-points within the aforementioned bounds. All set-points for a given clean, current and historical, are available from within the interactive IntelliFlux client software.

Table 2. IntelliFlux cleaning set-points.

Backwashes (Flux Maintenance, FM)				
Set-point	Description	Default	IFCTRL Min.	IFCTRL Max.
FM Clean Interval	Time between FM cleans	20 min	13 min	45 min
Air Scrub Water Flow Rate	Flow Rate that the reverse filtration pump will maintain during air scrub	320 gpm	0 (“Relaxation")	320 gpm
Air Scrub Air Flow	State of Air Scrub Valve during FM	ON	OFF	ON
Air Scrub Cycle Time	Duration of Air Scrub during FM	60 Sec	30 Sec	100 Sec
Pulsed Air Scrub Enable	Whether pulsed air scrub is enabled or disabled during FM	Disabled	Disabled	Enabled

6.2 FM and EFM Cleaning Recipe Variable List

With instructions from the MF system manufacturer and the operator guidance, the IntelliFlux cleaning modes were defined in two matrices, one defining the variables used for the FM mode (which involves the backwash of the membrane with variable flow rates, backwash duration, as well as use of air scour and air pulse). The key parameters adjusted were backwash flow rate and backwash duration, with air pulse and air scour switched on and off in certain modes.

Tables 4 and 5 depict the different FM and EFM cleaning modes used for the study. All variable boundaries were defined in coordination with membrane manufacturer and system operator to ensure all operating limits and constraints of the membrane are adhered to.

Table 3. IntelliFlux cleaning set-points.

Daily Chemical Cleans (Enhanced Flux Maintenance, EFM)				
EFM Clean Interval	Time between EFM cleans	Every 534 kgal production or 24 h	12 hr	168 hr
EFM Circulation time	How long the EFM process will run	120 min	0 min	240 min
Caustic Addition Quantity	The amount of caustic dosed into the EFM cleaning solution	10 gal	0 gal	128 gal
Chlorine Addition Quantity	The amount of chlorine dosed into the EFM cleaning solution	9 gal	2 gal	9 gal
EFM Circulation Air Pulse Enable	Whether pulsed air scrub is enabled or disabled during EFM	Disabled	Disabled	Enabled
Tank Temperature	Target water temperature of the EFM cleaning solution	95 °F	Ambient (Heater OFF)	95 °F

Table 4. The 8 FM cleaning settings employed for the IntelliFlux mode of operation.

FM Cleaning Recipe List					
Intensity	Name	FM Duration (sec)	Air Scrub	Air Pulse	Backwash Flow Rate (gpm)
0	FM0	30	Disabled	Disabled	60
1	FM1	45	Enabled	Disabled	75
2	FM2	45	Disabled	Disabled	160
3	FM3	30	Enabled	Enabled	160
4	FM4	30	Enabled	Disabled	160
5	FM5	45	Enabled	Enabled	240
6	FM6 (default)	60	Enabled	Disabled	320
7	FM7	70	Enabled	Enabled	320

Table 5. The 9 EFM cleaning settings employed for the IntelliFlux mode of operation.

EFM Cleaning Recipe List					
Intensity	Name	EFM Duration (min)	Caustic (gal)	Chlorine (gal)	Tank Temp. (°F)
8	EFM1	30	0	3	70
9	EFM2	20	0	4	95
10	EFM3	30	2	6	70
11	EFM4	45	4	7	85
12	EFM5	20	7	9	95
13	EFM6	30	10	9	95
14	EFM7	60	11	9	95
15	EFM8 (default)	120	11	9	95
16	EFM9	240	12.5	9	95

7 Trends During Conventional Operation

7.1 Performance Trends

Figure 2 depicts the trend analysis in the conventional operation mode for train 1801/45. The average permeability of Rack A was 1.01 GFD/psi ($\sim$ 25 lmh/bar) whereas the average during this period for Rack B was 1.23 GFD/psi (30.7 lmh/bar). Both racks are supplied with the same feed water, and hence, their feed turbidities are identical. The turbidity ranged between $7 - 25$ NTU during this period, with an average of 12.03 NTU, generally showing a sinusoidal behavior with a daily recurring fluctuation pattern.

The spiky fluctuating nature of the permeability plots arise from the rapidly decaying flux due to fouling followed by flux recovery after the high frequency (FM) cleans. Typically, about 72 FM cleans based on a fixed time interval of 20 minutes between consecutive FM cleans, and one EFM clean were performed every day (spanning a 24-hour operating duration). A CIP was performed on the trains immediately following the conventional mode operation (April 10 through April 15).

It is worth noting that the average daily flux and permeability of rack B were higher during this phase of operation compared to rack A. Thus, although the two racks are supplied with the same feed-water, and they were recently commissioned in late 2017, different permeability and fouling trends set in for the two racks. This variation of the performance of individual racks points to the extreme difficulty in *a priori* predicting or theoretically capturing the fouling trends during the design phase of UF/MF systems. Although the systems were set up to deliver a fixed volume of water, with an underlying constant-flux-variable-pressure operation mode, it is easily discernible that the daily average production from the two trains were different.

7.2 Average Performance Statistics

Table 6 summarizes the average production and performance statistics of racks A and B of train 1801/45.

The gross daily production is a product of the daily average flow through the train (flux $\times$ membrane area) and the daily production hours. As the

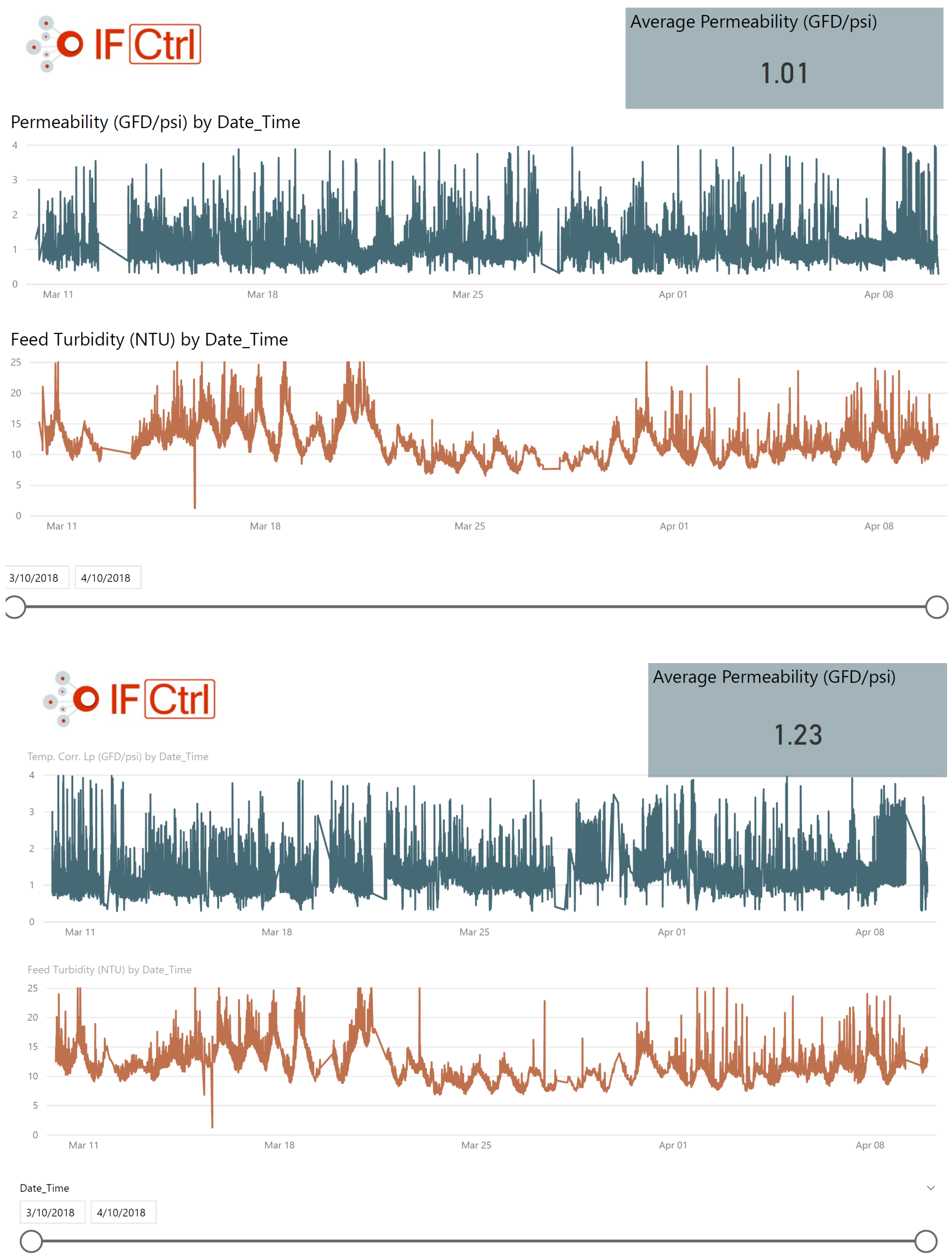

Figure 2. Temperature corrected (20 °C) permeability and feed turbidity trends for racks A and B (March 10 – April 10). The membrane cleaning was performed in the default cleaning mode.

production is related to the uptime of the plant, the average production of the two racks differ. All associated filtration performance parameters (water consumption, net yield, *etc.*) of the racks depend on the overall daily filtrate production and daily uptime, whereas the energy consumption is further dependent on the average transmembrane pressure (TMP) of the rack, which affects the filtration energy. It is evident that the energy consumption in these filtration plants is greater during the cleaning process (primarily owing to the energy intensity of EFMs) compared to the filtration process. Thus, improved and more efficient cleaning of these processes can lead to a higher sustainable permeability, which can reduce both the filtration and cleaning energy consumption.

Table 6. Baseline performance for the two trains (racks) A and B of Train 45 (1801) related to production and performance aggregated between March 10 through April 10.

Parameter	Rack A	Rack B
Average daily gross production (kgal/day)	246	292
Average daily net production (kgal/day)	223	269
Average Filtrate Flow (gpm)	230.2	261.8
Average filtration TMP (psi)	15.0	13.7
Average temperature corrected permeability (GFD/psi)	1.0	1.23
Average daily FM cleans (#)	72	72
Average daily EFM cleans (#)	1	1
Average daily production time (%)	75%	77%
Average daily cleaning energy consumption (kWh/day)	63.4	63.4
Average daily filtration energy consumption (kWh/day)	36.3	41.5
Specific energy consumption (SEC) (kWh/kgal)	0.45	0.39
Average daily net yield (%)	90.4%	91.9%
Average daily chemical use (gal/day)	19	19

The average daily net yield from the two racks were between 90 to 92% during this period. The net yield is related to the consumption of filtrate during the FM cleaning (320 gallons per FM) whereas the overall waste generation from the plant can be attributed to the EFM (each EFM uses 600 gallons of fresh RO filtrate water to prepare the cleaning solutions). It is discernible that reducing the intensity of the FMs, as well as the interval between FMs will lower the filtrate consumption, increasing the yield. Furthermore, reducing the frequency of EFMs will lower the demand on RO water (which is a more expensive water), cleaning chemicals, and volume of waste generated.

8 IntelliFlux Performance Improvement over Baseline

In this section, we compare the average performance of Train 45 (1801) optimized by IntelliFlux during the period of April 16 through June 26 against the baseline performance of the same train operated conventionally between March 10 to April 10 (as described in the previous section).

Table 7 shows the daily average performance parameters of racks 45A and 45B against the baseline values (shown previously in Table 6). A substantial increase (30% or more) in net daily production was observed during these ~70 days of operation in Train 45 (1801). Such increase in production was accompanied by an increase in the permeabilities of each of the racks (22% for rack A, and 45% for rack B). It is observed that the operating transmembrane pressure (TMP) for rack A was marginally (about 4%) higher than the baseline, whereas the average daily TMP for rack B was 11% lower than the baseline.

The improvement in the production rate can be attributed to the optimal cleaning, when we note that both racks A and B show 15% and 26% fewer FM cleans, respectively, compared to the baseline. The average intervals between the FM cleans were also increased from 20 minutes during baseline operation to 28 minutes for train 45 during the IntelliFlux managed operating period. The improved cleaning regime is reflected in a higher net yield, which increased by 7% over the baseline yield. We also observe a SEC reduction of 40% and 36% for racks A and B, respectively, compared to the baseline operation. Finally, the system also required fewer overall EFMs during this period, which enabled a substantial chemical and cleaning water savings over baseline (over 50% for each train).

Comparing the two months of performance of the train 45 in IntelliFlux mode against the baseline indicates that the three key KPIs stated in the objectives of this study were exceeded. The actual KPI's following the study were as itemized below:

- The net yield from the plant improved by 7% (KPI projection was 1 – 5%).

- The specific energy consumption (SEC) savings was 38% (KPI projection was 5 - 20%).
- Overall margin enhancement of approximately 23% (considering the additional filtrate production).

During the initial KPI projection phase, we only anticipated an OPEX savings of up to 20%. However, as we conducted the study, we realized that operation in the IntelliFlux mode increased the net yield of the filtrate (product). The filtrate is converted to RO permeate with an 85% recovery in the RO operation downstream, which has an average value of $919 per acre-foot. The net increase in projected yield by 7% over baseline predicts an average of 70 kgals (0.21 acre-ft) of daily increase in filtrate production by a 1 MGD capacity plant. With 85% of this filtrate converted to product water, the net revenue generation potential of this saved filtrate volume was estimated at $167.80 per day, or $5000 per month. The overall savings in OPEX achieved through reduced energy and chemical use, which were greater than 38% and 50%, respectively, was 6%. If we consider the savings in waste volume and ascribe standard commercial rates of waste disposal, the projected OPEX savings amount to 18%. In this analysis we did not account for any labor cost savings. In summary, we obtained an OPEX savings of 18% over baseline, and an overall margin enhancement of about 23% when we factor in the price of the increased filtrate production.

The turbidity ranged between $3.5 - 18$ NTU during this period, generally showing a sinusoidal behavior with a daily recurring fluctuation pattern. The average turbidity during this period of operation was 10.45 NTU. The slightly lower average and peak turbidity during this phase of operation could have contributed to the improved performance of trailer 45 during the IntelliFlux optimized phase of operation compared to the baseline operation.

The comparison of a system performance operated between two different time windows can raise questions regarding the validity of the comparison technique, particularly for a water treatment system that is subjected to changing influent water quality. There are other operating condition changes (such as seasonal variation of temperature) that can contribute to deviations of performance of a system from the baseline. To address such possibilities, this demonstration also included a side-by-side performance measurement of two systems, one operated using IntelliFlux, while the other operated in conventional mode. We discuss the results of this performance comparison study in the next section.

Table 7. Performance of Train 45 (Racks A and B) with IntelliFlux optimization mode enabled (April 16, - June 26, 2018) showing percent change from corresponding baseline parameters shown in Table 6. + indicates increase, − indicates decrease compared to baseline.

Parameter	Rack 45A	% Change	Rack 45B	% Change
Average daily gross production (kgal/day)	297.4	+21%	378.0	+29%
Average daily net production (kgal/day)	289.2	+30%	369.67	+37%
Average filtration TMP (psi)	15.55	+4%	12.20	−11%
Average temperature corrected permeability (GFD/psi)	1.22	+22%	1.78	+45%
Average daily FM cleans (#)	61	−15%	53	−26%
Average daily production time (%)	80%	+7%	71%	−8%
Specific energy consumption (SEC) (kWh/kgal)	0.27	−40%	0.25	−36%
Average daily net yield (%)	97%	+7%	98%	+7%
Average daily chemical use (gal/day)	9.48	−50%	7.15	−62%

9 Comparison of IntelliFlux and Conventional Operation

9.1 Production

From April 16, the performance of two trains, 45 (1801) and 46 (1802) were monitored side-by-side, where both trains were supplied with the same influent from a common headwater. Train 45 was operated using IntelliFlux, whereas Train 46 was operated in conventional mode. EAch train had two racks, which were designated as A and B. We received comparative operating data for Train 46 from the operator of the systems for the period of April 16 through July 3. After the systems underwent a CIP from June 24, there were several operational problems in both Trains 45 and 46 (such as malfunctioning flow-meters, feed-water quality excursions and inconsistent performance recovery, *etc.*) that prevented us from obtaining a comprehensive side-by-side comparative operating data for all the four racks of the two trains. Thus, we restrict detailed analysis of the performance of the two trains over the duration of 70 days spanning April 16 – June 26, 2018.

Figure 3 depicts the daily production for the two trains (45 and 46). The overall production from train 45 was about 4.5 MGD higher than train 46, representing a net 10% increased productivity of train 45 over the 70 days tracked. Figure 4 shows key performance metrics for the two trains, with details about production from each rack of these trains. During this period, the average daily net production from racks 45A and 45B was ~289 and ~370 kgals, respectively, which amounts to a total 659 kgals/day of filtrate production from Train 45, whereas the net production from Train 46 was 636 kgals/day (326.6 and 309.6 kgals/day from racks 46A and 46B, respectively). The increased production from train 45 is the outcome of the increased net yield from improved operation, which averages to approximately 97.5%, about 3.5% more than the 94% yield of Train 46. The average specific energy consumption (SEC) for Train 45 was 0.26 kWh/kgal, whereas the SEC for Train 46 was 0.32 kWh/kgal. The total production from Train 45 was 46.2 million gallons, whereas the total production from Train 46 was 41.7 million gallons during the 70 days of observation, which implies that Train 45 produced 4.5 million gallons more water than Train 46 over this period (approximately 10% increase in production). Assuming approximately 85% of this water can be converted to RO permeate, which is priced at $919 per acre-foot, the net revenue potential of this additional production is $10,800 (over the 70-day period).

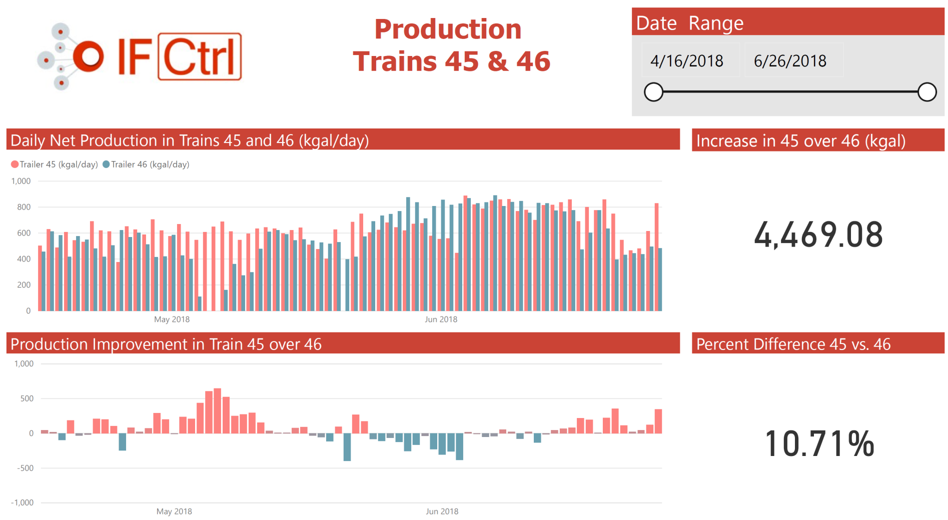

Figure 3. Comparison of daily production of Trains 45 and 46 during the side-by-side comparison phase spanning approximately 70 days of operation.

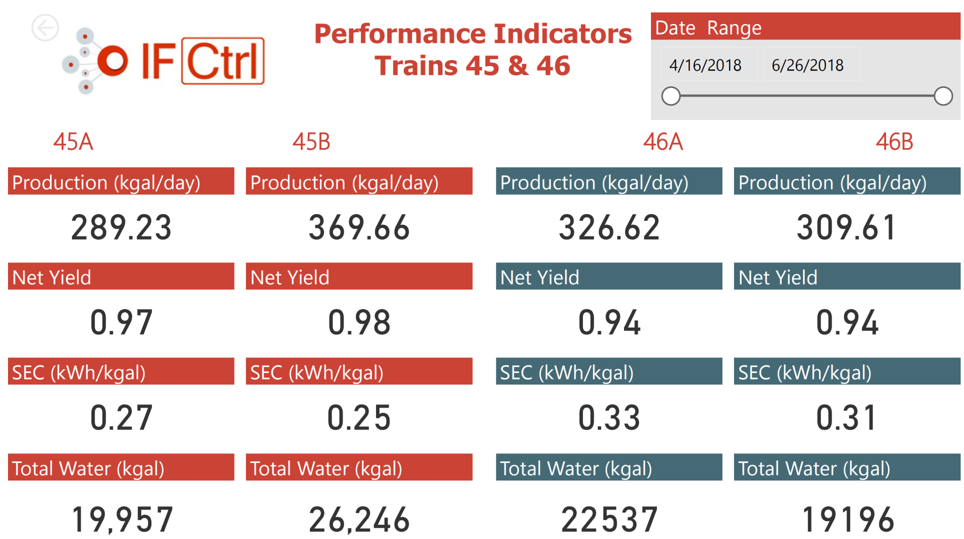

Figure 4. Key production performance indicators for Trains 45 and 46 during the side-by-side comparison phase. Train 45 was operated by IntelliFlux, whereas Train 46 was operated conventionally.

Figure 5 shows the reductions in specific energy, cleaning chemicals, and cleaning water consumption, as well as the overall reduction in waste volumes recorded for Train 45 in comparison to Train 46. The average specific energy consumption for Train 45 was 18.7% lower than that of Train 46 during this period. The daily cleaning energy consumption for Train 45 (averaging at 10.45 kgal/day) was 45.5% less than the corresponding cleaning water consumption of Train 46. The chemical use for cleaning Train 45 (8.32 gal/day) was 54.8% less than the daily chemical consumption in Train 46.

Finally, we estimated the daily waste volume generated in Train 45 to be 57% less than that of Train 46. The waste volume was calculated from the net yield.

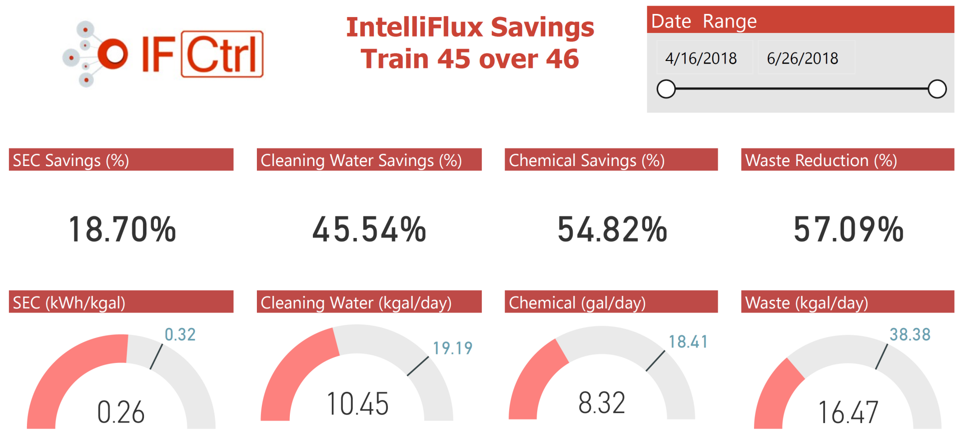

Figure 5. Key savings performance indicators for Trains 45 and 46. Train 45 was operated by IntelliFlux, whereas Train 46 was operated conventionally.

Figure 6 shows daily production performance parameters for the individual racks (A and B) of Trains 45 and 46, along with the average transmembrane pressure and the membrane permeability. For Rack 45A, the average TMP was 15.55 psi, whereas the average permeability was 1.22 GFD/psi. The corresponding TMP and permeability for Rack 45B was 12.2 psi and 1.78 GFD/psi, respectively. The higher permeability allowed Rack 45B to produce about 80 kgals/day more filtrate than Rack 45A. For Train 46, the net production from Racks 46A and 46B were more comparable, and the average TMP for these racks were 11.9 and 10.8 psi, while the average permeabilities of the membranes remained about 2.0 GFD/psi. It is interesting to note that although the average permeability of Train 46 was higher during this period, the net production from Train 45 was higher.

The daily production from the trains were higher in June compared to April and May, with the trains producing near their maximum capacity, albeit with a feed water quality that was relatively high in turbidity. Consequently, the fouling intensity during June was higher for both trains.

9.2 Permeability Trends

A closer look at the permeability and TMP trends for the two trailers can be obtained by considering the average values during the months of April (15 days), May (31 days), and June (26 days). Table 8 shows the average permeabilities (corrected to 20 °C), and in parentheses, the corresponding TMP values (in psi) for each train during these months. It is evident that between

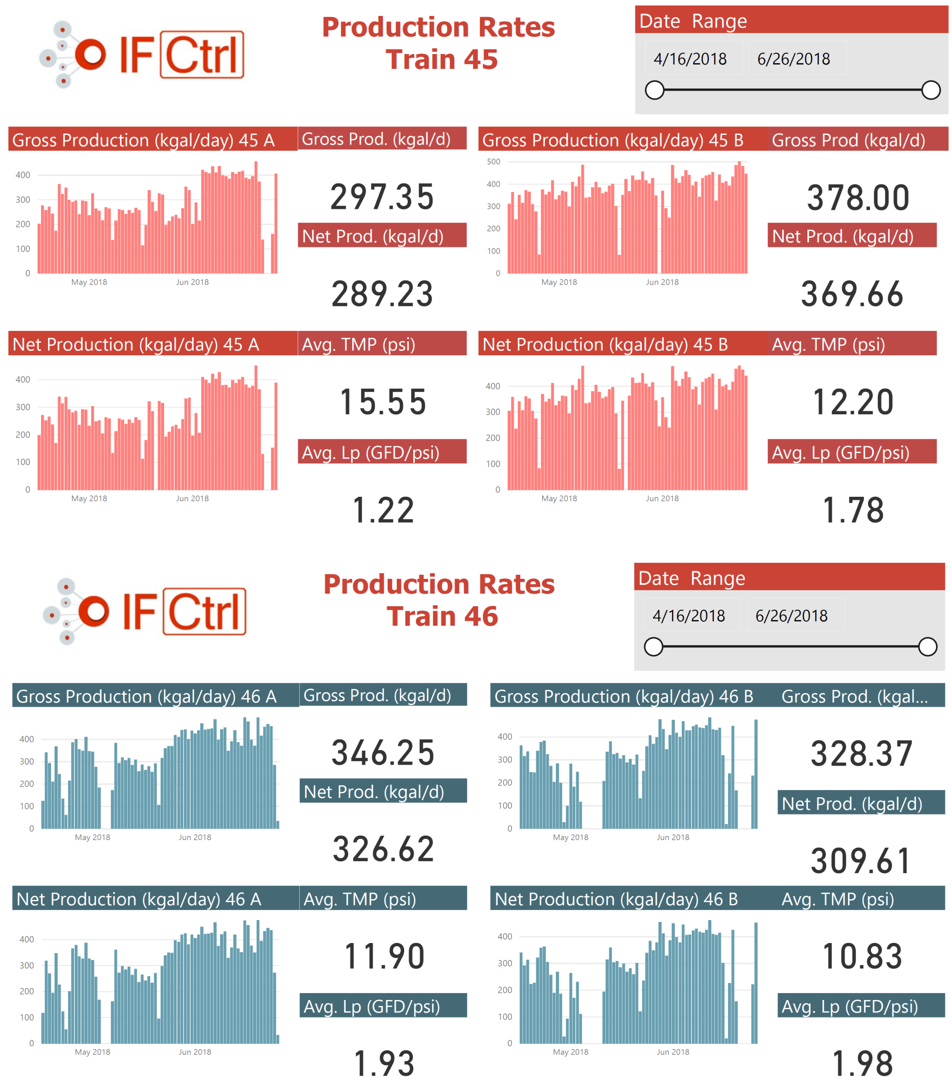

Figure 6. Daily and average production statistics for Trains 45 and 46, with performance broken down for each Rack.

April to June, all of the trains show a ∼50% increase in permeability. The permeability increase is not as pronounced between April to May, but the permeability of all trains show a marked increase in June. This can be attributed to a more effective clean in place (CIP) performed on these racks during the third week of May. Therefore, notwithstanding the lower starting permeability of Rack 45A, it showed similar membrane performance integrity as the other racks. Also, during this period, it did not appear that the performance of the membranes in Train 45 were in any way compromised either compared to the baseline performance from March - April 2018, or from the side-by-side comparison of Train 46 membranes.

Table 8. The permeability (GFD/psi) and the transmembrane pressure (psi) [shown in parenthesis next to the permeability] for each train during the months of April, May and June.

Timeframe	45A	45B	46A	46B
April 16 - April 30	1.05 (15.76)	1.46 (13.06)	1.64 (11.78)	1.63 (11.62)
May 1 - May 31	1.04 (15.84)	1.56 (12.97)	1.52 (13.80)	1.81 (11.61)
June 1 - June 26	1.57 (15.06)	2.21 (10.78)	2.53 (9.92)	2.41 (9.39)

9.3 Daily Averages

It is apparent that the average daily and the overall productions from Train 45, despite slightly lower average permeabilities and a higher TMP, were higher than Train 46. During the 15 days in April, Train 45 had 13.5% (about 1 MGD higher during the 15-day period) higher production compared to Train 46. In May and June, respectively, Train 45 had a 17.44% and 3.77% higher production than Train 46. This higher productivity despite a lower permeability and a higher average TMP of Train 45 clearly demonstrates the benefit of optimal cleaning that can be tuned with the time dependent (temporal) fouling trends of the membranes. The FM cleaning at intensities lower than 6 (Table 4) in Train 45 leads to savings in energy, water and downtime, increasing yield, and leaving more time for filtration. Furthermore, the flux management was able to respond to fouling spikes at certain times during these 70 days of operation for Train 45, and maintained the trains operational, whereas Train 46 underwent fouling and needed temporary shutdowns or EFM/CIP cleans owing to feed-water quality excursions. The increased downtime of Train 46 is reflected in the lower yield, lower net production, and increased energy consumption despite membranes with much higher permeability.

Figure 7, 8 and 9 show daily trends and overall averages of the net yield, specific energy consumption, and cleaning water consumption for Trains 45 and 46, respectively. All these metrics are better for Train 45 compared to Train 46.

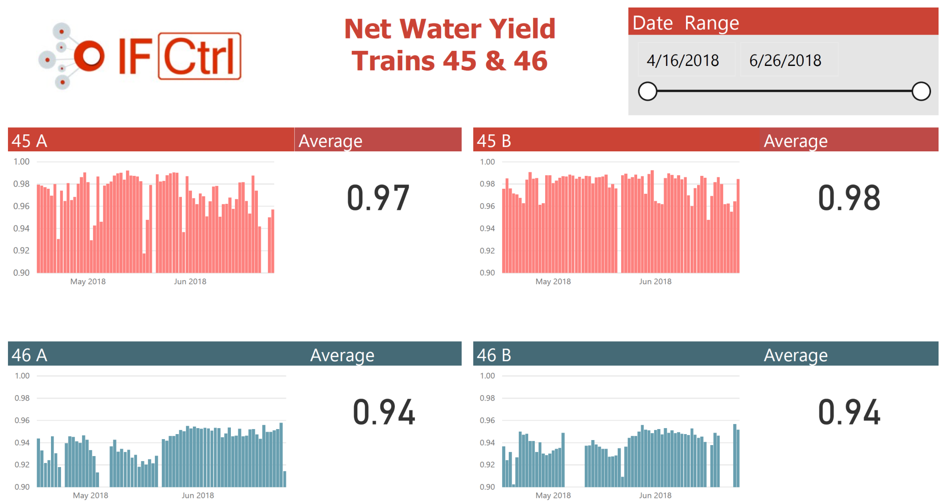

Figure 7. Daily and average Net Yield for Trains 45 and 46, with performance broken down for each Rack.

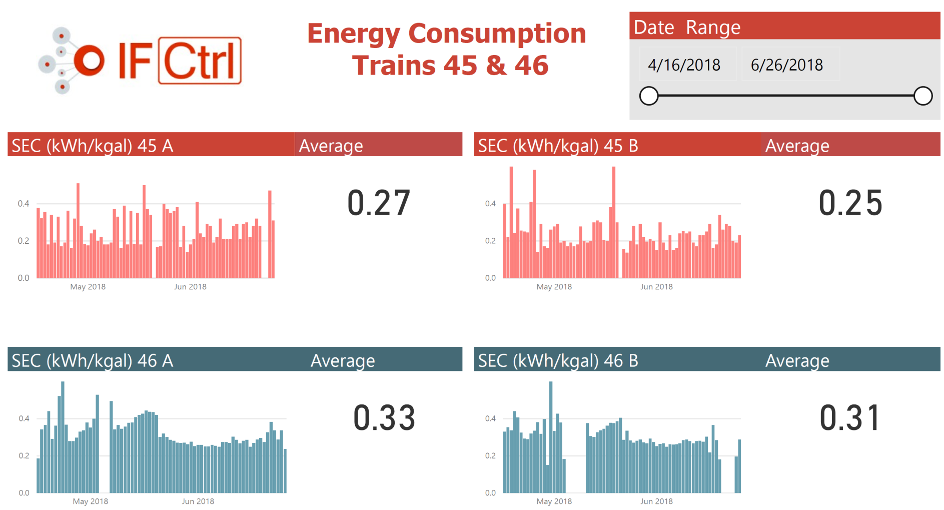

Figure 8. Daily and average specific energy consumption (SEC) in kWh/kgal for Trains 45 and 46, with performance broken down for each Rack.

9.4 Comparison of Cleaning Statistics

Two types of cleaning regimes were deployed in an automated manner in the trailers. The Flux Maintenance (FM) mode of cleaning involved backwashing the membrane along with air scour and air pulse. The Enhanced Flux Maintenance (EFM) mode of cleaning involved soaking the membrane in a recirculating chemical (Caustic + Bleach) solution for a fixed duration.

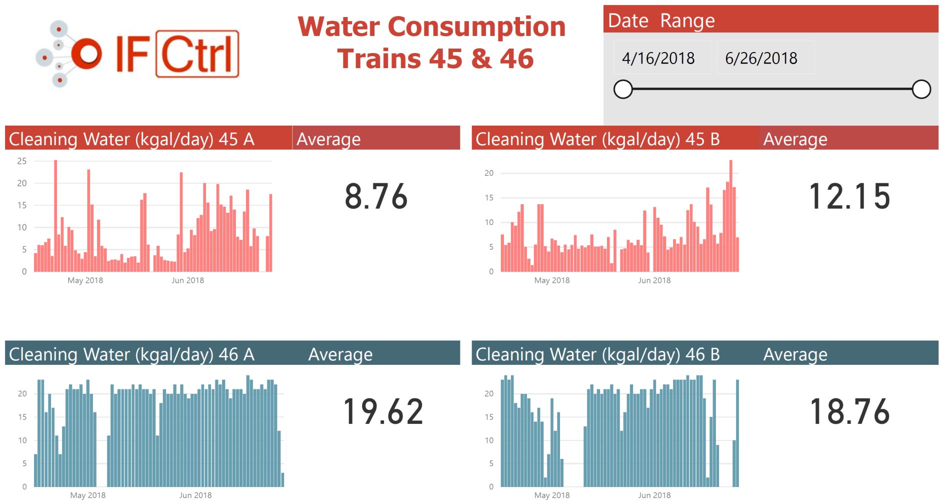

Figure 9. Daily and average specific energy consumption (SEC) in kWh/kgal for Trains 45 and 46, with performance broken down for each Rack.

In the IntelliFlux mode of operation, both the FM and EFM modes of cleaning were modulated by changing the intensity and duration of the back-flow, air pulse, and air scour for the FM cleans, whereas for the EFM mode the chemical cleaning duration, the circulation rate, and the chemical dosage were varied. Tables 4 and 5 depict the various settings at which the FM and EFM levels were modulated. It is discernible that each type of cleaning intensity setting will involve different amounts of energy where the energy consumption arises from the pumping rates for backwash or re-circulation, heating of the fluids to different temperatures, as well as the compressed air consumption for air pulse and air scour, different volumes of water use (due to different pumping rates and cleaning duration), and different chemical consumption rates (during the EFM).

Figure 10 shows the different levels of FM cleans deployed on racks A and B of Train 45 during the 70 days of operation from April 16 through June 26. The figure also shows the average interval between consecutive FM cleans for each rack. An important factor that is embedded in the IntelliFlux mode of flux optimization was the adjustment of cleaning interval depending on the severity of fouling. In Train 45, the average interval between consecutive FM cleans was more protracted compared to the fixed 20 minute interval for Train 46. Average interval between FM cleans was 26 and 25 minutes, respectively, for Racks 45A and 45B, both being approximately 5 minutes higher than the default FM interval for the conventional cleaning mode. The less frequent cleaning using IntelliFlux increases the effective filtration time, resulting in higher gross filtrate production, and less consumption of filtrate for cleaning, leading to higher yield. For Rack 45A, the most frequently de-

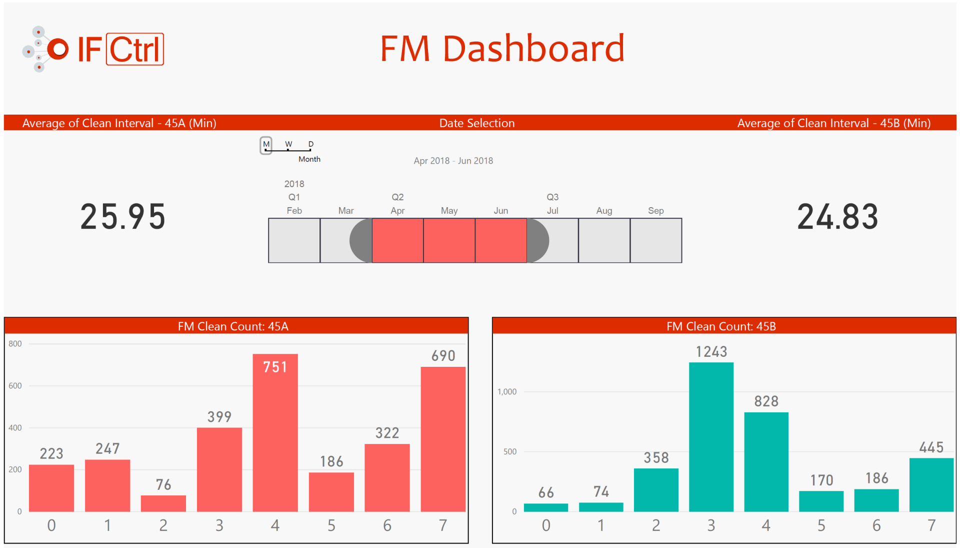

Figure 10. Flux maintenance (FM) cleans conducted on individual racks of train 45. The averaged interval between the back-washes as well as the distribution of clean types are shown.

ployed FM cleaning mode was level 4 with level 7 being the next frequent. In trailer 45B, the most frequent cleaning mode was FM 3 followed by FM 4.

Figure 11 depicts how the different modes of FM and EFM cleaning were deployed in Racks A and B of Train 45 during the 70 days of operation from April 16 through June 26. In both rackss, EFM 10 and 11 were most common. The slightly higher intensity of cleaning in rack 45A reflects the dirtier state of the membrane of this rack. For Train 46, the intensities of the default FM and EFM cleans were exclusively set at 6 and 15, respectively.

Figure 11 also depicts the total number of FM and EFM cleans performed in Racks 45A and 45B during the 70 days of operation in the IntelliFlux optimization mode. The total number of FM for Rack 45A was 2864, whereas for Rack 45B, it was 3345. Rack 45A required 46 EFMs, whereas rack 45B needed 52 EFMs during the same period. For Train 46, on average 72 FM cleans (of intensity 6) are required (with a fixed interval of 20 minutes between consecutive cleans) over each 24 hour operating period. This implies that over the 70 day duration, a total of 5000 cleans would be necessary for each rack of Train 46 if these were to operate continuously. However, given the down-times for CIP and other reasons, the net production time for Rack 46A averaged 65% (or about 16 hours per day). The total number of FM cleans in Rack 46A during this period was 4123, averaging 55 cleans per day. For Rack 46B, the total number of cleans during this period was 3872, with an average of 53 cleans daily. Rack 46B had an average uptime of 69%. For

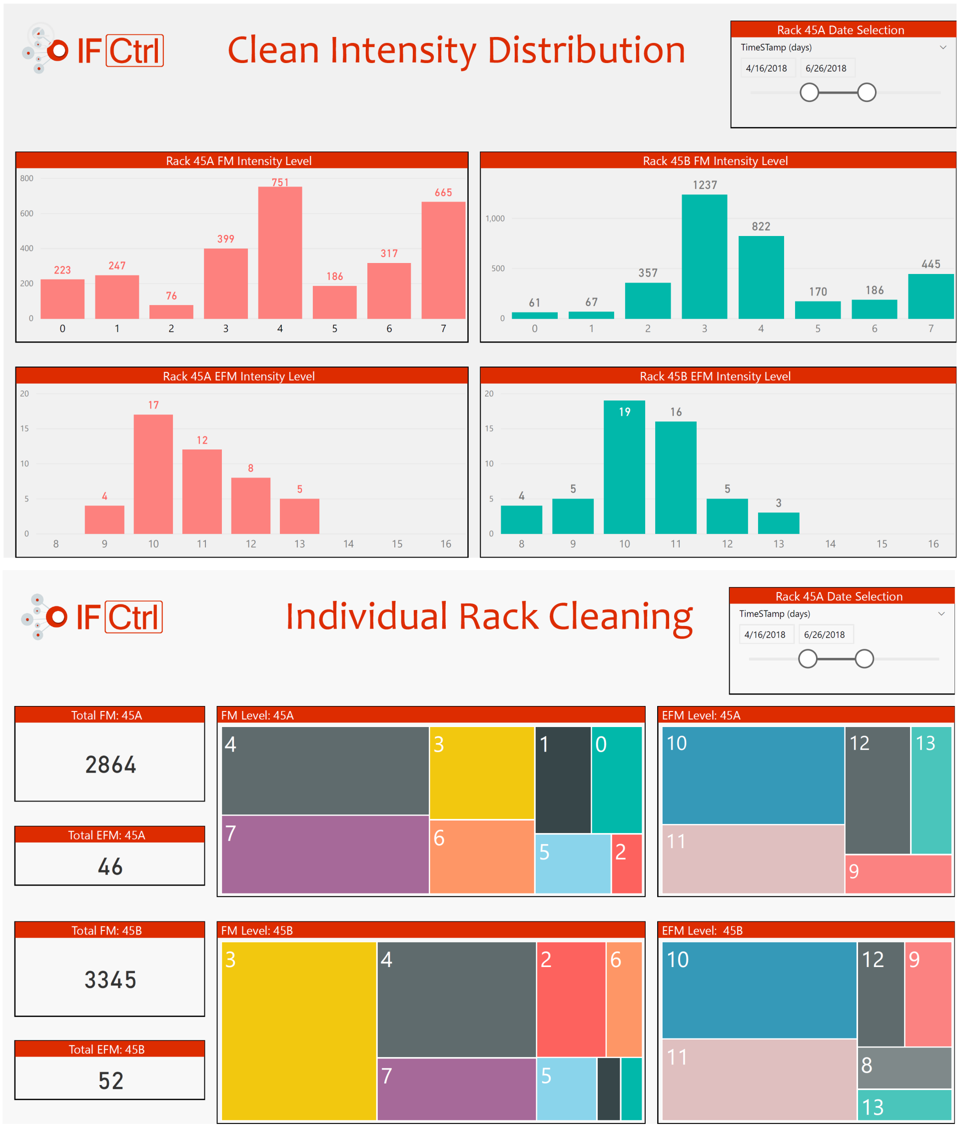

Figure 11. Distribution of various modes of FM and EFM performed on the two racks (A and B) of Train 45. Overall number of FM and EFM cleans for Racks 45A and 45B are also depicted. These visualizations and snapshots are generated from the dynamic dashboard tool of IntelliFlux and can also be plotted for different time ranges.

Rack 46A, the total number of EFMs during this period was 66, whereas for Rack 46B, the total was 61.

Combining these statistics, Train 45 required 22% fewer FM cleans and 22% fewer EFMs compared to Train 46 during the 70 days of operation.

Not only were the total number of FM and EFM cleans considerably fewer for Train 45, the distribution of the clean intensities in Figure 11 also shows that these maintenance modes were cumulatively a lot less energy intense compared to the FM mode 6 or the EFM mode 15 deployed In Train 46. These factors led to considerable savings in the cleaning energy for Train 45 compared to Train 46.

9.5 Effectiveness of FM Cleans

In this section, we demonstrate the efficacy of different types of FM cleans performed on Train 45. Figure 12 shows the overall statistics of the various modes of FM performed in Racks 45A and 45B (left column). The middle column shows the average cleaning effectiveness of each mode of FM clean. The cleaning effectiveness is simply defined as the ratio of the recovered permeability after each FM clean to the "clean membrane" permeability obtained after the previous CIP run. Thus, a value of the cleaning effectiveness close to 1.0 (or > 1) represents an effective clean, whereas a value significantly below 1.0 represents an ineffective clean. It is evident that FM modes 0, 2 and 7 were the least effective for both racks 45A and 45B. Mode 1 FM clean had the highest effectiveness.

It is not surprising that mode 0 was the least effective. This mode, normally referred to as “relaxation", uses the lowest backwash flow rate, and no air scour or air pulse. Such modes are only known to remove loosely held inorganic colloidal foulants deposited on the feed side surface of the membrane, and are generally ineffective in restoring membrane permeability during filtration of municipal wastewater. It was however, more unusual to see that mode 7, despite being the most intense FM, and despite being called a substantial number of times (776 times for Rack 45A, being the second most frequent type of cleaning mode, and 477 times for Rack 45B, the third most frequent), was only as effective as cleaning mode 2. This apparent ineffectiveness is an outcome of the fact that cleaning mode 7 was set as the upper limit of the FM cleaning matrix that could be deployed based on the constraints of the cleaning hardware. As mode 7 was the most intense level of FM cleaning that could be achieved, if IntelliFlux sensed the need for a more intense clean, it could not deploy any higher level of FM clean ow-

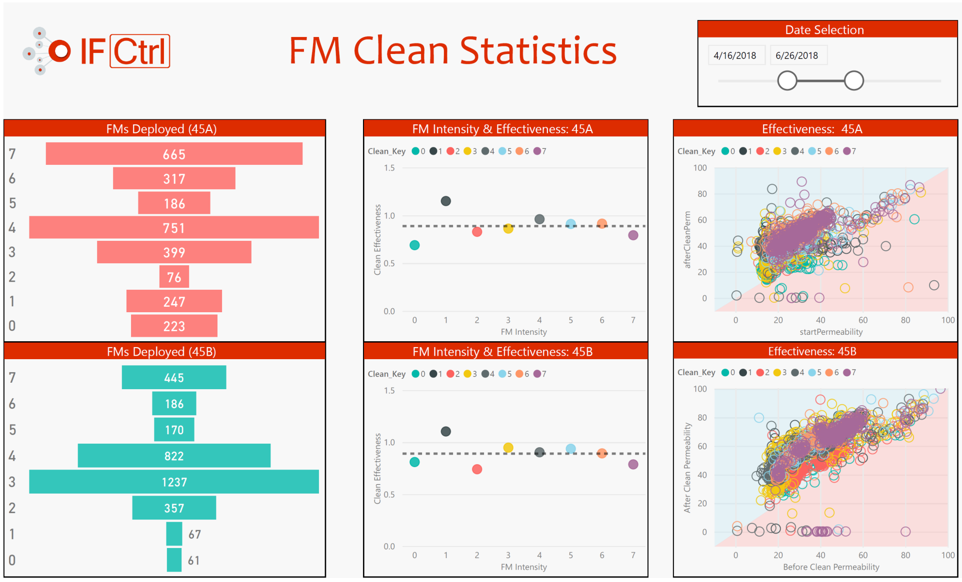

Figure 12. Comparison of the number of deployments, the average effectiveness, and the effectiveness scatter for the different modes of FM cleans for racks A and B of train 45. Note that for train 46 only FM mode 6 was deployed over the entire duration of the comparison from April 16 - June 26.

ing to hardware set-point limitations that were pre-programmed. The next higher level of clean available was mode 8, which was the least intense EFM; however, EFMs could be deployed much less frequently (with a minimum interval of 20 hours between consecutive EFMs). Consequently, during intense periods of fouling, the system performed cleans at the highest intensity of FM clean (mode 7) for several consecutive times, even though it was ineffective in restoring the membrane permeability to a higher level, before either an EFM could be called, or the influent water quality improved, thereby easing out the fouling rate.

The FM clean modes 3 and 4 were deployed most frequently, with mode 4 being most effective for Rack 45A, and mode 3 being most effective for Rack 45B. It is of interest to compare how the different FM clean modes perform. Without resorting to complex statistical analysis, we take a relatively simple approach of plotting every clean on a scatter graph with the horizontal axis showing the permeability of the membrane before the clean, and the vertical axis the permeability after the clean. The graphs on the right column of Figure 12 depict these scatter plots for Racks 45A and 45B. On each graph, if a scatter plot symbol falls on the region with the blue background, it indicates that the after clean permeability was higher than the permeability before that clean (or the clean was effective). In contrast, cleans that were ineffective would result in the symbols falling on the pink background region. A symbol falling on the diagonal of the plot (boundary of the blue and pink regions) will be considered ineffective in increasing the permeability. As shown in Figure 12, a majority of the cleans, irrespective of their type are in the blue region, indicating that they were able to increase the membrane permeability. The higher up the points are from the diagonal, the more effective the clean was. The plots also depict a number of symbols falling near the bottom horizontal axis, indicating that the permeability after the clean was nearly zero. These symbols signify the points where the system transitioned to either an EFM mode of cleaning or encountered a shutdown immediately after the previous clean was performed.

Figure 13. Distribution of cleaning modes FM0 (top) and FM3 (bottom) performed on the two racks (A and B) of Train 45.

Figure 13 shows the distribution of effectiveness of two modes of FM cleans on the two racks. These maps of the cleaning effectiveness can be instructive in identifying under what conditions different clean types were deployed on different racks, and how effective these cleans were. The effectiveness of a clean depends on multiple factors, including the initial state of cleanliness of the membrane (e.g. it's initial permeability), the influent water quality and its fouling potential, the nature of fouling (e.g. organic fouling, cake formation, or adsorption), and the operating conditions (temperature and the flux-pressure regime required to attain a certain level of production). All of these conditions change daily and seasonally, constantly changing the cleaning optimization regimen. Thus, what could be effective cleaning mode in April, may not be effective in June. Continuously optimizing the clean type in the face of such dynamic fouling conditions is virtually impossible for a human operator. Hence, filtration systems are designed by often erring on the side of conservative over-cleaning, putting in an aggressive mode of FM and EFM maintenance both with respect to intensity and frequency. This is where we find the machine learning and artificial intelligence guided operation of IntelliFlux delivering groundbreaking advantages for optimizing the cleaning operations.

10 Benefits of Adaptive Cleaning by IntelliFlux

10.1 Economic Benefits

The adaptive cleaning performed by IntelliFlux leads to certain operational and economic benefits over the conventional mode of operation. This section aims to determine the extent of such benefits.

To perform these calculations, we use the following parameters, all of which were provided by the end user (the municipal water district management):

Price of RO treated water:	$919 / acre-ft ($2.82 /kgal)
Cost of Energy:	$0.09 / kWh
Cost of Caustic:	$0.42 / lb
Cost of Chlorine:	$0.70 / gal
Cost of labor:	$55 / hr
RO recovery:	85%

From the price of caustic and chlorine provided to us, the cost of chemicals for EFM was calculated as $0.06 per gallon. For cleaning water (used for EFM and CIP), we assumed that water was RO product, and assessed a price of $2.82 / kgal. Furthermore, we estimate the price of waste disposal as $0.06 (sewer) per gallon.

The overall economic benefits were determined from the difference between the increased revenue generated from the additional filtrate production and the net savings generated by chemical, cleaning water, energy, waste volume, and potential labor savings.

During the 70 days of comparative study, both the trains (45 and 46) produced a gross output of 675 kgals/day. The net outputs were 659 kgals/day for train 45 and 636 kgals for train 46. Thus, on average, train 45 had an excess production of 22.67 kgals/day. Factoring in the RO recovery, the net excess product water from the plant is assessed at 19.26 kgal/day. In Table 9, we show the overall revenue increase and the OPEX savings by prorating the revenue increase based on daily averages over a month and a 1 MGD plant throughput.

Table 9. Calculations of the revenue increase, OPEX savings, and overall margin enhancement from the comparative performance metrics of Train 45 compared to Train 46. The prorated values are based on a 1 MGD plant throughput ($/month/MGD).

Revenue Increase	$	OpEx Savings	$
Daily revenue from increased product ($/day)	54.32	**Energy**	
Monthly revenue from increased product ($/month)	1629.48	Daily energy savings @ $0.09/kWh ($/day)	3.62
Prorated monthly revenue ($/month/MGD)	2,473.07	Monthly energy savings ($/month)	108.68
		Prorated monthly energy savings ($/month/MGD)	164.94
		Cleaning Chemical	
		Daily chemical savings @ $0.06/gal ($/day)	0.61
		Monthly chemical savings ($/month)	18.20
		Prorated monthly chemical savings ($/month/MGD)	27.62
		Cleaning Water (for EFM/CIP)	
		Daily cleaning water savings ($/day) @ $2.82/kgal	1.56
		Monthly cleaning water savings ($/month)	46.70
		Prorated monthly cleaning water savings ($/month/MGD)	70.88
		Waste	
		Daily waste disposal savings @ $0.06/gal ($/day)	33.12
		Monthly waste disposal savings ($/month)	993.60
		Prorated monthly waste disposal savings ($/month/MGD)	1,507.99
		Labor	
		Daily labor savings @ $55/hr ($/day)	27.50
		Monthly labor savings ($/month)	825.00
		Prorated monthly labor savings ($/month/MGD)	1,252.11
Revenue Increase ($/month/MGD)	2,473.07	OpEx Savings ($/month/MGD)	3,023.53

The overall margin enhancement (Revenue increase + OPEX savings) for train 45 was $5,496.60 per month, factoring in the labor and waste disposal costs.

When the waste disposal cost was is discounted from the calculations, the overall monthly margin enhancement was $4,244.50.

Finally, only considering the OPEX due to energy and cleaning (chemicals and cleaning water), the monthly margin enhancement was $2,736.50.

All the above figures are prorated for a 1 MGD plant throughput.

With the above calculations, it is safe to estimate that the annual benefits for a 1 MGD capacity plant will be between $32,838.00 and $65,959.00 depending on the cost factors accounted for.

10.2 Other Benefits not Accounted for in Economic Calculations

The aforementioned estimates only pertain to immediate economic benefits. Here we present several other benefits of IntelliFlux that are not embedded in the economic calculations. These include IntelliFlux' ability to provide a long term reduction in life cycle costs of a plant, reducing labor, and the liability of an operator, and ability to provide asset management and risk management for the plant. We have not accounted for any benefits of increasing module life (although we project at least a 2 year increase in module life owing to deployment of more gentle cleaning through reduction of chemical cleaning frequencies).

We have not assessed any value of the plant data acquired by IntelliFlux, and the context based information and actionable analytics delivered by it. In most applications of IntelliFlux, the data is used to generate reports (automated or on demand), alarms and notifications, which aid in the management of the asset. For the demonstration project we automatically generated these daily reports, but we could not measure the conventional data and performance logging practices at the site, and hence, did not have a benchmark to compare this against. Another component that has increasing value is the cumulative learning from the plant experience that remains embedded in the system enriching its knowledgebase and the sophistication of its actions. Over the lifetime of a plant, IntelliFlux will learn from every change in operating environment, and will progressively improve and optimize its performance.

In this study, we did not assess fault diagnostics capabilities and ERP / MES integration of the plant data. During any water quality excursion, or any equipment fault, IntelliFlux was the the first responder that contacted the plant operators upon identification of a problem. There were incidents where the cleaning intensity and frequency changes in Train 45 (which was operated by IntelliFlux) made the operators aware of influent water quality excursion, and use that to protect Train 46 (which they were operating conventionally). In another case, operating information and analysis performed by IntelliFlux led to discussions among various partnering organizations, leading to the assessment that cleaning chemistries for maintenance cleans were either off-specification, or were different from what the equipment manufacturer recommended. These examples point to the ability of IntelliFlux as a plant reliability enhancement and risk management tool. The key difference here from other plant monitoring services is that IntelliFlux manages a problem through its adaptive control within its bounds while informing the operator, whereas all other plant monitoring systems only inform the operator and transfer the liability of correcting the problem entirely to the operator.

Finally what is being delivered in this project from the point of view of automation is not vastly different from what exists in advanced manufacturing or smart manufacturing environments. These types of automation can be done and exist in other industries. However, what is remarkable here is that IntelliFlux delivered a sophisticated smart manufacturing solution in an *already operating and previously automated /instrumented plant* without requiring any expensive shutdown, upgrade, engineering, or hardware addition. No other automation space competitor will consider this achievable at this speed, at the price point, and at the level of effectiveness and scalability at which IntelliFlux delivers this solution.

11 Membrane Irreversible Permeability Trends

The economic benefits analysis performed in the previous chapter does not consider any potential benefits to the membrane life due to the gentler and less frequent cleaning delivered by IntelliFlux. We have not conducted these calculations here as the two-month study may be deemed too short to assess the long-term consequences of adaptive cleaning on membrane life. However, it is worth assessing the condition of the membranes after the demonstration period. Figure 14 depicts the overall flux, permeability, and TMP trends for the two trains of trailer 45 over the entire duration of the demonstration from March 10 through August 21.

The flux, permeability, and TMP of rack 45A remained almost unchanged during this period. For rack 45B, the flux and permeability trended upward, with a significant increase in the flux and permeability starting from the last week of May. However, as the production rate of the rack was increased, it started encountering a more aggressive rate of fouling, which is evident form an increase in TMP from June 2018. Notwithstanding, we note that the permeability of rack 45B in August was slightly higher than the baseline permeability average calculated in March – April 2018.

Although these permeability trends indicate that the membranes were not compromised during this demonstration, it is clearly evident that increasing the production rate without regard to the feed-water fouling potential can accelerate the membrane fouling rates. In MF and UF, the limiting or sustainable flux behavior must be ascertained for every type of feed-water, and excursions of feed-water quality from design levels can lead to severe fouling if the production rate cannot be adjusted to achieve a sustainable flux. IntelliFlux was not allowed to conduct such optimization of sustainable flux in its optimization profile during this study. Considering such modes of optimization could have greater impact on sustainable operation of the membrane filtration process under high fouling feed-waters.

It should be noted that the performance of IntelliFlux manifested in this demonstration with the discrete cleaning matrix, limited range of set-points, and inability to optimize the sustainable flux, represent some of the limitations imposed during installation of this software in retrofit plants. Furthermore, during this demonstration phase, the operation of IntelliFlux was

Figure 14. Trends of the filtration flux (lmh), permeability (lmh/bar), and the transmembrane pressure (bar) for racks 45A and 45B aggregated over the entire duration of the demonstration (March 10 through August 21, 2018). This includes the baseline performance data acquisition phase (March 10 - April 10), the phase of side-by-side comparison with train 46 reported here (April 16 - June 26), and the additional duration of operation till August 21. While rack 45A did not show any marked change In flux or permeability, there was a marked Increase In flux and permeability of rack 45B in June.

interrupted on multiple occasions owing to operator intervention, equipment (such as flow meters or pump) failure, communication errors, shutdowns, and feed-water quality excursions. In many situations, IntelliFlux was able to warn the operators of equipment malfunctions. These are all standard challenges of IntelliFlux installation in retrofit scenarios with already specified hardware and existing operating procedures. Such hardware restrictions lead to different extents of performance enhancement in retrofit plants after installation of IntelliFlux. Notwithstanding these restrictions, our ability to adapt IntelliFlux to these variations makes IntelliFlux different from competition, and uniquely positioned to serve the retrofit plant upgrade markets. This is why, in retrofit installations we do not *a priori* claim the economic benefits of IntelliFlux, and propose to our customers to install the software on their plant and assess the value propositions before making a long-term purchase commitment. Clearly, the flexibility of IntelliFlux is much higher when it can be implemented during the design and integration of a new plant.

12 Conclusions

IntelliFlux was installed on MF train 45 (1801) at a tertiary municipal wastewater treatment plant site for six months, conducting various types of tests. During this period, it's performance was compared with the baseline performance data of the MF plant as well as measured side-by-side against another Identical system (train 46) with the same influent. Both these comparisons demonstrate the ability of IntelliFlux to deliver multiple benefits from adaptive cleaning. The most pertinent benefits demonstrated were:

- A higher net filtrate yield compared to the baseline (7%) as well as the conventionally operated train 46 (3.5%).
- A 38% savings in energy compared to baseline and 18% energy savings compared to train 46.
- Over 50% or higher chemical savings compared to both baseline operation and to train 46.
- Overall OPEX savings of 18 % compared to baseline operation
- Overall monthly economic benefit of IntelliFlux translated into a prorated $/month/MGD value ranging between $2,736.50 to $5,496.60.
- During the six-month demonstration period, the permeabilities of the two racks of train 45 either remained constant or slightly increased from the baseline values.

Appendix A: About IntelliFlux

A.1 Overview of the Product Offering

IntelliFlux is an expert system for process control, helping operators of process and water treatment plant to lower OPEX, and improve plant efficiency through intelligent decision-making. IntelliFlux is based on an expert knowledge-base and engineering fundamentals of the processes it controls, and is driven by machine learning and artificial intelligence engines that enhance the knowledge-base for specific plant adaptations.

The core software platform underlying IntelliFlux product lines is referred to as **Augmented Process Recommendation & Industrial Control Optimization Toolbox (APRICOT)**. Engineered with novel machine learning algorithms, the software enables optimization of multiple process components at a plant individually or synergistically. It means that IntelliFlux can optimize any process sequence containing multiple treatment technologies, such as biological treatment, membranes, media filtration, coagulation, bio-processes, thermal and reactive systems. With this capability, IntelliFlux Controls can now provide end-to-end decision automation for water treatment and process plants.

IntelliFlux provides immediate response to process condition variations, as well as thoughtful and learned response based on its machine learning and predictive analytics. The result is a continuously improving smart automation framework that progressively improves it's knowledge of plant operation, enhancing efficiency, adaptability, and reliability of the plant.

IntelliFlux consists of hardware and software components that augment the supervisory control and data acquisition (SCADA) and/or the distributed control system (DCS) framework at a process or water treatment plant to deliver:

- Autonomous optimization of the unit operations or processes at the plant, providing real-time feedback control and adaptive set-point regulation.
- Improved learning from event logs through predictive analytics, statistical correlations, and advanced AI modules, delivering an improved deci-

sion support and automation framework that not only provides operators better insight about the plant, but also circumvents performance loss or plant damage arising from influent quality fluctuations or unexpected perturbations.

The award-winning IntelliFlux filtration software provides an artificial intelligence-guided control philosophy that optimizes flux maintenance and cleaning protocols in filtration operations in response to influent water quality fluctuations and fouling – the technology deploys cleaning only when it is necessary. Furthermore, the intensity and nature of the cleaning deployed is also commensurate with the extent of fouling. This provides unprecedented improvement in system recovery, water use, uptime, cleaning chemical usage, and energy consumption. This product line is mainly applicable to membrane and media filtration processes. Other variations of the software are also available, and IntelliFlux can be customized for reverse osmosis, biological treatment, mixing, and full plant process control.

A.2 How IntelliFlux Works

Figure A1 depicts the hardware-software architecture of IntelliFlux. IntelliFlux delivers the services as a virtual assistant to the plant operator and engineer using a client-server architecture. The IntelliFlux Client is installed at the customer plant site, where it performs all the real time process control and optimization tasks for the plant. The IntelliFlux server is hosted by IntelliFlux Controls remotely, and provides advanced machine learning, predictive analytics, system identification and optimization tasks to deliver process information to the customer to assist in operational decision-making. This server engine acquires data from the IntelliFlux Client through a secure dedicated connection, processes this information to provide advanced analytics, and delivers decision support to the designated operators and plant personnel. In Ultrafiltration applications with high solids and turbidity influents, difficult to treat waters, as well as highly fluctuating feeds, IntelliFlux has a demonstrated track record of lowering OpEx, energy intensity, chemical consumption, and waste volume, as well as extending membrane useful life, thereby providing tremendous life cycle treatment cost benefits for such plants. Furthermore, the ability to autonomously mitigate water quality excursions and resulting downtime, unscheduled maintenance, and membrane damage improves the reliability and sustainability of the membrane plant.

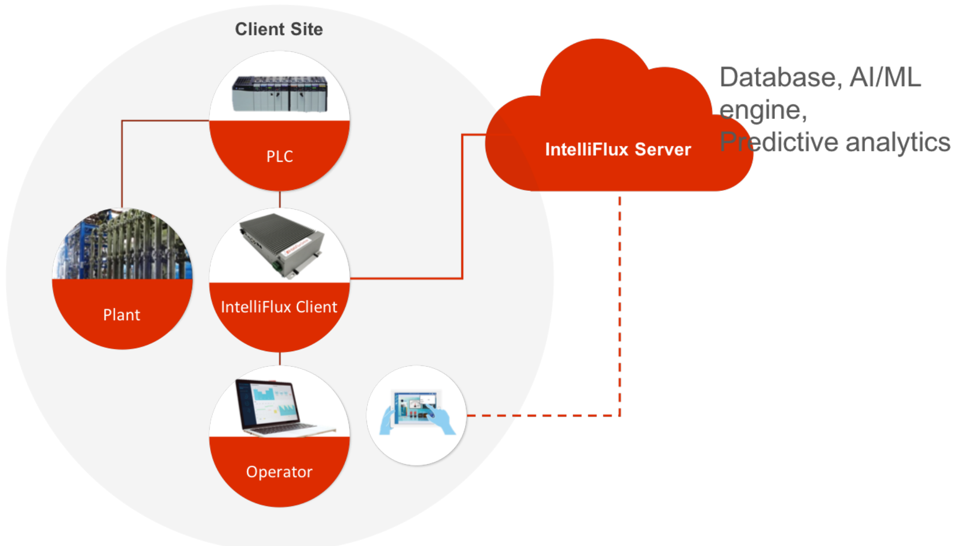

Figure A1. How IntelliFlux works. The system can be easily integrated into any existing plant and starts delivering values immediately after installation and commissioning.

A.3 Applications

IntelliFlux has been deployed on several water treatment plants spanning many types of applications, including

- tertiary treatment of secondary clarifier effluent from municipal sewage plants,
- recycle of cooling tower blow-down water in conjunction with a chemical de-silication process at a power plant,
- wastewater treatment in the food and beverage industry to meet discharge regulations,
- treatment of bioreactor effluent from a mobile sewage treatment plant,
- treatment of oilfield produced water for agricultural reuse, and
- Membrane bioreactors, among other applications.

A.4 Benefits

The key benefits of IntelliFlux include:

- Lower specific energy consumption

- Lower cleaning chemical consumption
- Extended component (cartridges, filter modules, etc.) life
- Increased uptime of plants
- Reduced chances of catastrophic failure or fouling of membranes arising from uncharted excursions of the influent water quality from standard operating range

Depending on the influent water quality and application, the system provides $5-40\%$ savings in system OPEX, $15-70\%$ savings in chemical consumption, between $5-50\%$ energy savings, $20-60\%$ savings in waste volumes, and generally a $2-7\%$ increase in net UF process water recovery.

Application Case Studies

Version: IntelliFlux Ultrafiltration APRICOT™

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