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Impact of Ammonia-Based Aeration Control (ABAC) on Energy Consumption

Victoria R. Medinilla [1,*], Travis Sprague [2], Jason Marseilles [2], Jerry Burke [2], Shivaji Deshmukh [2], Saied Delagah [3] and Mohamadali Sharbatmaleki [1]

1 Civil Engineering Department, California State Polytechnic University, Pomona, CA 91768, USA; sharbat@cpp.edu
2 Inland Empire Utilities Agency, Chino, CA 91708, USA; tsprague@ieua.org (T.S.); jmarseilles@ieua.org (J.M.); jburke@ieua.org (J.B.); sdeshmukh@ieua.org (S.D.)
3 U.S. Bureau of Reclamation, Denver, CO 80234, USA; sdelagah@usbr.gov
* Correspondence: vrmedinilla@cpp.edu

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Abstract: An Ammonia-Based Aeration Control (ABAC) system is installed in the primary aeration basins of a regional wastewater treatment facility. The energy consumption of the system of air blowers, measured in kilowatts per hour by an existing meter, is analyzed for seven months after the installation of the ABAC system and compared to system performance prior to commissioning of the ABAC system. Processed data, including volume flow rate, ammonia loading, and treatment equipment efficiency, are evaluated for periods before and after the ABAC system installation. Ammonia mass loading and air transfer ratio in the aeration basins are determined to be the leading factors affecting the performance of the ABAC system and thus impacting the metered energy consumption. The metered energy consumption data are normalized by the two calculated ratios, which reflect the change in ammonia loading and air transfer ratio. The normalized and metered energy consumption data are compared, and the results show a reduction in energy consumption since the installation of the ABAC system. A yearly savings of approximately 9 ± 1% in energy costs is estimated with the installation of the ABAC system. The savings in energy consumption calculated as well as the improvements in nitrification efficiency confirm the benefit of an ABAC system in reducing operation costs and enhancing process control.

Keywords: aeration; nitrification; ammonia loading; air transfer efficiency; energy consumption

1. Introduction

Recent advances in technology have improved the efficiency of the wastewater treatment process and paved the way for recycled water use. Nonetheless, the challenge of optimizing the treatment process while reducing operational and capital costs continues. The process of nitrification is often utilized by wastewater treatment facilities to meet ammonia effluent permit levels. To achieve full nitrification, that is, the conversion of ammonia to nitrate, the nitrifying biomass requires enough dissolved oxygen (DO), several nutrients, and an appropriate retention time [1]. One area of potential operational savings in the nitrification process is energy consumption, specifically from the mechanical blowers needed to support the aerobic portion of the treatment process [2]. The optimization of aeration through ammonia-based aeration control (ABAC) systems encourages operation at low DO concentrations. An ABAC system is composed of an open-loop and closed-loop controller that sets DO setpoints in the treatment aeration basin to maintain a predetermined ammonia setpoint at the effluent [3,4]. This decreases the overall energy consumption of the facility while maintaining high-quality effluent. Since aeration typically contributes a large percentage of a wastewater treatment plant's energy costs due to the operational cost associated with large blowers, the development of control efforts to optimize the aeration process is essential. Moreover, utilization of novel aeration control strategies to optimize the biological processes such as nitrification or phosphorus removal, has shown to decrease plant chemical usage without sacrificing effluent quality [2].

Wastewater treatment facilities with nitrification systems typically operate at elevated levels of aeration with a concentration above 2 mg DO/L to avoid nitrification failures and satisfy biological oxygen demand (BOD) removal as well. Studies have shown, however, that complete nitrification can occur at low levels of DO concentrations [2]. Operating at 0.5 mg DO/L rather than 2 mg DO/L, the overall oxygen transfer efficiency increases by 16%, which translates to a 10% energy saving for the overall treatment plant [1,2]. Low DO operation can, however, create a treatment environment susceptible to sludge bulking due to the growth of filamentous bacteria. Studies have shown that lower DO concentrations (0.5–2.0 mg DO/L) produced sludge with poorer settling properties and higher turbidities in the effluent than higher DO concentrations (2.0–5.0 mg DO/L). The cause was found to be the growth of filamentous bacteria; filamentous microorganisms can compete with floc-forming organisms at low DO levels (<1.5 mg/L) [2].

Strategies to control aeration use specific parameter-measuring devices in combination with control programs to provide cost-saving alternatives. Sensors are used to measure nutrients such as ammonia, nitrate, nitrite, phosphorus and DO are used to operate the aeration control strategy. As a result, the application of these measuring instruments must be appropriate to avoid measuring errors and minimize the risk of violating permit limits. Most conventional wastewater treatment plants are not originally designed for use with real-time control (RTC) systems and thus require equipment upgrades. Nonetheless, the evolution of Supervisory Control and Data Acquisition (SCADA) systems in treatment facilities has allowed facilities to remotely monitor and control the process. RTC can therefore be integrated into SCADA through the capacity of distributed control systems (DCS), which control plant operation through remote terminal units (RTUs) and proportional-integral-derivative (PID) control algorithms [5].

With the increasing global demand for water accessibility and improved sanitary standards, the advancement of wastewater treatment processes and technologies is critical for societies to thrive. Although advanced technologies may exist and improve the wastewater treatment process, the decision to implement these technologies must often meet the criteria of functionality, cost, and long-term environmental impact. Current technologies, such as ABAC systems, offer a long-term, cost-effective solution to a significant energy demand issue associated with wastewater treatment, without sacrificing the quality of the final water product. The findings of this study will contribute to the understanding of ABAC systems and their benefit of reducing energy consumption costs for wastewater treatment facilities. Moreover, this study contributes to the larger effort to reduce the industry's carbon-footprint through the overall reduction of energy consumption. Through collaboration between an academic institution and a public utility agency, this study will pave the path for future research and development efforts in the local and broader wastewater treatment community.

2. Materials and Methods

For this study, an ABAC system was installed at the Inland Empire Utility Agency's Regional Water Recycling Plant No. 1 (RP-1), located in Ontario, California. The Inland Empire Utilities Agency (IEUA) is a regional wastewater treatment and water agency providing sewage treatment, biosolids handling and recycled water to portions of the San Bernardino County in the state of California. RP-1 is currently the largest treatment plant within IEUA's service area with a design capacity of 44 million gallons per day (MGD) [5]. The RP-1 treatment process includes three activated sludge systems consisting of two aeration trains each for a total of six trains. A combined flow of primary effluent and return activated sludge is diverted by influent gates to each train. Each train contains three basins that function as conventional bardenpho treatment system: the first basin mixes flow and provides anoxic treatment, the next three basins can add air through fine bubble diffusion system supplied by four large blowers to provide aerobic treatment. In 2015, a pilot study was initiated at RP-1 to test the compatibility of an ABAC system. In 2019, the ABAC unit was purchased and installed in the aeration system for further testing.

The metered energy consumption (kWh) of the aeration four-blower system was reviewed from 2018 to present day. Working with the IEUA Planning Department, a cost of $0.10 per kWh was used for the cost analysis; this cost-per-kWh accounts for the multiple energy power agreements honored in the facility. The energy consumption data were normalized by what were determined to be the largest contributing factor: contaminant (i.e., ammonia and total organic carbon (TOC)) mass loading and air transfer ratio. The ammonia mass loading normalizing ratio was calculated by averaging the daily samples of influent ammonia concentration as well as the metered influent plant rate and converting to mass basis, as shown in Equation (1) [6].

$$M_{NH4} = C_{NH4} * V_{inf} * 8.34 \quad (1)$$

where M_{NH4} is the ammonia mass loading in units of pounds per day (lbs/d), C_{NH4} is the daily average ammonia concentration sampled and tested in units of milligrams per liter (mg/L), V_{inf} is the daily average plant flow rate in MGD, and 8.43 is a constant used for unit conversion.

The air transfer ratio (ATR), which is a measure of the cubic feet of air needed to transfer a pound of dissolved oxygen within a treatment train, was calculated using the metered air flow rate to the system, the metered total influent rate to the treatment basin, and the measured DO concentration in the system. Equation (2) below describes the calculation further [6].

$$ATR = (A_{Train} * 24)/([(V_{Inf\text{-}Train} + V_{RAS\text{-}Train})/2)] * C_{DO\text{-}Train} * 8.34) \quad (2)$$

In the above, ATR is the air transfer ratio for a given treatment train in units of cubic feet per pound of dissolved oxygen (CF/lbs DO), A_{Train} is the air flow rate in units of standard cubic feet per hour (SCFH), $V_{Inf\text{-}Train}$ and $V_{RAS\text{-}Train}$ are the volume flow rates from the influent pump station and returned activated sludge pump station, respectively, in units of MGD, $C_{DO\text{-}Train}$ is the dissolved oxygen concentration in units of milligrams per liter (mg/L), and 8.34 is a constant used for unit conversion.

Normalizing the data by these factors adjusted the metered energy consumption to account for the changes in contaminant loading as well as the change in air transfer ratio since the change of aeration diffuser panels within the facility in early 2018. Metered data were collected by a variety of existing probes and sensors located in the treatment process: DO probes, ammonia analyzer, suspended solids sensor, UV nitrate sensor. The real-time controller module and digital controller were the main control modules of the ABAC system installed. Depending on the meter, equipment calibration is scheduled on a monthly or quarterly basis per manufacturer recommendations, and to the system operating pressure and temperature. The data measured by this equipment are collected and historized by IEUA's SCADA system. Other plant factors, such as influent feed rate, BOD, total organic carbon (TOC), and total suspended solids (TSS), were analyzed as well to identify drastic changes that could have contributed to the energy consumption rate. Lab-analyzed sample data were used for influent ammonia, and TOC, BOD, and TSS, which was also accessible through SCADA Daily data points, were queried from SCADA and averaged on a monthly basis; a standard deviation of <10% was achieved during data analysis for all data parameters utilized. Figure 1 is a schematic of the aeration system and shows the location of probes specific to the ABAC system.

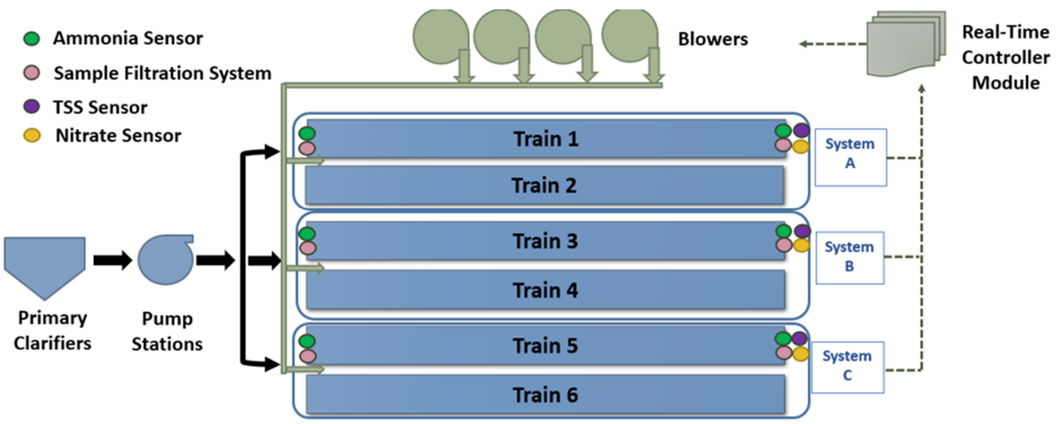

Figure 1. RP-1 aeration treatment process schematic with locations of an Ammonia-Based Aeration Control (ABAC) system components3. Results.

2.1. Process Data

The analysis of average monthly metered energy consumption for the months the ABAC has been in service, August 2019 through March 2020, demonstrated larger rates when compared to the same months in 2018, as show in Figure 2. The increase in energy consumption is related to the increase in air flow rates [2]. The air flow rates supplied to the aeration basin by the four blowers also demonstrated an increase when comparing the periods before and after the ABAC unit was commissioned, as shown in Figure 3.

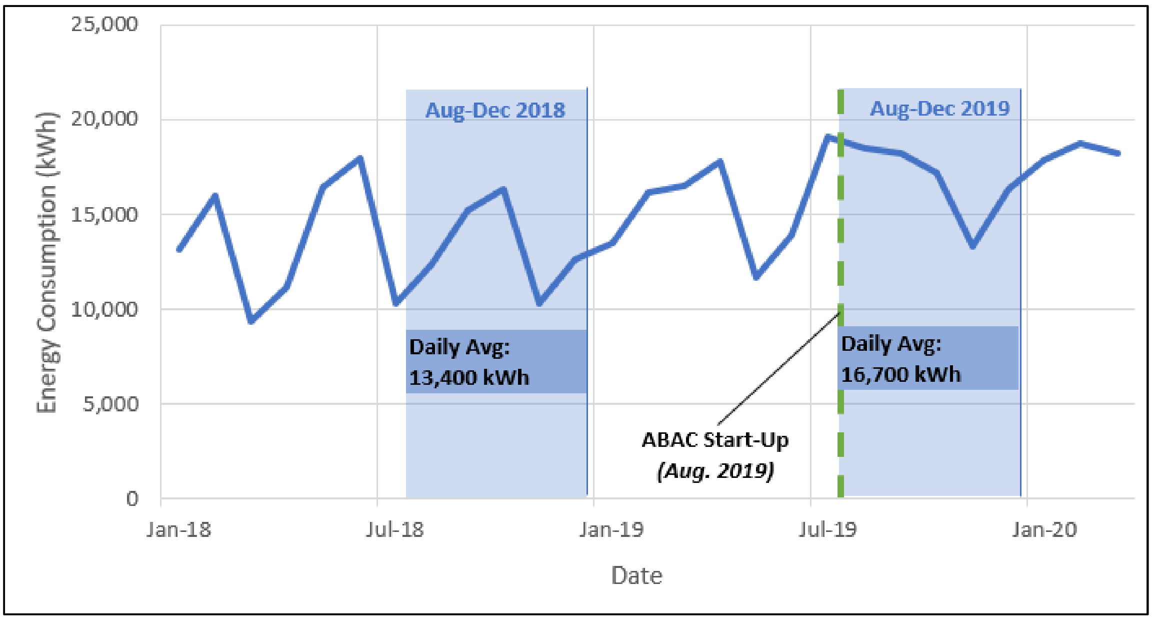

Figure 2. Average daily energy consumption in kWh, as measured by existing meter on aeration blowers. August through December 2018 showed a daily average energy consumption of 13,400 kwh, while the same months in 2019 showed 16,700 kWh.

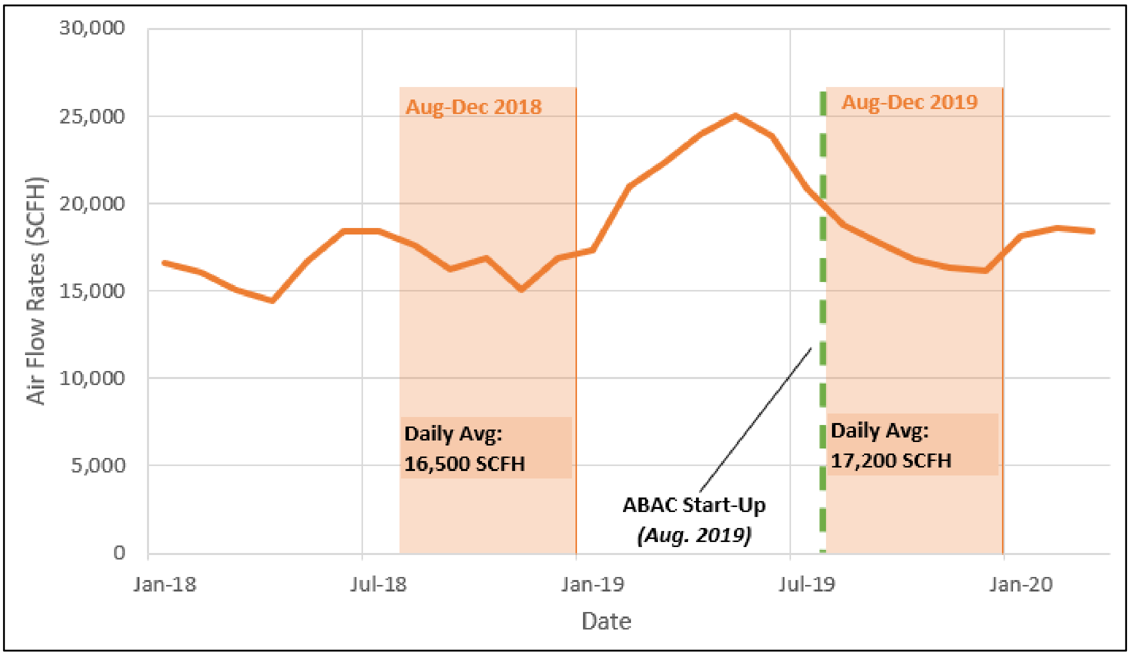

Figure 3. Average daily air flow rate in standard cubic feet per hour (SCFH), as measured by existing meter on aeration blowers. August through December 2018 showed a daily average air flow rate of 16,500 kWh, while the same months in 2019 showed 17,200 kWh.

2.2. *Ammonia Mass Loading*

Increased air rates are typically a result of increased contaminant load to the system [7]. As shown in Figure 4, the plant influent volumetric flow rate remained steady throughout the period studied. Figure 5 shows, however, a reduction in ammonia loading to the plant during the same period. Nonetheless, other contaminant loading to the plant, such as TOC, BOD, and TSS demonstrated an increase since the installation of the ABAC unit, as shown in Figures A1–A3, Appendix A. Although the aeration process treats primarily for ammonia, other oxygen-demanding components, such as those mentioned, are expected to increase the need for dissolved oxygen in the basins [5].

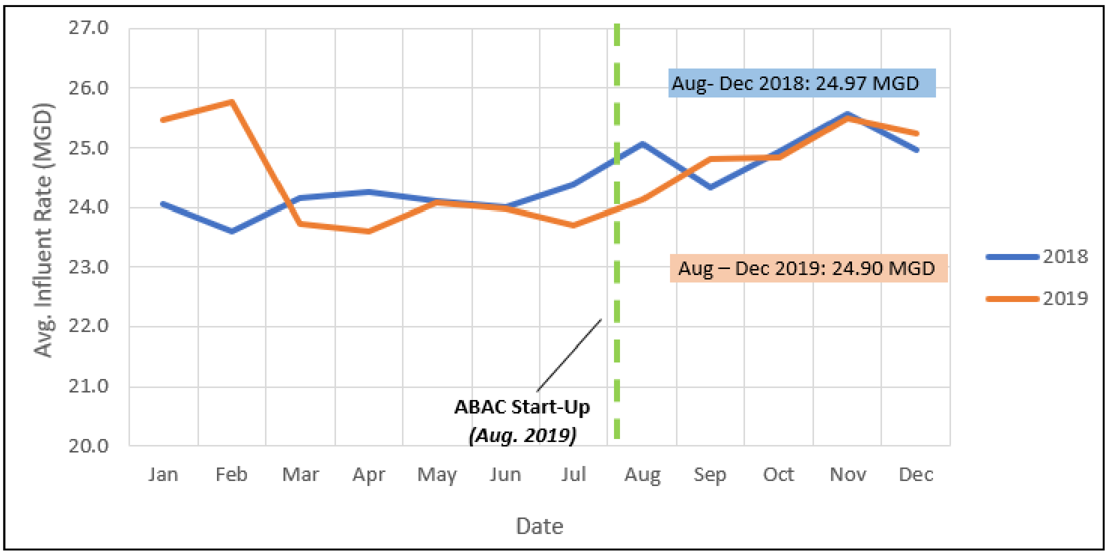

Figure 4. Average daily plant influent flow rate in million gallons per day (MGD). August through December 2018 showed a daily average influent feed rate of 24.97 MGD, while in 2019 it was 24.90 MGD.

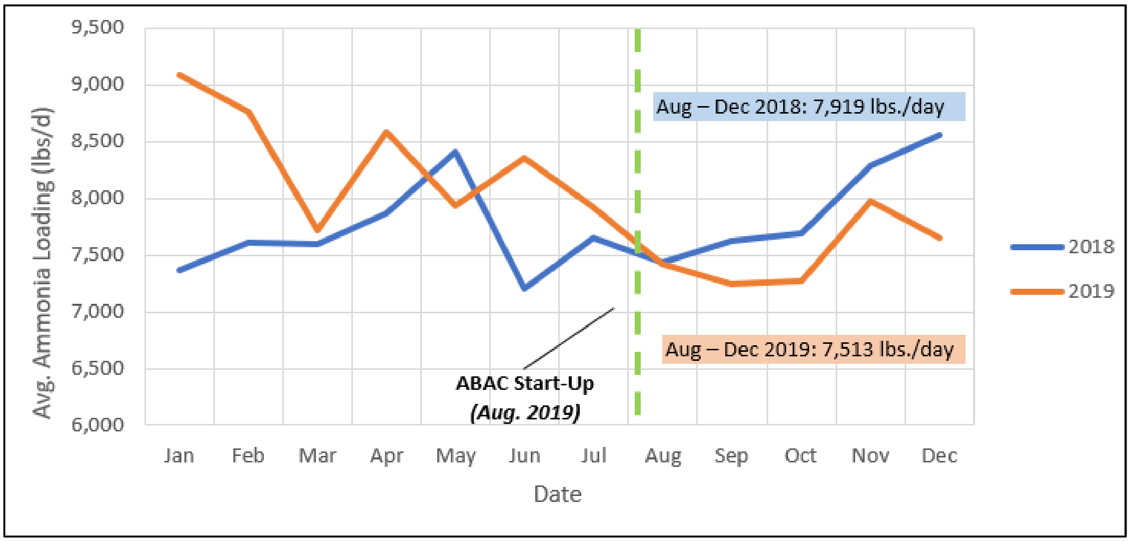

Figure 5. Average daily influent ammonia mass loading rate in pounds per day. August through December 2018 showed a daily average ammonia loading of 7919 lbs/day. August through December 2019 had an average daily ammonia loading of 7513 lbs/day.

Evaluating the correlation between the individual contaminant loading and the air flow rates, ammonia loading had the largest correlation with air rates at 25%, as shown in Figure A4, and calculated in Table A1, Appendix A; TOC, TSS and BOD have correlations of 20%, 19% and 18%, respectively. Using Equation (1), an ammonia mass loading average ratio of 1.70 was calculated from the measured data and used to normalize 2019 metered energy consumption data, as shown in Table A3, Appendix C. Similarly, a piece of TOC mass loading data was used to normalize 2018 energy consumption to account for the increase in loading seen in 2019. Tables A4–A6, Appendix C show the calculation of a TOC loading normalization ratio of 0.38, and those for TSS and BOD as well.

2.3. Air Transfer Ratio

In addition to the contaminant load increase, mechanical changes to the process during the time that the ABAC system was commissioned were considered, including the air transfer ratio from the diffuser panels to the basins [8]. The air transfer ratio is a measure of the cubic feet of air at standard temperature and pressure conditions needed to transfer a pound of DO within a treatment train and is found using the Equation (2) [9]. As shown in Figure 6, the air transfer ratio for System B, Train 3, increased since early 2018. This indicates that the amount of air needed (cubic feet) has increased per pound of dissolved oxygen transferred to the system.

In 2015, the air transfer ratio was determined for the aeration basins, and it was determined that new diffuser panels were needed, especially in Train 3, due to the amount of air needed to reach a desirable DO level [10]. In 2018, the diffuser panels were replaced, and a drastic improvement occurred as shown in Figure 7. However, over time, the air transfer ratio has begun to increase, thus indicating an increase in the air flow rate required to meet DO levels [10]. This trend is expected as the service life of the diffuser panels increases [10,11]. Using air transfer ratio data for Train 3 during peak performance, as shown in Figure 7, a ratio of 1.40 was calculated to further normalize the metered energy consumption data and account for the degradation of the panel over time (see Tables A7–A9, Appendix C for calculations).

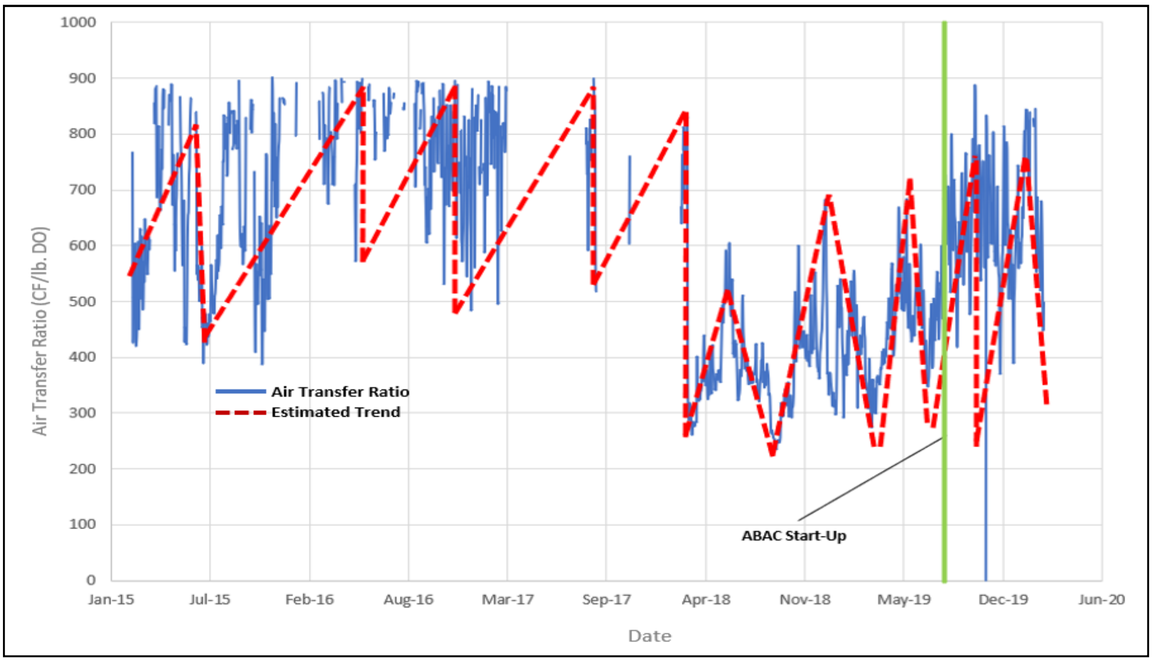

Figure 6. Air transfer ratio calculated in cubic feet per pound of dissolved oxygen for System B, Train 3, per Equation (2).

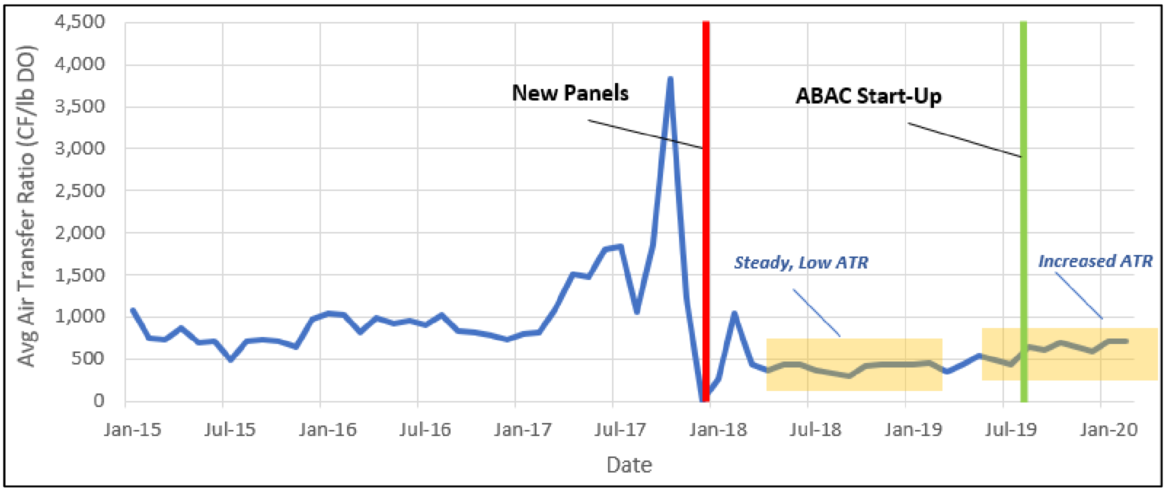

Figure 7. Monthly average air transfer ratio calculated in cubic feet per pound of dissolved oxygen for System B, Train 3, per Equation (2).

2.4. Normalized Energy Consumption

By considering ammonia mass loading and air transfer ratio, the 2019 energy consumption measured by the existing meter was normalized by two ratios: 1.70 for ammonia mass loading and 1.40 for air transfer (Appendix C). Similarly, 2018 energy consumption data were normalized using the TOC normalization ratio of 0.38 (Appendix C). By comparing the normalized energy consumption rates between both years as shown in Figure 8, the estimated savings due to the installation of the ABAC system can be captured in the months of August–December 2019. This approach decreases the effect of contaminant loading and the degradation of the diffuser panels on the metered energy consumption data and thus creates a fair comparison. Table 1 (below) summarizes the savings determined. Considering the capital cost of the ABAC system, the energy savings result in a return on investment of four years.

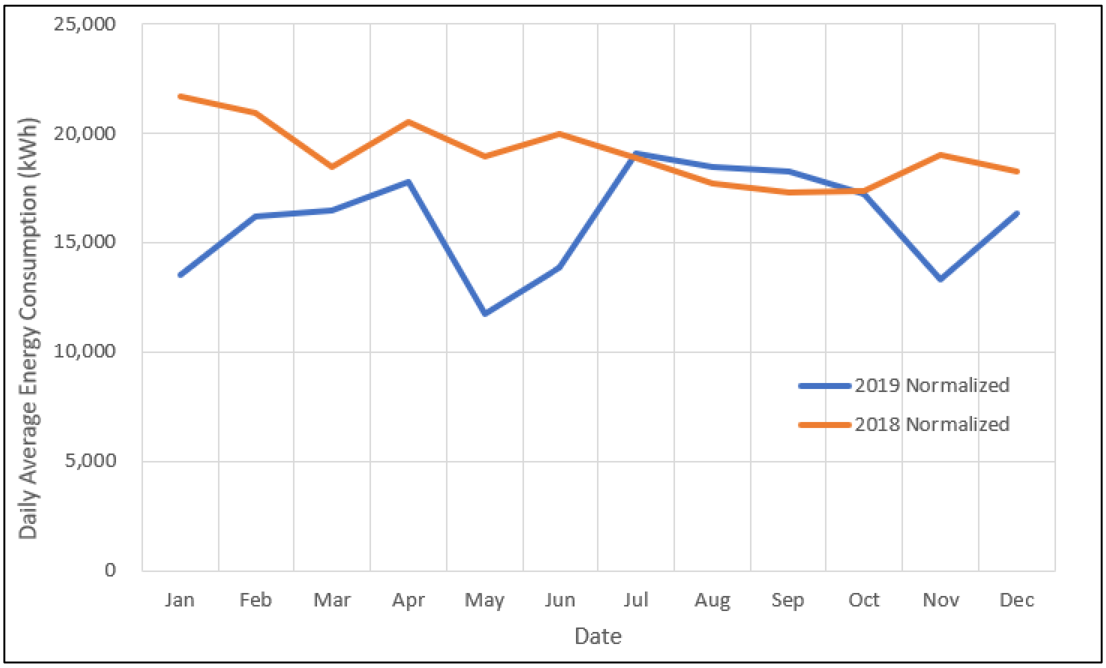

Figure 8. Average daily energy consumption in kWh for normalized data.

Table 1. Energy consumption cost analysis for August–December 2019.

Parameter.	Value	Error	Unit
2018 (normalized)	17,927	±390	Avg. daily kWh
2019 (normalized)	16,502	±422	Avg. daily kWh
Energy Savings	1425	±30	Avg. daily kWh
Cost Savings *	$149	±$3	Daily avg.
Cost Savings	$54,474	±$1100	Per year
2019 Actual Cost	$630,633	±$15,400	Per year
Estimated Savings	9%	±1%	Per year
Capital Cost of ABAC Unit:	$223,273		Equipment/Installation
Return of Investment:	4		Years

* $0.10 per kWh was used for the cost analysis.

2.5. ABAC System Performance

The performance of the ABAC system was also evaluated as part of this analysis. There is a significant correlation between the DO set point established by the ABAC system and the DO sensor reading in both System A and System B of 54% and 64%, respectively; System C shares DO set point and DO readings with System B (see Figures A5–A7, and Table A2, Appendix B). Additionally, there is a similar trend with ammonia mass loading in each system. This demonstrates that the ABAC system successfully reacts to changes in ammonia loading by adjusting the DO set point accordingly [3,4].

The benefits of an ammonia-based aeration control system also have the potential to impact downstream chlorine dosage [12,13]. Chlorine dosage at RP-1 is based on a chlorine residual setpoint. The residual chlorine, or free chlorine, is the remaining chlorine after the supplied chlorine dosage is consumed through treatment. If the chlorine analyzer reading of free chlorine is lower than the desired setpoint, the pump output is increased by setting of a higher dosage. This change in operation is typically a reaction to higher ammonia loading to the chlorination plant during tertiary treatment. Additionally, free chlorine can react with ammonia to form chloramines. This disinfectant byproduct will reduce the concentration of free chlorine as it is not registered by the chlorine analyzer [14]. Prior to the use of ABAC, plant operations took multiple hand samples of the aeration treatment process to determine if ammonia treatment was compromised (i.e., ammonia break-through). This was done as a reaction to observing a higher chlorine dosage at the end of the process. The hand samples were often inconclusive as they failed to capture the ammonia spike when it occurred. With the ABAC units, plant operations staff is notified of real-time ammonia spikes and can mitigate chlorine overdose by reducing flows as well as through the automatic increase of aeration at the basins. Figure A7, Appendix B displays the improvement in chlorine dosage in accordance to ammonia loading since the installation of the ABAC units in August 2019.

3. Discussion

Based on the process data analyzed for the ABAC system currently installed at the IEUA RP-1 facility, it is recommended to continue monitoring the energy consumption of the unit to obtain at least a full year of data (i.e., August 2019 through August 2020). The data must be normalized to influent contaminant loading as well as air transfer ratio, as these factors have been shown to impact energy consumption the most. With the four months analyzed as part of this study (August through December 2019), the ABAC system is demonstrating energy consumption savings of approximately 9% and the three months of 2020 data collected demonstrate promising trends for a continued savings. Additionally, trends of system ammonia loading, DO set point and readings as well as the improvements in bleach dosage demonstrate the ABAC units are working appropriately. IEUA senior operation staff members have supported the use of the ABAC system as it provides a reliable tool to mitigate high ammonia loading episodes. Limitations to this study include the use of less than one year of process data to determine trends; as more data are collected with the ABAC unit in service, the accuracy of the cost savings analysis is expected to increase.

The ABAC system installed in IEUA RP-1 facility has been successfully proven to reduce energy consumption costs for facility operation as expected from by the ABAC application theory. The control system and equipment that make up the ABAC system have the capability to accurately set the appropriate DO level based on incoming ammonia loading and consequently reach the corresponding DO concentrations in the aeration basins through control of the air supply. As suggested by the preliminary date, the overall use of bleach in the facility has shown a reduction but whether it can be fully attributed to the ABAC system is yet to be further investigated. In addition to the cost savings demonstrated, the real-time ammonia loading data supplied by the ABAC system have given RP-1 operators improved control and optimization opportunities for the process. This improvement in control has increased treatment efficiency and long-term operation strategy. The results of study therefore warrant further investigation of energy consumption and chemical usage reductions in large-scale wastewater treatment application. Moreover, this study provides a framework for the analysis of data collected from an ABAC system to appropriately consider system factors.

Author Contributions: V.R.M. and T.S. presented the idea and together designed the data-gathering approach. V.R.M. processed the data and wrote the original manuscript. T.S. reviewed the data and provided input for data normalization. J.M. contributed institutional knowledge of the facility and created the air transfer ratio equation. M.S., J.B., S.D. (Saied Delagah), J.M., and T.S. reviewed and edited the manuscript and made key contributions to the background and discussion sections. S.D. (Shivaji Deshmukh) reviewed the manuscript and supported funding for the APC. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

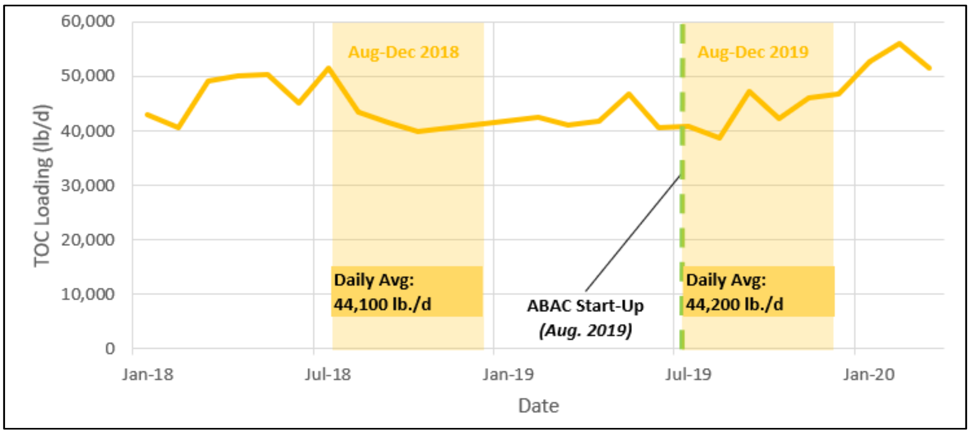

Figure A1. Average daily total organic carbon (TOC) loading measured in pounds per day (lbs/day). For August–December of 2018, a daily average TOC loading was 44,100 lbs/day while 44,200 lbs/day for the same time period in 2019.

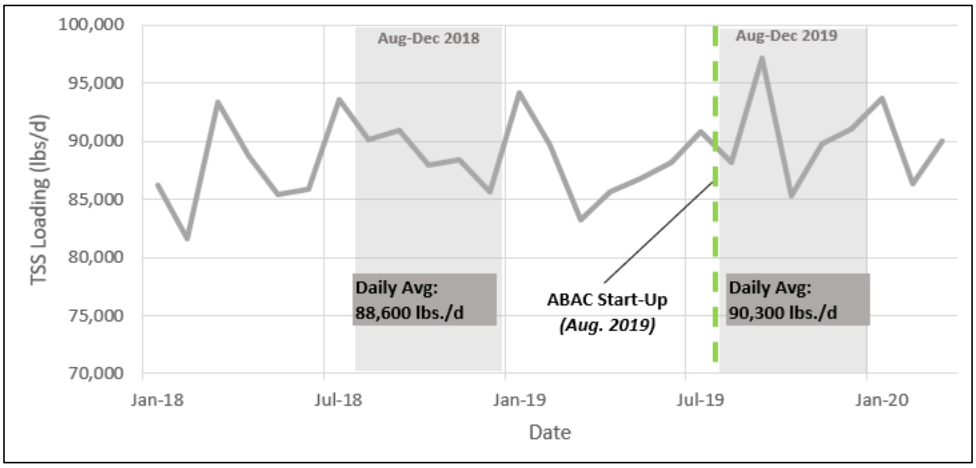

Figure A2. Average daily total suspended solids (TSS) loading measured in pounds per day (lbs/day). For August–December 2018, a daily average TSS loading was 88,600 lbs/day while 90,300 lbs/day for the same time period in 2019.

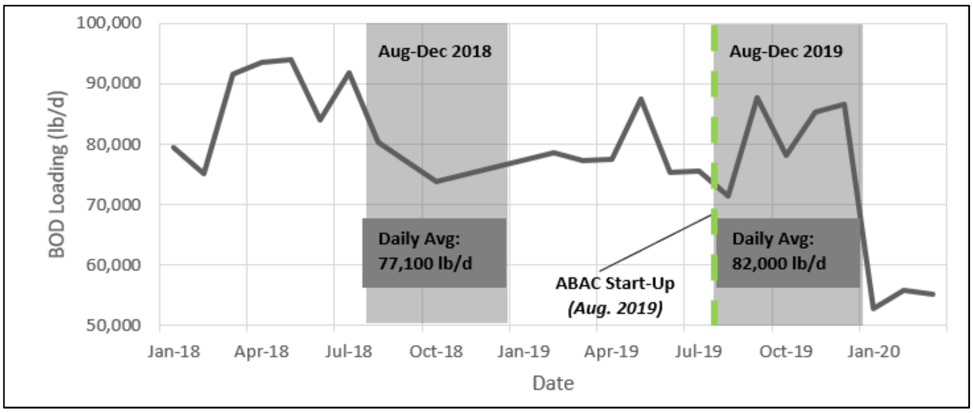

Figure A3. Average daily biological oxygen demand (BOD) loading measured in pounds per day (lbs/day). For August–December 2018, a daily average BOD loading was 77,100 lbs/day while 82,000 lbs/day for the same time period in 2019.

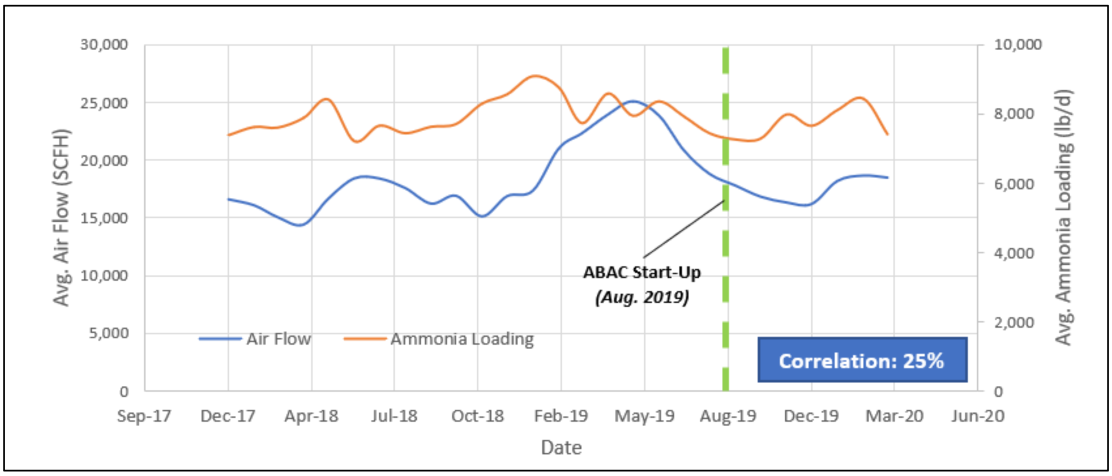

Figure A4. Average daily ammonia loading measured in pounds per day (lbs/day) as compared to average daily air flow rate measured in standard cubic feet per hour (SCFH). Using a correlation function, a 25% correlation is found between both parameters.

Calculation Appendix A: Correlation of Contaminant Loading and Air Flow Rates
Equation (A1):

$$\text{Correlation }(X, Y) = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right.}} \quad \text{(A1)}$$

where X and Y are the calculated means for the data sets and n is the sample size. In this case, X is Average Daily Air Flow (SCFH) and Y is the contaminant loading (lb/day).

Table A1. Correlation Calculation Results.

Date	Average Daily Air Flow Rate (SCFH)	Average Daily Ammonia Loading (lb/day)	Average Daily TOC Loading (lb/day)	Average Daily TSS Loading (lb/day)	Average Daily BOD Loading (lb/day)
January 2018	16,585.06	7369.25	43,030.87	86,180.39	79,483.35
February 2018	16,063.90	7611.25	40,614.63	81,647.46	75,244.57
March 2018	15,039.29	7591.59	49,229.47	93,405.89	91,720.42
April 2018	14,385.80	7870.27	50,195.34	88,808.87	93,561.69
May 2018	16,656.15	8409.86	50,370.99	85,384.35	93,917.26
June 2018	18,400.43	7197.76	45,202.81	85,852.81	84,007.68
July 2018	18,389.68	7651.13	51,501.27	93,583.23	91,876.91
August 2018	17,563.42	7430.12	43,342.82	90,191.13	80,313.99
September 2018	16,210.81	7617.75	41,670.15	90,990.46	77,187.15
October 2018	16,891.28	7697.64	42,066.05	87,970.58	73,818.29
November 2018	15,101.90	8291.36	41,600.87	88,441.15	N/A
December 2018	16,855.85	8560.39	41,727.03	85,673.32	N/A
January 2019	17,333.03	9090.04	44,214.72	94,205.88	N/A
February 2019	20,994.76	8765.44	42,461.94	89,715.26	78,538.47
March 2019	22,322.08	7722.53	41,135.69	83,236.07	77,308.66

Table A1. *Cont.*

Date	Average Daily Air Flow Rate (SCFH)	Average Daily Ammonia Loading (lb/day)	Average Daily TOC Loading (lb/day)	Average Daily TSS Loading (lb/day)	Average Daily BOD Loading (lb/day)
April 2019	23,941.26	8585.05	41,853.19	85,653.56	77,621.16
May 2019	25,082.73	7936.83	46,702.41	86,827.87	87,417.61
June 2019	23,856.50	8356.03	40,688.80	88,175.73	75,343.26
July 2019	20,828.54	7918.57	40,841.94	90,807.43	75,669.57
August 2019	18,774.50	7424.37	38,697.31	88,185.80	71,500.95
September 2019	17,769.22	7246.81	47,214.88	97,164.49	87,775.92
October 2019	16,812.06	7273.33	42,272.47	85,258.11	78,285.17
November 2019	16,310.47	7975.88	46,036.25	89,794.23	85,433.92
December 2019	16,176.83	7644.84	46,663.56	91,099.20	86,667.92
January 2020	18,177.00	8103.53	52,732.74	93,692.37	52,732.74
February 2020	18,645.65	8439.18	55,952.96	86,381.25	55,952.96
March 2020	18,464.40	7399.27	51,455.11	90,081.12	55,130.48
Average (X,Y)	18,282.69	7895.56	45,165.79	88,829.93	78,604.59
Sample Size (n)	28	28	28	28	25
CORREL:		25%	20%	19%	18%

Appendix B

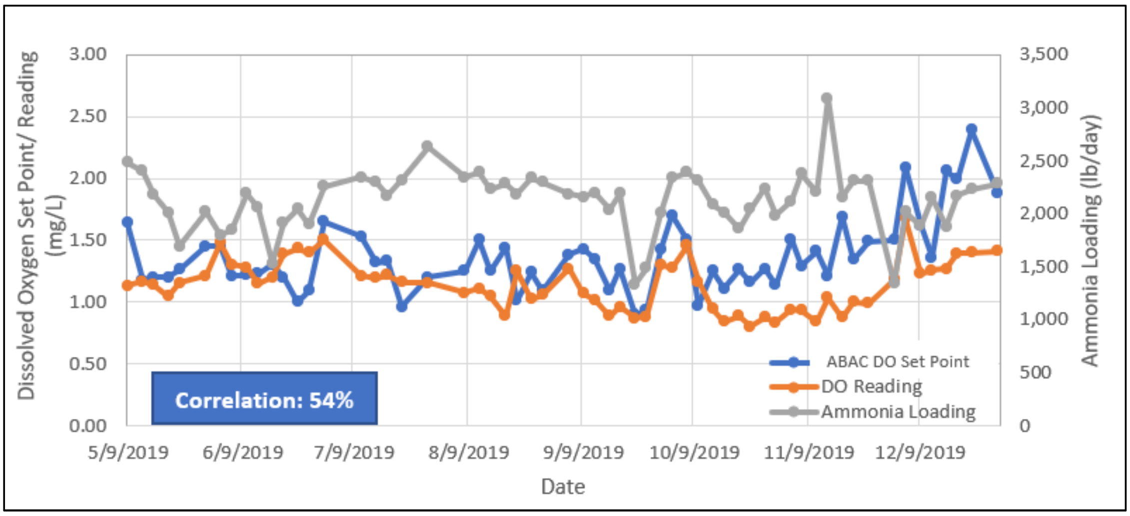

Figure A5. Average daily ammonia loading measured in pounds per day (lbs/day) as compared to ABAC dissolved oxygen (DO) set point and measured DO in aeration basins for System A. There is 54% correlation between the ABAC set DO set point and the measured value.

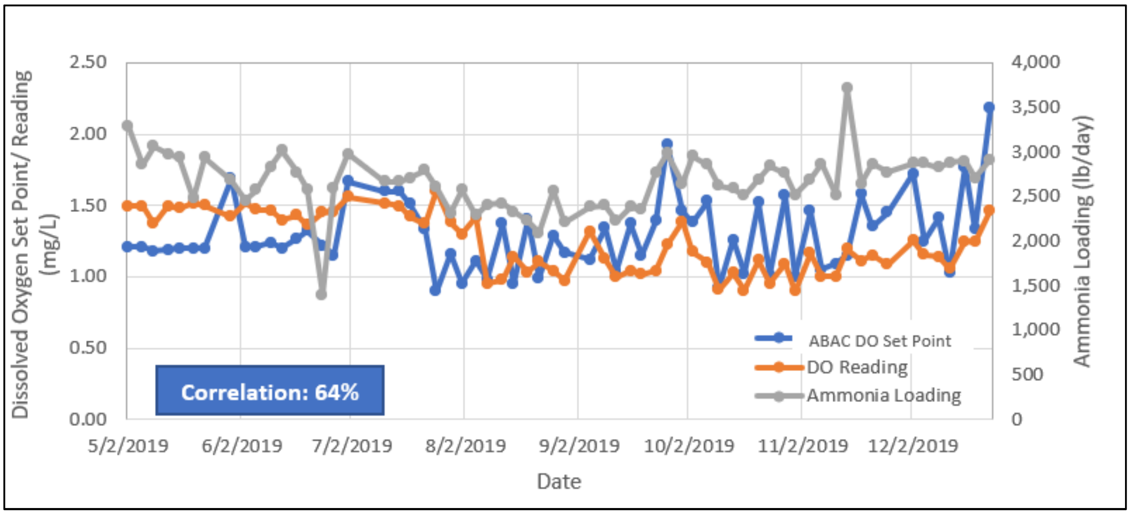

Figure A6. Average daily ammonia loading measured in pounds per day (lbs/day) as compared to ABAC DO set point and measured DO in aeration basins for System B. There is 45% correlation between the ABAC set DO point and the measured value.

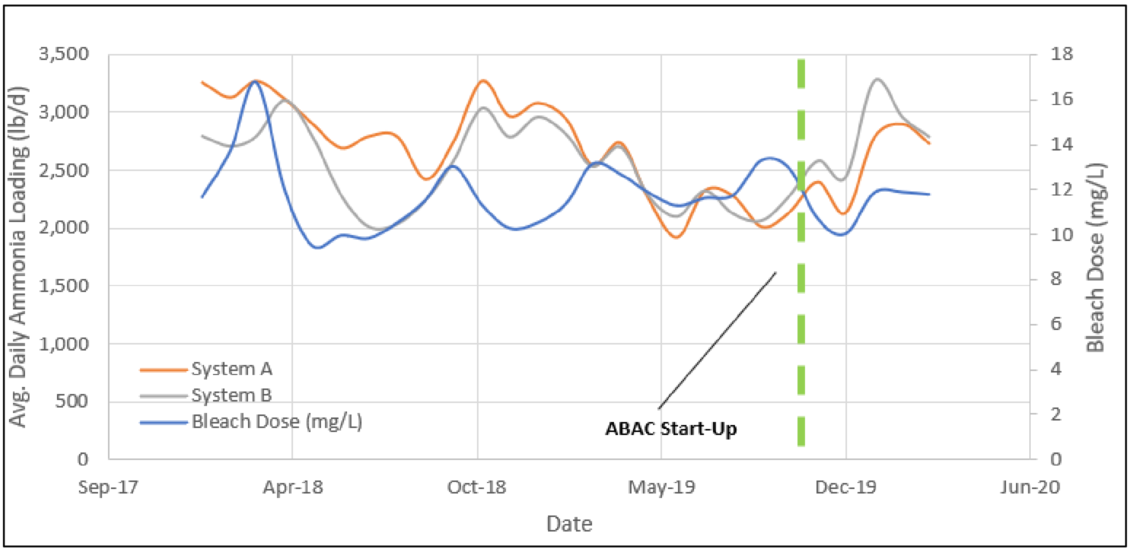

Figure A7. Average daily ammonia loading for System A and B as compared to bleach dose.

Calculation Appendix B: Correlation of ABAC DO Set Point and Measured DO
Equation (A2):

$$\text{Correlation }(X, Y) = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}} \tag{A2}$$

where X and Y are the calculated means for the data sets. In this case, X is ABAC DO Set Point (mg/L) and Y is the measured DO level (mg/L).

Table A2. Correlation calculation results.

	SYSTEM A		SYSTEM B	
Date	**Average Daily Hach DO Set Point (mg/L)**	**Average Daily IEUA DO Reading (mg/L)**	**Average Daily Hach DO Set Point (mg/L)**	**Average Daily IEUA DO Reading (mg/L)**
May 2019	1.48	1.15	1.39	1.47
June 2019	1.31	1.34	1.27	1.45
July 2019	1.30	1.29	1.40	1.50
August 2019	1.16	1.05	1.07	1.08
September 2019	1.25	1.02	1.25	1.12
October 2019	1.21	1.03	1.17	1.03
November 2019	1.41	0.97	1.29	1.09
December 2019	1.86	1.36	1.47	1.25
Average (X, Y)	1.37	1.15	1.29	1.25
Sample Size (n)	8	8	8	8
CORREL:	54%		64%	

Appendix C

Calculation Appendix C: Normalization Ratios

Ammonia Loading Normalization Ratio

Equation (A3):

$$\text{Ammonia Loading Normalization Ratio} = \frac{\text{2018 Energy Consumption (kWh)}}{\text{2018 Ammonia Loading (lb/day)}} \tag{A3}$$

Equation (A4):

$$\text{Standard Deviation (STDV)} = \sqrt{\frac{\sum (x - \overline{x})^2}{(n-1)}} \tag{A4}$$

where X is the sample value, $\overline{x}$ is the average, and n is the sample size.

Table A3. Ammonia loading normalization ratio calculation.

Date	**Daily Average Energy Consumption 2018 (kWh)**	**Daily Average Ammonia Loading 2018 (lb/day)**	**Ratio**
January	13,114.85	7369.25	1.78
February	15,983.75	7611.25	2.10
March	9331.03	7591.59	1.23
April	11,166.25	7870.27	1.42
May	16,418.89	8409.86	1.95
June	17,942.03	7197.76	2.49
July	10,272.24	7651.13	1.34
August	12,405.56	7430.12	1.67
September	15,258.06	7617.75	2.00
October	16,363.45	7697.64	2.13
November	10,346.88	8291.36	1.25
December	12,633.41	8560.39	1.48
Average Aug-Dec ($\overline{x}$)	13,401.47	7919.45	1.70 *
Sample Size (n)	4	STDV	0.40

* Ratio (kWh/(lb/day) will be multiplied by 2019 Daily Average Ammonia Loading.

Other Contamination Loading Normalization

Equation (A5):

$$\text{Contaminant Normalization Ratio} = \frac{\text{2019 Energy Consumption (kWh)}}{\text{2019 Contaminant Loading (lb/day)}} \quad \text{(A5)}$$

Table A4. TOC normalization ratio calculation.

Date	2019 Energy Consumption (kWh)	Daily Average TOC Loading 2019 (lb/day)	Ratio
January	13,529.64	N/A	N/A
February	16,186.63	42,461.94	0.38
March	16,502.88	41,135.69	0.40
April	17,802.77	41,853.19	0.43
May	11,717.01	46,702.41	0.25
June	13,888.64	40,688.80	0.34
July	19,099.25	40,841.94	0.47
August	18,454.94	38,697.31	0.48
September	18,244.68	47,214.88	0.39
October	17,201.09	42,272.47	0.41
November	13,314.42	46,036.25	0.29
December	16,360.59	46,663.56	0.35
Average Aug-Dec (X)	16,715.15	44,176.89	0.38 * +
Sample Size (n)	4	STVD	0.07

* Ratio (kWh/(lb/day) will be multiplied by 2018 Daily Average TOC Loading. + This ratio was used due to the correlation of TOC and air flow rate. TSS and BOD ratios produced similar normalized data results.

Table A5. TSS normalization ratio calculation.

Date	2019 Energy Consumption (kWh)	Daily Average TSS Loading 2019 (lb/day)	Ratio
January	13,529.64	94,205.88	0.14
February	16,186.63	89,715.26	0.18
March	16,502.88	83,236.07	0.20
April	17,802.77	85,653.56	0.21
May	11,717.01	86,827.87	0.13
June	13,888.64	88,175.73	0.16
July	19,099.25	90,807.43	0.21
August	18,454.94	88,185.80	0.21
September	18,244.68	97,164.49	0.19
October	17,201.09	85,258.11	0.20
November	13,314.42	89,794.23	0.15
December	16,360.59	91,099.20	0.18
Average Aug-Dec (X)	16,715.15	90,300.37	0.19 *
Sample Size (n)	4	STVD	0.03

* Ratio (kWh/(lb/day) will be multiplied by 2018 Daily Average TSS Loading.

Table A6. BOD normalization ratio calculation.

Date	2019 Energy Consumption (kWh)	Daily Average BOD Loading 2019 (lb/day)	Ratio
January	13,529.64	N/A	N/A
February	16,186.63	78,538.47	0.21
March	16,502.88	77,308.66	0.21
April	17,802.77	77,621.16	0.23
May	11,717.01	87,417.61	0.13
June	13,888.64	75,343.26	0.18
July	19,099.25	75,669.57	0.25
August	18,454.94	71,500.95	0.26
September	18,244.68	87,775.92	0.21
October	17,201.09	78,285.17	0.22
November	13,314.42	85,433.92	0.16
December	16,360.59	86,667.92	0.19
Average Aug-Dec (X)	16,715.15	81,932.77	0.21 *
Sample Size (n)	4	STVD	0.04

* Ratio (kWh/(lb/day) will be multiplied by 2018 Daily Average BOD Loading.

Air Transfer Ratio (ATR) Normalization Ratio

Equation (A6):

$$\text{ATR Normalization Ratio} = \frac{\text{"Low" Average ATR (CF/lb DO)}}{\text{"Increased" Average ATR 2019 (CF/lb DO)}} \tag{A6}$$

Table A7. ATR normalization ratio calculation.

Date	"Low" Average ATR (CF/lb DO)	Date	"Increased" Average ATR (CF/lb DO)
April 2018	362.86	June 2019	491.97
May 2018	438.23	July 2019	437.33
June 2018	427.91	August 2019	634.48
July 2018	368.61	September 2019	609.85
August 2018	336.74	October 2019	698.14
September 2018	289.77	November 2019	649.47
October 2018	414.89	December 2019	596.48
November 2018	427.93		
December 2018	435.56		
January 2019	427.24		
February 2019	453.61		
March 2019	343.15		
April 2019	434.04		
May 2019	530.77		
Average	406.52		588.25
Sample Size	14		7
Ratio		1.4	
STDV		0.18	

Normalized Energy Consumption Energy

Equation (A7):

$$\text{2018 Normalized Energy Consumption} = (\text{Daily Average Ammonia Loading 2019}) \times (1.7) \times (1.4) \quad \text{(A7)}$$

Table A8. Normalized 2018 energy consumption data.

Date	Daily Average Ammonia Loading 2019 (lb/day)	Normalized 2018 Energy Consumption (kWh)
January	9090.04	21,690.49
February	8765.44	20,915.92
March	7722.53	18,427.35
April	8585.05	20,485.48
May	7936.83	18,938.71
June	8356.03	19,939.01
July	7918.57	18,895.15
August	7424.37	17,715.90
September	7246.81	17,292.20
October	7273.33	17,355.49
November	7975.88	19,031.90
December	7644.84	18,241.97
AVERAGE AUG-DEC		17,927.49

Equation (A8):

$$\text{2019 Normalized Energy Consumption Data} = (\text{Daily Average TOC Loading 2018}) \times (0.38) \quad \text{(A8)}$$

Table A9. Normalized 2019 energy consumption data.

Date	Daily Average TOC Loading 2018 (lb/day)	Normalized 2019 Energy Consumption (kWh)
January	43,030.87	16,438.28
February	40,614.63	15,515.25
March	49,229.47	18,806.22
April	50,195.34	19,175.19
May	50,370.99	19,242.29
June	45,202.81	17,267.98
July	51,501.27	19,674.07
August	43,342.82	16,557.45
September	41,670.15	15,918.47
October	39,953.52	15,262.70
November	45,511.19	17,385.79
December	45,511.19	17,385.79
AVERAGE AUG-DEC		16,502.04

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