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Effects of Water Conservation and Nutrient Source Reduction on Wastewater Treatment Facility Performance

Anna Marie McKenna
University of Colorado at Boulder, anmc4456@colorado.edu

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Effects of Water Conservation and Nutrient Source Reduction on Wastewater Treatment Facility Performance

Anna Marie McKenna

B.S., University of California, Davis 2013

A thesis submitted to the
Faculty of the Graduate School of the
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This thesis entitled:
Effects of Water Conservation and Nutrient Source Reduction on Wastewater Treatment Facility Performance
written by Anna McKenna
has been approved for the Department of Civil and Environmental Engineering

JoAnn Silverstein

Sherri Cook

*Date*__________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Abstract

McKenna, Anna Marie (M.S., Civil and Environmental Engineering Department)

Effects of Water Conservation and Nutrient Source Reduction on Wastewater Treatment Facility Performance

Thesis directed by Professor JoAnn Silverstein

As fresh water supplies continue to dwindle, many communities turn to water conservation measures. Water conservation is a low cost and simple way to combat the water supply deficit. This project used BioWin process modeling to evaluate the impacts of water conservation and nutrient source reduction on wastewater treatment facility performance. Several water conservation and nutrient source recovery scenarios were modeled using BioWin models of the Boulder, Longmont, and Metro wastewater treatment facilities. The modeling results suggest that water conservation may negatively impact wastewater effluent quality and that nutrient source recovery improves wastewater effluent quality. This project focused on the nitrogen and phosphorous effluent concentrations, due to the nationwide trend of more stringent effluent nitrogen and phosphorous concentration limits.

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Introduction

Water scarcity continues to intensify with population growth and persistent drought conditions. Many communities across the United States and worldwide have turned to water conservation as a cost effective and simple answer. Water conservation can reduce water usage significantly, which saves water but it can negatively impact wastewater treatment facility (WWTF) performance. The purpose of this report is to evaluate the impacts of water conservation on WWTF performance.

Water conservation can be achieved in many ways, but this report focuses on indoor conservation, source separation, and graywater reuse. Indoor conservation is a broad category of all the measures that can be taken to reduce water use within a household, business (commercial or industrial), or municipality. Indoor conservation does not impact contaminant mass loading rates (Dezellar, 1980), but can significantly decrease water usage through simple retrofits and behavioral changes. Graywater reuse and source separation decrease influent contaminant loading and reduce wastewater flow (Wilsenach & van Loosdrecht, 2003)(Eriksson, Auffarth, Henze, & Ledin, 2002)(Nolde, 2000). Although source separation improves influent wastewater quality, there are additional social, economic, and infrastructure challenges that face wide spread source separation (Fewless, Sharvelle, & Roesner, 2011).

Water conservation impacts wastewater influent quality and quantity, which has the potential to impact WWTF performance. This project evaluates the effects of indoor conservation, source separation, and graywater reuse using BioWin process modeling. Several flow reduction percentages and adoption populations were simulated using a Boulder WWTF calibrated BioWin model. Indoor conservation scenarios were also modeled using Longmont and Metro WWTF models.

Effluent nitrogen and phosphorous concentrations with conservation were evaluated in this report. In Colorado, Regulation 85 dictates that WWTFs cannot discharge more than 15 mg TIN/L as N and 1 mg TP/L as P. These stringent regulations make even slight effluent concentration changes important. With indoor conservation, effluent TIN and TP concentrations have the potential to increase which is concerning and should be considered while WWTFs are redesigned for nutrient removal in the years to come (Dezellar, 1980). Source separation can significantly decrease the effluent TIN and TP concentrations, which suggests that if the barriers to adoption can be overcome, it is a viable solution for nutrient removal.

As freshwater supplies decrease, innovative technologies and conservation strategies must be employed to save water. The objective of this project was to determine if water conservation significantly impacts nutrient removal at WWTFs. The modeling results indicate that although saving water is important, WWTFs should design their facilities with conservation impacts in mind. Conservation and drought conditions can adversely impact existing pipeline and pump station infrastructure as well, but that is not within the scope of this research effort. Developing plant process designs that account for conservation impacts now could help WWTFs avoid costly retrofits and permit violations in the future. Another question that arises from this project is whether or not WWTF permits should be based on concentration of mass loading permits.

Model Calibration

The Boulder WWTF model was calibrated to 2014 WWTF process data. The data set included process data for 2010-2015, but using the most recent full year of data that did not include extreme storm events was the most accurate basis for calibration. During 2013 and 2015, there were extreme rain events and the 2010-2012 data sets did not include chemical oxygen demand (COD) data, which rendered the data sets less valuable for calibration. The Boulder WWTF also provided the BioWin model of the WWTF that was calibrated to 2014 process data. The Metro and Longmont models used were calibrated prior to this study. Refer to Appendix 1 for the BioWin schematic.

Data Determination

Using the process data provided, the inputs for the BioWin COD influent were determined. Refer to Appendix 2 for the links to the influent and effluent data Tables. Both average and median values were used as the inputs, depending on the skew of the data. If the data appeared to be skewed in the box plot, then the median was used. Once all of the influent parameters were determined, the Boulder WWTF was contacted and confirmed that the influent inputs aligned with the typical influent wastewater quality at the Boulder WWTF. The effluent parameters were determined using the same methods, refer to Appendix 2 for data Tables and boxplots. The estimated COD influent inputs and effluent quality are displayed in

Table 1. The COD influents are based on average and median values. Median values were used if the box plots indicated that the data were skewed.

Table 1: Observed COD Influent Inputs. Determined from 2014 process data and model calibration process.

Influent	
Flow	14.82
TCOD (mgCOD/L)	430
TKN (mgN/L)	33.92
TP (mgP/L)	4.5
Nirate N (mg/L)	0.5
pH	7.6
Alkalinity (mmol/L)	4.76
ISS (mgISS/L)	12
Calcium (mg/L)	192
Magnesium (mg/L)	30
DO (mg/L)	0
WW Fractions	
Fbs - Readily biodegradable (including Acetate) [gCOD/g of total COD]	0.14
Fac - Acetate [gCOD/g of readily biodegradable COD]	0.15
Fxsp - Non-colloidal slowly biodegradable [gCOD/g of slowly degradable COD]	0.73
Fus - Unbiodegradable soluble [gCOD/g of total COD]	0.05
Fup - Unbiodegradable particulate [gCOD/g of total COD]	0.13
Fna - Ammonia [gNH3-N/gTKN]	0.6
Fnox - Particulate organic nitrogen [gN/g Organic N]	0.5
Fnus - Soluble unbiodegradable TKN [gN/gTKN]	0.02
FupN - N:COD ratio for unbiodegradable part. COD [gN/gCOD]	0.035
Fpo4 - Phosphate [gPO4-P/gTP]	0.47
FupP - P:COD ratio for unbiodegradable part. COD [gP/gCOD]	0.011
FZbh - OHO COD fraction [gCOD/g of total COD]	0.02
FZbm - Methylotroph COD fraction [gCOD/g of total COD]	1.00E-04
FZaob - AOB COD fraction [gCOD/g of total COD]	1.00E-04
FZnob - NOB COD fraction [gCOD/g of total COD]	1.00E-04
FZamob - ANAMMOX COD fraction [gCOD/g of total COD]	1.00E-04
FZbp - PAO COD fraction [gCOD/g of total COD]	1.00E-04
FZbpa - Propionic acetogens COD fraction [gCOD/g of total COD]	1.00E-04
FZbam - Acetoclastic methanogens COD fraction [gCOD/g of total COD]	1.00E-04
FZbhm - H2-utilizing methanogens COD fraction [gCOD/g of total COD]	1.00E-04
FZe - Endogenous products COD fraction [gCOD/g of total COD]	0
Settling Parameters	
Percent Removal	99.84
Kinetic Parameters	
AOB Max. spec. growth rate (1/d)	0.7
NOB Max. spec. growth rate (1/d)	0.5
PAO Max. spec. growth rate (1/d)	0.95

Table 2: Observed effluent wastewater quality using the Boulder 2014 process data and observed BioWin effluent wastewater quality for the calibrated model.

Effluent	Observed (Boulder 2014 Process Data)	Standard Deviation (Boulder 2014 Process Data)	Minimum (Boulder 2014 Process Data)	Maximum (Boulder 2014 Process Data)	Observed (Calibrated Model)	Percent Difference*
Ammonia N (mgN/L)	0.09	0.07	0.02	2.9	0.09	0.0%
Nitrate N (mgN/L)	13.92	3.06	6.6	20.1	12.72	8.6%
Nitrite N (mg/L)	0.03	0.07	0	0.33	0.03	0.0%
Filtered TKN (mgN/L)	1.76	0.3	1.2	2.9	1.93	9.7%
TIN (mgN/L)	#N/A	#N/A	#N/A	#N/A	12.83	#N/A
TN (mgN/L)	15.77	3.18	8.78	22.6	15.19	3.7%
TP (mgP/L)	2.66	0.53	0.67	3.54	3.07	15.4%
TSS (mgTSS/L)	6.54	2.94	2	21	6.69	2.3%
TCOD (mgCOD/L)	#N/A	#N/A	#N/A	#N/A	31.25	#N/A
TCBOD (mg/L)	3.3	1.21	1	8	3.1	6.1%
pH**	7.28	0.11	6.82	7.56	6.74	7.4%

*The percent difference was calculated as the absolute value of (observed (calibrated model) - observed (Boulder 2014 process data))/observed (Boulder 2014 process data)

**The observed (Boulder 2014 Process Data) pH is much higher than the calibrated model, because the pH at the Boulder WWTP is raised after treatment due to a mixing zone that it enters prior to discharge into the Boulder Creek that is not included in the model. Boulder WWTF officials confirmed that the pH of the treated wastewater effluent from the secondary clarifier should be near pH 6.74.

The parameters in Table 1 were determined using the 2014 process data and through model simulation iterations. Refer to Appendix 3 for the model simulations. The best-fit model was determined as the model that resulted in effluent water quality that was within 15% of the estimated effluent water quality that appears in Table 2. All effluent parameters were within 15% of the estimated effluent except for total phosphorous (TP), were the modeled effluent TP 15.41% greater than the observed average effluent wastewater quality.

Sensitivity

The biodegradable COD fraction, ammonia oxidizing bacteria (AOB) maximum specific growth rate, and nitrite oxidizing bacteria (NOB) maximum specific growth rate were adjusted to calibrate the model. These values are typically kept as the BioWin default values, but the default values yield values that were close enough to the observed effluent wastewater quality. The model is very sensitive to decreasing the AOB and NOB maximum specific growth rates below 0.6/day and 0.375/day, respectively (Figures 1, 2, 3).

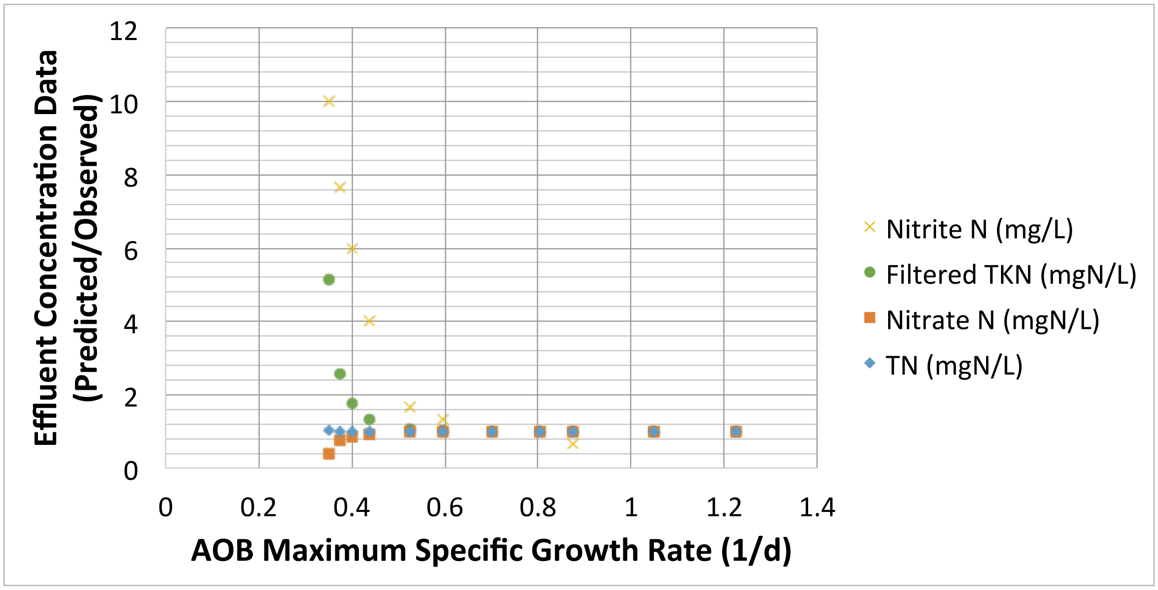

Figure 1: Nitrate, nitrite, TKN, and TN sensitivity to AOB maximum specific growth rate changes.

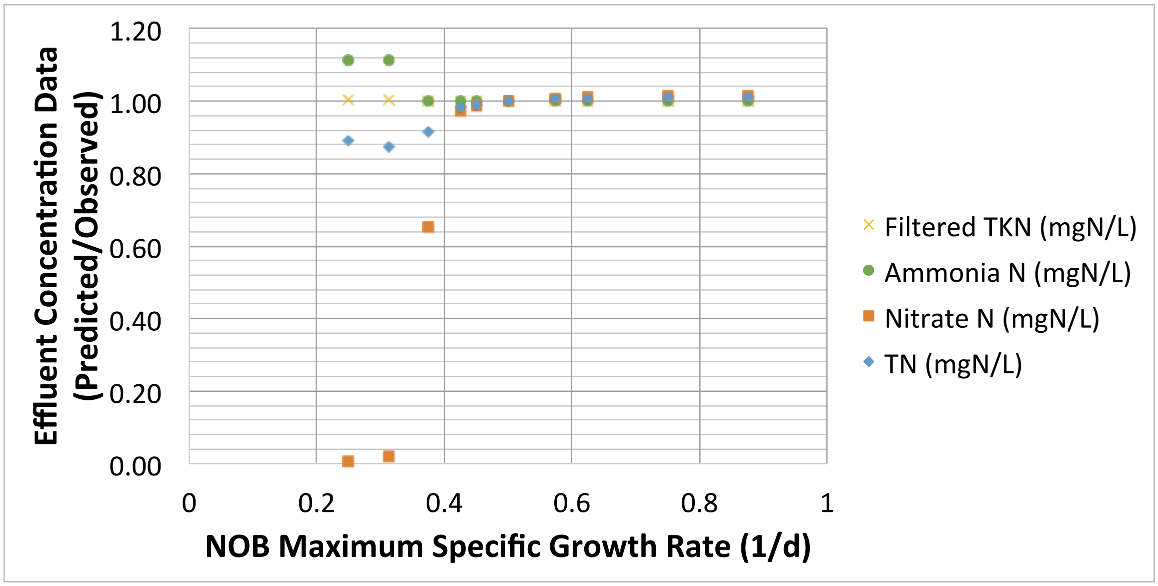

Figure 2: Nitrate, nitrite, TKN, and TN sensitivity to NOB maximum specific growth rate changes.

Nitrite concentrations are very sensitive to NOB maximum specific growth rates less than 0.425/day (Figure 3).

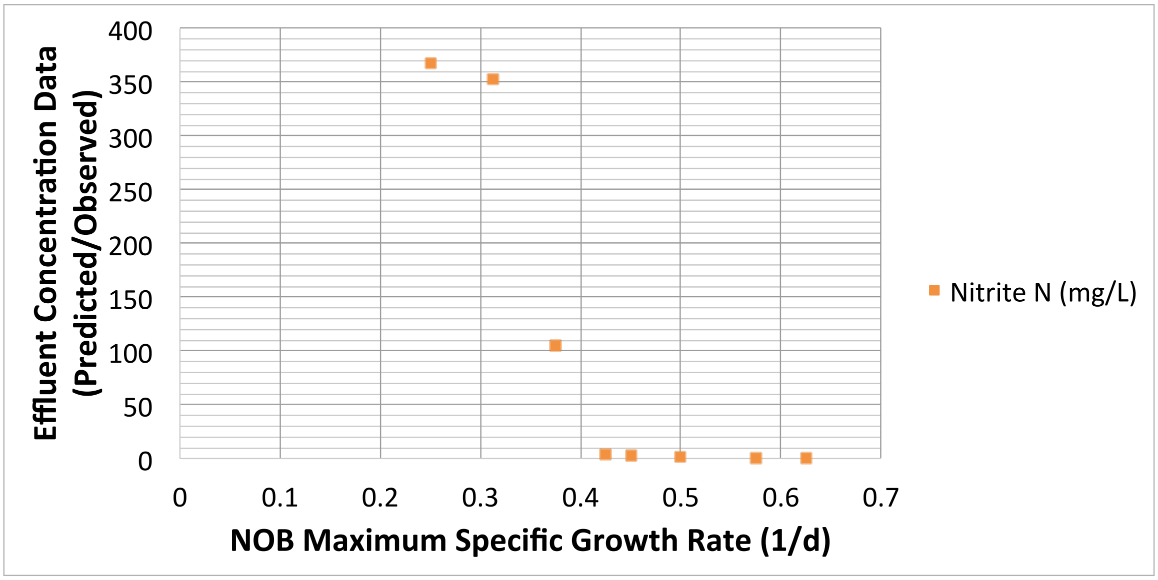

Figure 3: Nitrite sensitivity to NOB maximum specific growth rate.

The sensitivity analysis shows that the NOB and AOB growth rates did not decrease enough to deviate far from the results expected with the default BioWin values. Decreasing the AOB and NOB maximum specific growth rates to 0.7/day and 0.5/day, respectively, generated better fitting model results for effluent ammonia and nitrite concentrations. The default AOB and NOB maximum specific growth rates overestimate ammonia and nitrite removal.

The biodegradable COD fraction was decreased from the BioWin default and yielded a model that fit the observed effluent water quality better than the effluent water quality with the BioWin default biodegradable COD fraction. Nitrate and TN concentrations are more sensitive to changes in the biodegradable COD fraction than other effluent parameters (Figure 4). The default biodegradable COD fraction overestimates denitrification.

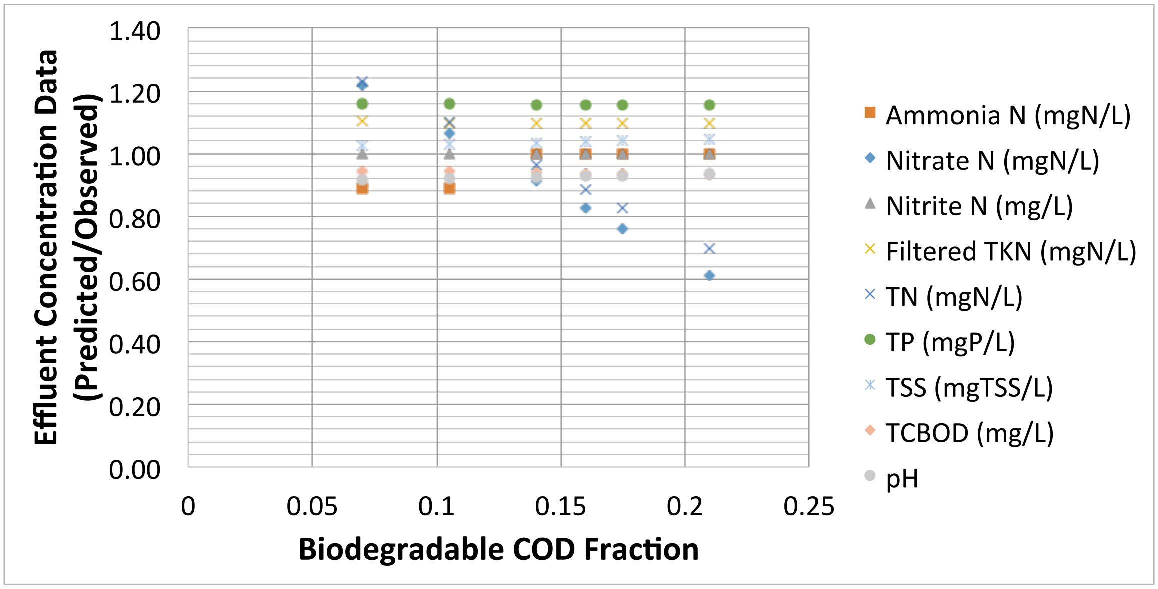

Figure 4: Effluent wastewater quality sensitivity to the biodegradable COD fraction

Refer to Tables 1 and 2 and Appendices 1 and 2 for process data and model calibration ranges.

Methods

Using a calibrated BioWin model of the Boulder Wastewater Treatment Facility (WWTF), several conservation scenarios were evaluated. The model was calibrated using 2014 Boulder WWTF data and the input data can be found in Table 3 below. The conservation scenarios were divided into four major conservation types: indoor conservation (IC), source separation (SS), graywater reuse for toilet flushing (GWT), and graywater reuse for irrigation (GWI).

Table 3: Boulder Base Case Influent Water Quality

Influent	Base Case
Flow	14.82
BOD (mg BOD/L)	217
TCOD (mgCOD/L)	430
TKN (mgN/L)	33.92
TP (mgP/L)	4.5
TSS (mgTSS/L)	176.2
ISS (mgISS/L)	11.98
Nirate N (mg/L)	0.5
pH	7.39
Alkalinity (mmol/L)	4.76
Calcium (mg/L)	192
Magnesium (mg/L)	30
DO (mg/L)	0

Indoor Conservation (IC)

Indoor conservation was evaluated by analyzing the impact of influent flow reductions, assuming no influent BOD, TKN, TP, and TSS load changes. Although the loads remained constant, the concentrations increased with flow reductions. Influent nitrate concentration, pH, alkalinity, calcium concentration, magnesium concentration, and dissolved oxygen concentration were assumed constant for all scenarios. Flow reductions of 15-54% from the base case influent flow were evaluated. Fifteen IC scenarios were analyzed and influent water quality percent changes are shown in Figure 5 below. For each scenario, contaminant concentrations were calculated by multiplying the base case concentration by the ratio of the base case flow to the scenario flow. The COD was calculated by multiplying the biological oxygen demand (BOD) by a COD/BOD ratio of 1.94 mg COD/mg BOD. The COD/BOD ratio was calculated from the Boulder 2014 process data.

Example:
Scenario 1 Flow = 12.54 MGD
Baseline Flow = 14.82 MGD
Baseline BOD = 217 mg BOD/L

Scenario 1 BOD = 217 mg BOD/L * (12.54 MGD/14.82 MGD)
Scenario 1 BOD = 256.5 mg BOD/L

Scenario 1 COD = 1.94 mg COD/mg BOD*256.5 mg BOD/L
Scenario 1 COD = 498 mg COD/L

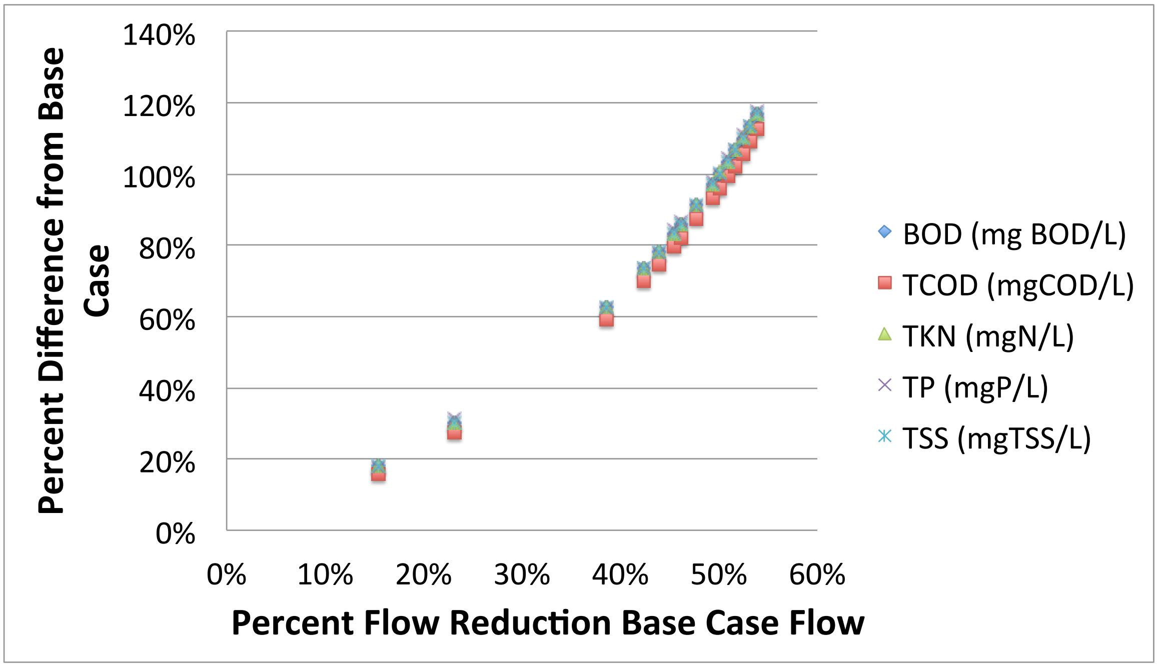

Figure 5: IC influent BOD, TCOD, TKN, TP, and TSS concentration percent change with flow reduction

Source Separation (SS)

Source Separation (SS) was evaluated assuming population adopting of 5,000, 15,000, 30,000, 75,000, and 114,195 people (4%, 13%, 26%, 66%, and 100% of the people in the city of Boulder, respectively), and calculating the resulting flow and influent water quality changes. Flow reductions were determined by multiplying the adoption populaiton by 10 gallons/capita/day (Wilsenach & van Loosdrecht, 2003) and subtracting that value from the base case influent flow. Influent water quality changes were determined by calculating the estimated nitrogen and phosphorous load reductions. Assuming that urine contains 11 gN/person/day and 1 gP/person/day ((Fewless et al., 2011), (Wilsenach & van Loosdrecht, 2003)) the TKN and TP concentrations were determined as shown in equations 1 and 2 For the SS scenarios, BOD and TSS loads were assumed constant for all scenarios and the concentrations were calculated using a flow rate ratio as done for the IC scenarios. The COD was determined using the same method described for the IC scenarios.

Equation 1: $L_{SS} = L_{BC} - [(G_{SS}*P)/453.592]$

L_{SS}: Influent TP or TKN load for SS scenario (lbpd)
L_{BC}: Base case TP of TKN load (lbpd)
G_{SS}: 11 g N/capita/day or 1 g P/capita/day
P: adoption populaiton (people)

Equation 2: $C_{SS}=(L_{SS}*453592)/(Q_{BC}-Q_{SS})$

C_{SS}: Scenario Influent TKN or TP conentration (mg/L)
Q_{BC}: Base case flow (L/day)
Q_{SS}: Flow reduction due to SS (L/d) (assumed 36.25 L/capita/day flow reduction (Wilsenach & van Loosdrecht, 2003))

Five SS scenarios were evaluated and the influent water quality percent changes graphed against the percent flow reductions from the base case are shown in Figure 6.

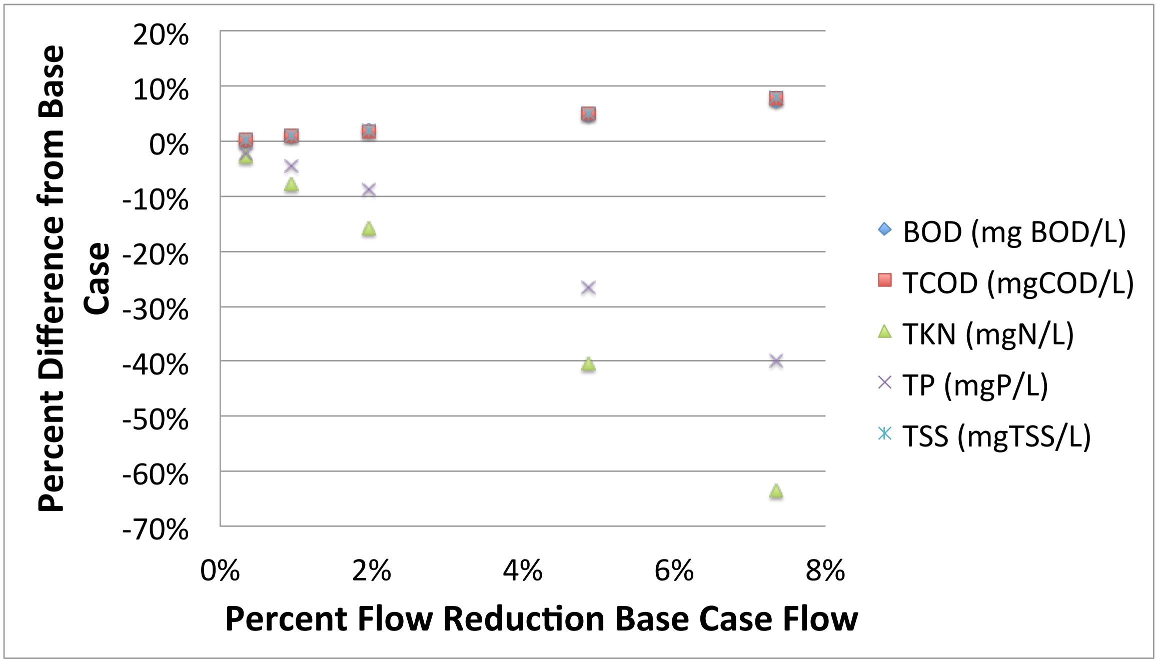

Figure 6: SS influent BOD, TCOD, TKN, TP, and TSS concentration percent change

with flow reduction

Graywater (GW) Reuse with Irrigation (GWI) and Toilets (GWT)

Both graywater scenarios, GWI and GWT, were evaluated assuming adoption populations of 5,000, 15,000, 30,000, 75,000, and 114,195 people (4%, 13%, 26%, 66%, and 100% of the Boulder population, respectively), and calculating the resulting flow and influent water quality changes. Flow reductions were determined by multiplying the adoption populaiton by 12 gallons/capita/day and 25 gallons/capita/day (Eriksson et al., 2002), for GWT and GWI respectively, and subtracting that value from the base case influent flow. Graywater scenario influent water quality parameters were determined using the graywater quality stated in Table 4.

Table 4: Graywater Water Quality (Eriksson et al., 2002)

	BOD	TSS	TKN	TP
Graywater (mg/L)	100	100	10	2.5

Influent BOD, TSS, TKN, and TP for each scenario were determined as indicated in equation 3. The COD was determined using the same method described for the IC scenarios.

Equation 3: $C = [(C_{BC} * Q_{BC}) - (C_{GW} * Q_{GW})]/(Q_{BC} - Q_{GW})$

C: BOD, TSS, TKN, or TP influent concentration (mg/L)
C_{BC}: Base case BOD, TSS, TKN, or TP influent concentration (mg/L) (Table 1)
Q_{BC}: Base case influent flow (L/d) (Table 1)
C_{GW}: BOD, TSS, TKN, or TP concentration of graywater (mg/L) (Table 2)
Q_{GW}: Graywater reused (L/d)

Five GWI and GWT scenarios were evaluated and the influent water quality percent changes with percent flow reduction from the base case are displayed in Figures 7 and 8 on the following page.

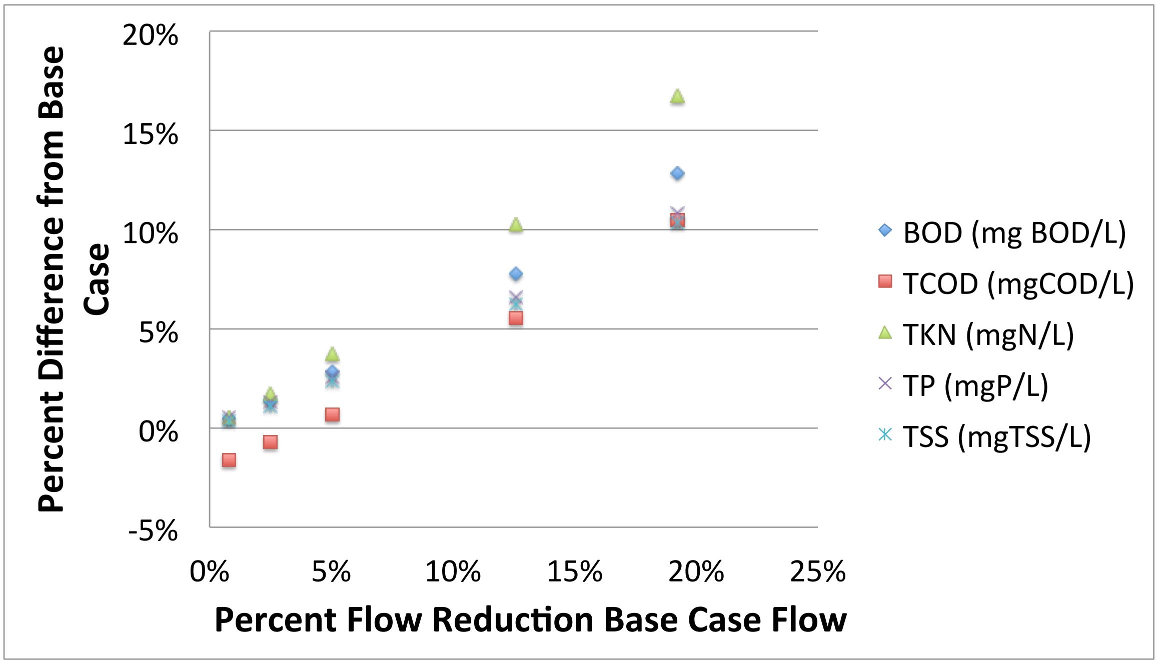

Figure 7: GWI influent BOD, TCOD, TKN, TP, and TSS concentration percent change with flow reduction

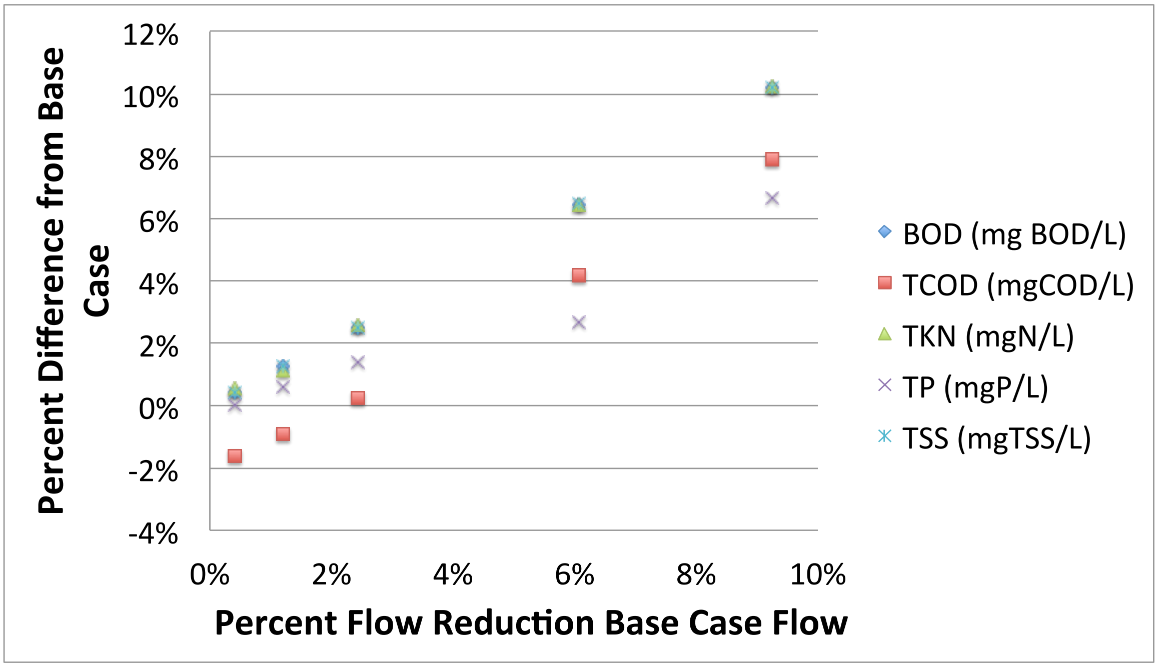

Figure 8: GWT influent BOD, TCOD, TKN, TP, and TSS concentration percent change with flow reduction

These influent wastewater flow and quality values were then used as new input values for the calibrated BioWin models. The influent flow and quality values changed, but the aeration scheme, SRT, flow pacing, and operational features of the models remained constant for each scenario.

Results

Indoor Conservation (IC)

The modeling results indicate that contaminant concentrations increase with decreased flow rates. Of particular interest are the TIN and TP effluent concentrations. TIN and TP are strictly regulated by Colorado Regulation 85, 15 mg N/L (TIN) and 1 mg P/L (TP), and even slight concentration increases can render a WWTF out of permit compliance.

Nitrogen Species

Effluent ammonia concentrations steadily increased with flow reduction, using the Boulder, Metro, and Longmont models, until the flow was reduced by 48% and 42%, respectively (Figure 9). Reducing the flow by more than 48% (Boulder, Metro) and 42% (Longmont) resulted in a higher rate of concentration increase. Ammonia concentrations increased from 0.09 mg N/L (base case) to 1.5 mg N/L (54% flow reduction), 0.13 mg N/L (base case) to 3.09 mg N/L (54% flow reduction), and 0.22 mg N/L (base case) to 6.05 mg N/L (54% flow reduction), using the Boulder, Metro, and Longmont WWTF models, respectively.

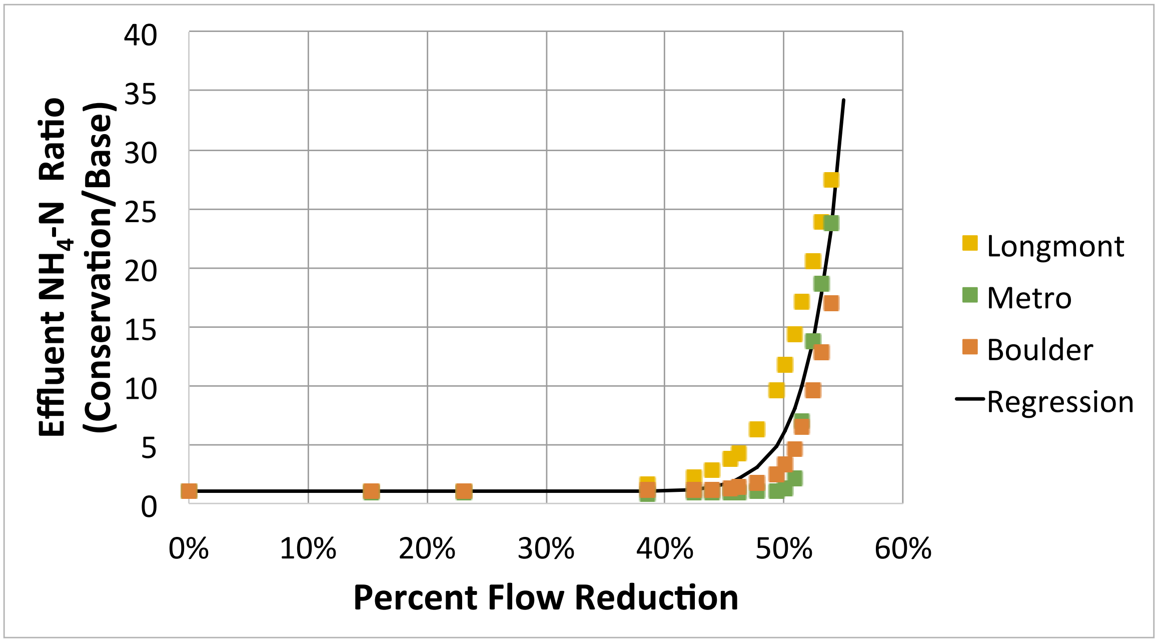

Figure 9: Effects of flow reduction resulting from IC on effluent ammonia concentrations using the Boulder, Metro, and Longmont models.

The concentration increases indicate that ammonia is not oxidized at the same rate as the base case and that nitrification is inhibited. The Boulder, Metro, and

Longmont WWTF models followed a similar trend and fit the regression line in Figure 9. The Boulder and Metro effluent ammonia concentrations are less sensitive to flow reduction than the Longmont model, especially with less than 48% flow reduction (Figure 9).

Nonlinear regression analysis was preformed using R version 3.2.1 and the regression relation with the best fit can be found on the next page (equation 4).

Equation 4: $Y=(18364)*x^{16.529}*(654.30^{x})+1.0069$

Y: ratio modeled ammonia effluent

X: fractional reduction in flow

The Longmont, Metro, and Boulder AOB concentrations vary with flow reduction (Figure 10). The Longmont AOB concentrations decreased by 1-14%, which is significant but does not account for the extreme effluent ammonia concentrations, up to 2700% increases, observed with flow reduction. Nitrification is more sensitive to flow reduction using the Longmont model. The Boulder and Metro AOB concentrations did not change significantly with flow reduction, with maximum percent differences of 2% and 3%, respectively, indicating that the AOB concentration is not a significant factor in the effluent ammonia concentrations observed with flow reduction (Figure 9).

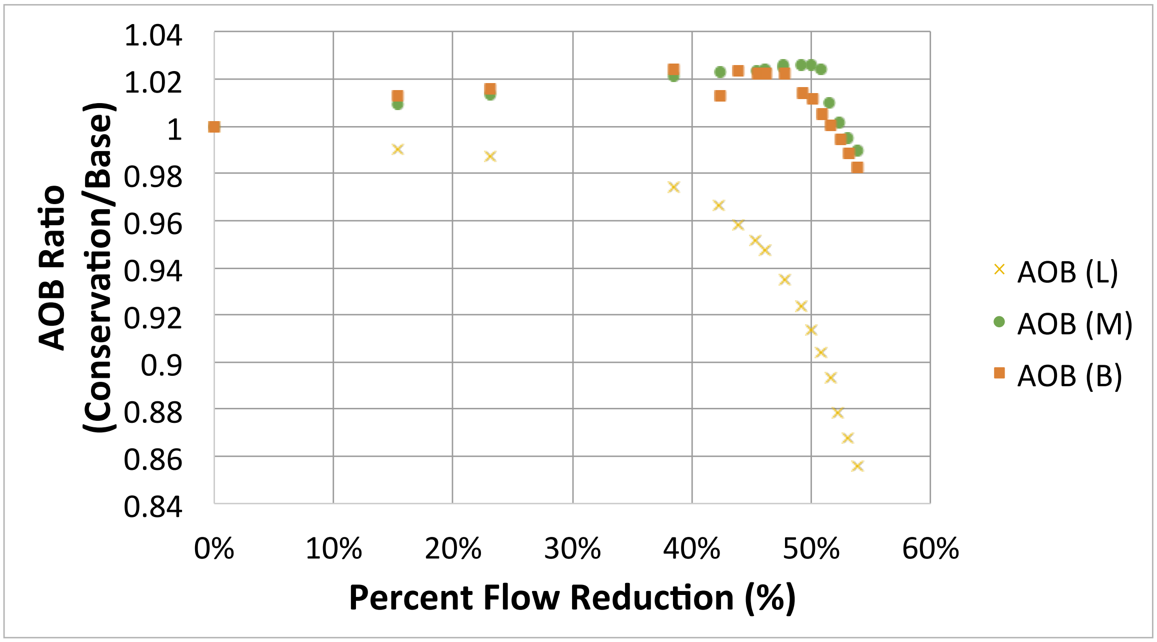

Figure 10: The effects of indoor conservation on AOB concentrations for the Boulder, Metro, and Longmont model

Effluent nitrate, nitrite, and TIN concentrations vary with flow reduction. The effluent TIN and nitrate concentrations are approximately the same until the flow is reduced by more than 50%, 48%, and 39% for the Boulder, Metro, and Longmont WWTF models, respectively (Figures 11,12, and 13).

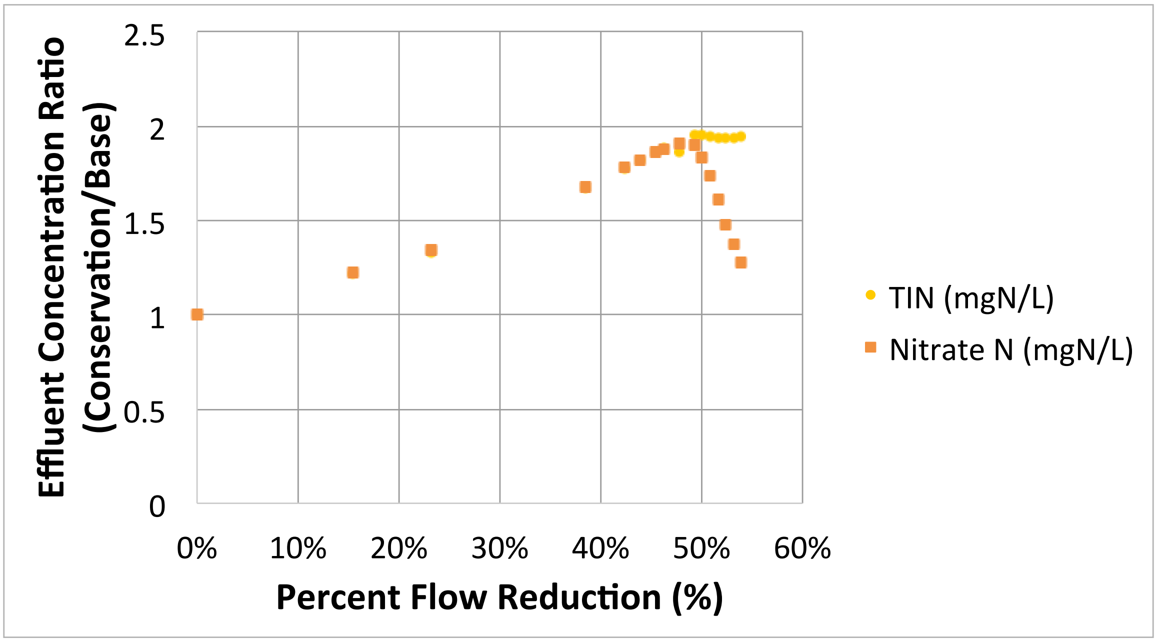

Figure 11: Effects of indoor conservation on nitrate and TIN concentrations using the Boulder WWTF Model

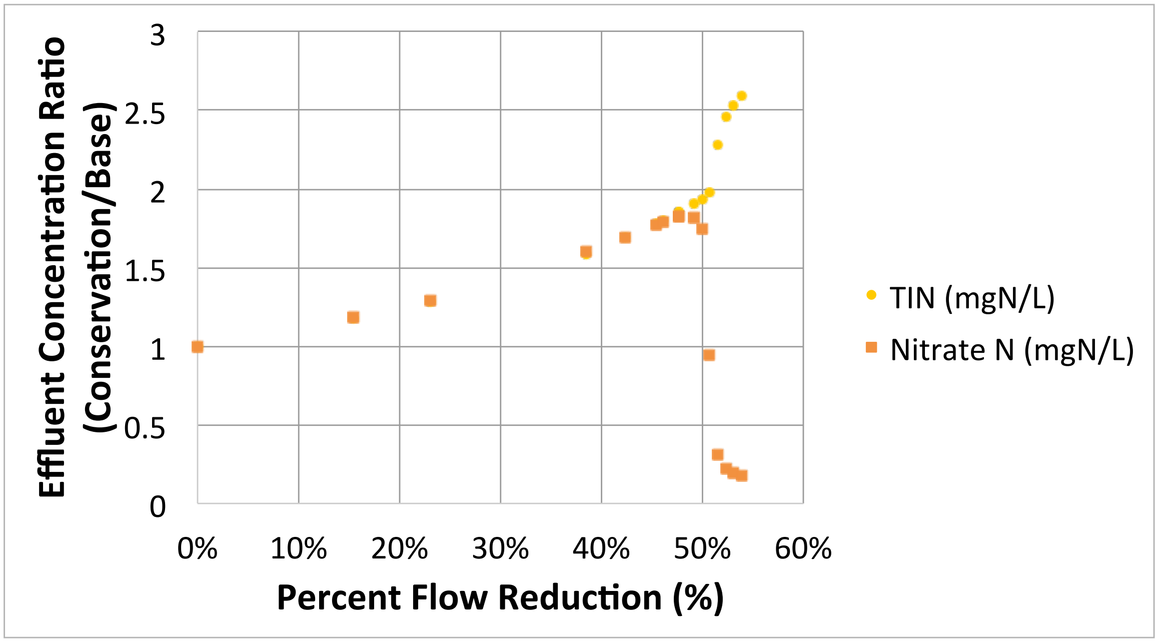

Figure 12: Effects of indoor conservation on nitrate and TIN concentrations using the Metro WWTF model

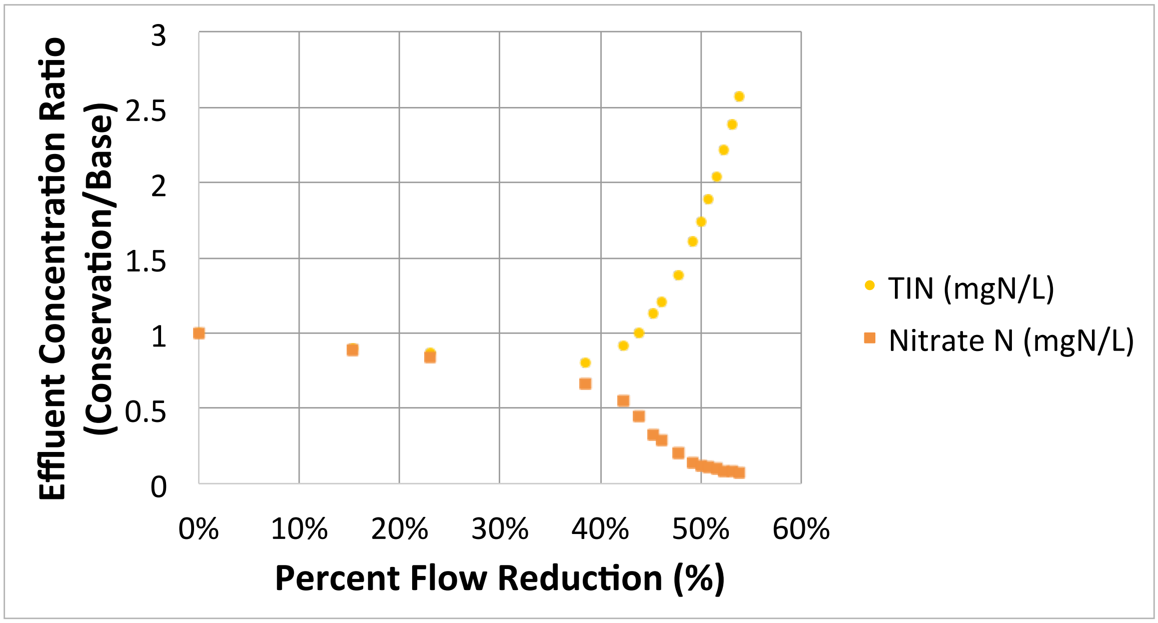

Figure 13: Effects of indoor conservation on nitrate and TIN concentrations using the Longmont WWTF model

Using the Boulder and Metro WWTF models, the effluent TIN concentrations increased with any flow reduction (Figure 6). Using the Longmont model, the effluent TIN concentration decreased with flow reductions less than 44% and increased with flow reductions greater than 44% (Figure 14). If the flow is reduced by less that 44% at the Longmont WWTF, then denitrification improves and the TIN concentration decreases despite increasing ammonia and nitrite concentrations. Improved denitrification is most likely attribuTable to the longer hydraulic residence time in the anoxic zone with reduced flow. With greater than 44% flow reduction, Longmont continued to denitrify but nitrification was inhibited and the ammonia and nitrite concentrations increased rapidly. The Longmont model used was optimized for nutrient removal, so the trend difference is understandable.

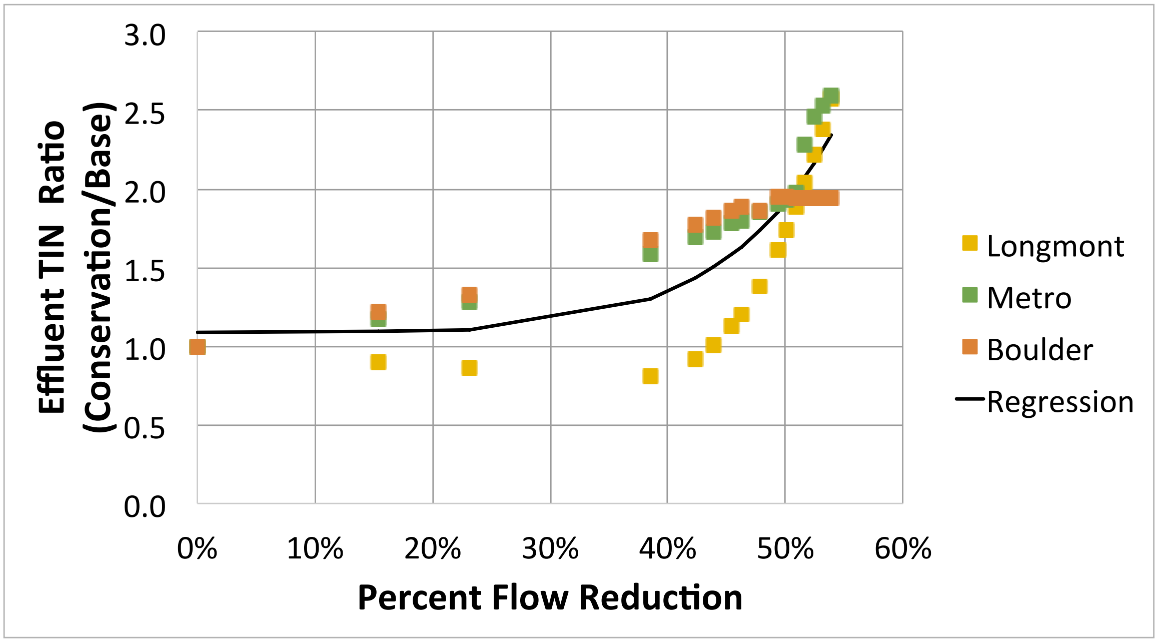

Figure 14: Effects of indoor conservation on effluent TIN concentrations using the Boulder, Metro, and Longmont models

Nonlinear regression analysis was preformed using R version 3.2.1 and the regression relation with the best fit is stated below (equation 5).

Equation 5: $Y=(2.1004)*x^{3.7908}*(29.822^{x})+1.0883$

Y: ratio modeled TIN effluent

X: fractional reduction in flow

If the flow rate is reduced by more than 50%, 48%, and 39% at the Boulder, Metro, and Longmont WWTFs, respectively, then nitrate concentrations decrease and nitrite concentrations increase by 500-24000% (Figure 15,16). The rapid increase in nitrite concentrations indicates that nitrification is inhibited with extreme flow reduction and less ammonia and nitrite are being oxidized to nitrate. Since there is less nitrate entering the anoxic zones, denitrification is less effective and an overall increase in TIN is observed.

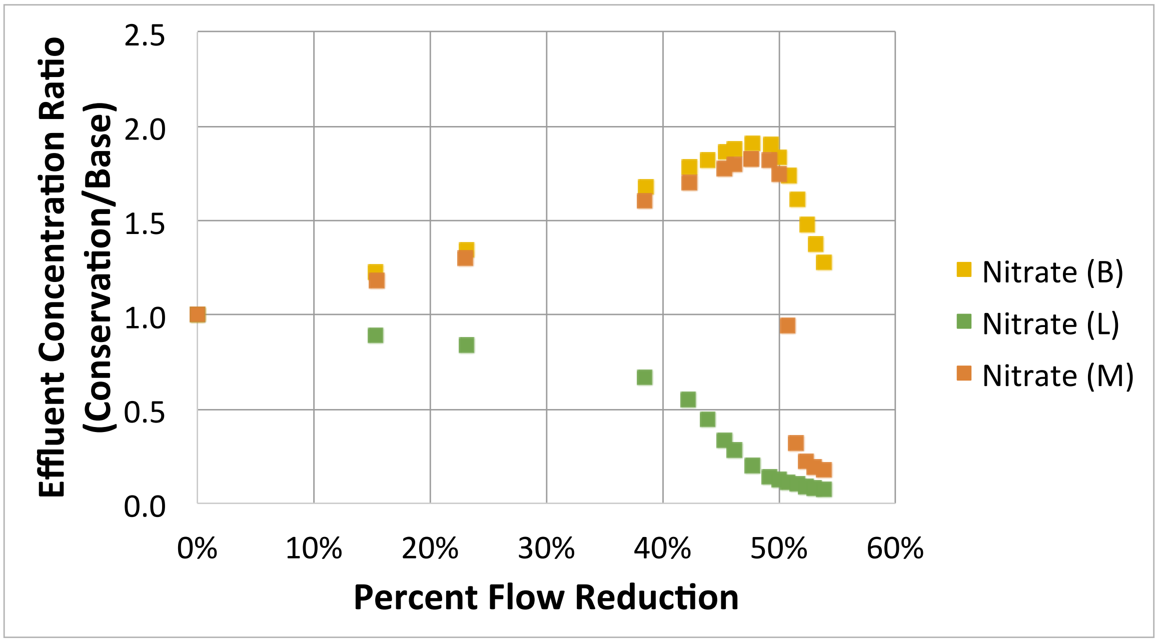

Figure 15: Effects of indoor conservation on effluent nitrate concentrations using the Boulder, Metro, and Longmont WWTF models

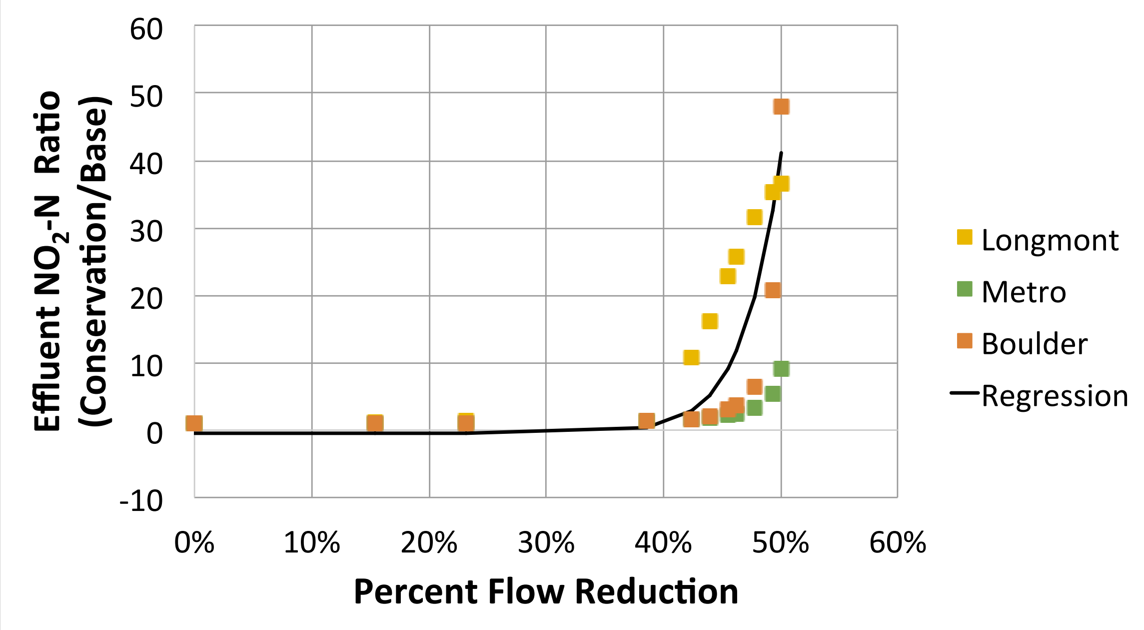

Figure 16: Effects of indoor conservation on effluent nitrite concentrations using the Boulder, Metro, and Longmont models. Regression line determined using R version 3.2.1. Refer to equation 3 for the regression relation.

Nonlinear regression analysis was preformed using R version 3.2.1 and the regression relation with the best fit is stated below (equation 6).

Equation 6: $Y=(2565.2)*x^{11.569}*(2332.8^{x})-0.51356$

Y: ratio modeled effluent

X: fractional reduction in flow

Nitrite oxidizing bacteria (NOB) concentrations could explain the nitrite and nitrate concentrations observed with the Boulder, Longmont, and Metro models. If the NOB concentration decreases, then the nitrite concentration increases and the nitrate concentration decreases. NOB concentration decreases coupled with flow reduction suggest that there are fewer NOBs available to oxidize nitrite into nitrate in the aerobic zone. The Boulder and Metro WWTF NOB concentrations were stable until the flow was reduced by more than 50% (Figure 17). The Longmont NOB concentration decreased significantly with more than 23% flow reduction and then the concentration stabilized with more than 50% flow reduction (Figure 17). The NOB concentrations follow the same trends as those observed for effluent nitrate concentrations (Figure 15), indicating that increasing the NOB population could mitigate conservation impacts on nitrite concentrations.

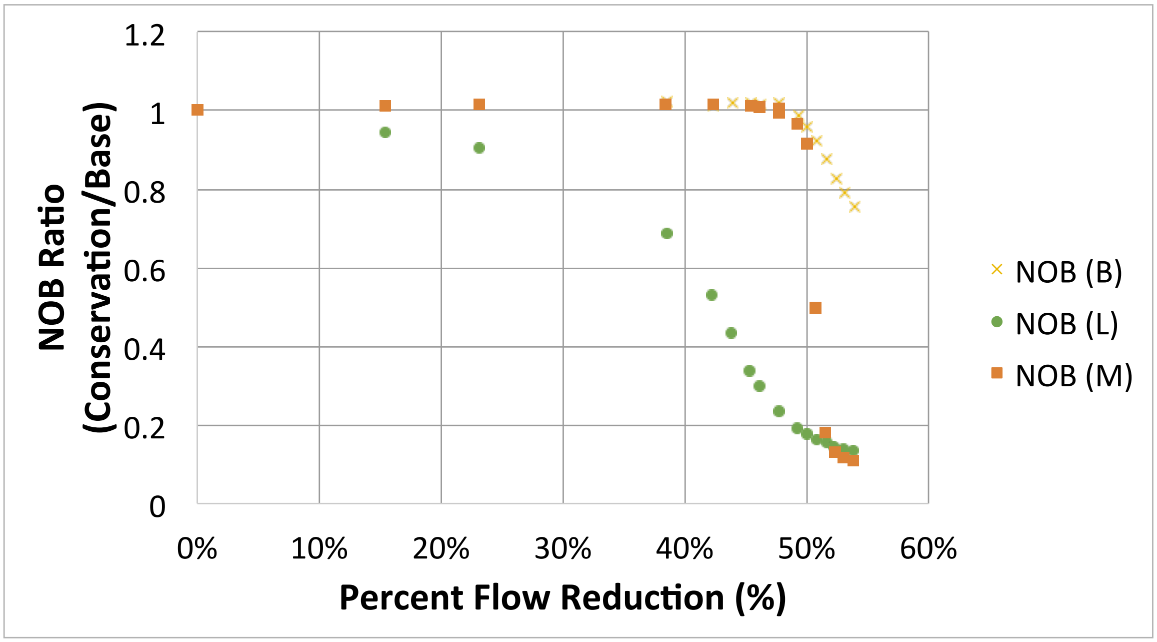

Figure 17: Effects of indoor conservation on the NOB concentration for the Boulder, Metro, and Longmont models.

Phosphorous Impacts

Total phosphorous increased with flow reduction using the Boulder model and decreased using the Longmont and Metro models (Figure 18). The Boulder WWTF does not currently employ phosphorous removal technologies, so increasing the influent concentration simply increased the effluent concentration. With current operations, Boulder reduces the influent TP concentration by 40%. The Metro and Longmont WWTF models indicate that the effluent TP concentrations are 70% and 97% lower than the influent concentrations, respectively. The Longmont model was optimized for phosphorous removal, using a 5-stage Bardenpho process, which is why such a high TP reduction is observed. If a WWTF employs phosphorous removal technologies, then extreme flow reduction may improve phosphorous removal. The enhanced phosphorous removal is most likely due to longer hydraulic residence times during biological treatment.

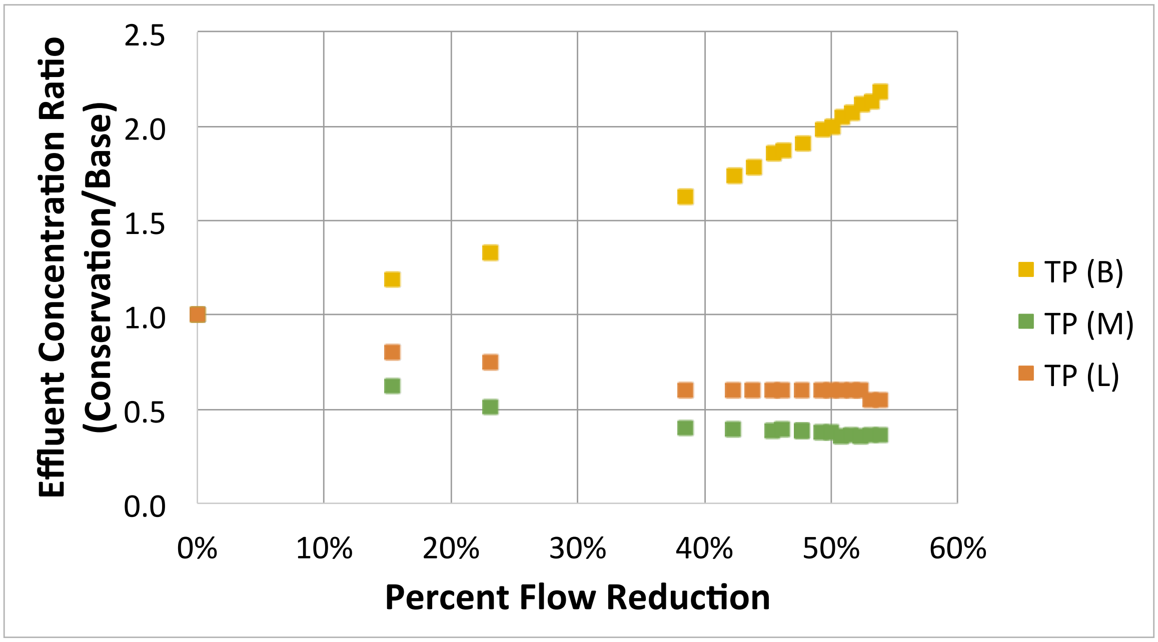

Figure 18: Effect of indoor conservation on TP concentrations using the Boulder, Metro, and Longmont models.

pH Impacts

The pH decreased with increased flow reduction using the Boulder, Metro, and Longmont models (Figure 19). Many of the processes in wastewater treatment are pH dependent and wastewater must be discharged at a neutral pH. The pH significantly impacts the organisms involved in nitrification and denitrification, indicating that alkalinity addition could remedy the contaminant concerns described in the previous sections. Regardless of treatment impacts, WWTFs must consider the cost of alkalinity addition with high levels of conservation or drought scenarios because wastewater must be discharged at a neutral pH (typically 6.0-9.0).

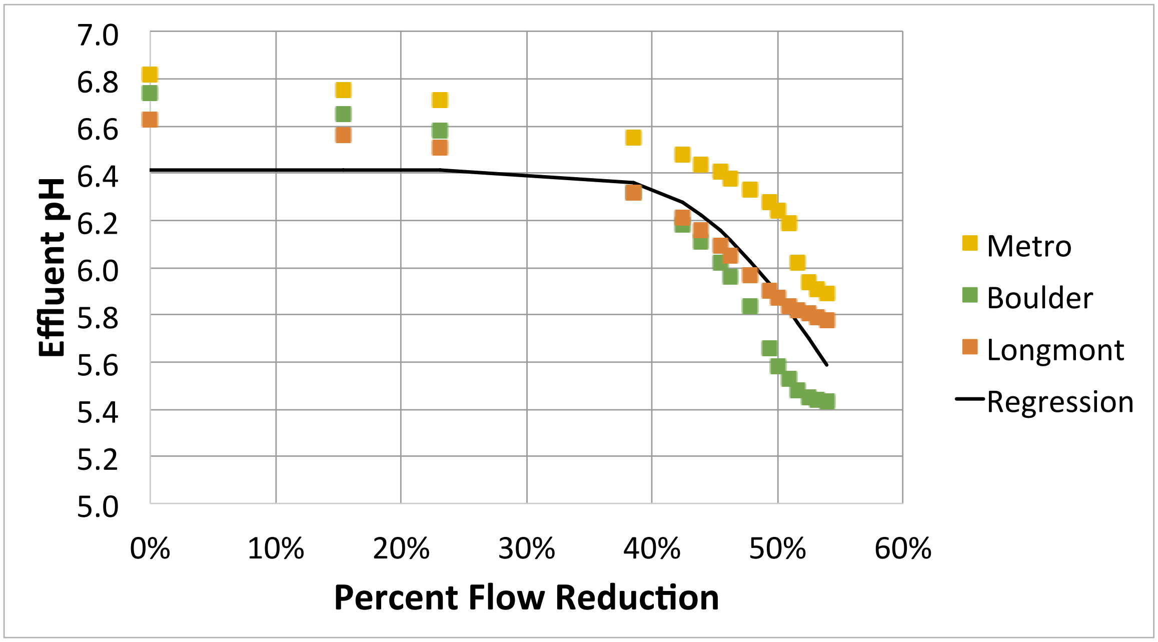

Figure 19: Effect of indoor conservation on pH using the Boulder, Metro, and Longmont models

Nonlinear regression analysis was preformed using R version 3.2.1 and the regression relation with the best fit is stated below (equation 7).

Equation 7: $Y=-\log((0.00108)*x^{10.984}*(2.9779^{x})+(3.8*(10^{-7})))$

Y: pH

X: fractional reduction in flow

Oxygen Uptake Rate (OUR) Impacts

The total OUR is not significantly impacted by flow reduction. The nitrogenous and carbonaceous OURs do not change significantly using the Boulder model. The nitrogenous OUR decreased using the Boulder model with more than 46% flow reduction, but the maximum percent difference was 5% with 54% flow reduction (Figure 20).

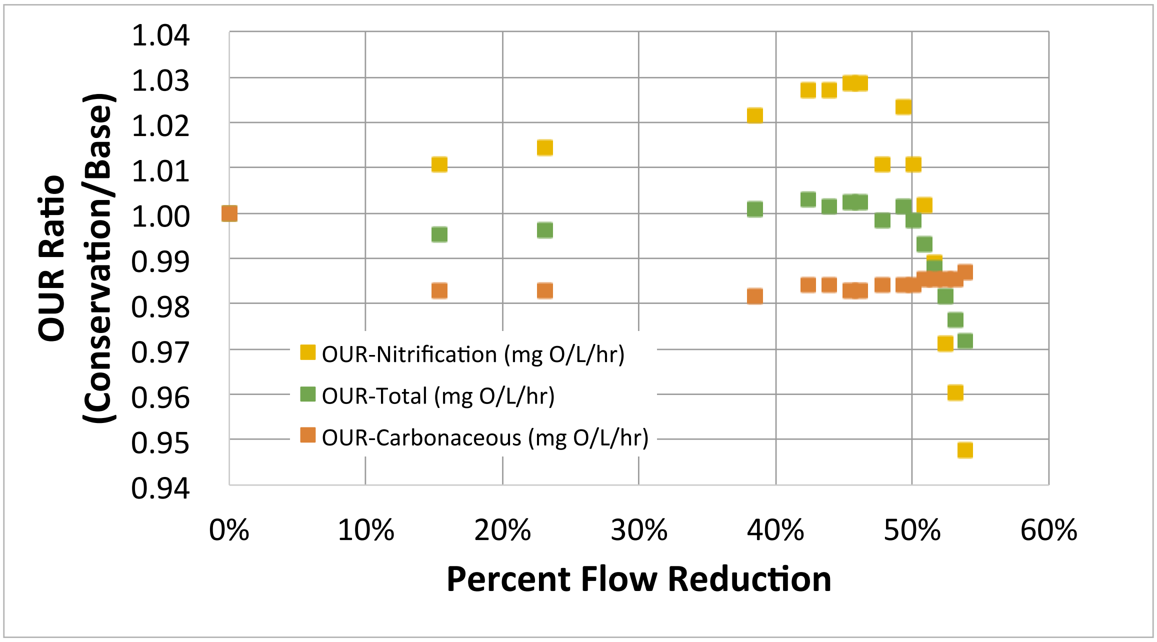

Figure 20: Effect of indoor conservation on the total, carbonaceous, and nitrogenous OURs using the Boulder model

The nitrogenous OUR decreases, because nitrification is inhibited and the nitrifying organisms are not oxidizing ammonia and nitrite at the same rate as the scenarios with less than 46% flow reduction. Overall, the percent differences are not significant and the total OUR changes by a maximum of 3% with 54% flow reduction.

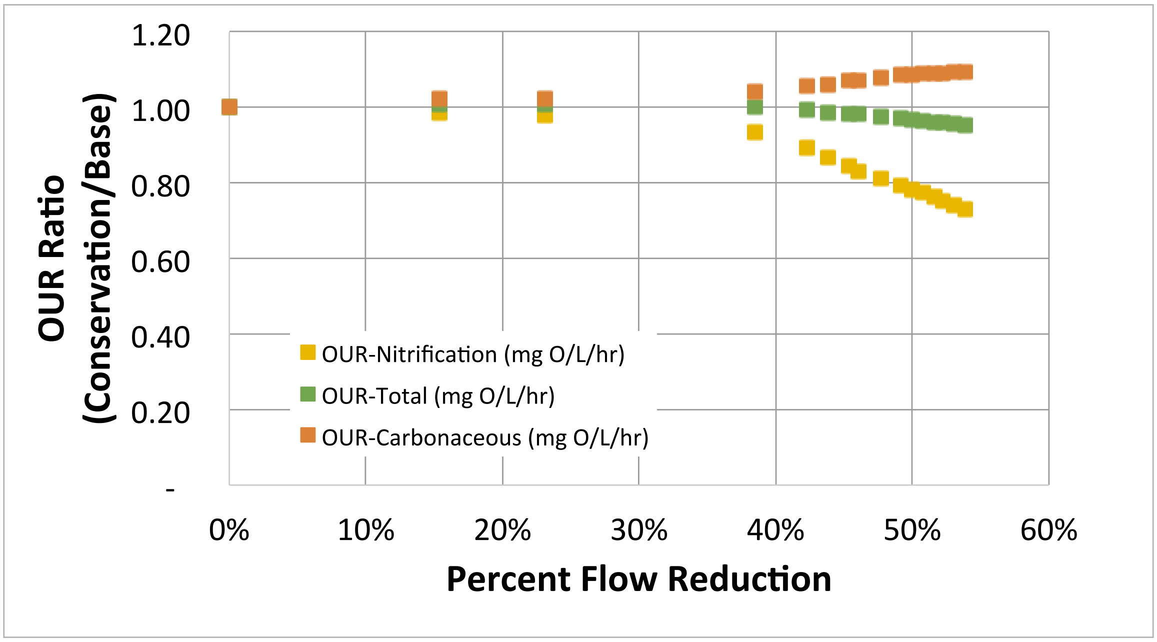

Figure 21: Effect of indoor conservation on the total, carbonaceous, and nitrogenous OURs using the Longmont model

The nitrogenous OUR decreased significantly using the Longmont model (Figure 21) and the carbonaceous OUR increased. Although the nitrogenous OUR demand decreased significantly, the increased carbonaceous OUR offset the nitrogenous OUR demand decrease. The total OUR decreased by a maximum of 5% with 54% flow reduction, indicating that flow reduction does not significantly impact the total OUR. From these results it is clear that the total OUR does not change significantly with flow reduction.

Mitigation Strategies

In the case of extreme conservation or drought, WWTFs will need to implement process changes to avoid the effluent contaminant concentration increases observed using the Boulder, Metro, and Longmont models. Based on the trends observed above, increasing the SRT, alkalinity addition, and acetic acid addition were evaluated as possible mitigation strategies using the Boulder WWTF model.

SRT

Using the Boulder WWTF model, SRTs of 6-15 days were modeled with 42%, 48%, and 54% flow reduction. Increasing the SRT had minimal impacts on ammonia, nitrate, and TIN concentrations with the 42% flow reduction scenario (Figures 22, 23, 24). Reducing the SRT resulted in poorer performance and the data are not shown.

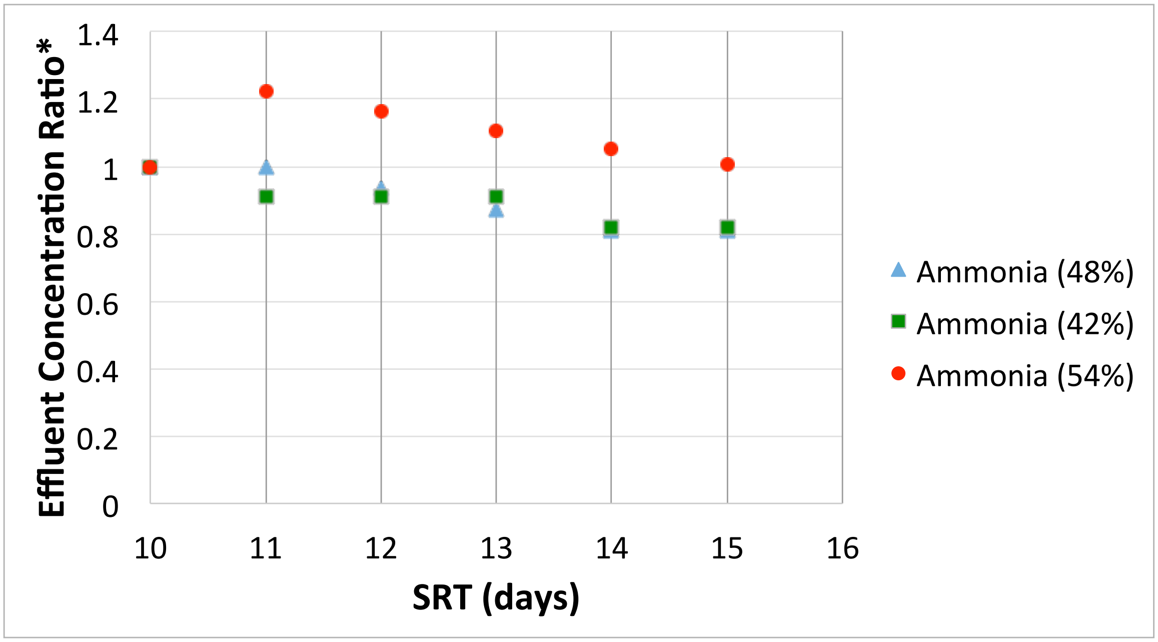

Figure 22: Effect of SRT on Ammonia concentrations using the Boulder Model at 42%, 48%, and 54% flow reduction.

*The effluent concentration ratio is the conservation scenario (42%, 48%, or 54%) with SRT = 10-15 days normalized to the conservation scenario with SRT=10 days.

Increasing the SRT significantly decreased nitrite concentrations and increased NOB concentrations for the 42%, 48%, and 54% flow reduction scenarios (Figure 23, 24). Decreasing the nitrite concentration resulted in greater effluent nitrate and TIN concentrations (Figure 23). Increasing the SRT enhances nitrification, but does not significantly impact denitrification.

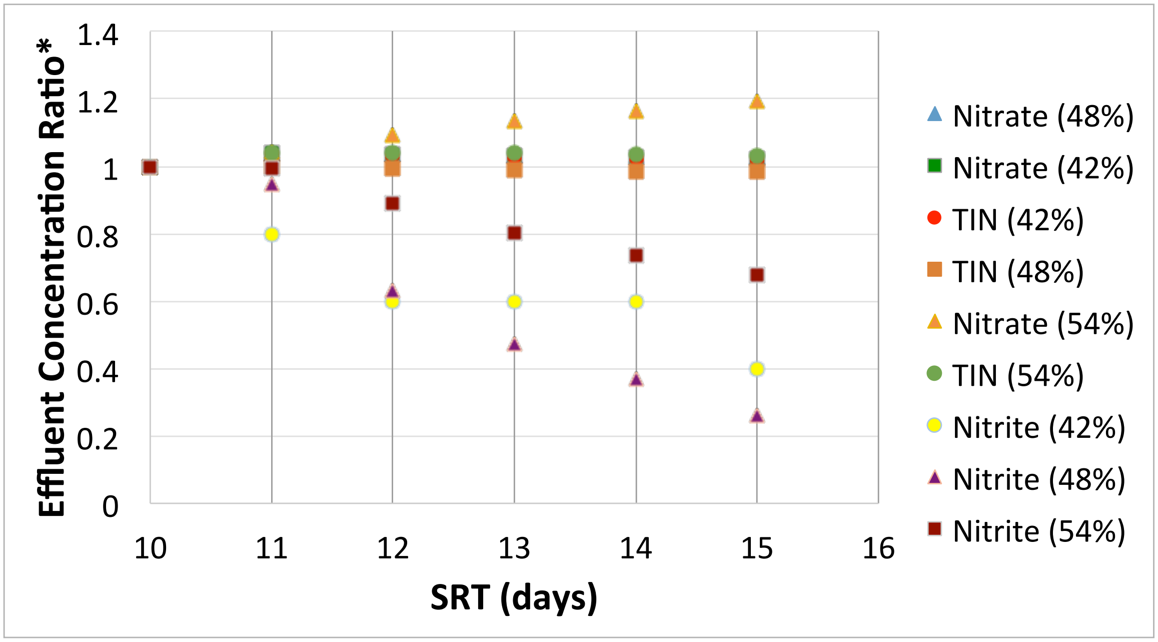

Figure 23: Effect of SRT on nitrite concentrations using the Boulder Model at 42%, 48%, and 54% flow reduction. The nitrite (54%) is on the secondary axis on the left. *The effluent concentration ratio is the conservation scenario (42%, 48%, or 54%) with SRT = 10-15 days normalized to the conservation scenario with SRT=10 days.

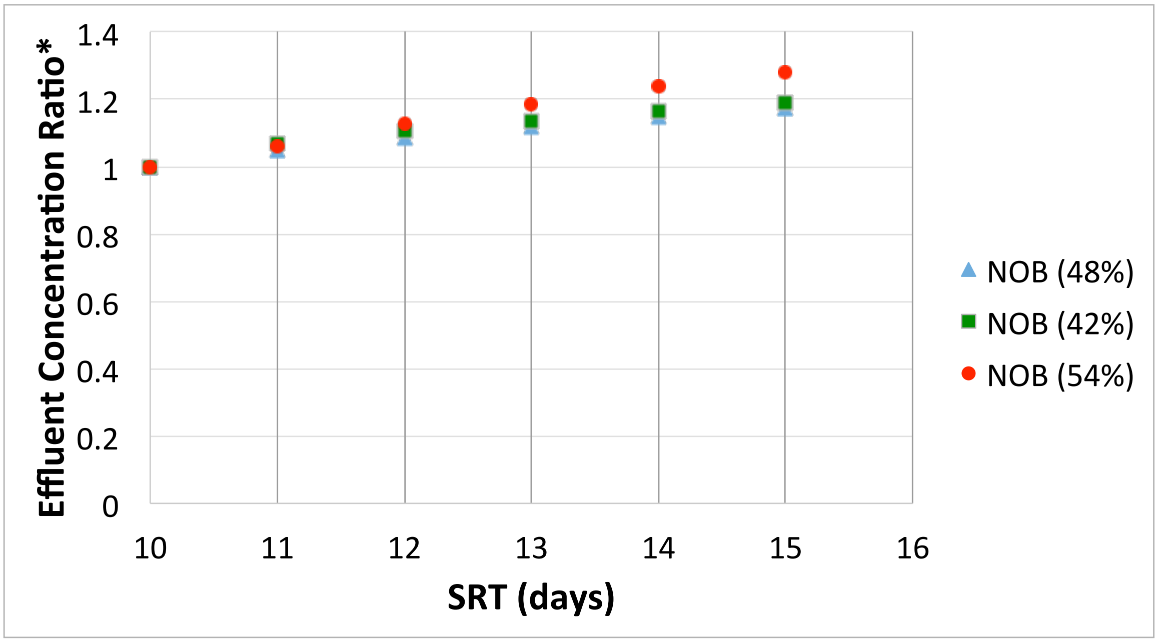

Figure 24: Effect of SRT on NOB concentrations using the Boulder Model at 42%, 48%, and 54% flow reduction.
*The effluent concentration ratio is the conservation scenario (42%, 48%, or 54%) with SRT = 10-15 days normalized to the conservation scenario with SRT=10 days.

Alkalinity Addition

The pH decreased significantly with flow reduction. Alkalinity addition stabilizes the pH and could improve plant performance. Fifty to 2000 gpd of three molar sodium bicarbonate were added to the 48% and 54% flow reduction scenarios of the Boulder model to evaluate alkalinity addition. The pH stabilized with alkalinity addition (Figure 25), but the effluent TIN and nitrate concentrations increased (Figure 26).

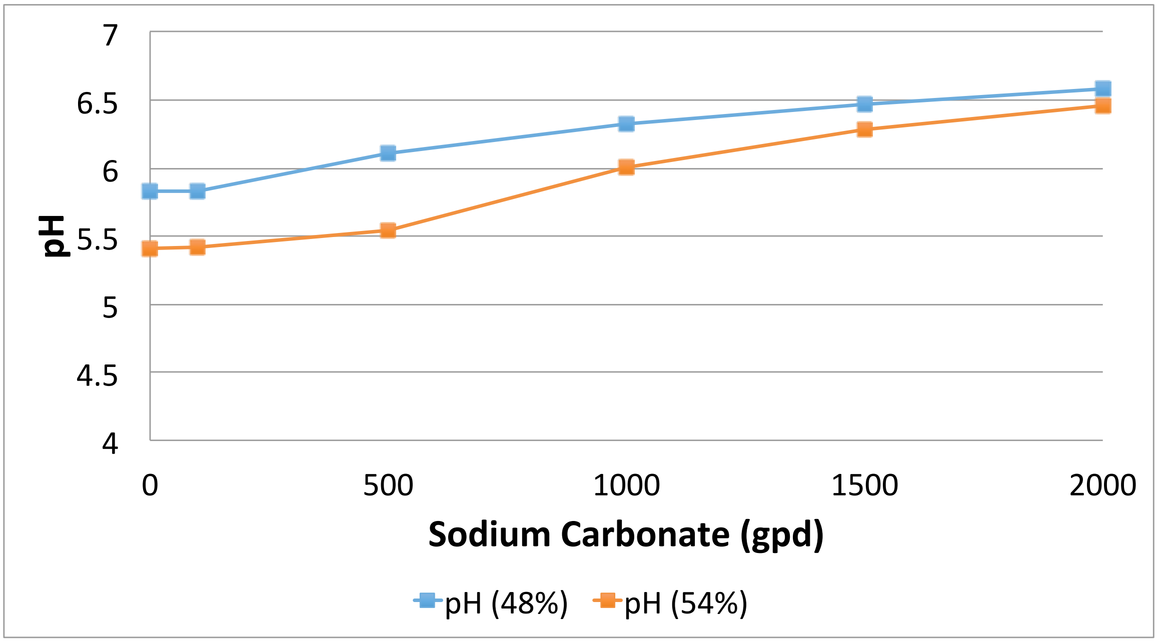

Figure 25: Effect of alkalinity addition on pH using the Boulder model.

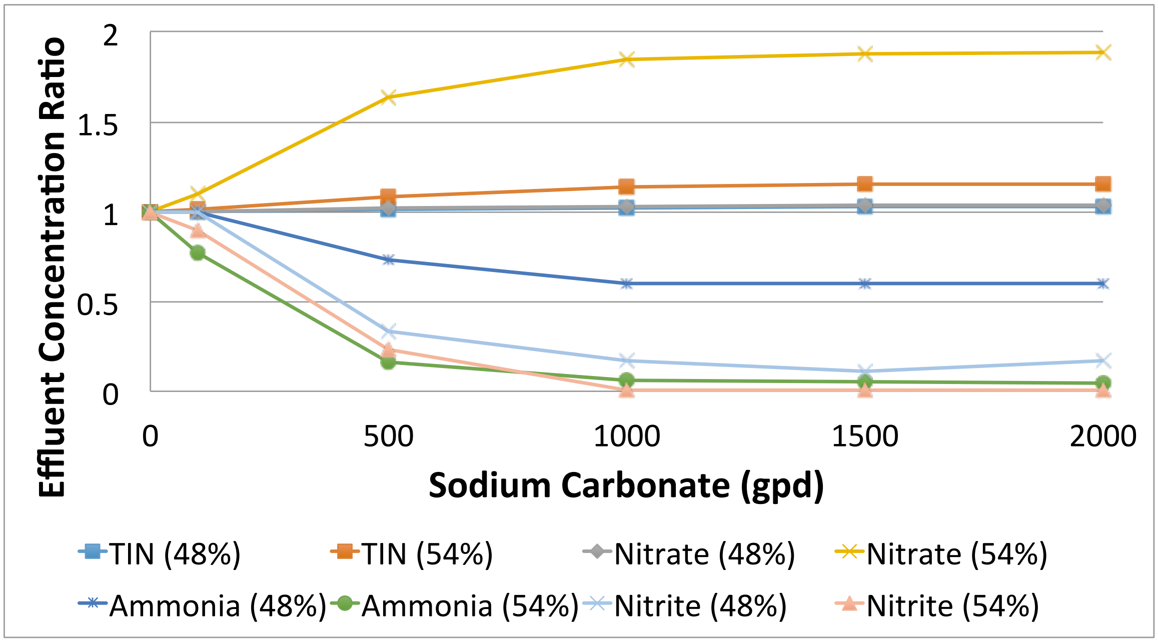

Figure 26: Effect of alkalinity addition on 48% and 54% flow reduction scenario TIN, nitrate, nitrite, and ammonia concentrations.

Ammonia and nitrite concentrations decrease significantly, indicating that alkalinity addition enhances nitrification but does not enhance denitrification (Figure 26).

Acetic Acid Addition

Increasing the SRT and adding alkalinity enhanced nitrification, but failed to enhance denitrification. Adding acetic acid prior to the anoxic zone could enhance denitrificaiton and improve plant performance. The Boulder WWTF is carbon limited, and acetic acid should have a significant impact. Acetic acid addition was modeled using the Boulder model with 15%, 23%, 39%, 42%, and 54% flow reduction scenarios. Acetic acid, 0-1000 gpd, was added until the effluent TIN concentration was below 15 mg N/L (Figure 27).

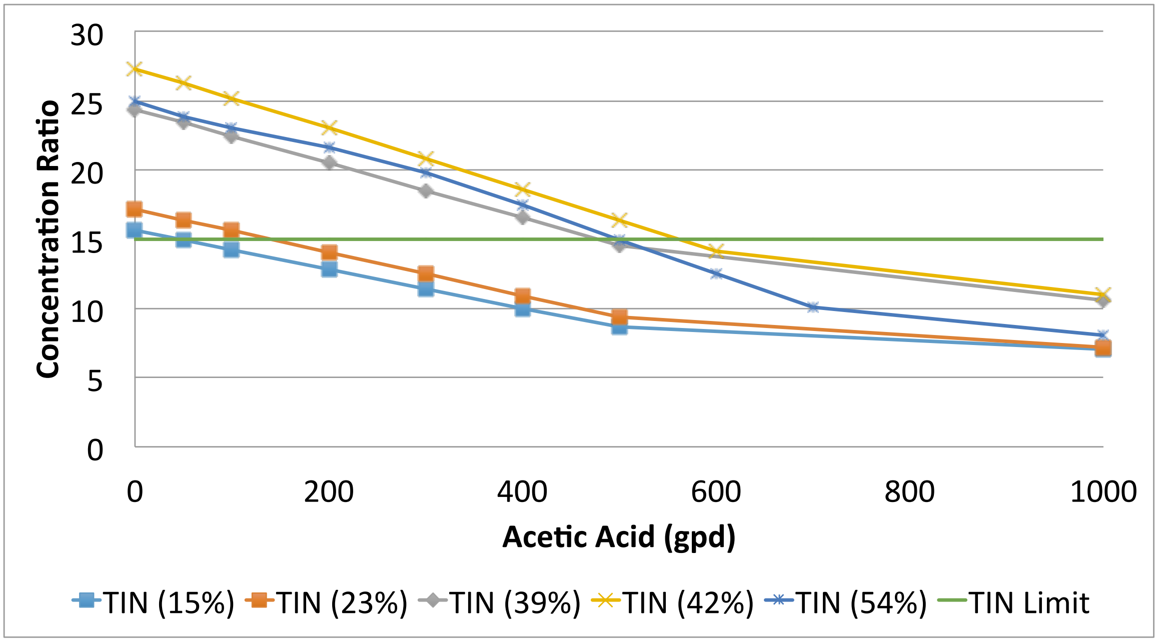

Figure 27: Effect of acetic acid addition on TIN concentration for 15%, 23%, 39%, 42%, and 54 % flow reduction.

Although acetic acid effectively reduced the effluent TIN concentration, acetic acid addition is expensive (Table 5). Using cheaper carbon sources, such as brewery waste, could reduce the cost of

carbon addition.

Table 5: Cost of Acetic Acid Addition. Assuming $6/gallon acetic acid

Acetic Acid Addition Rate gpd	**Cost per day** $/day	**Cost per year** $/yr
0	-	-
50	300.00	109,500.00
100	600.00	219,000.00
200	1,200.00	438,000.00
300	1,800.00	657,000.00
400	2,400.00	876,000.00
500	3,000.00	1,095,000.00
600	3,600.00	1,314,000.00
700	4,200.00	1,533,000.00
1000	6,000.00	2,190,000.00

All three mitigation strategies improve plant performance, but none effectively solve all of the performance problems observed. If high levels of conservation occur, then WWTFs will need to consider process optimization strategies that can appropriately manage increased nutrient loading and lower pHs.

Source Separation (SS)

Effluent TKN, TIN, TN, nitrate, and TP concentrations decreased significantly with increased SS.

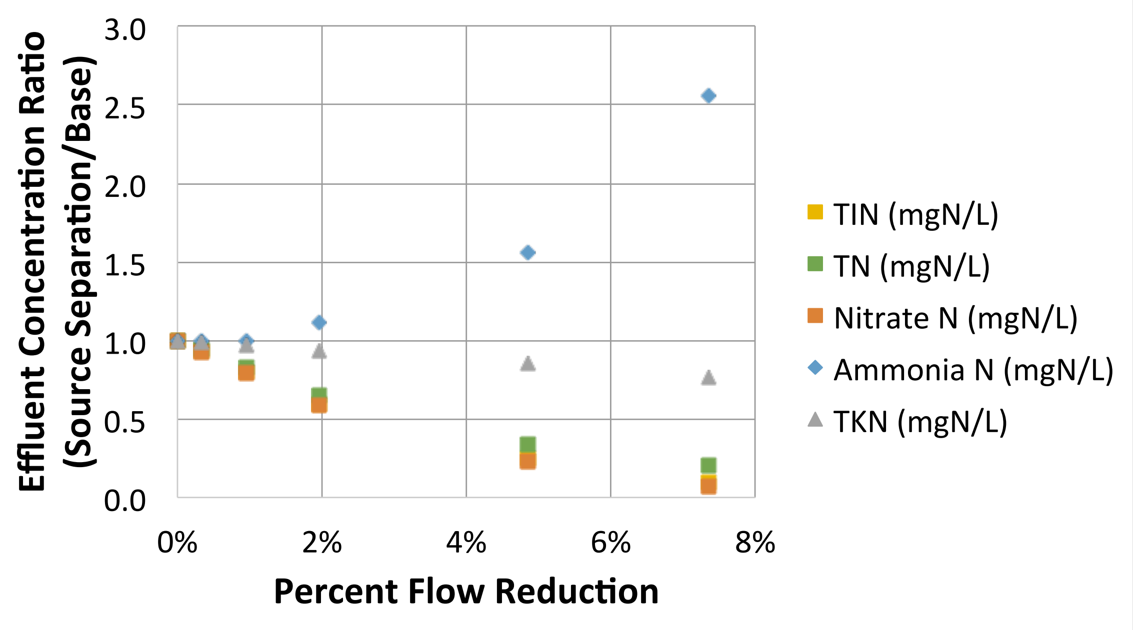

Figure 28: Effects of source separation on the TKN, TIN, TN, ammonia, and nitrate concentrations for the Boulder model.

The effluent ammonia concentration increased with increased SS adoption populations (Figure 28). Effluent TN, TIN, and TKN concentrations decreased with increasing SS (Figure 28). Significantly reducing influent nitrogen concentrations with minimal flow reduction yields more efficient nitrification and denitrifaction. There is less nitrogen to remove and the reduced flow increases the hydraulic residence time in each basin, which results in better nitrification and denitrification. The most significant effluent concentration reductions occur with 26-66% SS adoption. SS does not impact effluent TIN, TN, nitrate, and TKN concentrations as significantly with more than 66% SS.

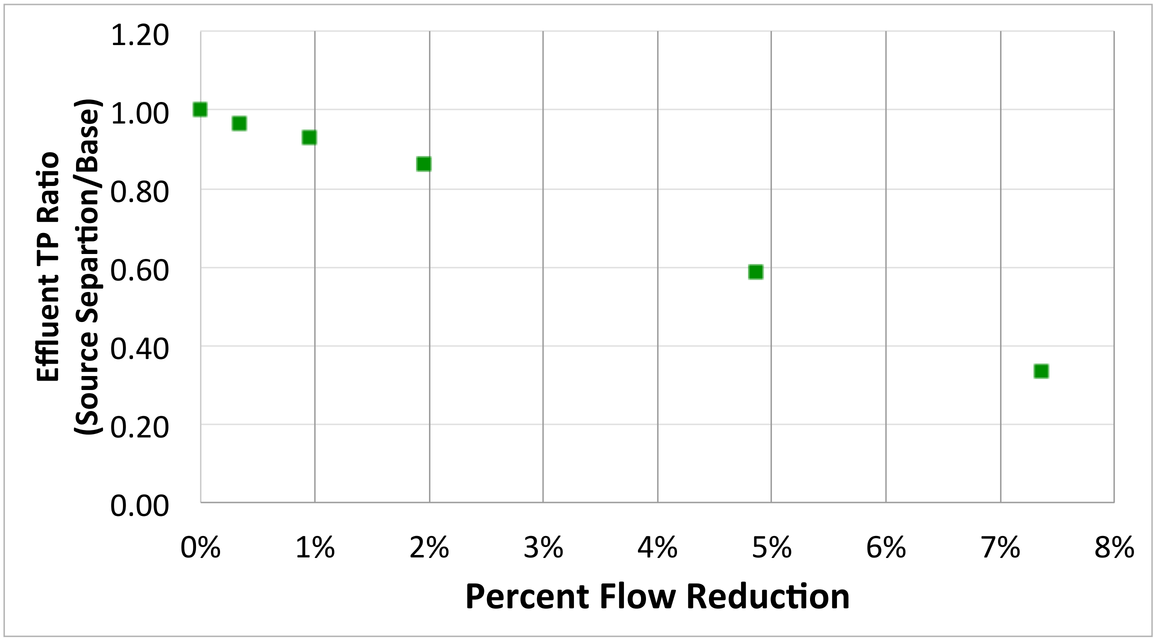

Figure 29: Effect of source separation on effluent TP concentration

Effluent TP concentrations decrease linearly by 3-46% with SS (Figure 29). The Boulder WWTF operates a modified Ludzak-Ettinger (MLE) process, which is not designed for phosphorous removal. Phosphorous removal may have been more significant if the Boulder WWTF were designed for enhanced phosphorous removal. Modeling source separation using a WWTF model that removes phosphorous may yield different results.

Modeling studies done by Wilsenach and van Loosdrecht yielded the same results using a theoretical University of Cape Town (UCT) WWTF. These results were confirmed with the calibrated Boulder WWTF model.

Operational Impacts

Oxygen requirements for nitrification decreased with increased SS adoption populations, which would reduce Boulder WWTF's operating costs. Due to the reduced nitrogen loading, less oxygen is required for nitrification. The oxygen uptake rate (OUR) for nitrification decreases linearly with SS. SS reduced the nitrification OUR by 16-84% (Figure 23). The total OUR decreased by 7-34% with SS (Figure 30). Considerable cost savings could be achieved by adjusting the aeration basin DO set points, given the decreased nitrogenous OUR with SS.

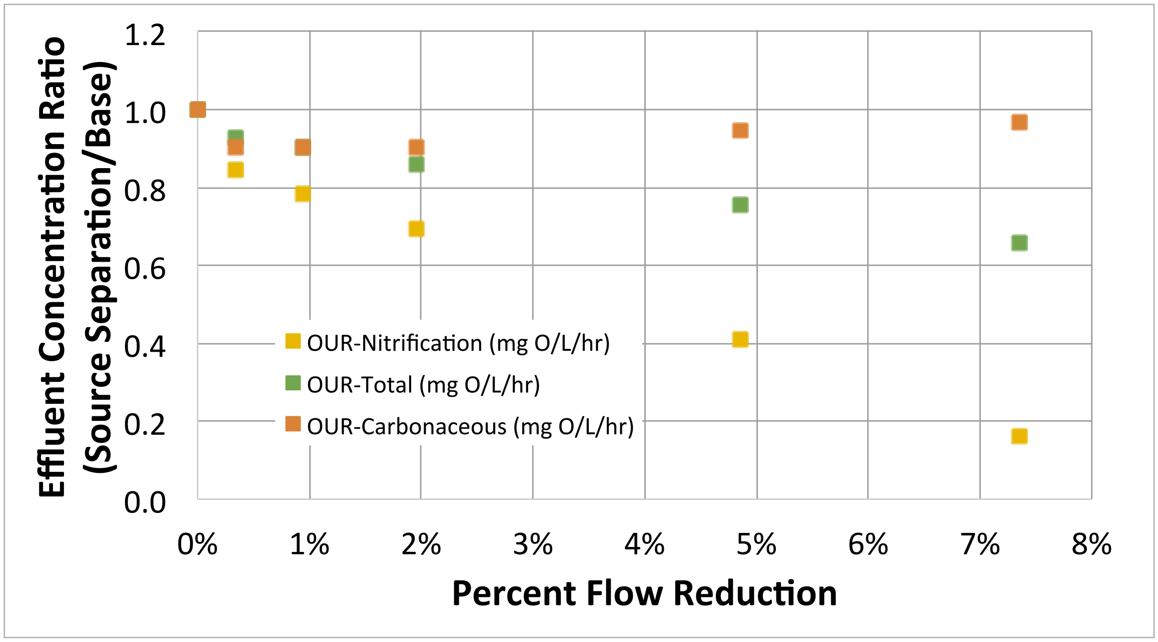

Figure 30: Effects of SS on the carbonaceous, nitrogenous, and total OUR.

SS does not significantly impact solids loading rates (data not shown).

Graywater Reuse

GWI and GWT do not significantly impact effluent contaminant concentrations (data not shown).

Discussion

The demand for potable water is growing, but fresh water supplies continue to dwindle. In addition to dwindling supplies, source water quality is decreasing. Due to environmental concerns, wastewater discharge limits are becoming more and more stringent. Nitrogen and phosphorous limits are particularly stringent and difficult for WWTFs to meet. Colorado Regulation 85 requires that WWTFs discharge no more that 1.0 mg P/L TP and 15 mg N/L TIN, which poses treatment challenges for most Colorado WWTFs. Understanding how conservation measures impact wastewater effluent quality can help WWTFs design with the future in mind.

Analysis of the modeling results indicates that water conservation measures significantly impact WWTF performance. Source separation decreases effluent TIN and TP concentrations, but there are several implementation barriers. Graywater reuse is a useful water conservation tool that should not impact WWTF performance. Indoor conservation can save significant amounts of water, but it negatively impacts WWTF performance.

Modeling results suggest that indoor conservation will increase effluent TIN, TN, BOD, COD, TP, and TKN concentrations. Extreme conservation also decreases the effluent pH. An evaluation of 14 WWTFs in California during the 1970s drought observed that BOD and effluent ammonia concentrations increase with flow reduction (Dezellar, 1980). Although effluent ammonia concentrations increased at the 14 WWTFs, some WWTFs observed effluent ammonia loading decreases (Dezellar, 1980). A study in New York found that water conservation resulted in lower effluent TN loading, but the WWTFs studied were typically space limited. Conservation may increase the hydraulic residence time, increase the MLSS, and increase the mean cell residence time at space limited WWTFs and ultimately decrease effluent contaminant loads (Paulsen, Kurt, Featherstone, Jeffrey, Greene, 2007). Although contaminant loads may decrease, many WWTF regulations are concentration based and this research focused on concentration impacts.

Based on the modeling results, conservation efforts poses treatment performance issues. In order to avoid costly retrofits in the future, communities should develop plans that consider how water conservation practices will impact WWTFs. WWTF treatment upgrades and retrofits are costly, and reevaluating permit structures and the environmental impacts of regulated contaminants may be a more viable option. Regulating on a load basis may aid WWTFs ability to satisfy discharge permits. If nutrients are regulated on a load basis, then many WWTFs may be able to meet the limits without costly process retrofits. Although load based limits may be more attainable, the environmental impacts of using load-based limits must be evaluated.

Conservation is the most economical way to preserve freshwater supplies and is inevitable in drought scenarios. This research does not imply that conservation is not worthwhile; rather it suggests that WWTFs must be prepared for the treatment challenges that arise with reduced flows. WWTFs ought to consider adding design features that will allow for simple treatment changes that can mitigate the treatment impacts of reduced flows. Reevaluating how WWTFs are regulated, concentration or load basis, is another step that could be taken to avoid costly WWTF process changes. Factoring these concerns into WWTF designs today could save money and improve water quality in the future.

Future Steps

The knowledge gleaned from this project suggests that further modeling should be completed. It would be beneficial to model different plant configurations, such as a plant that utilizes enhanced biological phosphorus removal. Modeling more advanced and paired mitigation strategies should be modeled as well. Modeling conservation impacts on WWTFs in states other than Colorado should be looked into as well. Lastly, modeling at different seasons would provide more insight into conservation impacts as well. With further modeling, a more holistic picture of the conservation impacts would be established.

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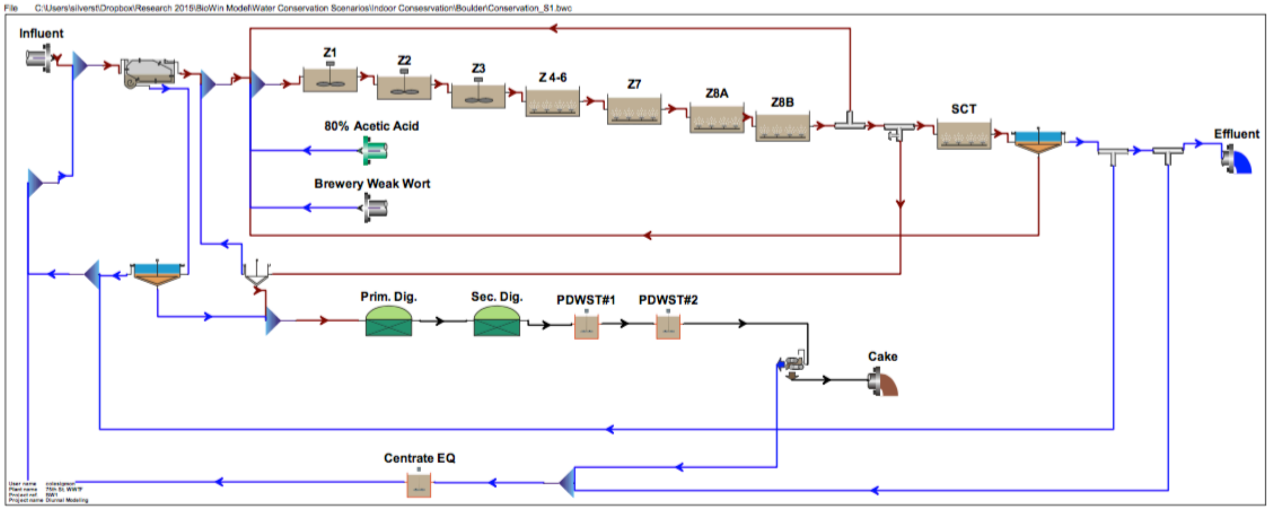
Appendix 1: Boulder BioWin Schematic



Appendix 2: Boulder WWTF Process Data
https://www.dropbox.com/sh/blwazj13q4j3jqg/AACN6vAU61kicDhbG71VUAdta?dl=0

Appendix 3: Model Calibration Data

https://www.dropbox.com/s/jrhmmqd9ap6715n/BioWin%20Model%20Runs.xlsx?dl=0

Appendix 4: Simulation Data

Indoor Conservation (Metro, Boulder, Longmont):
https://www.dropbox.com/s/fska12rgdg6pg8a/Indoor%20Conservation%20Boulder%20Longmont%20Metro_Ratio%20Graphs.xlsx?dl=0

Source Separation:

https://www.dropbox.com/s/i946s5qa0vt0ayc/Alternative%20Analysis_copy%20with%20alternative%20graphs.xlsx?dl=0

Graywater:
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Acetic Acid Addition:
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Alkalinity Addition:
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SRT:
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