OPTIMIZING THE DESIGN AMMONIA LOADING RATE OF SUBMERGED ATTACHED-GROWTH REACTORS IN WARM AND COLD CONDITIONS

by

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ABSTRACT

Lagoons are commonly used to treat wastewater in North America – primarily by small towns and municipalities. Ammonia in lagoon effluent is known to be toxic to aquatic environments. The ability of lagoons to remove ammonia from wastewater is highly temperature-dependent. Total Ammonia Nitrogen (TAN) -related regulatory limits for lagoon effluent are increasingly stringent. Where additional ammonia removal from lagoon effluent is required, post-lagoon nitrification reactors might be used, such as the Submerged Attached Growth Reactor (SAGR).

The SAGR is a technology owned by Nexom. It is sized using a typical design maximum TKN loading rate (per unit volume of the SAGR). Historic studies have shown that nearly full TAN and TKN removal can be consistently achieved in SAGRs sized using these design parameters at very low sustained water temperatures of even less than 1^{o}C. Some have shown that this is even possible with reduced SAGR volume. This suggests that the design ammonia loading rate values might be increased to optimize the SAGR size.

The current typical design loading rate is 12.8g-TKN/m$^{3}\cdot$day (0.8lb-TKN/1000ft$^{3}\cdot$day). The chapters in this thesis show that a value of 31.1g-TKN/m$^{3}\cdot$day (1.96 lb-TKN/1000ft$^{3}\cdot$day) might be used in 'warm' conditions with lagoon effluent temperature greater than 20^{o}C, and a value of 21.9 g-TKN/m$^{3}\cdot$day (1.38lb-TKN/1000ft$^{3}\cdot$day) might be used in moderately cold conditions where lagoon effluent temperature might drop to between 3 and 4^{o}C in winter.

The first pilot study, completed in the summer of 2022, observed SAGR operation at influent temperatures greater than 20^{o}C and loaded at an average loading rate of at least 31.1g-TKN/m$^{3}\cdot$day (1.96 lb-TKN/1000ft$^{3}\cdot$day). The pilot reactor recorded nearly 100% removal of TAN consistently during stable operation.

The second pilot study, completed in the winter of 2022/2023, observed SAGR operation at influent temperatures below 4^{o}C, and loaded at an average loading rate of 21.9 g-TKN/m$^{3}\cdot$day (1.38lb-TKN/1000ft$^{3}\cdot$day). The pilot reactor recorded nearly 100% removal of TAN consistently during stable operation.

The results of these studies indicate that SAGRs might be designed in the future with significant reductions in footprint and, therefore, significant reductions in cost to the end user, many of which are rural municipalities struggling to meet regulatory limits. The consequences of these design size reductions will include increased access to suitable wastewater treatment technology and, therefore, higher quality lagoon discharges to surface water bodies on a broad scale.

LIST OF ABBREVIATIONS

AOA	Ammonia Oxidizing Archaea
AOB	Ammonia Oxidizing Bacteria
ATP	Adenosine Tri-Phosphate
BAF	Biological Aerated Filter
BBR	BREW Bioreactor
BREW	Bioreactor Engineered Wetland
BOD	Biological Oxygen Demand
$CaCO_3$	Calcium Carbonate
cBOD	Carbonaceous BOD
CEC	Compounds of Emerging Concern
C/N	Carbon:Nitrogen Ratio
COD	Chemical Oxygen Demand
CSLM	Confocal Laser Scanning Microscopy
CSTR	Completely Stirred Tank Reactor
DO	Dissolved Oxygen
EPS	Extracellular Polymeric Substance
ESEM	Environmental Scanning Electron Microscopy
FISH	Fluorescent In-Situ Hybridization
FNA	Free Nitrous Acid
HDPE	High Density Polyethylene
HRT	Hydraulic Retention Time
IFAS	Integrated Fixed-film Activated Sludge
MBBR	Moving Bed Biofilm Reactor
$-NH_2$	Amine Group
NH_3	Ammonia Oxidizing Bacteria
NH_4^+	Ammonium
NO_2^-	Nitrite
NO_3^-	Nitrate
NOB	Nitrite Oxidizing Bacteria
PE	Polyethylene
PFR	Plug Flow Reactor
PP	Polypropylene
RBC	Rotating Biological Contactor
ROS	Reactive Oxygen Species
SAGB	Submerged Attached Growth Bioreactor
SAGR	Submerged Attached Growth Reactor
SALR	Surface Area Loading Rate
SARR	Surface Area Removal Rate
SBR	Sequencing Batch Reactor
SF	Surface Flow
SSF	Subsurface Flow
SOD	Superoxide Dismutase
TAN	Total Ammonia Nitrogen
TKN	Total Kjeldahl Nitrogen
TF	Trickling Filter
TSS	Total Suspended Solids
WWTF	Wastewater Treatment Facility

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CHAPTER 1. INTRODUCTION AND THESIS ORGANIZATION

1.1. Objectives and Hypothesis

The objectives were to:

1. Determine whether SAGR design might be optimized to use a higher design TKN loading rate – resulting in smaller reactors – for installations where lagoon effluent might be expected to remain above 20°C. Example wastewater sources might include municipalities in warm or hot climates or industries with elevated wastewater temperature. 20°C was chosen as an objective due to the need on the market for efficient reactors suitable for effluent at this temperature.
2. Determine whether SAGR design might be optimized to use a higher design TKN loading rate – resulting in smaller reactors – for installations where lagoon effluent might be expected to decrease to 3-4°C in winter. Example wastewater sources might include municipalities in moderate climates such as states in middle latitudes, or municipalities across Canada for whom lagoon discharge is only allowed in warm seasons. 3-4°C was chosen as an objective due to the need on the market for efficient reactors suitable for effluent at this temperature

1.2. Hypotheses

1. The SAGR has been developed for cold winter conditions where lagoon effluent temperature might fall below 1°C. It is therefore hypothesized that a pilot SAGR receiving lagoon discharge wastewater at temperatures over 20°C will consistently remove over 99% of the influent TAN when operated at a loading rate of approximately 32g-TKN/$m^3\cdot$day (2 lb-TKN/1000$ft^3\cdot$day) rather than the modern typical design loading rate of 12.8 g-TKN/$m^3\cdot$day (0.8 lb-TKN/1000$ft^3\cdot$day).
2. Nexom noticed in studies in moderate and cold climates that SAGRs were able to meet regulatory effluent quality requirements with reasonable consistency using significantly reduced SAGR footprint. It is therefore hypothesized that a pilot SAGR receiving lagoon discharge wastewater at temperatures dropping to 3-4°C in the winter will consistently remove over 99% of the influent TAN when operated at a loading rate of approximately 19.0 g-TKN/$m^3\cdot$day (1.2lb-

TKN/1000ft^{3}·day) rather than the modern typical design loading rate of 12.8 g-TKN/m^{3}·day (0.8 lb-TKN/1000ft^{3}·day).

1.3. Academic Need for This Research

Should these hypotheses prove false, the justifications for the hypotheses will remain, and the target loading rates should be re-estimated and researched to find what loading rate increases are possible. However, should the hypotheses prove true, SAGRs might be designed in the future at significantly reduced size and therefore reduced cost to the end user, directly increasing the access they have to suitable wastewater treatment solutions. With this increased access, the users, many of which are rural municipalities struggling to meet regulatory limits, should more easily be able to upgrade their lagoon facilities to meet regulatory limits and increase the quality of their discharges, resulting in a net environmental and social benefit on a broad scale.

1.4. Organization

This thesis is organized into five chapters:

- This first chapter, introducing the thesis and providing the hypothesis.
- Chapter 2 provides a literature review covering the SAGR and the effects of temperature on the efficiency of nitrification.
- Chapters 3 and 4 provide summaries of the research completed, addressing the objectives and hypotheses above.
- The final chapter provides a summary and conclusion of the thesis and suggests topics for future research.

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

2.1.1. Background

Lagoons are widely used for wastewater treatment in rural Canada. The process whereby ammonia is oxidized to nitrite and nitrite is oxidized to nitrate, all mediated by microorganisms, is collectively termed “Nitrification”. Nitrification is a very temperature-sensitive process and is not well-achieved in lagoons during Canadian winters where lagoon effluent can reach temperatures less than 1° C (such as, for instance, in Anderson et al., 2020, Young et al., 2016a, Young et al. 2017a). Ammonia is known to be toxic to aquatic ecosystems, and Canadian regulations on ammonia concentration in wastewater effluent have grown increasingly stringent due to the toxic effects. This is reflected in the federal regulations and guidelines (Canada Gazette, 2012, CCME, 2010).

Total Ammonia (Termed Total Ammonia Nitrogen, or TAN, when measured as mass of Nitrogen) is the sum of ammonia (NH_3) and the ionized form, ammonium (NH_4^+). The proportions of the species depend mostly on pH and temperature (see Figure 2.1). Ammonia (principally the un-ionized form, NH_3) is

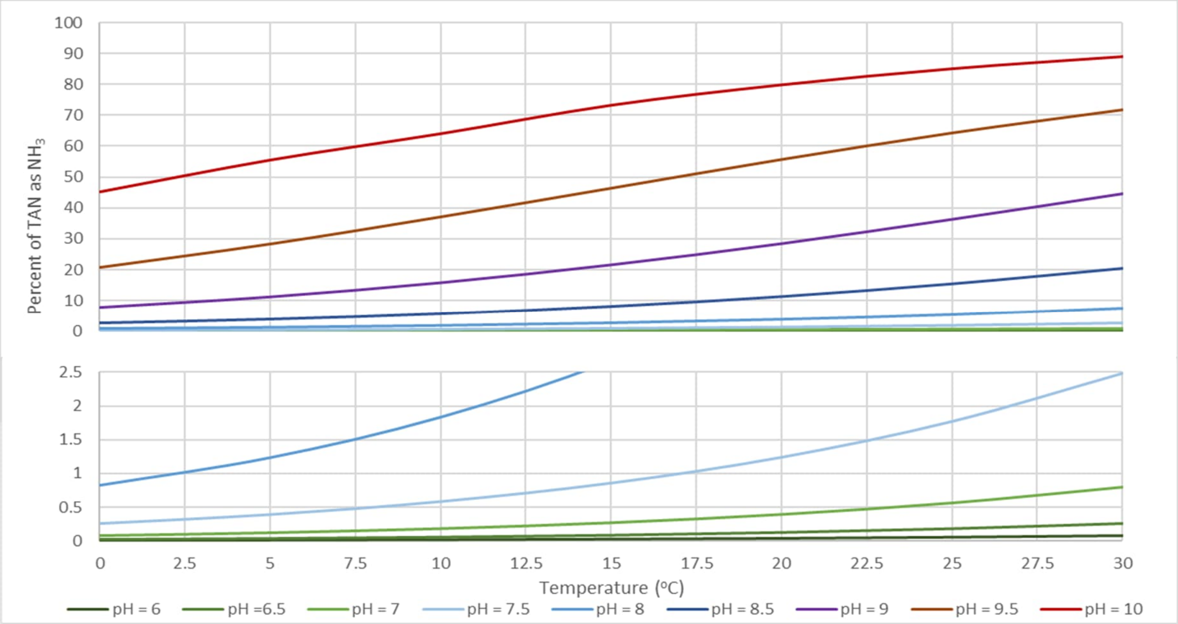

Figure 2.1: NH_3 / NH_4 Equilibrium in Aqueous Solutions Expressed as the Percent NH_3 in TAN as a Function of pH and Temperature (Adapted from Emerson et al., 1975)

understood to have greater harmful effects on invertebrates and fish than on vegetation (Constable et al. 2003). Fish – being at the top of the aquatic food chain – are the most at risk of NH_3 bioaccumulation, and the known effects include changes in hematological properties, changes in antioxidant-to-oxidant balance and corresponding oxidative damage, impairment of immune responses, and neurotoxicity (Xu et al., 2021). Finally, NH_3 and NH_4^+ contribute to the depletion of oxygen in surface water bodies through nitrification and by contribution of the nutrient nitrogen to eutrophication.

The traditional strategy to meet TAN-related limits with lagoons is to provide storage in the system such that effluent can all be released at an ideal time (warm weather) where nitrification can be partially achieved and the impacts in the downstream surface water are mitigated. The increasing knowledge of the detrimental impacts of NH_3 in aquatic environments, and the corresponding increasingly strict regulations, naturally put pressure on owners of wastewater lagoon facilities that are typically unable to consistently remove TAN to upgrade their facilities. Should adding storage not be feasible, or should a continuous discharge of the lagoon through cold weather be necessary, a downstream nitrification reactor may be required. Reactors that may be retrofit to a lagoon facility for the removal of TAN from the wastewater are therefore becoming increasingly beneficial and common.

Traditional (activated sludge) reactors designed to achieve nitrification in addition to removal of organics grow bacteria (including nitrifying bacteria) primarily in a ‘planktonic’ state where they are free-floating in the water (‘suspended growth’), whereas biofilm technologies grow the nitrifying bacteria (nitrifiers) in a ‘sessile’ or fixed state (‘attached growth’), adhered to ‘media’. Nitrifiers are relatively sensitive to low temperature (as compared to common heterotrophs in wastewater), which decreases their growth rate in cold-water conditions. Suspended growth reactors have been shown to be severely inhibited at temperatures lower than 10^{o}C, with nitrification nearly ceasing at or below 5-8^{o}C (Hwang & Oleszkiewicz, 2007; Oleszkiewicz & Berquist, 1988; Shammas, 1986). Despite this inhibition, biofilm technologies have been shown to achieve significant nitrification down to 1^{o}C (Young et al., 2017a; Anderson et al., 2020; Hoang et al., 2014a & 2014b; Ahmed et al., 2019; Ahmed & Delatolla, 2020; Ahmed & Delatolla, 2021;

Nexom, 2021b). A significant part of the reason for this is that the nitrifiers, being grown as a biofilm, are retained in a reactor better than they would be in the planktonic state. Because they do not flow freely out of the reactor with the effluent, they are not as easily “washed out” of the reactor when temperature decreases cause the growth rate to decrease. Reactors commonly proposed as retrofit upgrades of lagoons for ammonia removal include the Moving Bed Biofilm Reactor (MBBR) and the Submerged Attached Growth Reactor (SAGR). The SAGR is a trademarked term and proprietary technology.

Though MBBRs and SAGRs have been shown to be able to achieve full nitrification at low temperature, there is evidence that some of these reactors may be over-designed (Hoang et al., 2014a; Mattson et al., 2018a, 2018b). Being over-designed means that the reactors are designed to be too large, complex, or more costly than is actually required to achieve desired treatment levels. Therefore, with rural municipalities growing in need for cost-efficient nitrification solutions, there is growing industry desire to optimize the reactor designs through a better understanding of the processes involved in nitrification and the effects of rapid and gradual temperature change.

2.1.2. MBBR and SAGR

Aside from the MBBR and SAGR, other attached growth reactors include, but are not necessarily limited to Rotating Biological Contactors (RBC), Trickling Filters (TF), and Biological Aerated Filters (BAF). These will not be significantly reviewed as MBBRs and SAGRs are more commonly used as lagoon retrofits. As the majority of research into nitrifying biofilm post-lagoon reactors has been completed on MBBRs, they are briefly described below. The SAGR is covered in more detail in Section 2.4.

MBBR biofilms are grown on media (usually plastic) with high surface area to volume ratio to promote biofilm growth. The media are in free suspension and mixed. Sometimes the reactor is mixed mechanically but usually (and especially when nitrification is targeted) the reactor is mixed by bubbling air from the base of the reactor (similar to a Sequencing Batch Reactor (SBR), providing oxygen for nitrification as well as mixing). An important design assumption for the MBBR is that sufficient mixing is supplied that substrate (in this case TAN) concentrations are constant across the reactor. The reaction rates are therefore calculated with respect to the ammonia concentration (and other quality parameters) of the reactor taken as a whole. This class of reactors are known in the industry as Continuously Stirred Tank Reactors (CSTRs) and the TAN concentration (as well as other constituent concentrations) are determined by mass balance equations that account for influent concentration, effluent concentration (assumed to be the same as the reactor), reaction rates, and accumulation rates.

The media have a density usually near – or just below – the density of water (such as polyethylene – 0.95g/cm^3) to promote good mixing properties. Traditional media has large openings and pores such that the formation of thick biofilms does not clog the openings and reduce effective surface area. However, thinner biofilms such as those involved in nitrification are benefitted by media with smaller openings due to the increased specific surface area. MBBRs come equipped with screens on the effluent ports to ensure that the media and biofilm are retained within the reactor as effluent leaves. MBBRs are not only used for nitrification, but are commonly used for organics removal in primary treatment processes. They have also been shown to be able to treat chemicals of emerging concern and other micropollutants, which has been summarized well by di Biase et al. (2019). Figures 2.2 & 2.3 illustrate MBBR operation.

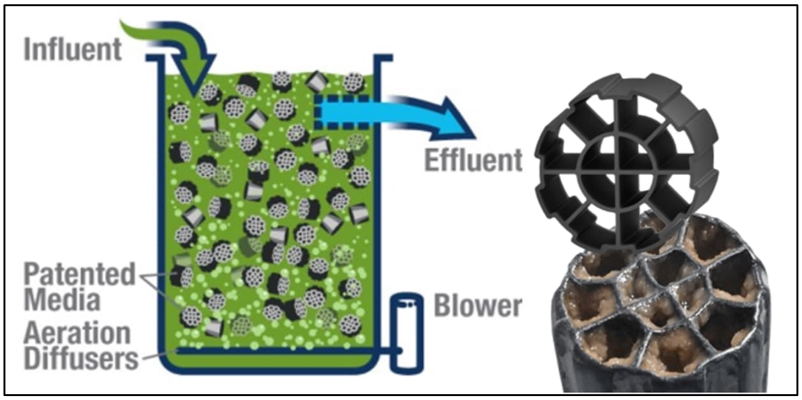

Figure 2.2: MBBR and Media Diagram – Courtesy of Nexom (Nexom, 2021a)

The reactor is depicted on the left with influent entering at the green arrow. Effluent leaves the reactor at the blue arrow. Mixing and dissolved oxygen are provided by the aeration diffusers and blower at the base. The media is depicted on the right in both a clean state and in a used state with biofilm growing in the voids

Figure 2.3:Working MBBR – Courtesy of Nexom (Nexom, 2021a)

2.2. Nitrification

2.2.1. Definition and Factors

As noted above. nitrification is defined as the two-step process by which TAN (specifically, by the equations below, NH_4^+) is oxidized to nitrite (NO_2^-) and nitrite is subsequently oxidized to nitrate (NO_3^-). See Equations 2.1-2.4. The mechanism is not known for certain, and though these equations assume NH_4^+ is the substrate, it is thought that NH_3 is the true substrate (Suzuki et al. 1974). Regardless of which species is the true substrate, nitrification is defined as the removal of TAN, in this review.

The nitrification reaction, in general, occurs according to Equations 2.1 and 2.2 below, and a combined form is given as Equation 2.3. (Metcalf & Eddy, 2014)

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O \qquad (2.1)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \qquad (2.2)$$

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \qquad (2.3)$$

Notice that there are two protons produced per mole of NH_4^+, which consume alkalinity in solution and reduce the pH. Metcalf & Eddy (2014) gives Equation 2.3 in an alternate form to predict alkalinity consumption, and this is given as Equation 2.4 below.

$$NH_4^+ + 2HCO_3^- + 2O_2 \rightarrow NO_3^- + 2CO_2 + 3H_2O \qquad (2.4)$$

The pH-related concern most relevant to SAGR operation is a low-pH scenario on account of the pH-lowering kinetics. If the solution does not contain sufficient alkalinity to keep the pH in a practical ideal range (6.8 – 8.0 according to Metcalf & Eddy, 2014), the reaction is inhibited.

It is standard practice to keep alkalinity in the solution at or above 70 mg/L as $CaCO_3$ to prevent this inhibition (Metcalf & Eddy, 2014). In practice, however, much higher alkalinity is often required to adequately buffer against pH depression. Alkalinity is often dosed according to the well-known, stoichiometric rate of 7.14 g-$CaCO_3$ / g-TAN (Metcalf & Eddy, 2014). Metcalf & Eddy (2014) suggest that this rate is, in practice, sufficient to also account for the use of the carbon provided in alkalinity for cell synthesis – noting that nitrifiers are autotrophs that might utilize $CaCO_2$.

Although low pH is generally a more common problem than high pH, it should be noted that overdosing alkalinity is possible – as di Biase et al. (2020) noted in a bench-scale SAGR experiment where alkalinity overdosing caused pH to rise to approximately 8.5, severe and permanent nitrification inhibition occurred. This was attributed to the high pH driving up the equilibrium NH_3 (here called “Free Ammonia”) concentration fraction of TAN, which caused Free-Ammonia inhibition, another well-known risk to biological nitrification. The inhibition, in turn, resulted in greater concentration of free ammonia, causing a positive inhibition feedback loop with permanent effect.

Dissolved Oxygen (DO) consumption is understood to be in the range of 3.21 – 3.43 g O_2 / g N for TAN oxidation and 1.06 – 1.14 g O_2 / g N for nitrite oxidation (Metcalf & Eddy, 2014). These ranges agree generally with the values that can be calculated using Equations 2.1-2.3, and account for the fraction of TAN consumption that is used for cell synthesis rather than respiration. The range of required DO for complete nitrification is therefore 4.27 – 4.57 g O_2 / g N. Metcalf & Eddy (2014) recommends maintaining a minimum DO concentration of 4 mg/L for designs targeting nitrification using biofilms and this agrees generally with conservative SAGR design guidelines (for instance, the Iowa Department of Natural Resources (2016) requires a minimum maintained DO concentration of 3 mg/L). This is generally greater than the requirement for suspended growth because the diffusion of DO into a biofilm must be considered.

For reference, the minimum DO concentration recommended in Metcalf & Eddy (2014) for suspended growth nitrification is 2.0 mg/L. In general, if a nitrifying biofilm is not substrate-limited, it is DO-limited, and the kinetics calculations should be based on the limiting factor. See Figure 2.5.

Finally, a major factor in attached growth nitrification is the presence of BOD because the autotrophic nitrifiers must compete for space and oxygen with BOD-consuming aerobic heterotrophs that generally grow faster and out-compete nitrifiers (Metcalf & Eddy, 2014). The Biological Oxygen Demand (BOD) is an indirect measure of organics (or microorganism food) that is found by measuring the oxygen consumed by microorganisms as they consume the organics. It is a useful measure for determining the potential for biological growth. The portion of BOD consumed by carbonaceous (in this case, heterotrophic) bacteria, as opposed to nitrogenous bacteria, is termed "carbonaceous" BOD (cBOD). Other measurements used to estimate the impact of organics on nitrification include the Chemical Oxygen Demand (COD) and Carbon-to-Nitrogen Ratio (C/N). Delatolla et al. (2010) found while testing a BAF reactor and MBBR, and through comparison to Delatolla (2009b), that COD concentrations below 100 mg/L did not significantly affect the ammonia removal rate of biofilms.

Hem et al. (1994), recognizing the detrimental impact of BOD on the ability of a biofilm to achieve nitrification in an MBBR, produced the Figure 2.4, showing that, at a given DO concentration, higher BOD loading rates correspond (almost linearly) with lower ammonia removal flux in the biofilm. Further discussion is outside the scope of this review. Nitrifying biofilm reactors are ideally placed downstream of lagoons which still achieve moderate treatment of BOD in cold weather, such that the nitrifiers are competing less with heterotrophs for Dissolved Oxygen (DO) and area on the media. In general, reactor placement downstream of lagoons is effective in limiting BOD in the influent. Some design guidelines have BOD limits on the reactor influent such as in Iowa where there is a conditional limit is 30 mg/L on SAGR influent (Iowa Department of Natural Resources, 2016) and a statement that ideally, influent cBOD is below 50 mg/L.

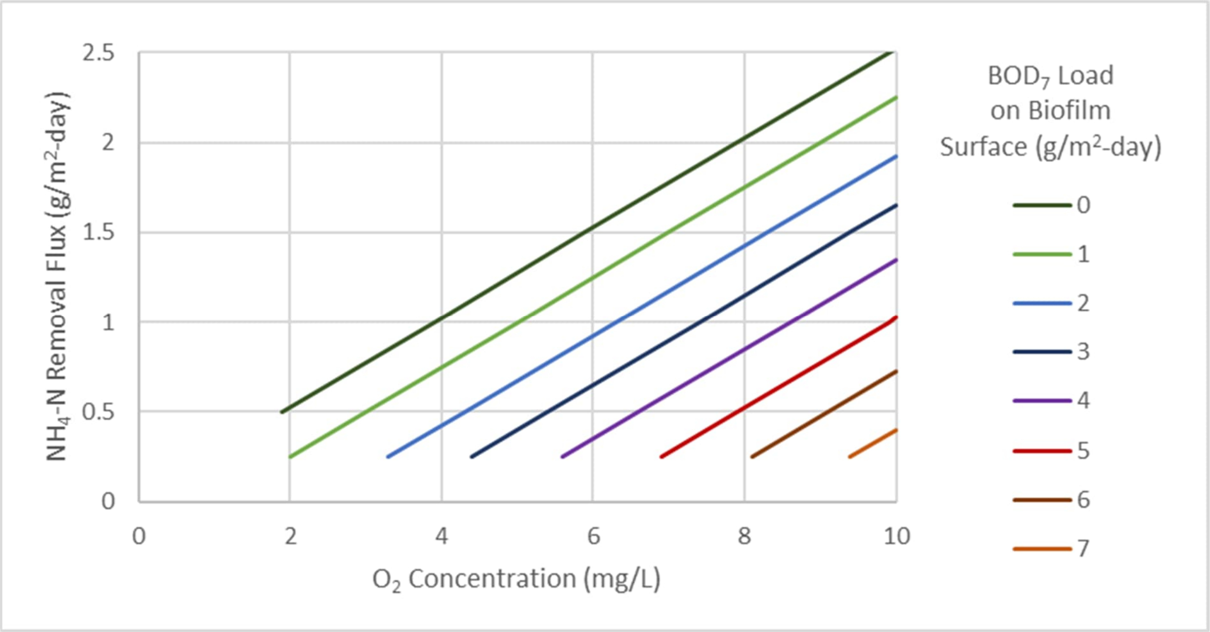

Figure 2.4: Effect of DO Concentration and BOD Surface Area Loading Rate on Nitrification (Adapted from Hem et al. 1994)

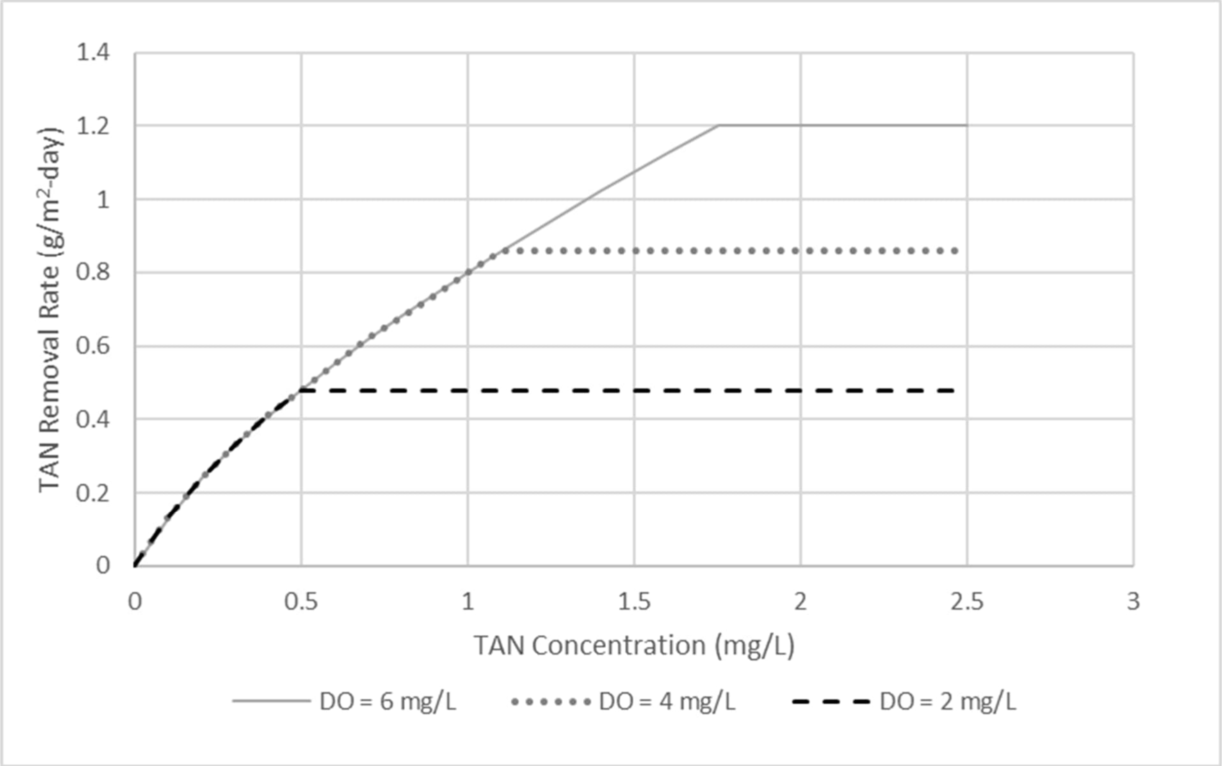

Figure 2.5: Approximate Effect of TAN and DO Concentrations on Nitrification at Low Influent BOD (Adapted from Rusten et al., 2006; Rusten et al., 1995)

2.2.2. Nitrifying Biofilms

The two classes of nitrifiers required for full nitrification are Ammonia Oxidizing Bacteria (AOB) and Nitrite Oxidizing Bacteria (NOB). AOB convert TAN to nitrite and NOB convert nitrite to nitrate. These bacteria are chemoautotrophic and obligate aerobes. The functional AOBs in post-lagoon reactors are generally *Nitrosomonas* and *Nitrosospira* and the functional NOBs are generally *Nitrospira* and *Nitrobacter* (Metcalf & Eddy, 2014). In recent studies regarding nitrifying biofilms, AOBs are generally dominated by *Nitrosomonas* and NOBs are generally dominated by *Nitrospira* (Young et al., 2017a, Hoang et al., 2014a). Mattson (2018a) identified significant levels of Ammonia Oxidizing Archaea (AOA) in a biofilm, and cited Bai et al. (2012) and Sauder et al. (2012) as the only two other studies investigating AOA in biofilms to their knowledge. The presence of AOA in nitrifying biofilms is therefore a potential subject of future study. Modern industry practice is to focus on AOBs and NOBs in biofilms.

Nitrification is often quantified by measuring ammonia removal only, however for research purposes it can be important to distinguish between the two steps of nitrification (ammonia oxidation and nitrite oxidation) when analyzing nitrification. This is especially true when it is important to delineate the activity differences between AOBs and NOBs. For instance, if nitrite accumulation is observed in the reactor, it is generally assumed that AOBs are at that moment outperforming NOBs in the biofilm (or – conversely – the NOBs are inhibited to a greater extent than the AOBs). This effect was, for instance, observed in Young et al. (2017a). This can be important because if any excess nitrite exists in the wastewater due to NOBs being inhibited more than AOBs, Free Nitrous Acid (FNA – the protonated form of nitrite) may be formed, and it is a known inhibitor of many species of bacteria (Zhou et al, 2011). Environmental factors that may contribute to disproportionate NOB inhibition include, but are not necessarily limited to:

- NH_4^+ and inorganic carbon concentrations as well as depressed pH (Durán et al., 2014).
- Low DO and high free ammonia (FA) concentrations, and high temperature (Sinha et al., 2007).
- Rapid temperature change (observed in Young et al., 2017a).

AOBs and NOBs are generally divided by species by their strategy for growth and are categorized as ‘r-strategists’ (favored relatively at high NH_4^+ concentrations) and ‘K-strategists’ (favored relatively at low NH_4^+ concentrations) (Metcalf & Eddy, 2014). Further discussion of nitrification kinetics is outside the scope of this review.

Denitrification is also a known and targeted wastewater treatment process by which nitrite and nitrate is removed by conversion to molecular nitrogen gas through several intermediate steps. Although denitrification is important, it is often not required of small wastewater systems by regulation, and is outside the scope of this review. Total Nitrogen limits in wastewater discharge regulations are generally less common than ammonia-related limits because nitrate and nitrite are less toxic to aquatic life than NH_3.

Biofilms grown in nitrification reactors are generally thinner than the biofilms grown in high-organic environments such as raw (untreated) municipal wastewater. Growth of the biofilm includes initial attachment of bacteria to the media (usually preceded by the attachment of macromolecules and nutrients to the media), followed by the development of an Extracellular Polymeric Substance (EPS) matrix and microcolonies embedded within. EPS is the matrix (excreted by the attached bacterial cells) in which the cells are confined and secured to the media. Mature biofilms operating in steady state are generally at an equilibrium where the various mechanisms causing death and/or detachment balance the continued growth of the biofilm. Factors affecting the biofilm attachment and detachment balance include the attachment rate (of cells to the media), bacterial growth rate, death rate, slough rate (that is natural detachment), shear stresses and impacts, and ‘grazing’ or attack by biofilm predators (Barwal & Chaudhary, 2014). Biofilm loss is not necessarily detrimental, one notable benefit is that it keeps biofilms thin – which is preferable for the diffusion of substrate and oxygen through the depth of the biofilm. Maintaining a biofilm attachment-to-detachment balance is therefore an important study. Despite this, Barwal & Chaudhary, (2014) found in their MBBR review that biofilm detachment is understudied and poorly understood as compared to the other factors.

Biofilms in nitrifying reactors do not contain only nitrifiers, but include diverse heterotrophic bacteria that would outcompete nitrifiers in an environment containing large amounts of biodegradable organics such as raw wastewater (Metcalf & Eddy, 2014). These, however, are thought to act symbiotically with nitrifiers in environments where biodegradable organics are less available, such as those in post-lagoon reactors. Heterotrophs may act beneficially by consuming metabolites, waste products, and EPS-related products of AOBs and NOB, preventing harmful buildups, and aiding in the development of the biofilm matrix and adhesion of bacteria to media (Kindaichi et al., 2004; Bae et al., 2015; Hibiya et al., 2000). Mature biofilms are known to generally have an EPS matrix with a relatively high protein-to-polysaccharide ratio – which is well summarized in di Biase et al. (2019).

With biofilms in general, concentration gradients drive the diffusion of substrates and oxygen through the thickness of the biofilm (Metcalf & Eddy, 2014). The concentration decreases with depth in the biofilm, and therefore the rates of cell growth are different throughout the depth. With thin biofilms (such as are typical of nitrification reactors), diffusion gradients are less impactful.

2.3. Factors Involved in Biofilm Nitrification

The factors known to influence the nitrification efficacy for all biofilm reactors include (but are not limited to) the substratum (media or carrier) properties, the organic load, dissolved oxygen concentration, ammonia concentration, temperature, pH, and alkalinity (Barwal & Chaudhary, 2014). Some of these are interrelated – for instance, the NH_3/ NH_4^+ balance is affected by pH and temperature. pH is affected by alkalinity, and nitrification itself affects pH as the oxidation of TAN releases protons. Some of these effects were briefly outlined in Section 2.2.1. For consistency with the subject matter of this review, only ammonia loading rate and temperature will be thoroughly reviewed below.

2.3.1. TAN Loading Rate

The TAN removal is generally positively correlated with the concentration of TAN. TAN removal by biofilms is well-described by a first-order reaction with respect to TAN concentration at low concentrations, with a transition to a zero-order reaction at high concentrations. The transition is approximated by a half-order reaction (Henze et al., 1997). Some of the studies summarized in this review indeed observed a transition to zero-order rates with respect to TAN at concentrations above an observed maximum (Young et al., 2017a, Young et al., 2016a). When DO becomes the limiting factor, the reaction also transitions to zero-order with respect to TAN concentration (Rusten, 2006).

As lagoons cool during winter, their effluent often contains elevated TAN concentrations on account of the inhibition of the nitrifiers in the lagoon. Therefore, temperature decrease to post-lagoon reactors often corresponds with TAN load increase. TAN concentration is an implicit variable in the surface area loading rate of attached growth reactors, discussed below.

Surface Area Loading Rate (SALR) is arguably the most important design parameter for MBBRs. It is calculated by dividing the loading rate of TAN (the product of influent TAN concentration and influent flow rate) by the total surface area of the media. Typical SALR ranges for full-scale aerated nitrifying MBBRs are reported by di Biase et al. (2019) to be between 1.5 and 1.7g-NH_4^+-N/m^{2}d. Young et al. (2017a) claimed an "optimal" SALR for a nitrifying MMBRs at 20^{o}C is 2.36g-NH_4^+-N/m^{2}d and that a typical design SALR value for these reactors at low temperature (in this study, between 1^o-5^{o}C) is 1.0g-NH_4^+-N/m^{2}d. These studies give the SALR in terms of NH_4^+ rather than TAN because NH_4^+ is assumed in the reaction equations to be the substrate, and at the measured temperature and pH conditions, NH_4^+ dominates the TAN speciation.

Typically, the surface area of an attached growth reactor is constant (though one of the benefits of the MBBR is the ability to easily change the surface area within), therefore the effects of SALR as a factor are implicitly similar to the 'TAN Concentration' factor discussed previously. Though SALR may be a useful parameter for the design of SAGRs, it is less useful than it is in MBBR design because the surface area of the clean rock bed of a SAGR is difficult to determine with accuracy. SAGRs also – being idealized (or partially idealized) as "Plug Flow" reactors – have concentration gradients through the reactors, leading to gradients in actual SALR along the length of the reactor as well as gradients in biofilm growth and qualities throughout the reactors. Nexom therefore typically uses a volumetric loading rate for SAGRs of up to 0.8lb-TKN/1000ft$^{3}\cdot$day (12.8g-TKN/m$^{3}\cdot$day) as a conservative design parameter. Mattson et al. (2018) estimated that based on modern design methods, SAGRs may only have SALR values of 0.007 – 0.025 g-NH_4^+-N/m^{2}d.

In general, so long as nitrifiers are not starved of substrate, nitrification is benefitted by low loading rates. Although Surface Area Removal Rates (SARR) increase with SALR, the efficiency of removal (that is the removal rate *per unit loading rate*) is increased at low SALR values. This can be seen in the slight downward curve of Figure 2.5 and is identified in Young et al. (2017a), Young et al. (2016b), Ahmed & Delatolla (2020).

SALR variations appear to have an exaggerated effect on nitrification when at low temperatures such as those in Young et al. (2017a). In particular, it appeared in this study that low SALR values are beneficial for promoting resistance to low temperatures. This study utilized an MBBR and dropped the temperature from 20^{o}C to 1^{o}C. They used 2.36gN/m^{2}d as an ‘ideal’ SALR at 20^{o}C by which to measure the effects of low temperature across other SALR values. At 1^{o}C they recorded a significantly lower TAN removal rate in a reactor loaded at 1.43gN/m^{2}d than in one loaded at 1.25gN/m^{2}d. It was theorized that low temperatures may exacerbate inhibition such as Free-Ammonia inhibition. Two reactors loaded at lesser rates recorded almost full TAN removal despite the temperature change. Young et al. (2016a) also recorded significant reductions of TAN removal efficiency with increased loading rates at 1^{o}C.

Young et al. (2017a) also showed that SALR variations at low temperature also affected microbial populations. At 1^{o}C, the MBBR with the lowest loading rate had a significantly more diverse biome than all of the more highly loaded MBBRs. It was theorized that the substrate-limited condition inherent in low SALR values allows for what they term ‘peripheral bacteria’ (that is bacteria other than those targeted for growth – in this case nitrifiers) to grow and thrive. Note that although the common AOBs and NOBs were monitored specifically, the measurements of diversity included non-nitrifying heterotrophs (a significant portion of the ‘peripheral bacteria’). Finally, Young et al. (2017a) found during MBBR pilot tests that the

SALR was an important factor in enriching low-temperature stress response pathways of the nitrifiers – theorizing that these enriched stress-response pathways are indicative of increased stress in the more highly loaded reactors.

2.3.2. Temperature

Table 2.1 summarizes the findings of some modern investigations into the population proportions of nitrification reactors (with low influent carbon), and the effects of temperature-reducing strategies. Note that the studies where the temperature decrease was rapid (corresponding to possible "cold-shock") are shown in bold. One notable trend is the thickening of biofilms in response to low temperature stress. The studies by Ahmed and Delatolla (2020, 2021) observed that though the thickness increased, mass generally did not, and therefore it was noted that the density of the biofilms decreased. They theorized that the decrease in density may aid diffusion of substrate into the biofilm and therefore help to offset the reduced kinetics associated with reduced temperatures. Barwal & Chaudhary (2014) and di Biase et al. (2019) give brief reviews of detachment mechanisms in MBBRs including:

- Abrasion by media collision,
- Erosion of biofilm,
- Natural sloughing,
- Grazing (predation) by protozoa and metazoan.

The increasing thickness of biofilm corresponding with temperature drop suggests that the kinetics these detachment mechanisms may be reduced more than the growth rates. The loss in biofilm density reported by Ahmed and Delatolla (2020, 2021) suggests swelling as a possible alternative mechanism by which the biofilm thickness increases. As noted above, Barwal & Chaudhary (2014) identified detachment mechanisms as an understudied area subject to further future research.

Table 2.1: Biofilm Nitrifier Population Proportions in MBBR and Response to Temperature Decrease Strategies

Reference			Young et al. (2017a)[1]	Hoang et al. (2014a)[2]	Ahmed & Delatolla (2020)[3]	
Temperature Decrease (°C)			20-1	20-1	10-1	10-1
Rate of Temperature Drop			Mix[4]	Gradual	Rapid	Gradual
Biofilm Thickness Before (μm)			93	~110-175	~271	~230
Biofilm Thickness After (μm)			263-300	~160-225	~370[5]	~365[5]
Municipal Wastewater Type			Real	Synthetic	Real	Real
AOB Before	Relative Abundance	*Nitrosomona*	~6-7%	2.5-3.7%	~4.1%[6]	~3.1%[7]
		Nitrosospira		0.63-1.8%		
NOB Before		*Nitrospira*	~30%	3.8-20%	~0.62%	0.62%
		Nitrobacter	<1%	--		
AOB After		*Nitrosomona*	~6-7%	0-9.4%	~4.1%[6]	~3.1%[6]
		Nitrosospira		0-0.41%		
NOB After		*Nitrospira*	~10-15%	7.9-31%	~0.62%	5.13%
		Nitrobacter	<1%	--		

[1] For each comparison from 20°C to 1°C in this study, note that the reactor producing the recordings at 20°C was operated at a different SALR than the reactors producing the recordings at 1°C. Results were measured across varying SALR values. Outlier value measured at lowest SALR excluded from this table.

[2] Ranges represent different values measured between two reactors. Hoang et al. (2014a) attributed several differences to differences in biofilm age

[3] For further insight into the gradually acclimatized reactor, see Ahmed & Delatolla (2021)

[4] Though the temperature decrease occurred over many days, Young et al (2017a) claims that cold shocks likely occurred

[5] Specifically, these measurements were taken after 50 days of operation at 1°C. Note importantly that the density was measured to decrease so no significant mass change was measured.

[6] *Nitrosomoneca* (AOB) and *Nitrospiraceae & Bradyrhizobiaceae* (NOB) families measured to quantify total AOBs and NOBs. No change in relative abundance or cell viability was measured.

[7] *Nitrosospira* was not measured but the similar *Nitrosovibrio* was instead. No change in relative abundance was measured. With the measured net increase in viable cells, an increase in AOB quantity is estimated

Another notable trend is that the relative abundance of each species in biofilms are generally constant across rapid temperature decreases. Other trends are not easily visually identifiable, though they may be more easily observed in Table 2.2. Note that in Table 2.1 population percentages should not be directly compared between studies – not only due to the many differing factors between the studies, but because the proportions were estimated by relative coverage of media surface area.

Cell response to low temperature stress depends on several factors including (but not limited to) the rate of temperature change, the magnitude of temperature change, the initial and final temperatures, the length of time that the cell was allowed to acclimatize to the initial temperature, the culture medium, the duration of time spent at low temperature, and the presence of other microbial strains (Beales, 2004). Young et al. (2017a) found *Nitrosomonas* and *Nitrospira* to be the dominant AOB and NOB, respectively, across various ammonia loading rates at all temperatures across a decrease from 20^{o}C to 1^{o}C.

Table 2.2: Summary of Microbial Changes in MBBR over Temperature Change

Reference		Young et al (2017a)	Hoang et al (2014a)	Ahmed & Delatolla (2020)	
Temperature Decrease (^{o}C)		20-1	20-1	10-1	10-1
Rate of Temperature Drop		Mix[1]	Gradual	Rapid	Gradual
Biofilm Thickness Relative Change		↑ 283-323%	↑ 30-45%	↑ ~37%	↑ ~59%
AOB Change in Relative Abundance	*Nitrosomonas*	~0%	↓ 3.7% ↑ 6.9%[2]	~0%[2]	~0%[3]
	Nitrosospira		↓ 0.6-1.4%		
NOB Change in Relative Abundance	*Nitrospira*	↓ 15-20%	↑ 4.1-11%	~0%[2]	↑ ~4.5%
	Nitrobacter	- -	- -		
Municipal Wastewater		Real	Synthetic	Real	Real

[1] Though the temperature decrease occurred over many days, Young et al (2017a) claims that cold shocks likely occurred

[2] *Nitrosomoneca* (AOB) and *Nitrospiraceae & Bradyrhizobiaceae* (NOB) families measured to quantify total AOBs and NOBs. No change in relative abundance or cell viability was measured.

[3] *Nitrosospira* was not measured but the similar *Nitrosovibrio* was instead. No change in relative abundance was measured. With the measured net increase in viable cells, an increase in AOB quantity is estimated

Table 2.2 is a summary of the levels of change of the data presented in Table 2.1 over the corresponding temperature change strategies. Upward arrows represent an increase in the statistic, downward represents decrease, and the change is measured relative to the original statistic at the initial temperature. Due to differences in reactor design, water quality, controls, and methods, the studies cannot be directly compared against each other, but a relative comparison may be useful for identifying trends. For each AOB or NOB, the change represents a difference in *relative* abundance. The trends that are associated with temperature reduction, as outlined previously, include the development of a thicker biofilm and relatively unchanged proportions of AOB. Hoang et al. (2014a) reported different results. During their experiment, two MBBRs were tested with biofilms of differing age. In response to cold-shock, the more mature biofilm saw a significant decrease in *Nitrosomonas* (the dominant AOB) whereas the younger biofilm saw a significant increase. The difference was theorized to be attributable to differing microbial population and diversity of the biofilms. The increase in NOB *relative* abundance recorded may therefore be partially attributable to differing AOB abundance data.

It should be noted that some of the articles reviewed that investigated suspended growth nitrification at low temperatures would vary the temperature from 20^o down to 10^o C, whereas others vary the temperature between 10^o and 1^o C. This difference will confound the comparison between the suspended and attached growth studies to some degree, though the similarities can still be observed. Ahmed et al. (2019) performed bench-scale MBBR experiments to find the natural threshold temperature at which nitrifying biofilms are significantly inhibited. The results indicated that this threshold temperature is between 2^o C and 4^o C. This "threshold temperature" was reflected in proceeding studies (Ahmed & Delatolla, 2020 & 2021) but all these studies were completed at a lab-scale in similar conditions and the conclusion has yet to be tested on a pilot scale or with differing conditions.

An interesting result of Young et al. (2017a), and Ahmed & Delatolla (2021) is that the percentage of viable biomass was seen to increase in response to a gradual temperature decrease. In this case the kinetics of death and detachment mechanisms are likely reduced to a greater extent than the growth and survival mechanisms – leading to net biofilm accumulation.

In the same experiment, Young et al. (2017a) recorded a significant decrease in microbial diversity with the decrease in temperature, theorizing this was simply due to the fact that a temperature of 1° C is less suitable to the greater portion of bacteria that are present at 20°C. Different results were, however, observed by Ahmed & Delatolla (2021) – where no statistical difference in diversity was measured. This may be due to the fact that Young et al (2017a) began at 20°C, allowing for a more diverse initial condition than was allowed at the 10°C initial condition of Ahmed & Delatolla (2021).

Despite the complexity of the various effects of low temperature, it is common practice in wastewater treatment to use the relatively simple Arrhenius equation (Equation 2.5) to predict differences in biological processes over changes in temperature. Generally, a unique Arrhenius temperature correction factor 'θ' can be applied to each biomass type or biological process, such as heterotrophic growth and organic removal in lagoons or nitrification by a nitrifying biomass in a nitrification reactor (Metcalf & Eddy Inc., 2014). Typically, a temperature range is identified where a certain θ value is valid. Outside of these ranges, θ might be varied to maintain predictive accuracy (Oleszkiewicz & Berquist, 1988). The value might differ depending on whether the reaction is limited by substrate or DO – though generally nitrification reactors are supplied with sufficient aeration to not be DO-limited. The equation is used most accurately for stable bacterial communities in a state of quasi-equilibrium at a given temperature and therefore should be used with caution as biofilms are dynamic communities in contact with sometimes rapidly changing wastewater parameters.

$$\mu_2 = \mu_1 \theta^{T_2 - T_1} \qquad (2.5)$$

'μ' denotes nitrification rate and 'T' denotes temperature, and the subscripts *1* & *2* denote the initial (reference) values and final (predicted) values, respectively.

Typical Arrhenius correction factors (θ) for nitrifying biomass have historically been between 1.072 and 1.127 (Hwang & Oleszkiewicz, 2007); however, 1.072 is widely recently accepted for designing wastewater treatment plants (Water Environment Research Foundation, 2003; Hwang & Oleszkiewicz, 2007). Hwang & Oleszkiewicz, (2007) indeed used $\theta=1.072$ successfully in a suspended growth reactor to predict the response to a gradual decrease in temperature from 20^o C to 10^o C. Interestingly, Young et al. (2017a) used $\theta = 1.086$ (from 12^o C to 7.4^o C) which falls into the accepted range for suspended growth nitrification reactors (1.072 - 1.127) reviewed by Hwang & Oleszkiewicz, (2007), though the temperature ranges differ somewhat. The temperature correction factor determined in Young et al. (2017a) is very similar to the results of Rusten et al. (1995), who found a factor of 1.09 for an MBBR between 12.4^o C to 7.8^o C.

When predicting the results of a decrease in temperature, using a larger value for θ corresponds to a greater predicted decrease in activity. Because the biofilms in the MBBR reactors cited in this review are generally reduced to lower temperatures than those used to develop the θ value in Hwang & Oleszkiewicz, (2007), it is understandable that a higher θ values should be used. Generally, the experiments that determine θ values deal with acclimatized bacteria – where the experiments include changing the temperature, allowing bacteria to recover, then measuring θ values – or else they measure θ values while gradually decreasing temperature, reducing the need for stress recovery at all (Hwang & Oleszkiewicz, 2007). Therefore, the θ values measured are meant for quasi-equilibrium data and generally not well applied to sudden temperature change. Delatolla (2009b) developed an equation for θ to be used in combination with Equation 2.5 to account for the effects of exposure time to low temperatures, and this has been used with some success to predict more transient data measured during a temperature change (Delatolla, 2010; Young et al., 2017a; Ahmed et al. 2019). Data for this modification is presented in Table 2.3 but is otherwise not discussed for the sake of brevity. It is important to note that the consistent findings of the articles here summarized is that biofilms subject to cold-shock remove TAN at significantly reduced efficiency, and measure significantly less recovery of efficiency following the temperature decrease, as compared to biofilms subject to gradual temperature decrease.

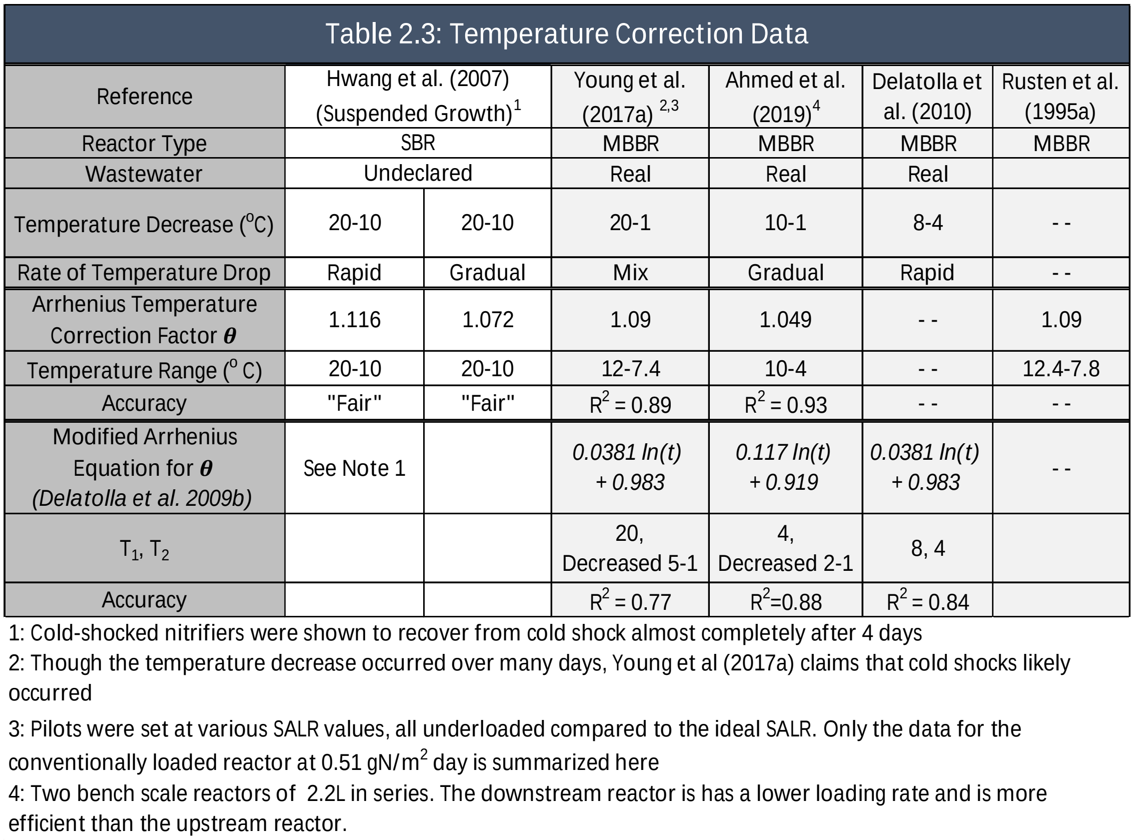

Table 2.3: Temperature Correction Data

Reference	Hwang et al. (2007) (Suspended Growth)[1]		Young et al. (2017a) [2,3]	Ahmed et al. (2019)[4]	Delatolla et al. (2010)	Rusten et al. (1995a)
Reactor Type	SBR		MBBR	MBBR	MBBR	MBBR
Wastewater	Undeclared		Real	Real	Real	
Temperature Decrease (^{o}C)	20-10	20-10	20-1	10-1	8-4	- -
Rate of Temperature Drop	Rapid	Gradual	Mix	Gradual	Rapid	- -
Arrhenius Temperature Correction Factor $\boldsymbol{\theta}$	1.116	1.072	1.09	1.049	- -	1.09
Temperature Range (^{o} C)	20-10	20-10	12-7.4	10-4	- -	12.4-7.8
Accuracy	"Fair"	"Fair"	$R^2 = 0.89$	$R^2 = 0.93$	- -	- -
Modified Arrhenius Equation for $\boldsymbol{\theta}$ *(Delatolla et al. 2009b)*	See Note 1		*0.0381 ln(t) + 0.983*	*0.117 ln(t) + 0.919*	*0.0381 ln(t) + 0.983*	- -
T_1, T_2			20, Decreased 5-1	4, Decreased 2-1	8, 4	
Accuracy			$R^2 = 0.77$	R^2=0.88	$R^2 = 0.84$	

1: Cold-shocked nitrifiers were shown to recover from cold shock almost completely after 4 days

2: Though the temperature decrease occurred over many days, Young et al (2017a) claims that cold shocks likely occurred

3: Pilots were set at various SALR values, all underloaded compared to the ideal SALR. Only the data for the conventionally loaded reactor at 0.51 gN/m^2 day is summarized here

4: Two bench scale reactors of 2.2L in series. The downstream reactor is has a lower loading rate and is more efficient than the upstream reactor.

2.4. Submerged Attached Growth Reactors (SAGR)

2.4.1. Description

SAGRs are set into the ground, with the volume (bed) being filled with porous, clean stone (the biofilm media), and the base being a plastic liner to prevent infiltration of natural groundwater or exfiltration of wastewater (Nexom, 2021b). The SAGR is topped by a layer of insulating material that may be reclaimed shredded rubber, mulch, or various other materials. The insulating material is designed to protect cell piping and prevent ice formation from reducing treatment volume. Lagoon effluent is introduced by a distribution chamber, travels through the clean stone media, and is collected at an effluent chamber. Aeration is proved by bubbling, utilizing air plumbing at the base of the reactor. The SAGR was specifically designed for post-lagoon nitrification but has also been shown to have the potential to treat for chemicals of emerging concern and other micropollutants (Anderson et al., 2020) as well as provide polishing for BOD, TSS, and moderate disinfection (Nexom, 2021b). Influent passes through the reactor in a semi-plug-flow regimen causing greater biofilm growth upstream in the reactor than downstream. To ensure the whole bed has sufficient biomass to be utilized for nitrification, in post-lagoon applications, generally a second influent distribution chamber is installed approximately in the middle of the bed. During favorable conditions this chamber is used to grow excess biofilm in the downstream portion of the bed, then as conditions (temperature) become less favorable, distribution is switched back to the main chamber allowing the whole bed to contain biomass and be used during winter. This is Nexom's patented "Step Feed" process.

The importance of the Step Feed process should not be underestimated. The implementation of the process was part of the early development of the SAGR. The unpublished reports that were generated utilizing Step Feed (Nelson Environmental, 2009; Oleszkiewicz & Hwang, 2010), demonstrating TAN removal of 98-100% in full scale application treating lagoon effluent at temperatures between 0-2^{o}C formed the basis of development of the regulatory acceptance and design basis for the SAGR such as in Iowa (Iowa Department of Natural Resources, 1987, 2016) and the foundational published literature on the SAGR (such as Higgins et al., 2017). In Nelson Environmental (2009 – unpublished), the importance of the Step Feed process was demonstrated by comparison of two parallel, identical SAGR trains, one operated with Step Feed, and the other acting as a control with no Step Feed. Operation was otherwise identical. As mentioned above, the SAGR operated with Step Feed demonstrated TAN removal of 98-100% (effluent TAN being less than 0.04 mg/L), whereas the control experienced a significant loss of TAN removal efficiency (over 50%) due to the decrease in temperature (~10^{o} to <1^{o}C over approximately one month) at the onset of winter in Steinbach, Manitoba. During this time effluent TAN in the control train rose to over 15mg/L, and it took the train over two months to acclimatize to cold temperatures and recover to provide full treatment again. In another study, following the regulatory approval of the SAGR and development of design guidelines by the Iowa Department of Natural Resources (2016), Mattson (2018a, 2018b) observed that a full-scale SAGR installation in Walker, Iowa only exceeded regulatory ammonia limits at the onset of cold weather prior to the annual implementation of the Step Feed process.

Generally, BOD polishing occurs primarily in the upstream zone due to the faster kinetics, with nitrification primarily occurring downstream of the BOD-consuming growth, where competition with the faster growing heterotrophs is reduced. This is illustrated by the biofilm differences shown in Figure 2.7. The influent may be directed along the length, width, or depth of the SAGR (these orientations having different cross-sectional areas) depending on lagoon effluent quality, in order to control substrate and BOD flux through the cross-section of the bed.

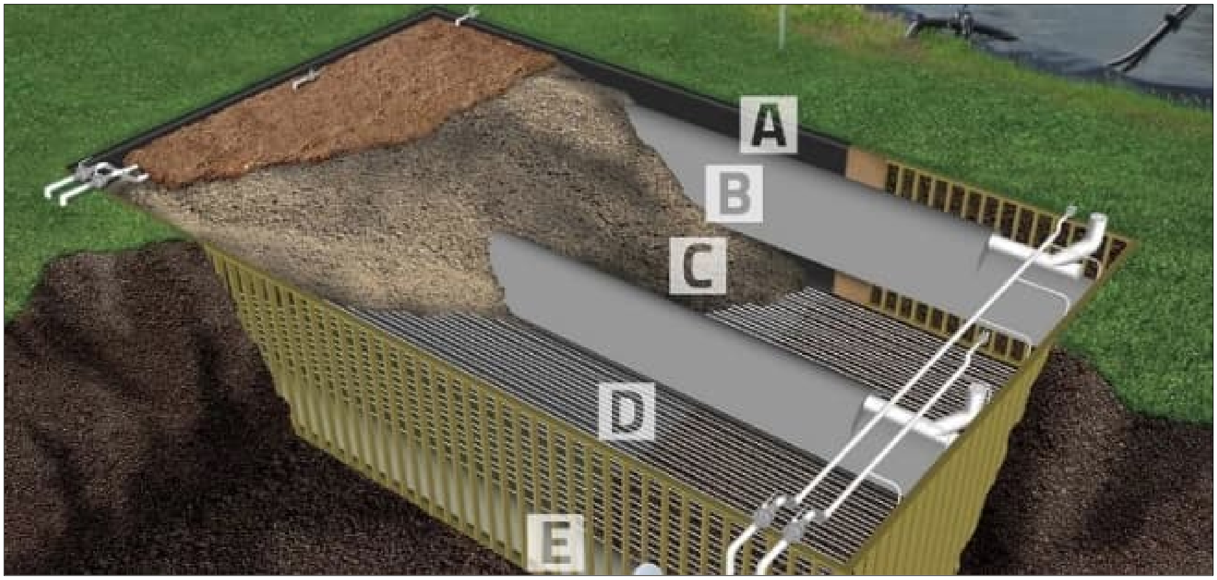

Figure 2.6: SAGR Diagram – Courtesy of Nexom (Nexom, 2021b)

A. HDPE liner prevents infiltration while sacrificial walls help the SAGR maintain its shape during construction.

B. Influent distribution chamber ensures influent is spread across the width of the bed.

C. Clean stone provides surface area for bacteria while preventing temperature shock. Mulch-covered for insulation.

D. Linear aeration covers the base for fully-aerobic conditions.

E. Effluent collection chamber is gravity fed to minimize operations and maintenance efforts.

Figure 2.7: Coarse Gravel Biofilm Growth Scenarios - Courtesy of Nexom

2.4.2. History of SAGR and Similar Technologies

Subsurface Flow (SSF) wetlands are perhaps the oldest technology directly comparable to the SAGR. The text “Treatment Wetlands” (Kadlec & Knight. 1996) provides a useful summary of these. The construction is shown in Figure 2.8. The development started as early as 1976 in America, with the treatment theory used for design being drawn directly from the more well-developed Surface Flow (SF) wetlands. The design uses simple kinetic equations for each constituent being reduced along with empirically determined constants to size the cells, and the rest of the design consists of hydraulic calculations to ensure head loss does not cause water levels to rise to the surface, selection of length-to-width ratios, media size, and the selection of plants to seed in the cells. SSF wetlands were not initially aerated and therefore did not typically *directly* target nitrification, however, it is well understood that wetlands reduce TAN by means of bacterial oxidization (nitrification) and the use of TAN as a preferred nutrient by wetland plant life. The primary constituents reduced in the design method given by Kadlec & Knight (1996) are BOD and TSS, as these constituents are far more efficiently removed in SSF wetlands, however, design information is provided for TAN reduction as well as many other constituents that may be potentially targeted. The kinetic equation given for TAN-removal design is empirical, not being based on biological nitrification kinetics and is acknowledged to include TAN removal action of plants as well as bacteria.

The development of wetland technologies has since evolved and there are now current installments of successful aerated SSF constructed wetlands (Higgins et al. 2017).

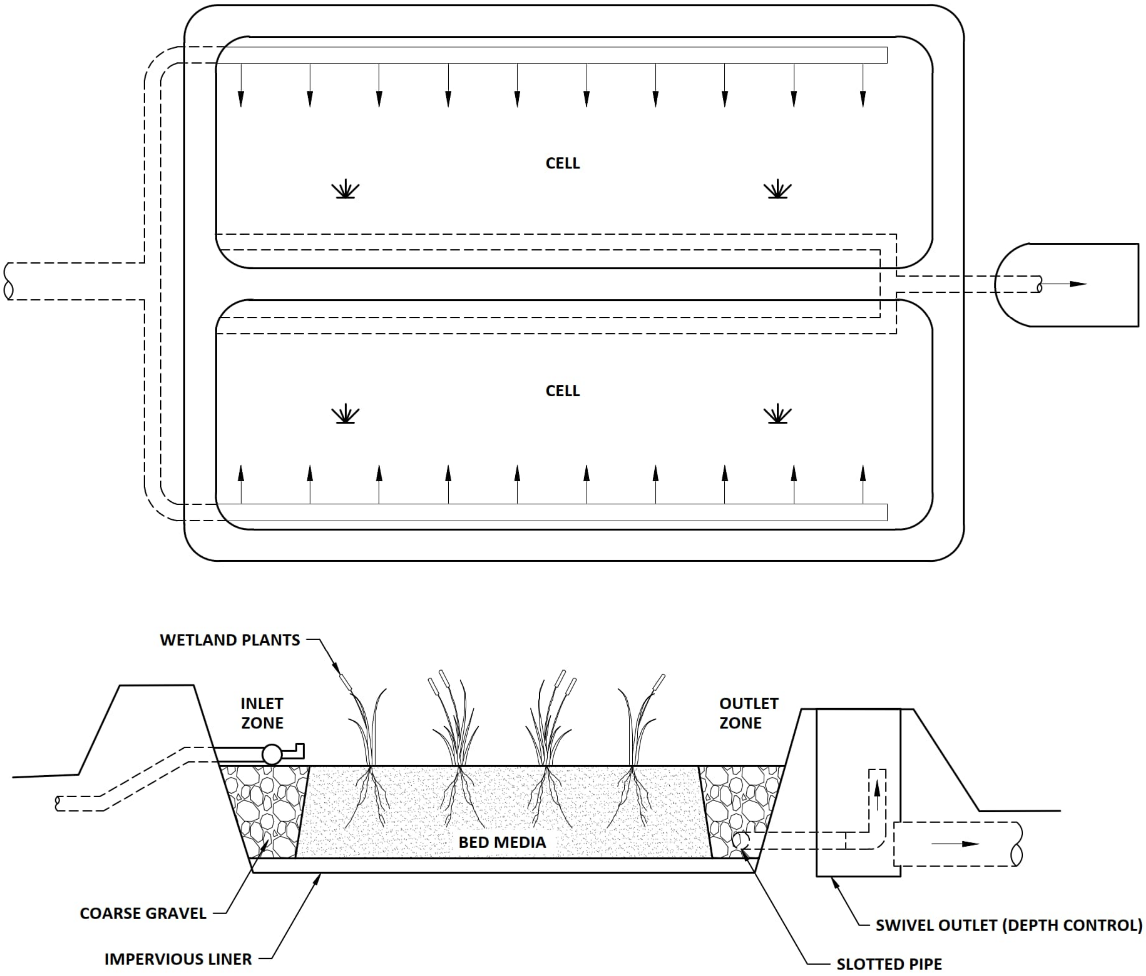

Figure 2.8: Subsurface Flow Wetland (Adapted From Kadlec and Knight 1996)

The “Wastewater Stabilization Ponds” textbook (Spellman & Drinan, 2014) provides a short summary of lagoon and wetland retrofit technologies targeting nitrification. Many of these utilize the principles of attached growth summarized previously. Two technologies of notable similarity to the SAGR that are presented in this text are the “Nitrification Filter Bed” and the “Aerated Rock Filter”.

The Nitrification Filter Bed (developed in Reed et al. 1995) is a gravel bed constructed on the surface of a wetland (either SF or SSF), over which influent is distributed by sprinkler and flows downward into the wetland. The design utilized the principles of a trickling filter. The major disadvantages as compared with the SAGR are the reduced hydraulic conductivity (because gravel is used rather than clean stone), the susceptibility to freezing in cold winters (being an exposed bed), and the low DO control.

The Aerated Rock Filter (developed in Mara & Johnson, 2006) is a reactor very similar in principle to a SAGR. At the time of this experiment, the authors claim that unaerated filters of the same design had been in use for approximately 30 years for effective BOD and solids removal, but were limited in application due to the formation of anaerobic conditions and correspondingly high TAN concentrations in the filter effluents. The filter was aerated in the experiment to address this issue and compared with a parallel unaerated filter. The reactors consisted of a limestone gravel bed of pilot-scale with the aerated reactor having a single fine bubble diffuser located at the inlet. Effluent from a pilot-scale facultative pond was passed through the filters and the aerated filter successfully achieved nitrification, noting a reduction in TAN and an increase in nitrate in the effluent. No nitrification was noted in the unaerated filter. In addition to nitrification, the aerated reactor achieved statistically significant increases in BOD, TSS, and fecal coliform removal as compared to the unaerated filter. A follow up study by the same researchers (Johnson & Mara, 2007) found that the aerated rock filter similarly outperformed a constructed wetland. From these results it is clear that optimizing the mechanisms of this simple reactor may provide a very desirable and cost-effective nitrification retrofit to lagoon-based facilities.

The major differences between the Aerated Rock Reactor and a SAGR include the optimized hydraulics and aeration design of the SAGR. Using larger clean rocks with no fines allows greater hydraulic conductivity and biofilm growth, whereas the Aerated Rock Filter used gravel in an attempt to provide filtration action. The disadvantage of including aggregate fines for filtration is that the reactor will more likely become “clogged” by biofilm. The DO is better optimized in the SAGR as well, as the aeration grid used in a SAGR provides oxygen throughout the bed to efficiently maintain kinetics and keep the reactions from being DO-limited. The Aerated Rock Filter, for reference, measured effluent DO concentrations as high as 8 mg/L (Mara & Johnson, 2006), which is over twice the recommended concentration of 3-4 mg/L recommended by Metcalf & Eddy (2014) for submerged aerated attached growth reactors for nitrification. Other major differences include the Step Feed process to enhance cold-weather performance, the influent distribution chambers for even distribution, the liner and insulating top layer, and the proprietary process/treatment design methods developed by the supplier.

The “Eco-Engineered Bioreactors: Advanced Natural Wastewater Treatment” textbook by Higgins et al. (2017) summarizes the modern state of many of these technologies and their developments admirably. Noting that the basic construction of these reactors is essentially similar, the category “Eco-Engineered Bioreactors” (EEBs) is applied to them and it is noted that, over many case studies of reactors of similar construction, ammonia removal is generally in the 30-70% range when unaerated but is often increased to 98-99% TAN removal when aerated. This text deals with two EEBs in particular, claiming both have evolved from the engineered wetland/rock bed reactors described above. These two are the BREW Bioreactor (BBR) and the SAGR. Other technologies are mentioned but outside the scope of this review.

The BBR is an aerated gravel bed that is usually oriented in a downward flow regimen with aeration from the base. Similar to the SAGR, it includes a top “mulch” layer and there are even variations that include a step-feed-like system by which a second distribution system at mid-depth “primes” the bed with bacteria prior to cold weather before distribution is switched back to the top system (Higgins et al. 2017). The construction of the BBR differs from the SAGR primarily in that it is designed to treat raw wastewater and is generally orientated for a vertical flow with some exceptions, whereas the SAGR is designed primarily as a lagoon retrofit specifically for ammonia reduction and is generally orientated for horizontal flow, with some exceptions. The BBR also has variations with and without wetland plant inclusion. Those with wetland plants may have increased treatment due to the plants but also increased maintenance on account of the harvesting needs (Higgins et al. 2017)

The BBR program began development in the 1990s, and the first pilot SAGR was installed in Steinbach, Manitoba in 2007, as a lagoon retrofit targeting nitrification only. The results were promising, achieving effluent TAN concentrations of approximately 0.1 mg/L in temperatures as cold as 1^{o}C, as well as polishing cBOD and TSS to near the detection limits, all of which is now advertised by Nexom (2021b), along with significant levels of disinfection which have been measured in pilot programs since.

In addition to pilot-scale and full-scale SAGRs, research may be performed at a “Laboratory” or “Bench” scale. A photograph of typical laboratory-scale SAGR reactors in use at the University of Manitoba is provided in Figure 2.9 below, courtesy of Nexom. For studies performed at laboratory scale, see Pedros et al. (2008), Gu et al. (2007), and Shannon et al. (2014).

Figure 2.9: Lab-Scale SAGR Photograph - Courtesy of Nexom

2.4.3. SAGR Design Background

The design method most obviously applicable that is presented in Metcalf & Eddy (2014) Section 7-7 is based on limiting substrate flux and monod-style utilization equations. In practice, however, the many variables of such an analysis make it impractical, and empirical design approaches with conservative assumptions and safety factors are preferred. These are generally based on Total Kjeldahl Nitrogen (TKN - the sum of TAN and organically-bound nitrogen), loading rates per unit volume of SAGR bed and BOD flux through the flow cross section. Nexom’s design method for the SAGR is proprietary and out of the scope of this literature review.

In general, SAGRs are sized based on TKN loading rates, which are kept low enough to avoid effluent TAN breakthrough in cold weather when kinetics decrease, and to therefore provide year-round nitrification needed to consistently meet ammonia discharge permit requirements. According to Nexom in 2011, this maximum loading rate was reported at 8.3 g-TKN/day per cubic meter of gross SAGR volume (0.52 lbs TKN/1000ft^3-day) for systems with water temperatures below 1 °C and effluent ammonia requirements of < 2 mg/l. (US EPA, 2021). Nexom has since continued to optimize the design of the SAGR to use higher loading rates and therefore reduce volume and the cost of construction.

2.4.4. Iowa State Design

Some local governments have published SAGR design guidelines that are generally more conservative than Nexom's methods. The Iowa Department of Natural Resources, for instance, has produced such a document (with accompanying MS Excel-based tool) that is summarized below. See Iowa Department of Natural Resources (2016) and Iowa Department of Natural Resources (1987).

The design flow is the 30-day average wet weather flow and a corresponding minimum system hydraulic retention time of 24 hours is specified. This design flow is also used to calculate constituent loading rates in the following paragraphs. Redundancy requires that at least 2 SAGR beds be installed, each with a Step Feed system dividing each bed into upstream and downstream zones for a minimum total of 4 zones. It should be noted that the Hydraulic Retention Time (HRT) is calculated by dividing the volume of the voids in the SAGR bed (empty space between rocks) by the design flow. See Equation 2.6.

$$HRT = \frac{V_p}{Q_{AWW}} = \frac{V \cdot \eta}{Q_{AWW}} \tag{2.6}$$

V_p = Void (Pore) Volume

V = SAGR Volume

η = Porosity (ratio of bed void volume to total volume)

Q_{AWW} = 30-day Average Wet Weather Flow

Other design requirements include simple calculations ensuring that $cBOD_5$ flux through the cross-section perpendicular to the flow be less than 12.2 kg-$cBOD_5$/100m^2-day (2.5 lb/100ft^2-day) and the TKN loading rate be less than 6.4 g-TKN/day per cubic meter of gross SAGR volume (0.4 lb-TKN/1000ft^3-day).

If the SAGR design simultaneously meets these HRT, cBOD, and TKN requirements at the design flow, the Iowa Department of Natural Resources is likely to accept the design. Modifications to this design method may be considered on a case-by-case basis and may require additional performance monitoring and the provision of a contingency plan for performance failure.

This document additionally provides construction specifications including requirements for rock bed size and gradation, a minimum maintained DO concentration of 3 mg/L. Minimum blower and electrical system redundancy, material specification for the liner and top insulation layer, length-to-width ratios, required monitoring and sampling protocol, and a reference to standard details.

2.4.5. Eco-Engineered Bioreactor Design

Higgins et al. (2017) consider the SAGR to be a type of Eco-Engineered Bioreactor (EEB) in their textbook "Eco-Engineered Bioreactors: Advanced Natural Wastewater Treatment". In this text they give general design methods for EEBs that may be applicable to the SAGR.

The starting point is a flow mass balance that should – if possible – include the effects of precipitation and evapotranspiration. The average flow is then used to calculate the HRT using the same method as given in Equation 2.6, but without reference specifically to the 30-day average wet weather flow. Flow and constituent flux and loading rate values, corresponding to the cross-sectional area perpendicular to the flow and the total bed volume, respectively, are then generated by simple calculations.

Load Limit Method

After these parameters are developed, the reactor may simply be sized using minimum and maximum HRT and constituent flux and loading rates, similar to the Iowa method presented above. No typical design values are specifically given for the SAGR in the textbood but the values can simply be determined by pilot testing.

Reaction Kinetics Method

A more complicated method of sizing the reactor is by using reaction kinetics and assuming some mix and flow scenario (such as complete mix, plug flow, tanks in series, etc.). A design suggestion in the text for reactors such as the BBR or SAGR is to model the kinetics, using both plug-flow assumptions and complete-mix assumptions, then calculate the footprint area required (using both methods) by assuming influent and effluent concentrations, a reactor depth, and a first-order rate constant that may be determined experimentally. Once the reactor has been sized by both methods, the actual required size may be selected within the range provided by these methods, because BBRs and SAGRs do not perfectly behave as either a plug-flow reactor or completely mixed reactor. The equations that are given for determining the footprint area required for the complete mix and plug flow scenarios are given below as Equations 2.7 and 2.8, respectively. The equations are meant to be applied for many constituents of concern for a system treating raw sewage, but for the SAGR, they must only be applied in relation to TAN removal.

$$A = -Q \cdot \frac{ln\left(\frac{[C_o]}{[C_i]}\right)}{\varepsilon \cdot h \cdot k_{PFR}} \qquad (2.7)$$

$$A = Q \cdot \frac{\frac{[C_i]}{[C_o]} - 1}{\varepsilon \cdot h \cdot k_{CSR}} \qquad (2.8)$$

A = Required Footprint Area

Q = Design Flow

$[C_i]$ = Influent TAN Concentration

$[C_o]$ = Influent TAN Concentration

ε = Porosity (ratio of bed void volume to total volume)

h = Assumed depth of the Reactor Bed

k_{PFR} = First-Order TAN Removal Rate Constant for Plug-Flow Regime

k_{CSR} = First-Order TAN Removal Rate Constant for Completely Mixed (or Completely Stirred) Regime

Though the design method is provided, relevant typical first-order rate constants are not given in the text and must be determined experimentally.

An important consideration for horizontal flow reactors is to maintain sufficient hydraulic conductivity such that head loss does not cause the water to rise above the gravel surface. It is also noted that BOD flux should be limited (speculative maximum values of 250 and 500 g BOD/m^2-day is given for horizontal flow and downward flow, respectively) to control clogging the reactors with biofilm near the inlet zone.

Other alternative methods of sizing are presented in the text but will not be summarized as there is either little relevance to the SAGR or little application to date for the design of a SAGR or SAGR-like reactor.

2.4.6. Design Summary

Both the Iowa Department of Natural Resources (2016) and the summarized text Higgins et al. (2017) gave simple methods for design using flow and volumetric TAN loading rate limits as well as BOD flux limits, and the Iowa document also provided construction specifications. More complex design theories include what is above called the "Reaction Kinetics Method" given by Higgins et al. (2017) and the biofilm-flux-theory based methods presented in Metcalf & Eddy (2014). These more complicated methods are not very practical due to the number of variables included for which typical design values do not exist in the literature. For the purposes of conceptual design, the simple "Load Limit Method" that is used described in Iowa Department of Natural Resources (2016) and Higgins et al. (2017) is likely sufficient, and – because the SAGR is a proprietary technology – detailed design and optimization will generally, in practice, be completed by Nexom engineers.

It should be noted, however, that the Iowa Department of Natural Resources (2016) method is currently understood to provide a design that is perhaps unnecessarily conservative. Mattson et al. (2018), for instance, in completing research for a M.Sc. thesis, studied a SAGR system installation in the town of Walker, Iowa and concluded that sufficient treatment would very nearly be achieved were the total system, consisting of 4 SAGR beds, were reduced to just 2 beds. It is useful to note again, here, that some deviation from the provided design guidelines is allowed by Iowa Department of Natural Resources (2016), to be determined on a case-by-case basis, so long as other conditions are met such as additional performance monitoring and the provision of a contingency plan for performance failure. Nexom is actively completing research intended to be used to further optimize SAGR sizing guidelines.

2.5. SAGRs in Research Literature

Although research into post-lagoon nitrification reactors largely consists of studies regarding the MBBR, there are some notable studies and articles regarding the SAGR which are here summarized. A Wastewater Treatment Facility (WWTF) consisting of two lagoon cells and a SAGR retrofit upgrade in the City of Kingsley, Iowa, received flows between 0.131 mega gallons per day (MGD) during dry weather, and 0.3 MGD during wet weather. The design influent TKN was 45 mg/L. The design influent cBOD was 262 lbs/day and the influent temperature could be as low as 0.5^{o}C. This project was featured in the “Innovative Nutrient Removal Technologies: Case Studies of Intensified or Enhanced Treatment” report (US EPA, 2021). The retrofit was a well-acknowledged success, and after over 3 years of monitoring, only 2 limit exceedances were reported, both being attributable to lag or operator error.

A lagoon-based Wastewater Treatment Facility with a SAGR retrofit for TAN removal in Walker, Iowa was studied by Rebecca Mattson et al. (2018) as a M.Sc. thesis project. Two SAGR trains were installed, with each train consisting of a primary and secondary SAGR with a combined HRT of over 26 hours (each cell had over 13 hours HRT). The study collected regular controlled samples for a period of 2.5 years. The SAGRs maintained an average TAN removal efficiency of approximately 94% throughout, and a removal efficiency of 97% was recorded during one notable cold period. The secondary SAGRs in each train were designed to have more ideal conditions for nitrification, however, in reality, the primary SAGRs still completed the majority of the nitrification. There were no limit exceedances in the duration, and it was found that – even were the secondary SAGRs removed from each train, there would have been only 4 limit exceedances during the entire study. This suggests that the design has a safety factor of approximately 2 and was overly conservative. The remainder of the work in this M.Sc. thesis project (Mattson et al., 2018) confirmed the benefits of the step-feed protocol in building a healthy and diverse population of nitrifying microorganisms (including AOAs) and maintaining high levels of TAN removal as compared to operation without the protocol.

Other notable studies include the successful removal of TAN from gold mining wastewater, high in ammonia and cyanide-related compounds (di Biase et al., 2020), and the successful removal of TAN as well as several Chemicals of Emerging Concern (CEC) in cold weather in two full-sized SAGR facilities located in First Nations communities in Manitoba, Canada, where lagoon effluent treated by the SAGRs is commonly at temperatures of 1^{o}C or below during winter operation (Anderson et al., 2020)

2.6. Summary

As need increases for municipal lagoon-based WWTFs to find means of reducing TAN in the effluent discharge, post-lagoon nitrification reactors are an increasingly popular solution. This is particularly true in climates with cold winters where nitrification in lagoons is severely inhibited at low temperature. Two promising reactors in particular, the MBBR and SAGR, are undergoing development to meet these needs. The greatest strength of these reactors is in the fact that they promote the growth of the nitrifying bacteria as biofilms on media that are retained within the reactor. This slows the rate at which nitrifiers leave the reactor and thus allows the reactor to operate at a stable and high biomass equilibrium despite the slow growth rates of nitrifiers in cold conditions.

The Arrhenius equation (usually based on a known nitrification rate at 20^{o}C) is often used to predict nitrification at low temperatures within a design range. Recent studies in the biofilms of MBBRs suggests the temperature correction factor Θ to be near 1.09 (see Table 2.3) for temperatures down to 4^{o}C. Though this method is meant to predict differences in nitrification efficiencies at equilibrium or quasi-equilibrium, a modification to the equation developed by Delatolla et al. (2009b) has been proposed to predict transient data across a temperature change, accounting for the effects of exposure time to low temperatures. These factors and methods were notably used accurately in Young et al. (2017a), though equation used in this study was slightly modified.

The design of the SAGR is proprietary as the reactor is owned by Nexom. Typical design procedures are simply based on maximum volumetric TAN or TKN loading rates (currently typically 12.8 g-TKN/m$^3\cdot$day), maximum BOD flux through the cross-section of the reactor, and sometimes a required HRT. Both the MBBR and SAGR have been shown in several studies to be capable of significant (nearly full) TAN removal in lagoon effluent down to 1^{o}C.

The SAGR has been developed specifically since 2007 at the time of the first pilot but has its roots in the theoretical development of engineered wetlands which has been ongoing for over 25 years (Higgins et al. 2017). The design is still being optimized by Nexom, as it has been noted that some installations may be able to achieve adequate treatment if it were approximately 50% the designed and constructed size (Mattson et al., 2018). This may be due to the fact that the SAGR has been developed in climates with highly variable wastewater temperature and dropping seasonally below 1^{o}C where design parameters must be made conservative. The further development of the SAGR will optimize the size and make it an increasingly feasible and cost-effective retrofit for municipalities struggling to meet TAN limits with lagoon-based WWTFs. This has the potential to significantly benefit small municipalities and other wastewater producers seeking to meet regulatory requirements and increase the security and health of surface water bodies. Exciting developments in the SAGR include applications in gold mine wastewater treatment for cyanide-related compounds (di Biase et al., 2020), and the cold weather removal of some contaminants of emerging concern (Anderson et al., 2020).

2.7. Research Gaps

Areas that have been identified as being in need of further research include:

- Investigation into optimizing the size of the typical SAGR. This may look like an investigation into the maximum volumetric TAN loading rates at which a SAGR can achieve significant TAN removal at various temperatures.
- Investigation into the presence of ammonia-oxidizing species other than AOBs and NOBs – such as AOAs (Mattson, 2018).
- The currently unknown mechanism by which SAGRs typically achieve significant disinfection.
- Investigation into biofilm detachment factors and their kinetics (Barwal & Chaudhary, 2014), and especially for biofilms subject to cold-shock.
- Investigation into the possible link between low SALR design values and a reactor's ability to promote cold-shock recovery in biofilms.
- Investigation into the current theories surrounding symbiotic relationships between nitrifiers and heterotrophs in biofilms – and the benefits regarding low temperature resistance (Young et al., 2017a; Kindaichi et al., 2004; Bae et al., 2015; Hibiya et al., 2000; Hoang et al., 2014a; Ducey et al., 2010).

Municipalities in Canada can be expected to benefit from increased research and development of these technologies, as they become more cost-efficient and consistent, allowing municipalities to meet increasingly stringent environmental regulations at low cost.

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CHAPTER 3. INCREASING THE TYPICAL DESIGN VOLUMETRIC AMMONIA LOADING RATE OF THE SAGR IN WARM CONDITIONS

Abstract

The Submerged Attached Growth Reactor (SAGR) is a proprietary technology owned by Nexom. It is essentially a synthetically lined cell filled with porous, clean stone (the biofilm media), and is aerated from the base. It generally includes two influent distribution chambers for lagoon effluent and one outlet structure. The use of the inlets alternates according to Nexom's patented "Step Feed" strategy. The SAGR has been shown through extensive testing to be a viable and practical technology for use in retrofitting lagoon-based wastewater treatment facilities to provide TAN removal in climates subject to cold winter conditions. It also provides cBOD polishing, TSS polishing, and disinfection.

The SAGR has been developed and optimized for cold conditions where lagoon effluent temperature might fall below 1^{o}C. The modern typical design loading rate developed under these conditions is 12.8 g-TKN/m$^{3}\cdot$day (0.8 lb-TKN/1000ft$^{3}\cdot$day). It is therefore hypothesized that a pilot SAGR receiving lagoon effluent at temperatures over 20^{o}C will consistently remove over 99% of the influent TAN when operated at an ammonia loading rate of approximately 32g-TKN/m$^{3}\cdot$day (2 lb-TKN/1000ft$^{3}\cdot$day). This pilot study observed SAGR operation at influent temperatures greater than 20^{o}C (simulating moderate-to-warm climates) at an average loading rate of 31.1g-TKN/m$^{3}\cdot$day (1.96 lb-TKN/1000ft$^{3}\cdot$day) and recorded nearly 100% removal of TAN during stable operation. This is a notable increase over the current typical design value of 12.8 g-TKN/m$^{3}\cdot$day (0.8 lb-TKN/1000ft$^{3}\cdot$day).

3.1. Introduction

3.1.1. Background

Many rural towns and municipalities in Canada treat wastewater using lagoon-based wastewater treatment facilities (WWTF). Lagoon-based WWTFs typically rely on biological nitrification (the oxidation of ammonium to nitrite and the oxidation of nitrite to nitrate by autotrophic bacteria) to remove ammonia.

Total Ammonia (Termed Total Ammonia Nitrogen, or TAN, when measured as mass of Nitrogen) is the sum of ammonia (NH_3) and ammonium (NH_4^+). TAN can have adverse effects on aquatic environments. It is directly toxic to fish and other aquatic life, being more toxic in the unionized form NH_3 than in the ionized form NH_4^+ (Constable et al. 2003). The speciation of the NH_3 / NH_4^+ balance depends on temperature and pH. TAN also contributes to nutrient enrichment and eutrophication of aquatic environments. Regulatory bodies have imposed increasingly stringent ammonia concentration limits on the discharges of WWTFs in recent years. One notable example is the federal Wastewater Systems Effluent Regulations (Canada Gazette, 2012). Many rural WWTFs risk exceeding these limits when treating wastewater using lagoons only, especially in winter months. Therefore, it is increasingly beneficial for WWTFs to install treatment systems downstream of the lagoons to achieve nitrification.

The Submerged Attached Growth Reactor (SAGR) is a biological nitrification system capable of removing nearly 100% of influent TAN, even in temperatures below 1°C (Nexom, 2021). A SAGR train generally consists of two aerated clean rock beds (zones 1 & 2), in series and often together in a single cell. A layer of mulch, woodchips, or shredded rubber tires is placed on top for protection and to reduce treatment volume lost to ice formation in the winter. The rock bed acts as media, providing surface area for fixed growth of bacterial biofilms. Under normal operation, lagoon effluent is distributed through the upstream portion of zone 1 and flows through zones 1 and 2 before being collected at the downstream end of zone 2. Nitrifying (autotrophic) biofilms suffer a loss of efficiency in high-BOD environments as they are outcompeted by heterotrophic micro-organisms. Therefore, in preparation for winter months, the Step Feed process is employed, during which lagoon effluent, typically low in BOD at this point, is fed directly to zone 2 to promote the growth of nitrifying biofilm in zone 2 only, bypassing zone 1 entirely. As temperatures in the lagoon cool and BOD rises, flow in the SAGR is returned to normal operation with influent directed to zone 1 and zone 1 feeding zone 2. In this way, a robust biofilm is prepared in both zones prior to winter, when temperatures are known to decrease, and BOD is known to increase. Zone 1 is used in cold months primarily to remove BOD (though nitrification still occurs in it) and zone 2 is provided more ideal conditions (along with a robust biofilm) to complete nitrification without being significantly hindered by BOD.

At temperatures above 20°C, SAGR conditions are favorable for nitrification as lagoon effluent generally has a relatively low BOD and this temperature is favorable for AOBs and NOBs. Recent research has suggested that typical SAGR design is overly conservative (resulting in SAGRs larger than they are required to be) and that the design might be optimized (Mattson et al., 2018). These overly conservative design parameters are optimized for cold conditions and are expected to be further optimizable in warm conditions.

3.1.2. Objectives

The goal of this experiment was to load a SAGR bed at 32g-TKN/$m^3\cdot$day (2 lb-TKN/1000$ft^3\cdot$day), which is approximately 2.5 times higher than the typical design rate, and measure the TAN removed to determine if TAN can be fully removed at the increased loading rate. For reference, TKN is the sum of TAN and organically-bound nitrogen, and TKN is generally similar to TAN in lagoon effluent (see Section 3.3.7). This was done during summer months when nitrification is most efficient. The lagoon effluent was directed to zone 2 of the west SAGR alone. The reduced volume achieved by using only one zone corresponds to an increased loading rate per unit volume for a given flow rate, which allowed the loading rate to be increased far beyond the original design rate achievable with the existing pumps and equipment.

3.2. Materials and Methods

3.2.1. Materials

The SAGR pilot in Blumenort, Manitoba consists of two SAGR trains (east train #1 and west train #2) in parallel, each with 2 zones as described above. They are installed on the site of the Rural Municipality of Hanover, Blumenort Wastewater Treatment Lagoons. The lagoon system consists of a single primary cell, two secondary cells, and two storage cells. Lagoon secondary cell effluent is pumped to a small building from which controlled volumes can be directed to each train as desired. The influent enters the building into a 1000L “splitter” tank which overflows into two 1000L “influent” tanks, each of which is directed to its corresponding SAGR train. Lagoon effluent can be sampled and dosed with ammonium-chloride

(NH_4Cl) from within the building before being directed to the SAGR trains. SAGR effluent is then pumped back into the building whereby it too can be sampled before being pumped back into the lagoons. Gate valves accessible at grade near the SAGR trains allow the influent flow to be opened and closed to each zone of each SAGR as required.

Each SAGR has a total volume of $204m^3$ ($7204ft^3$) and Nexom typically uses a design loading rate for SAGRs of up to $12.8g\text{-}TKN/m^3\cdot day$ ($0.8\ lb\text{-}TKN/1000ft^3\cdot day$) as a conservative design parameter. During this experiment, flow was shut off to both zones of the east SAGR train and to zone 1 of the west SAGR train such that only zone 2 of the west SAGR was operating. Zone 2 of the west SAGR has a volume of $102m^3$. A Surface Area Loading Rate (SALR) was not calculated as the surface area of the clean rock bed is unknown.

3.2.2. Methodology

The experiment spanned from July 11 to August 18 of 2022. During these months BOD concentration is expected to be low in lagoon effluent, so there was little risk of inhibiting nitrification in the single zone used. At the beginning of the experiment, TAN concentration in the lagoon effluent is high, and the loading rate of zone 2 of the western SAGR train was kept high simply by controlling the flow of lagoon effluent to the reactor. Over the course of the experiment the upstream lagoons began to achieve nitrification and effluent ammonia concentration decreased. As it decreased, TAN concentration was supplemented by dosing the influent tank in the building with an NH_4Cl solution mixed on site.

During each visit to the pilot, lagoon effluent was tested using HACH TNT832 kits to determine approximate TAN concentration. The results were used to adjust the flow (and dosing rate) to the SAGR zone, targeting a loading rate of approximately $32g\text{-}TKN/m^3\cdot day$ ($2\ lb\text{-}TKN/1000ft^3\cdot day$). SAGR influent and effluent samples were taken during each visit and analyzed for TAN, orthophosphate (OP), Nitrite (NO_2^-), Nitrate (NO_3^-), and Total Suspended Solids (TSS). Other parameters measured on-site included temperature, pH, and Dissolved Oxygen (DO).

The analysis methodology is as follows:

- *Flow:* Influent flow was estimated using a 5L container and a stopwatch.
- *TAN:* TAN in SAGR influent was first estimated using HACH TNT 832 for operational (load adjustment) purposes, then both SAGR influent and effluent samples were analyzed spectrophotometrically using the Lachat QuikChem 8500 Flow Injection Analysis (FIA) system at the University of Manitoba Environmental Engineering Laboratory. Samples were also periodically delivered to the ALS Environmental certified laboratory in Winnipeg for comparison and validation of the FIA results.
- *OP, NO_2^-, NO_3^-:* SAGR Influent and effluent was analyzed spectrophotometrically using the Lachat QuikChem 8500 FIA system at the University of Manitoba Environmental Engineering Laboratory. Samples were also periodically delivered to the ALS Environmental certified laboratory (ALS) in Winnipeg for comparison and validation of the FIA results.
- *TSS:* SAGR influent and effluent TSS was analyzed according to standard methods at the University of Manitoba Environmental Engineering Laboratory.
- *pH:* SAGR influent and effluent pH were measured in the building on-site using the Hanna HI98128.
- *DO and Temperature:* SAGR influent DO and temperature were measured in the influent tank in the building on-site using a YSI Handheld Optical Dissolved Oxygen Meter. SAGR effluent DO and temperature were measured using a YSI Handheld Optical Dissolved Oxygen Meter at the outdoor SAGR effluent manhole, with the probe directly in the effluent pipe such that no time was given for the effluent to change in DO or temperature in the manhole.

HACH TNT832 kits were used to test the lagoon effluent, and approximate calculations were completed using Microsoft Excel to determine the flow rate and dosing rate required to achieve the desired load rate. The flow was then adjusted to suit using a 5L container and a stopwatch. The actual loading rate was later calculated based on FIA results for TAN and the set flow rates. Flow was adjusted using a gate valve on the influent PVC piping system. Throughout the experiment, the approximate nature of the HACH kit testing, on-site calculations, and flow measurement led to varying results in actual loading rate, with an average actual loading rate of 31.1g-TKN/m^3·day (1.96 lb-TKN/1000ft^3·day). After TAN concentration in the lagoon effluent decreased to a point where NH_4Cl dosing was started to supplement it (July 28), both dosed and non-dosed lagoon effluent were tested using HACH TNT832 kits.

The pilot plant is equipped with a single positive displacement blower motor capable of conveying 56 standard cubic feet per minute (scfm) to the SAGR trains. When all zones of both trains are open, the blower can supply 14 scfm to each zone. During the first portion of the experiment, the air flow to all zones except zone 2 of the west SAGR was reduced such that the flow to this zone could be increased to 28scfm. On July 22, however, low Effluent DO measurements prompted a change in air flow as more air flow to the zone of interest was desired to increase the DO-governed nitrification reaction rate limit. At this point air flow to all zones except the west SAGR was closed. After this, measured air flow rates to this zone were between 28 and 30 scfm for the remainder of the experiment, however, a new flow meter was required to be installed to measure the increased flows and it is expected that the flow meter was faulty. The assumed actual air flow rate based on the capacity of the blower was between 48 and 56 scfm for the remainder of the experiment. The effluent DO was consistently measured to be below 3mg/L, which is below the recommended minimum of 4mg/L given in Metcalf & Eddy (2014). It is suspected that the loading rate might have been able to be increased beyond 32g-TKN/m^3·day (2 lb-TKN/1000ft^3·day) given increased DO availability.

When dosing became necessary (July 28), bags of NH_4Cl powder were mixed in a 1000L with a mechanical mixer to an approximate concentration of 5-6 mg/l NH_4-N. A peristaltic pump was then used to dose from the dose tank to the west SAGR influent tank at a rate of 25mL/minute.

3.3. Results and Discussion

3.3.1. Confounding Factors and Operational Issues

Flow and Load

Throughout the experiment it was noted that – between visits to the pilot – influent flow would sometimes reduce significantly. Upon opening of the influent gate valve to increase the flow, large amounts of sediment would pass through the influent piping. It was concluded that sediment would settle in the piping system between site visits, progressively restricting flow, and that once the gate valve was opened, the sudden increase in the flow would scour the sediment and return the flow to the desired set point. This interaction affected the flow and loading rate. The effects on flow rate and TAN loading rate can be viewed in Figures 3.1 and 3.2, respectively. It also had the effect of confounding TSS data as described below.

TSS

Several factors confounded TSS results. The first is that samples were taken where the “splitter” tank overflows to “influent” tank for the west SAGR. There is some settling of influent sediment that occurs in the influent tank before being directed to the western SAGR. The second factor is the sudden influx of sediment that occurred when flow was adjusted and the influent piping was scoured (as described above). Because samples were taken downstream of this point and after the flow was adjusted, the sudden increase in TSS would often artificially increase the influent TSS results. The result is that the samples were not truly representative of the TSS of the lagoon effluent. The samples were nonetheless still representative of the influent TSS for the pilot SAGR and can therefore be compared with the effluent measurements to draw conclusions regarding the efficacy of TSS polishing.

Air Flow

Air flow at the beginning of the experiment was distributed through working flow meters, however, as low effluent DO values began to be measured, the flow to the operating SAGR zone was increased and a larger flow meter was installed. It was discovered that the new larger flow meter was faulty. As mentioned in

Section 3.2.2, the actual air flow rate throughout most of the experiment is therefore unknown but was estimated at between 48 and 56 scfm.

After completing the experiment, it was determined that one of the two air laterals in zone 2 (the one further downstream) had been turned off at a buried valve. This was expected to be a primary cause for the operational issues in achieving constant high air flow to the zone and had the effect of reducing the aerated portion of the zone in use. This is expected to have limited the DO transfer to the SAGR and may, at times, have limited the nitrification reaction. Despite questionable air flow, the influent and effluent DO values measured are accurate and representative of the conditions of the pilot SAGR.

Dosing

Throughout the portion of the experiment where dosing was occurring, air bubbles would collect in the dosing tubes, restricting flow. The decrease in volume of the dosing tank was monitored and it was determined that an average rate of 25mL/minute was approximately maintained, however, the dosing rate was not consistent over time.

3.3.2. Operational Parameters

Throughout the experiment temperature and pH values stayed relatively stable. The average influent and effluent temperatures were 23.5°C and 22.8°C, respectively. The average influent and effluent pH values were 7.77 and 7.67, respectively. The influent DO was also generally stable through the experiment, with an average of 3.71mg/L. The effluent DO, however, decreased greatly between July 20 and July 22. The average effluent DO concentration before this is 7.12 mg/L and the effluent DO concentration after is 2.19 mg/L. The low effluent DO prompted a change in operation, directing more air flow to this zone on July 22 This increased the effluent DO marginally, but the overall lack of ability to raise the effluent DO above 3mg/L was attributed to the closed air lateral in zone 2 that was thought to be open (see Section 3.3.1).

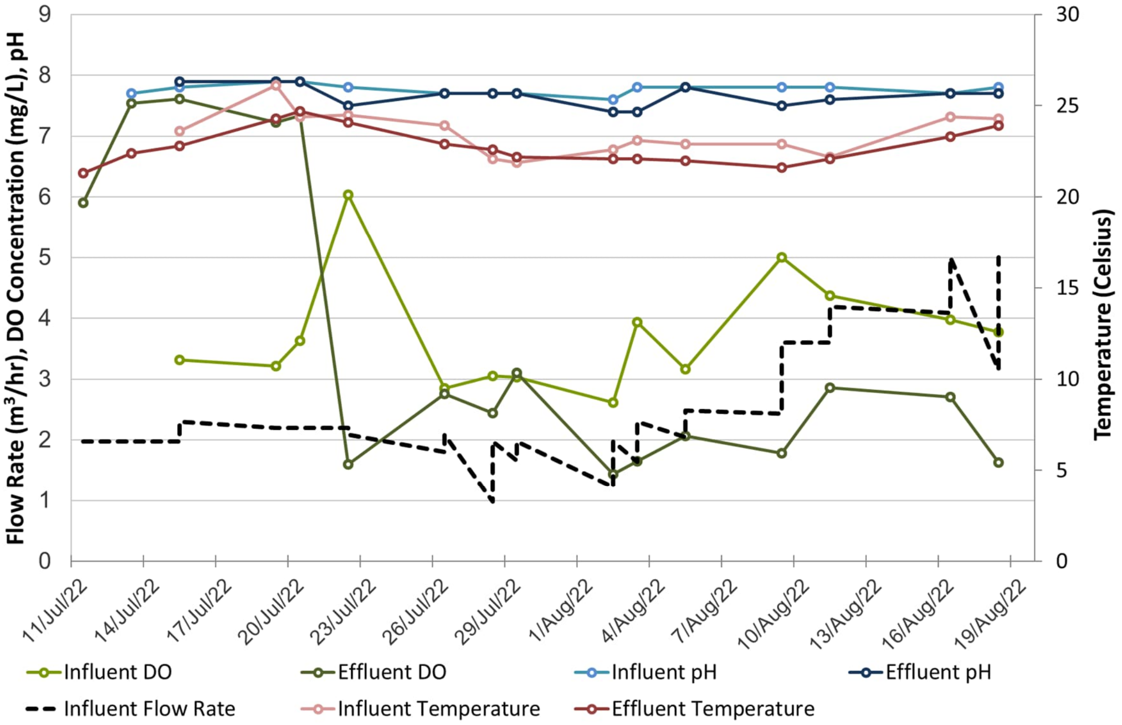

Figure 3.1: Warm Condition SAGR Load Testing - Operational Parameters

3.3.3. Total Ammonia Nitrogen

The TAN was nearly completely removed throughout the experiment. The highest recorded effluent TAN concentration is 0.57mg/L, measured on August 18, and the overall average is 0.13mg/L. The TAN removal efficiency was always over 99%.

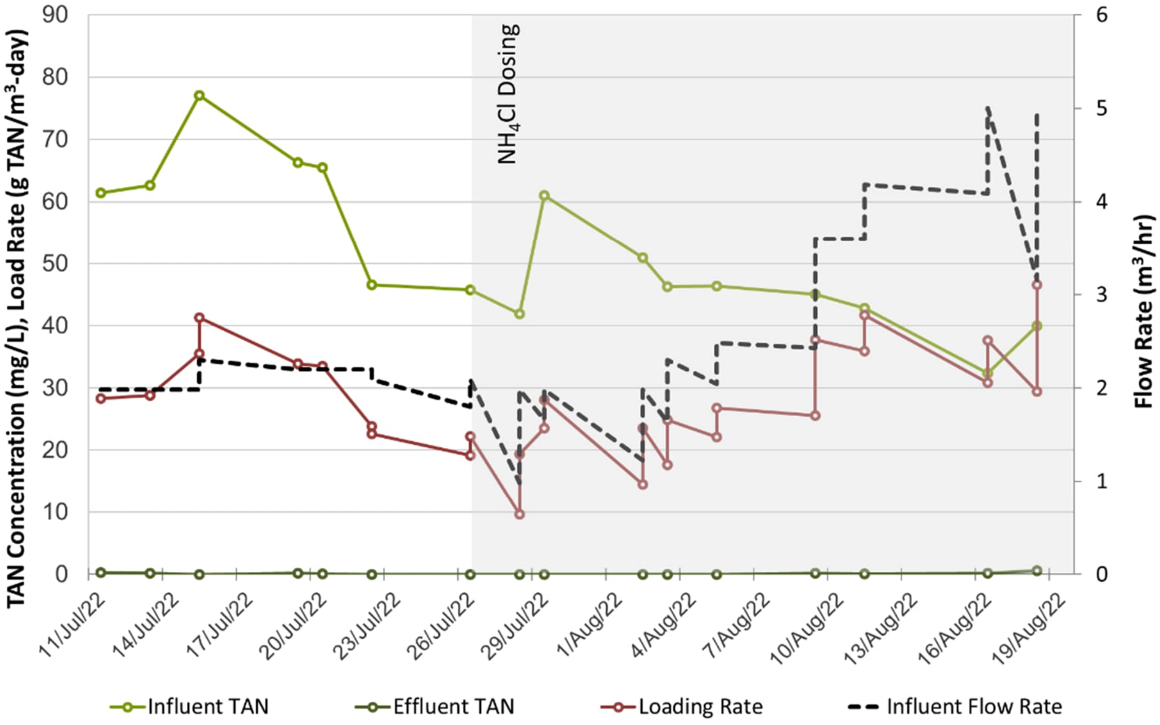

Figure 3.2: Warm Condition SAGR Load Testing - TAN Results

3.3.4. Nitrite and Nitrate

Effluent NO_2^- was consistently near zero and NO_3^- showed generally similar trends to the influent TAN concentrations. This suggests that nearly full nitrification was occurring consistently throughout the experiment.

The results show fluctuations in NO_2^- and NO_3^- in the SAGR influent – that is – in the lagoon effluent. However, the consistently low NO_2^- measured in SAGR effluent suggests that NO_2^- oxidation is not significantly affected by the fluctuations and that nearly all NO_2^- produced by TAN oxidation in the SAGR as well as the NO_2^- in the lagoon effluent is successfully oxidized to NO_3^-.

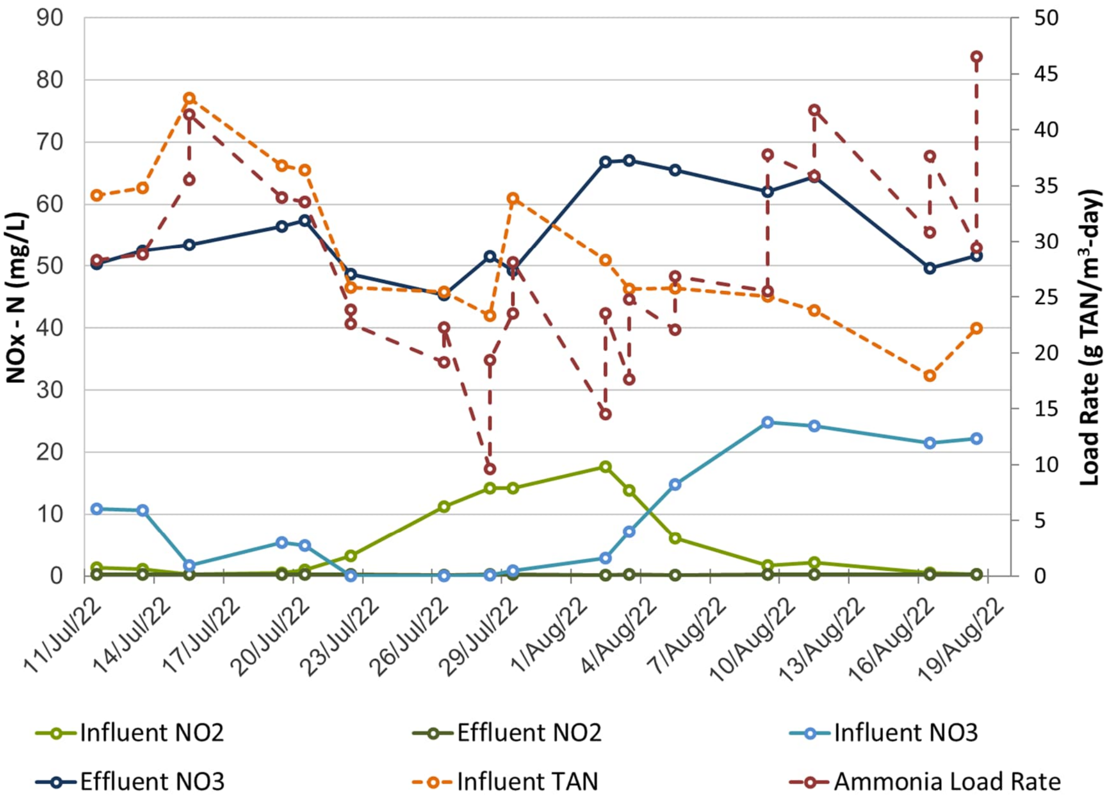

Figure 3.3: Warm Condition SAGR Load Testing - NOx Results

3.3.5. Phosphorus

The orthophosphate measured in the SAGR influent and effluent by FIA shows that phosphorus is being removed in the SAGR. These results were never validated by ALS Environmental because the SAGR is not specifically designed for phosphorus removal. The mechanism by which phosphorus was being removed is unknown.

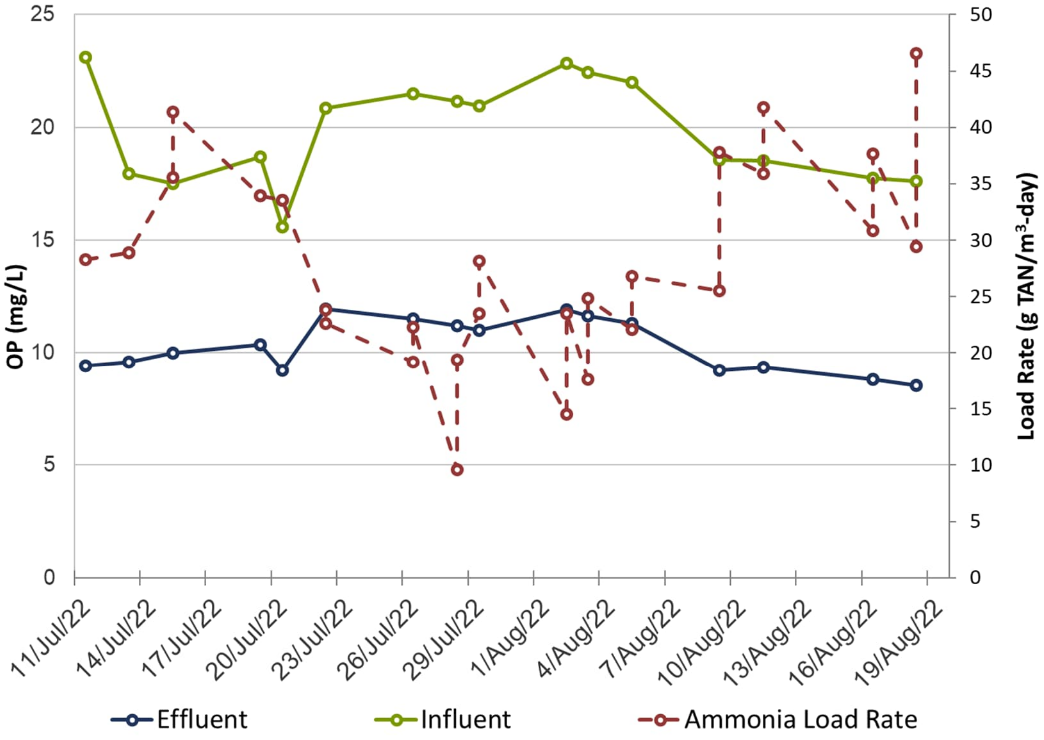

Figure 3.4: Warm Condition SAGR Load Testing - Phosphorus Results

3.3.6. Total Suspended Solids

Periodic TSS measurements began on July 20 and continued through August 18. As mentioned in Section 3.3.1, TSS data is expected to be confounded by several factors, however, the influent and effluent trends in the graph imply that the SAGR is providing TSS polishing, as it is advertised to do. The spike in both influent and effluent TSS on August 11 is suspected to be the result of a laboratory error, likely due to inadequate desiccation time allowed on that day.

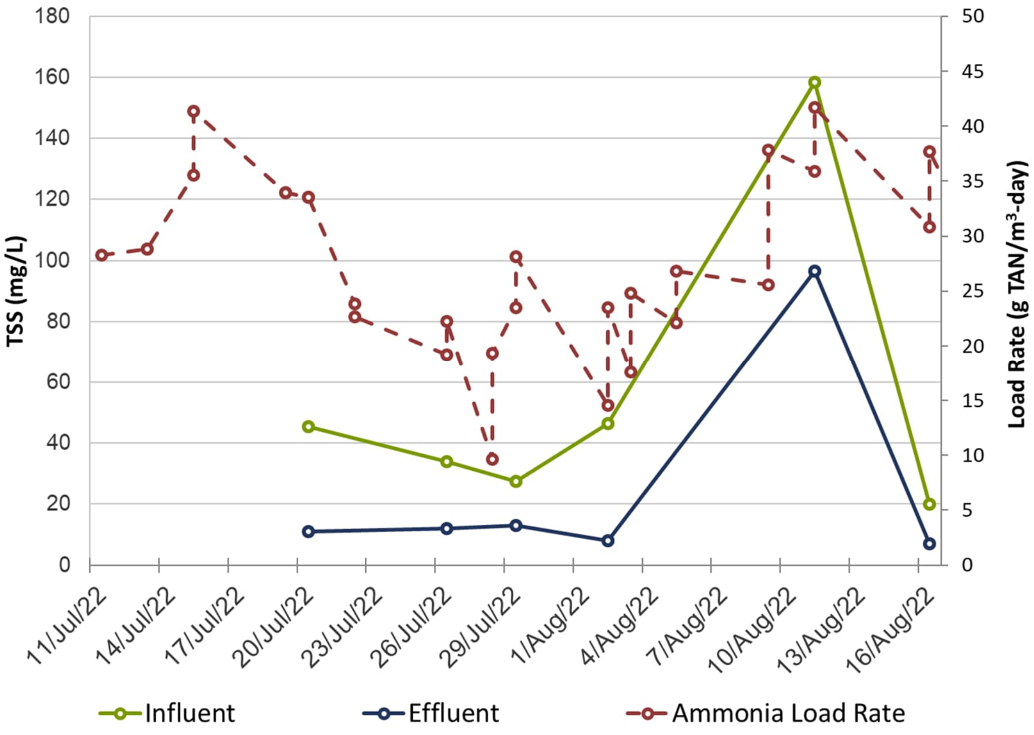

Figure 3.5: Warm Condition SAGR Load Testing - TSS Results

3.3.7. Total Kjeldahl Nitrogen and cBOD

The loading rates calculated and shown in the results above were calculated using TAN measurements gained by FIA, however, the target loading rate is stated in terms of TKN. The assumption is that in lagoon effluent, TAN concentration is only slightly less than TKN concentration because the high retention time and oxidation-reduction potential associated with aerated lagoons is conducive to the hydrolysis of organic nitrogen to TAN. ALS Environmental was engaged to provide TKN results. The table below outlines the results from ALS Environmental.

Date	Table 3.1 - Warm Condition SAGR Load Testing Data from ALS Environmental Certified Laboratory									
	Influent					Effluent				
	TKN (mg/L)	TAN as N (mg/L)	NO_2 as N (mg/L)	NO_3 as N (mg/L)	CBOD (mg/L)	TKN (mg/L)	TAN as N (mg/L)	NO_2 as N (mg/L)	NO_3 as N (mg/L)	CBOD (mg/L)
11-Aug-22	44.8	37.8	2.21	21.1	< 20	1.3	0.046	< 0.05	51.5	< 2.0

On August 11, the measured TKN in the SAGR influent was greater than the TAN. The difference may be attributed to the presence of recalcitrant organic nitrogen, however, the low TKN in the SAGR effluent suggests organic nitrogen is hydrolyzed in the SAGR and adds to the TAN that is oxidized and thus the actual TKN loading rate is higher than the calculated TAN loading rate. The data from ALS shows that the TKN loading rate assumptions of the experiment can be considered valid and conservative.

Additional TKN and TAN data was obtained from ALS following completion of the experiment on August 31, 2022. Though they showed TKN (14.8 mg/L) to be close to TAN (16.1 mg/L), the results were not considered valid because TAN was found to be greater than TKN. ALS gives the TAN and TKN analysis methods as “Colour” and “Colourimetry”, respectively, and qualifies these TKN values, stating in the analysis report that “TKN result may be biased low due to Nitrate interference. Nitrate-N is > 10x TKN.”

The Carbonaceous Biochemical Oxygen Demand (cBOD) values were also provided by ALS. The results show that the SAGR bed is performing BOD polishing simultaneously with nitrification.

3.3.8. Data Validation

Data gathered by FIA was validated using data provided by ALS Environmental using three date points of comparison. The results are summarized below.

Table 3.2 - Warm Condition SAGR Load Testing Data Validation

Date	Influent									Effluent								
	TAN (mg/L)			NO_2 (mg/L)			NO_3 (mg/L)			TAN (mg/L)			NO_2 (mg/L)			NO_3 (mg/L)		
	FIA	ALS	Diff.	FIA	ALS	Diff.	FIA	ALS	Diff.	FIA	ALS	Diff.	FIA	ALS	Diff.	FIA	ALS	Diff.
13-Jul-22	62.60	61.90	-0.70	1.14	< 0.05	< -1.1	10.63	< 0.1	< -10.5	0.23	0.15	-0.08	0.26	< 0.05	< -0.21	52.48	56.60	4.12
28-Jul-22	41.98	46.70	4.73	14.20	0.30	-13.90	0.10	12.80	12.70	0.00	0.06	0.06	0.21	< 0.05	< -0.16	51.60	47.20	-4.40
11-Aug-22	42.83	37.80	-5.03	2.18	2.21	0.03	24.20	20.10	-4.10	0.12	0.05	-0.08	0.24	< 0.05	< -0.19	64.38	51.50	-12.88

The results show that, though FIA and ALS produce sometimes significantly different results for NO_2^- and NO_3^-, the results for influent and effluent TAN are generally consistent. This implies that the TAN removal results of this study are trustworthy, while the nitrite oxidation results may be less so.

The differences between ALS and FIA results for NO_2^- and NO_3^- were not pursued further because, though NO_2^- and NO_3^- values are important for the purposes of assessing performance and troubleshooting, the main design criteria and objectives are based on TKN and TAN, which were stable.

3.3.9. Statistical Analysis

Because nearly full TAN removal was measured throughout, and the dependent variable (effluent ammonia) was consistently near 0 mg/L, loading rates were chosen as the statistics for comparison. A One-Sample t-Test was used to compare the sample mean with the typical SAGR design loading rate of 12.8 g-TKN/$m^3 \cdot$day (0.8 lb-TKN/1000$ft^3 \cdot$day) (assumed to be the mean loading rate for the SAGR under normal operation). A Shapiro Test confirmed that sample loading rate data was normally distributed ($p\text{-}value = 0.532 > 0.05$). The mean loading rate, calculated using data gathered at the end of each visit to the pilot, was 31.1 g-TAN/$m^3 \cdot$day (1.96 lb-TAN/1000$ft^3 \cdot$day), which is assumed to be the lower limit of the mean TKN loading rate. The median was 28.9 g-TAN/$m^3 \cdot$day (1.82 lb-TAN/1000$ft^3 \cdot$day). The standard deviation was 0.49. A Quantile-Quantile plot and Histogram (in imperial units) with associated probability curve are given below.

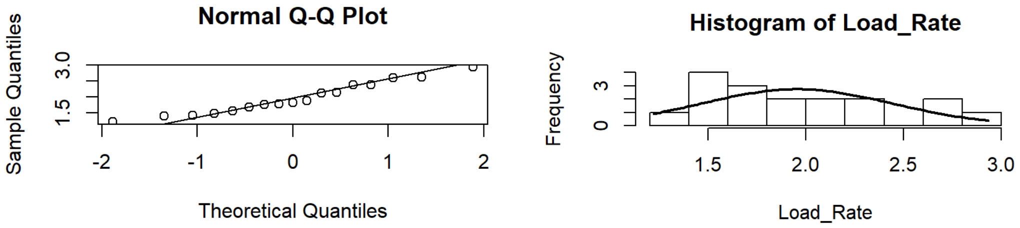

Figure 3.6: Warm Condition SAGR Load Testing - Demonstration of Normal Distribution of Load Rate

The One-Sample t-Test returned a t value of 9.61, which is greater than the critical t value of 1.746 (one tail, $\alpha = 0.05$, df = 16), indicating a statistically significant difference between the sample mean loading rate and the typical design loading rate of 12.8 g-TKN/$m^3 \cdot$day ($p\text{-}value = 2.372 \times 10^{-8}$).

The assumptions of these analyses are as follows:

- Full TAN removal would be at least as consistently achieved at the typical design loading rate of

12.8 g-TKN/$m^{3}\cdot$day (0.8 lb-TKN/1000$ft^{3}\cdot$day) as it was during the experiment.

- The sample variance in loading rate approximates typical variance in the loading rate of the SAGR under normal operation.
- The sample data is normally distributed (proved above).
- The data are continuous and have been randomly sampled.

The Student's t-test compares two overlapping probability distribution curves. The overlapping portion of the curves must be small in order for the distributions to be considered significantly different. The One-Sample t-Test is designed to compare a sample distribution to a standard value (or population mean), which in this case is the typical SAGR design loading rate. No sample distribution is developed for the standard value, therefore, the variance of typical SAGR loading rates must be assumed to be similar to that of the experiment. This is a significant assumption, however, it is suspected to be sound because typical SAGR operation should have less variance than was measured during the experiment, resulting in less overlap between the distribution curves, and therefore greater significance. Typical SAGR operation should have less variance on account of having more experienced, well-trained operators managing the treatment process, and less complications related to NH_4Cl dosing.

3.4. Conclusion

3.4.1. Discussion

The conclusions can be summarized as follows:

- The SAGR can be loaded at a rate of approximately 31.1g-TKN/$m^{3}\cdot$day (1.96 lb-TKN/1000$ft^{3}\cdot$day) which is approximately 2.5x the current typical design rate and still provide nearly complete TKN removal in warm conditions (20°C), given sufficient aeration, and assuming low-cBOD influent.
- While providing this TKN removal, the SAGR is also able to polish TSS and cBOD.
- The SAGR typically provides nearly full nitrification, leaving very little TAN & NO_2^- in the effluent.

These results may help to improve the efficiency of the design of SAGRs, especially in warmer climates. A greater design loading rate corresponds to smaller cheaper reactors. This may translate into potential savings for rural municipalities that are struggling to meet regulatory ammonia concentration limits in their lagoon effluent, and are in need of treatment such as is provided by the SAGR.

3.5. References

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CHAPTER 4. INCREASING THE TYPICAL DESIGN VOLUMETRIC AMMONIA LOADING RATE OF THE SAGR IN COLD CONDITIONS

Abstract

The Submerged Attached Growth Reactor (SAGR) is a proprietary technology owned by Nexom. It is essentially a synthetically lined cell filled with porous, clean stone (the biofilm media), and is aerated from the base. It generally includes two influent distribution chambers for lagoon effluent and one outlet structure. The use of the inlets alternates according to Nexom's patented "Step Feed" strategy. The SAGR has been shown through extensive testing to be a viable and practical technology for use in retrofitting lagoon-based wastewater treatment facilities to provide TAN removal in climates subject to cold winter conditions. It also provides cBOD polishing, TSS polishing, and disinfection.

Studies in moderately cold conditions have shown that SAGRs were able to meet regulatory effluent quality requirements with significantly reduced SAGR footprint. It is therefore hypothesized that a pilot SAGR receiving lagoon discharge wastewater at temperatures dropping to 3-4°C in the winter will consistently remove over 99% of the influent TAN when operated at an ammonia loading rate of approximately 19.0 g-TKN/$m^3 \cdot$day (1.2lb-TKN/1000$ft^3 \cdot$day) rather than the modern typical design loading rate of 12.8 g-TKN/$m^3 \cdot$day (0.8 lb-TKN/1000$ft^3 \cdot$day). This pilot study observed SAGR operation at influent temperatures below 4°C (simulating moderately cold climates such as states in middle latitudes) at an average loading rate of 21.9 g-TKN/$m^3 \cdot$day (1.38lb-TKN/1000$ft^3 \cdot$day) and recorded nearly 100% removal of TAN during stable operation. This is a notable increase over the current typical design value of 12.8 g-TKN/$m^3 \cdot$day (0.8 lb-TKN/1000$ft^3 \cdot$day).

4.1. Introduction

4.1.1. Background

Lagoon-based wastewater treatment facilities (WWTF) are commonly used in Canada, especially in the many rural municipalities. Lagoons rely on biological nitrification to remove ammonia. Nitrification is the removal of ammonia (NH_3) / ammonium (NH_4^+) by oxidation to nitrite (NO_2^-) and nitrite to nitrate (NO_3^-)

by autotrophic bacteria. Nitrifying bacteria include Ammonia Oxidizing Bacteria (AOB) and Nitrite Oxidizing Bacteria (NOB). Both of these bacteria categories are especially inhibited at low temperatures (as compared to heterotrophic bacteria typical to lagoons) and lose most of their capacity for nitrification at temperatures at or below 5-8°C (Metcalf & Eddy, 2014; Oleszkiewicz & Berquist, 1988; Shammas, 1986). Lagoon-based WWTFs in climates subject to cold winter conditions, such as in Canada, therefore, often fail to remove TAN to below regulatory requirements during winter when the lagoon water temperature can decrease below 1°C.

Total Ammonia Nitrogen (TAN) is the sum of NH_3 and the ionized form, NH_4^+, and is measured as mass of nitrogen. The equilibrium proportions of the TAN species depend on pH and temperature. The fraction of NH_4^+ is typically greater than the fraction of NH_3 at typical lagoon conditions. The NH_3 fraction is more toxic to aquatic ecosystems at sufficient concentration (Constable et al. 2003). TAN also contributes to the eutrophication of receiving water bodies by providing the nutrient nitrogen. The increased understanding of the costs of introducing TAN to water bodies by lagoon discharge have caused governing bodies in Canada to impose increasingly stringent TAN-related concentration limits on the discharges of WWTFs such as the federal Wastewater Systems Effluent Regulation (Canada Gazette, 2012). Many rural municipalities risk exceeding these limits (especially in winter months) when treating wastewater using lagoons only. It is therefore increasingly beneficial for municipalities to retrofit nitrification systems downstream of the lagoons. The Submerged Attached Growth Reactor (SAGR) is one such system.

Each SAGR generally consists of an aerated clean rock bed divided into upstream and downstream zones in series (zones 1 & 2). The bed is topped with mulch, woodchips, or shredded rubber tires. This provides frost protection and reduces treatment volume lost to ice formation. The SAGR promotes the growth of AOB and NOB as a fixed biofilm. The rock bed is the media surface on which the biofilms grow. Influent is normally directed into zone 1 from where it flows through the SAGR to the discharge point at the downstream end of zone 2. Because the flow through a SAGR can be approximated as 'plug-flow', biofilm concentration is greatest near the inlet and decreases with flow downstream. Nitrifying biofilms suffer a loss of efficiency in cold temperatures and in high-BOD environments as they are outcompeted by heterotrophic micro-organisms. Lagoons experience decreased temperature and loss of BOD treatment efficiency in winter, passing colder effluent with increased BOD to the SAGR in winter months. Therefore, in preparation for winter, it is beneficial to grow excess biofilm throughout the volume of the SAGR. The Step Feed process is thus employed while the lagoon effluent is still warm and low in BOD. During step-feed, lagoon effluent is fed directly to the inlet of zone 2 (bypassing zone 1) to promote the growth of robust nitrifying biofilm in zone 2. As temperatures in the lagoon cool and BOD rises, flow in the SAGR is returned to normal operation, with influent directed to zone 1. Following this regimen, the SAGR is used in cold weather to remove BOD and TAN, with the majority of BOD removal occurring in zone 1 and nitrification occurring throughout the volume. Nitrification is expected to be most efficient in zone 2 where there is less competition between nitrifiers and BOD-consuming heterotrophic bacteria.

A current typical design loading rate for SAGRs subject to cold winter conditions is 12.8 g-TKN/day per cubic meter of gross SAGR volume (0.8 lb-TKN/1000ft$^{3}\cdot$day). The SAGR has been demonstrated to be able to remove nearly 100% of influent ammonia from lagoon effluent during winters with water temperatures below 1°C (Anderson et al., 2020; Nexom, 2021). Earlier research, however, suggests that SAGR design might be optimized (Mattson et al., 2018). Because optimization is available at temperatures below 1°C, further optimization is expected in scenarios where lagoon effluent will only drop to 3-4°C.

4.1.2. Objectives

The goal of this experiment was to load a SAGR bed at a minimum of 19.0 g-TKN/m$^{3}\cdot$day (1.2lb-TKN/1000ft$^{3}\cdot$day), which is approximately 50% higher than the typical design rate, and measure the ammonia removed to determine if ammonia can be fully removed at the increased loading rate. For reference, TKN is the sum of TAN and organically-bound nitrogen, and TKN concentration is generally only slightly higher than TAN concentration in lagoon effluent. Because this was done during winter when nitrification is least efficient, ammonium chloride (NH_4Cl) was dosed to the influent as necessary to supplement the ammonia in the lagoon effluent to ensure the target loading rate was maintained.

4.2. Materials and Methods

4.2.1. Materials

The SAGR pilot in Blumenort, Manitoba consists of two SAGR trains (east train #1 and west train #2) in parallel, each with 2 zones. They are installed on the site of the *Rural Municipality of Hanover, Blumenort Wastewater Treatment Lagoons.* The lagoon system consists of a single primary cell, two secondary cells, and two storage cells. Secondary cell effluent is pumped to a small building from which controlled volumes can be directed to each train as desired. The influent enters the building into a 1000L "splitter" tank which overflows through flow control valves into two 1000L "influent" tanks, each of which is directed to its corresponding SAGR train. Lagoon effluent can be sampled and dosed with NH_4Cl from within the building before being directed to the SAGR trains. SAGR effluent is then pumped back into the building, whereby it too can be sampled before being pumped back into the lagoons. Gate valves accessible at grade near the SAGR trains allow the influent flow to be opened and closed to each zone of each SAGR as required. Zone 1 and zone 2 of the SAGR are equally sized with a volume of $102m^3$ each. During this experiment, flow was shut off to both zones of the west SAGR train due to ice build up in the pipes, causing back ups (December 2022). Therefore, only the east SAGR was operating.

4.2.2. Methods

The experiment spanned from September 22, 2022 to May 19, 2023. The temperature of the lagoon effluent fell from over 10^oC to less than 1^oC and returned to 17^oC, however, the temperature of the SAGR influent was controlled using bucket heaters to target a range of $3\text{-}4^oC$, simulating a WWTF scenario at a climate with warmer winters than Blumenort, Manitoba. During these months, BOD concentration is higher than average in lagoon effluent, and would also be higher than would be expected for a well-designed lagoon-based WWTF in a warmer winter. An identical WWTF with SAGR retrofit subject to warmer winter conditions, which might endure winter effluent temperature of $3\text{-}4^oC$, would therefore be expected to perform better than the pilot studied with all else held equal.

For each visit to the pilot, lagoon effluent, SAGR influent, and SAGR effluent were tested using HACH TNT kits to determine approximate TAN concentration. The results were used to adjust the flow and dosing rates to the SAGR, targeting a loading rate of at least 19.0 g-TKN/m$^3\cdot$day (1.2lb-TKN/1000ft$^3\cdot$day). SAGR influent and effluent samples were taken during each visit and analyzed for TAN, TKN, Nitrite (NO_2^-), Nitrate (NO_3^-), cBOD$_5$, TSS as well as *Escherichia coli (E. coli)* and Total Coliforms (TC). Other parameters measured on-site included temperature, pH, and DO.

The analysis methodology is as follows:

- *Flow:* Influent flow was estimated using a 5L container and a stopwatch.
- *TAN:* TAN in SAGR influent was first estimated using HACH TNT 832 for operational (load adjustment) purposes, then weekly samples were delivered to the ALS Environmental certified laboratory (ALS) in Winnipeg, Manitoba. The method of analysis listed in the analysis reports for TAN is “by Colour”.
- *TKN, cBOD$_5$, TSS, NO_2^-, NO_3^-, TC, and E. coli.:* Weekly samples were delivered to the ALS. The methods of analysis listed in the analysis reports for TKN is “by Colorimetry”. For TC and *E. coli*, the listed method for determining the most probably number (MPN) is by “Enzyme Substrate”.
- *pH:* SAGR influent and effluent pH were measured in the building on-site using the Hanna HI98128.
- *DO and Temperature:* SAGR influent DO and temperature were measured in the influent tank in the building on-site using a YSI Handheld Optical Dissolved Oxygen Meter. SAGR effluent DO and temperature were measured using a YSI Handheld Optical Dissolved Oxygen Meter at the outdoor SAGR effluent manhole, with the probe directly in the effluent pipe such that no time was given for the effluent to change in DO or temperature in the manhole.

As mentioned above, HACH TNT kits were used to test the lagoon effluent, and approximate calculations were completed using Microsoft Excel to determine the flow rate and dose rate required to achieve the desired load rate. The flow was then adjusted to suit using a 5L container and a stopwatch. The actual loading rate was later determined based on results from ALS. The flow was adjusted using a gate valve on the influent PVC piping system. Throughout the experiment, the approximate nature of the HACH kit testing, on-site calculations, and flow measurement led to varying results in actual loading rate.

The pilot plant is equipped with a single positive displacement blower motor capable of conveying 56 standard cubic feet per minute (scfm) to both SAGR trains. When all zones of both trains are open, the blower can supply 14scfm to each zone. During the first portion of the experiment the west SAGR was still in operation and air flow to all zones was near 14scfm consistently. On December 1 the west SAGR was shut down and all air diverted to the east SAGR to ensure DO was not limiting nitrification through the experiment. For the duration of the experiment after December 1, 2022, the air flow to each zone of the east SAGR was consistently between 19-22scfm.

Dosing was completed by mixing bags NH_4Cl powder with SAGR effluent (nearly free of TAN) in a 1000L with a mechanical mixer. A diaphragm pump was then used to dose from the dose tank to the west SAGR influent tank. A sump pump was used in this tank to circulate flow and mix the dose with lagoon effluent.

The east SAGR used for this experiment had been shut off through the preceding summer with no flow. Therefore, prior to the beginning of data collection on September 22, 2022, flow (0.7L/s) and aeration (14 scfm to each zone) were started on August 31 to the SAGR to acclimatize it and begin developing biofilm. The Step Feed process was initiated on September 22 and at this point the dosing rate was intended to be increased significantly to drive the loading rate to 14.3 g-TAN/$m^{3}\cdot$day (0.9lb-TAN/1000$ft^{3}\cdot$day), corresponding to a TKN loading rate of approximately 15.7 g-TKN/$m^{3}\cdot$day, to promote rapid biofilm growth in zone 2. This was an important process as zone 2 had been depleted of biofilm during the prior summer of no operation. The actual loading rate recorded at this time was, however, only approximately 4.8 g-TAN/$m^{3}\cdot$day (0.3 lb-TAN/1000$ft^{3}\cdot$day) until it was adjusted on October 26 to 14.3 g-TAN/$m^{3}\cdot$day.

The Step Feed process was therefore not properly implemented to grow a robust biofilm in zone 2. Note that by convention the loading rate during Step Feed is still based on the entire SAGR volume even though only half the volume is loaded during this time. The Step Feed process was ended on November 7 when flow was returned completely to zone 1.

4.3. Results and Discussion – Phase 1

The results and discussion are divided into two sections based on a date range. This first phase covers the beginning of the experiment (September 7, 2022) to January 9, 2023. This was an operationally unstable period from startup, through Step Feed, until the plant and data stabilized for the remainder of the winter. The second phase covers the remaining period, from January 10, 2023 to the end of the experiment, where operational parameters had stabilized and the SAGR acclimatized to provide treatment.

The east SAGR train used for this experiment was brought online on August 31, 2022 to begin to grow biomass after having been turned off the preceding summer. Some data collection started on September 7, however most data collection began near October 4, 2022. Step Feed was started on September 22.

4.3.1. Confounding Factors and Operational Issues

The operational issues and confounding factors are summarized In Appendix A. In general, it should be noted that this phase was a period of significant operational instability, extending from the beginning of the experiment to January 9, 2023.

4.3.2. Operational Parameters

Throughout the period, the pH remained stable. DO concentration fluctuated slightly more and is assumed to be partially dependent on the operational changes to the air flow to zones 1 and 2 of the SAGR. The air flow was shared between this SAGR train and the parallel west train until the west train was shut down on December 1, 2023, and all air flow available from the blower on site was directed to the east train. This happened at the same time as heaters were added to the influent tank of the east SAGR. Until November 1, zone 2 only received air flow to the upstream lateral as the downstream one was closed at a buried valve. The air flow between the two zones was held equal throughout except for a period from late October to early November where air flow was directed from zone 1 to zone 2 instead to promote growth in zone 2 during Step Feed. SAGR influent temperature fell rapidly from 8°C on November 3 to 1.5°C on November 13. The temperature stayed low until heaters were installed in the influent tank on December 1, after which it remained largely between 3-5°C with some exceptions. See Appendix A for more information.

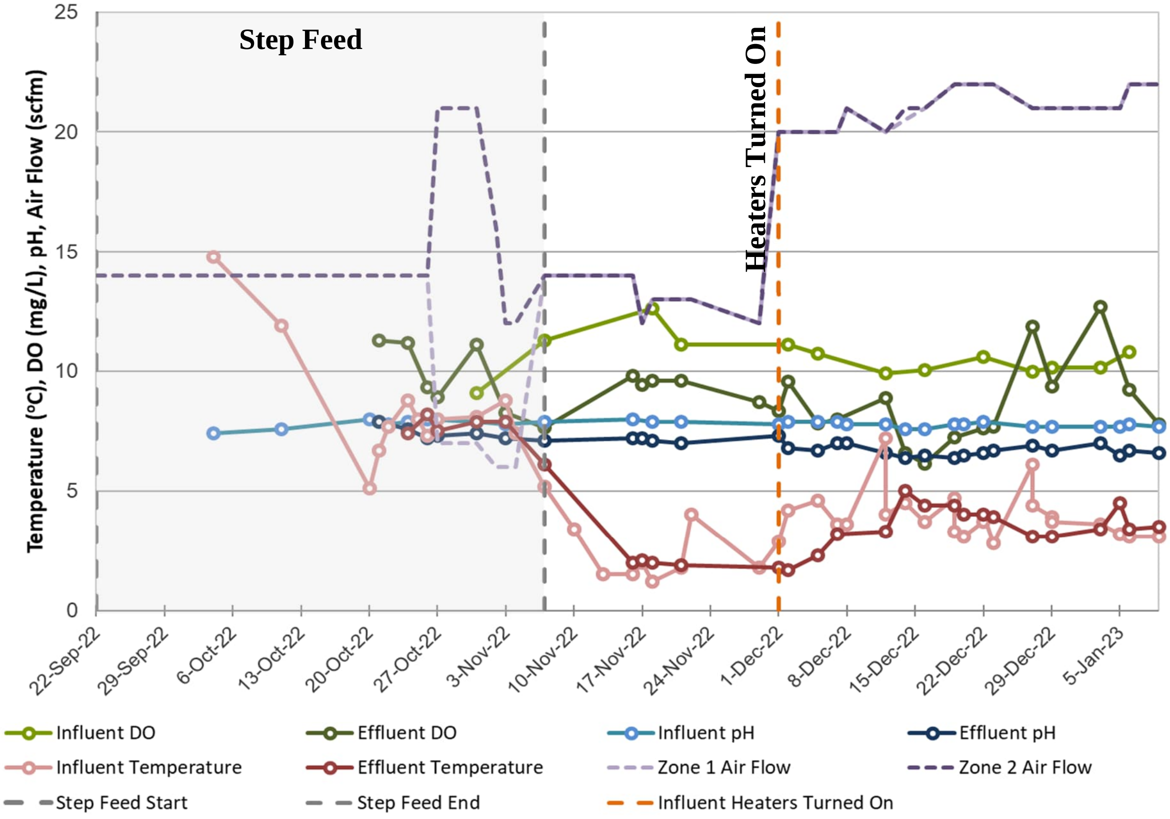

Figure 4.1: Cold Condition SAGR Load Testing - September 7, 2022 – January 9, 2023 Operational Parameters

4.3.3. Total Ammonia Nitrogen

Over 50% of the influent TAN was consistently removed by the SAGR, however, the low NH_4Cl dose rate used prior to October 26 did not promote sufficient biomass growth in zone 2 during the Step Feed process to provide full TAN removal throughout this period. This, in combination with the increased TAN loading rate following the dose increase and the rapidly falling influent temperature, resulted in a high effluent TAN concentration until the SAGR recovered in late November. It is important to note the speed of the recovery though – as nearly full TAN removal was achieved by November 17, 2022.

Operational issues caused the influent to be dosed to very high concentrations on the weekend of December 3 and on December 8. Only the influent peak on December 8 was captured in the graph below as December 3 occurred on a weekend when no testing was occurring. During the monitoring period, some samples were susceptible to third-party lab errors, resulting in TKN values being lower than TAN (see Appendix A).

TAN results were recorded once prior to the date when the dose was adjusted to target a loading rate change from approximately 4.8 g-TAN/m^3·day to 14.3 g-TAN/m^3·day (0.3 lb-TAN/1000ft^3·day to 0.9 lb-TAN/1000ft^3·day). Note again that by convention, the loading rate is here still based on the entire SAGR volume even though only half the volume is loaded during Step Feed).

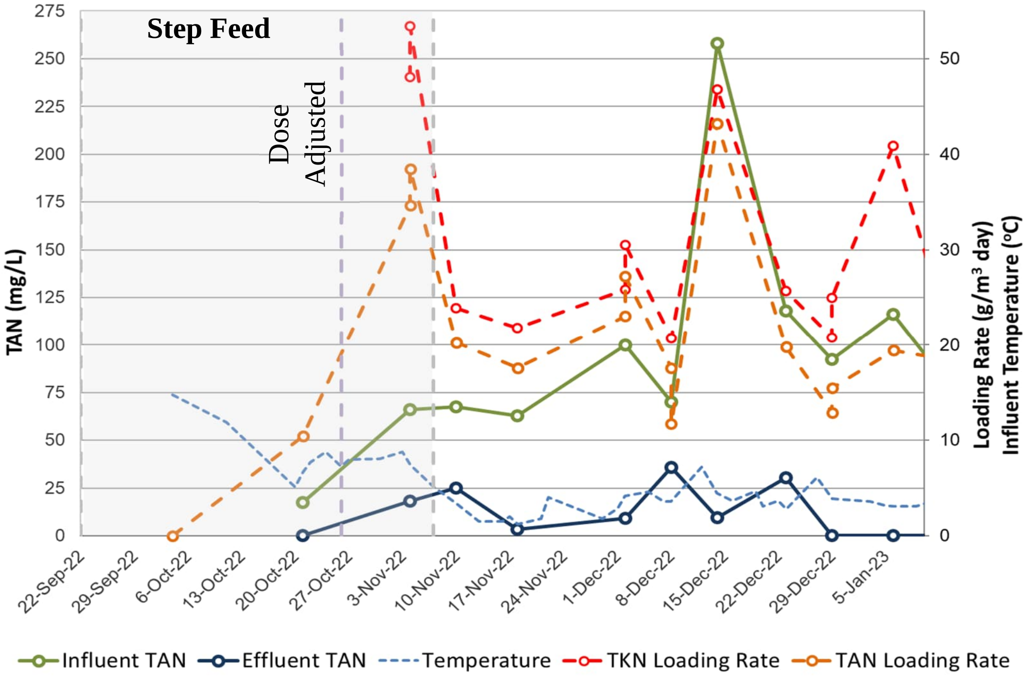

Figure 4.2: Cold Condition SAGR Load Testing - September 7, 2022 – January 9, 2023 TAN Results

4.3.4. Nitrite and Nitrate

Effluent nitrite was consistently near zero and nitrate showed similar trends to the influent TAN concentrations. This suggests that, though full nitrification was not consistently achieved during this period, NOB were never significantly inhibited or unable to oxidize all nitrite produced by AOB – except for a short period after the influent TAN peaked on December 8.

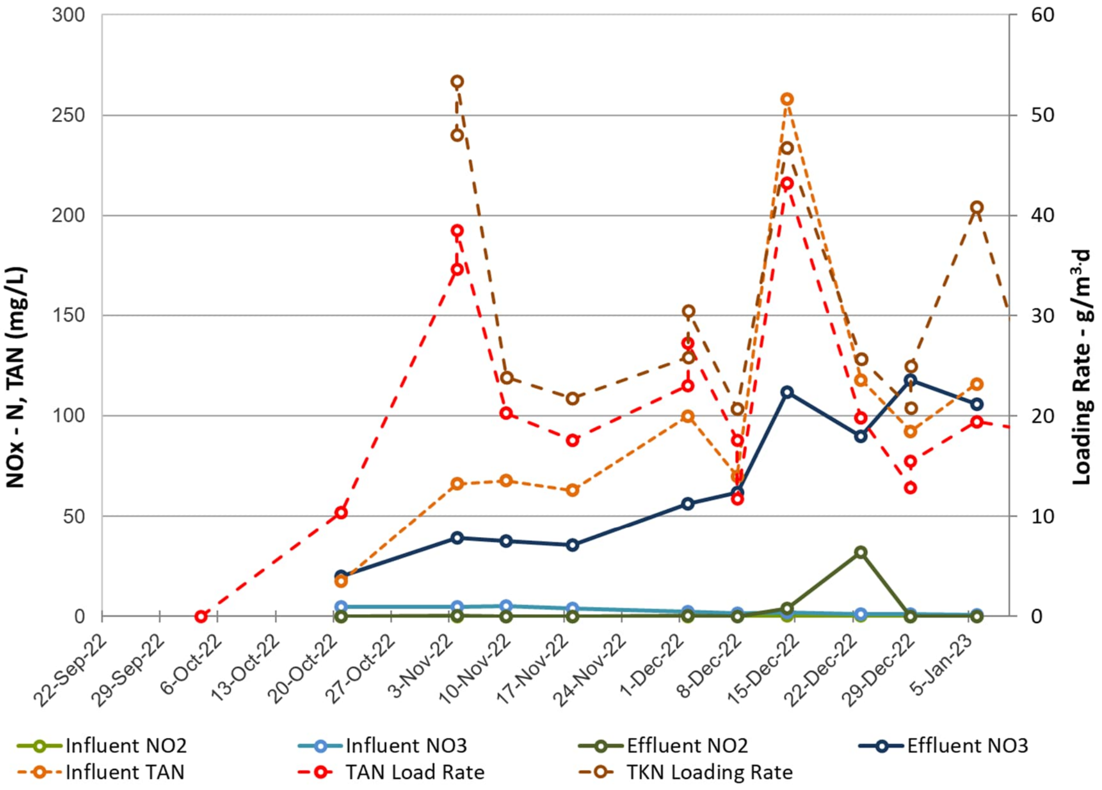

Figure 4.3: Cold Condition SAGR Load Testing - September 7, 2022 – January 9, 2023 NOx Results

4.3.5. cBOD$_5$ and TSS

Even through a period of operational instability, the SAGR polished cBOD$_5$ and TSS in a manner consistent with historic pilot and full-scale SAGR installations.

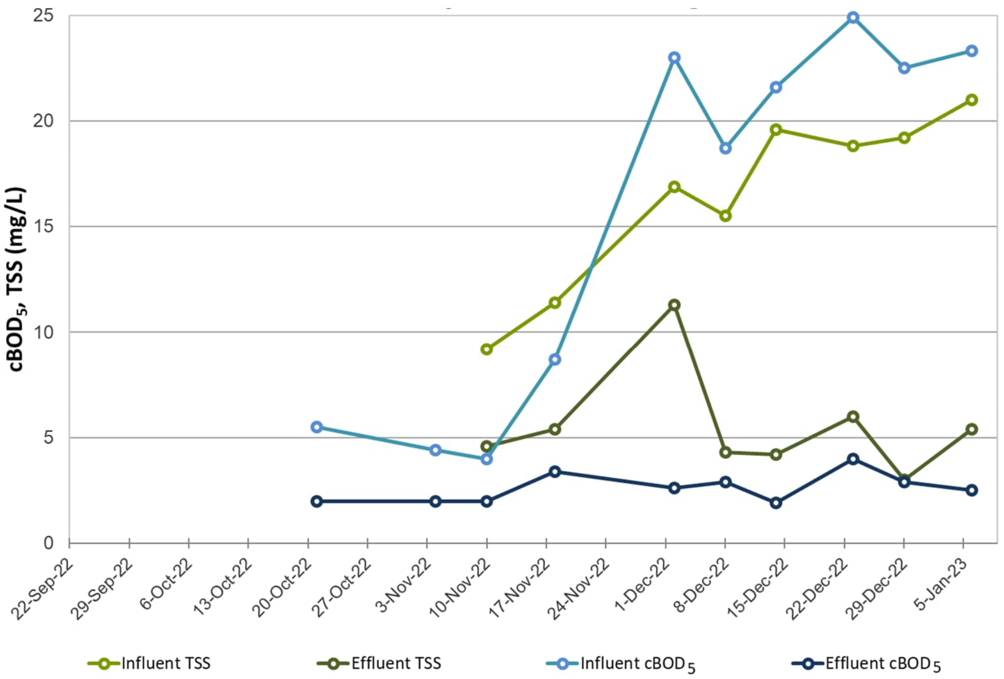

Figure 4.4: Cold Condition SAGR Load Testing - September 7, 2022 – January 9, 2023 cBOD & TSS Results

4.4. Results and Discussion – Phase 2

This second phase (January 9, 2023 – May 16, 2023) was a period of consistent operational stability. This consistent period of TAN removal by the SAGR occurred after the SAGR acclimatized to conditions and stabilized. Consistent data was gathered suitable for statistical analysis. The experiment ended when the temperature in the influent began to rise, signaling a rise in the lagoon water temperature and an increase in the lagoon's capability to provide partial nitrification. All measurements collected and delivered to ALS Laboratories were collected at the end of the visits to the pilot, following operational adjustments.

4.4.1. Confounding Factors and Operational Issues

The operational issues and confounding factors are summarized in Appendix A. In general, it should be noted that this period was operationally stable relative to the period of significant operational instability recorded from the beginning of the experiment to January 9, 2023.

4.4.2. Operational Parameters

Throughout this period, all parameters stayed relatively stable except for temperature which increases sharply at the end of the experiment. The average influent and effluent temperatures (excluding data after May 1, 2023) were 3.4°C and 3.3°C, respectively. The temperature was under 4°C in 95% of the measurements. The average influent and effluent pH values were 7.6 and 6.9, respectively. The average influent and effluent DO concentrations were also stable, though influent DO measurements ceased on April 24 and the effluent concentration decreased after May 1, corresponding to the decrease in DO saturation of water as the temperature rose during this period. The average influent and effluent DO concentrations (excluding data after May 1, 2023) were 10.0 and 12.1mg/L, respectively.

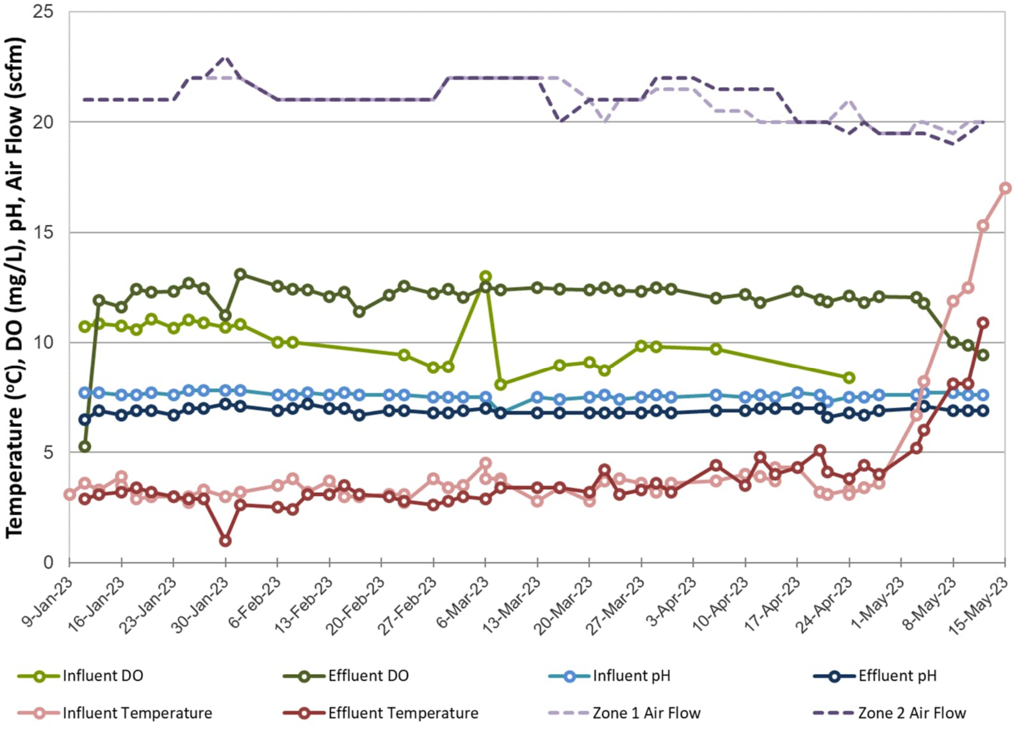

Figure 4.5: Cold Condition SAGR Load Testing - January 9, 2023 – May 16, 2023 Operational Parameters

4.4.3. Total Ammonia Nitrogen

The TAN was nearly completely removed throughout this period. The recorded effluent TAN concentration was always less than 0.1mg/L, and the overall average was 0.02mg/L. TAN removal efficiency was always over 99%. The targeted minimum TAN loading rate was 19 g-TAN/m^3·day (0.9 lb-TAN/1000ft^3·day) and a consistent average of 21.9 g-TAN/m$^{3}\cdot$day (1.38lb-TAN/1000ft$^{3}\cdot$day) was actually achieved. The average TKN loading rate was also 21.9 g/m$^{3}\cdot$day which is 72.5% greater than the typical SAGR design value of 12.7 g/m$^{3}\cdot$day (0.8lb/1000ft$^{3}\cdot$day). The identical averages of TAN and TKN suggest that nearly full hydrolyzation of organic nitrogen was occurring in the lagoon throughout this period. It is important to notice that during the monitoring period, some samples were susceptible to third-party lab errors, resulting in TKN values being lower than TAN (see Appendix A)

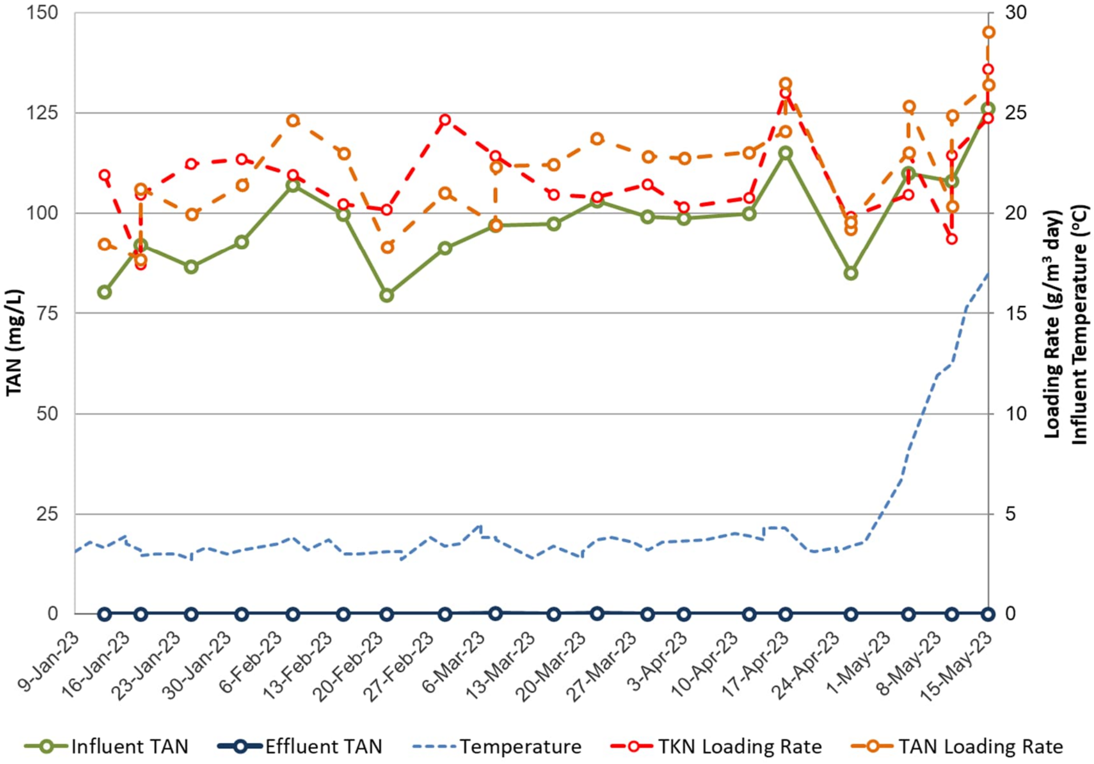

Figure 4.6: Cold Condition SAGR Load Testing - January 9, 2023 – May 16, 2023 TAN Results

4.4.4. Nitrite and Nitrate

Influent NO_2^-, NO_3^-, and effluent NO_2^- were all consistently near zero. Effluent NO_3^- showed generally similar trends to the influent TAN concentrations. This suggests that nearly full nitrification was occurring consistently throughout the period.

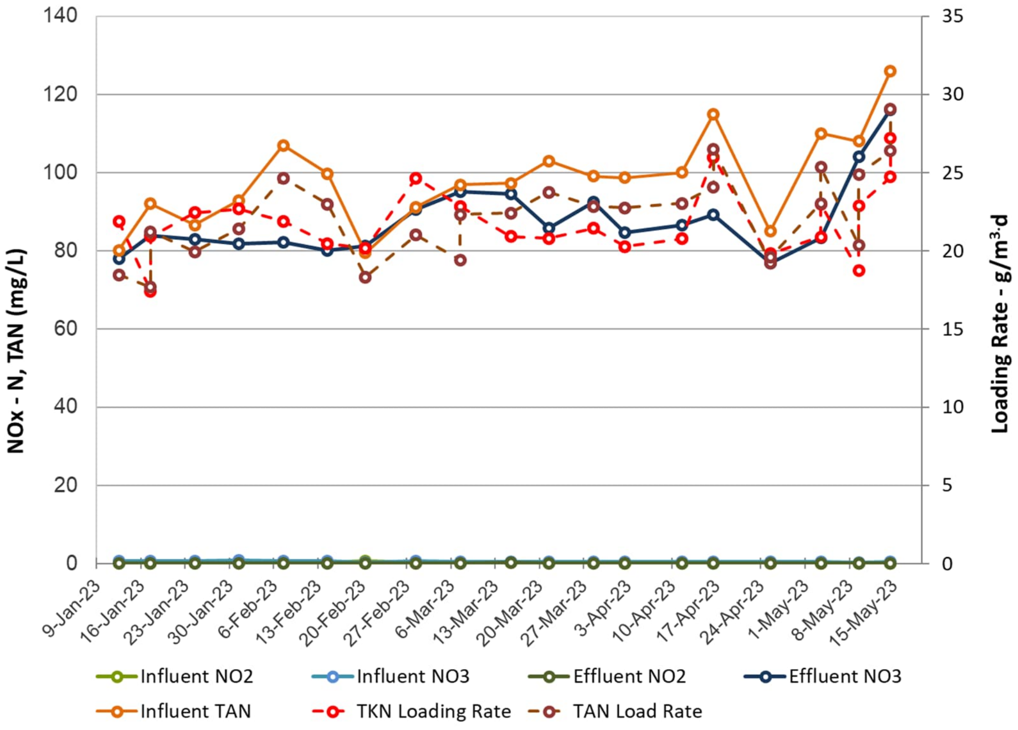

Figure 4.7: Cold Condition SAGR Load Testing - January 9, 2023 – May 16, 2023 NOx Results

4.4.5. cBOD$_5$ and TSS

The SAGR polished cBOD$_5$ and TSS in a manner consistent with historic SAGR installations.

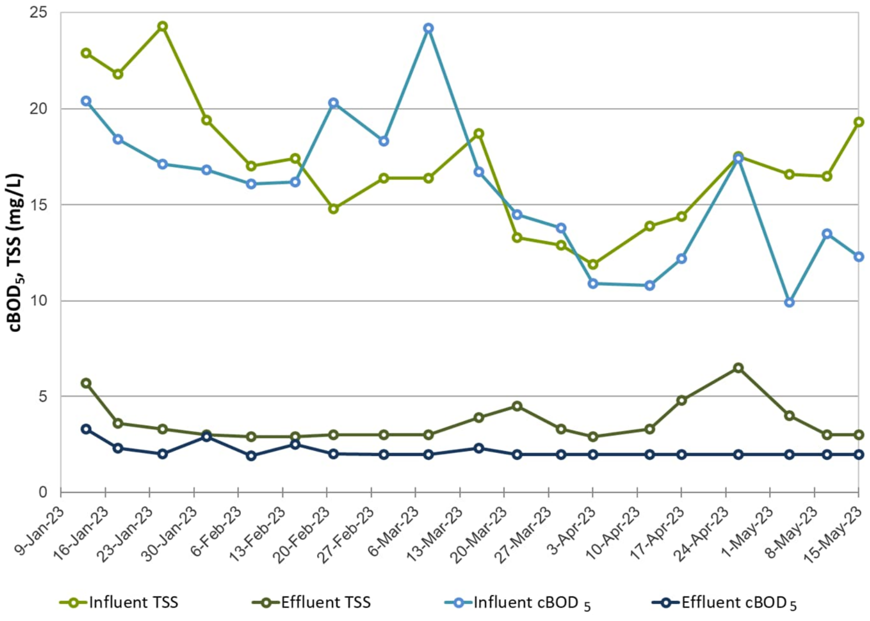

Figure 4.8: Cold Condition SAGR Load Testing - January 9, 2023 – May 16, 2023 NOx Results

4.4.6. Disinfection

The SAGR provided consistent significant disinfection. The average *E. coli* removal efficiency was 99.5% and the minimum was 97.4%. The average TC removal efficiency was 94.5% and the minimum was 60.7%.

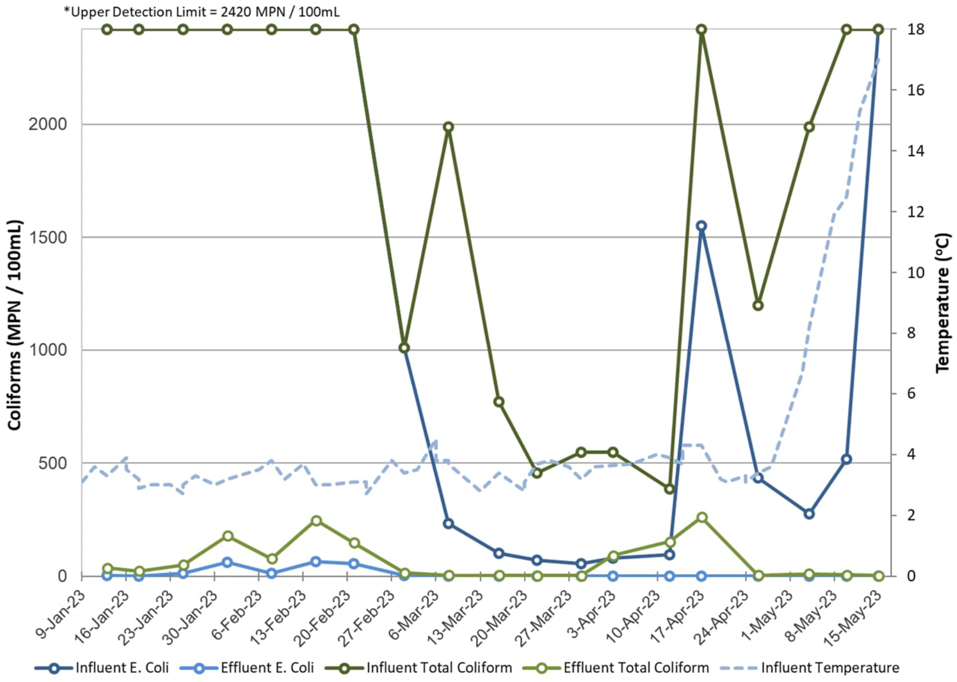

Figure 4.9: Cold Condition SAGR Load Testing - January 9, 2023 – May 16, 2023 Disinfection Results

4.4.7. Statistical Analysis

A simple statistical analysis of the loading rate data from January 9, 2023 – May 4, 2023 is presented below as this data represents a SAGR under stable operation at equilibrium, and does not include the effects of the rapidly increasing temperature in May. Because nearly full TAN removal was measured throughout, and the dependent variable (effluent TAN) was consistently near 0 mg/L, loading rates were chosen as the statistics for comparison. A One-Sample t-Test was used to compare the sample mean with the typical SAGR design loading rate of 12.7 g-TKN/m^3·day (0.8lb-TKN/1000ft^3·day) which is assumed to be the mean loading rate for the SAGR under normal operation. Loading rates were calculated for the beginning and end conditions of each site visit (to record adjustments made). The loading rates data from the end of each site visit are more representative of the stable SAGR conditions and were therefore used in this analysis. A Shapiro Test confirmed that sample loading rate data was normally distributed (*p-value* $= 0.07 > 0.05$). The mean loading rate was 21.9g-TKN/m^3·day (1.38lb-TKN/1000ft^3·day). The median was 21.4g-TKN/m^3·day (1.35lb-TKN/1000ft^3·day). The standard deviation was 0.10. A Quantile-Quantile plot and Histogram with the associated probability curve are given below. Note the units of the statistical analysis are imperial.

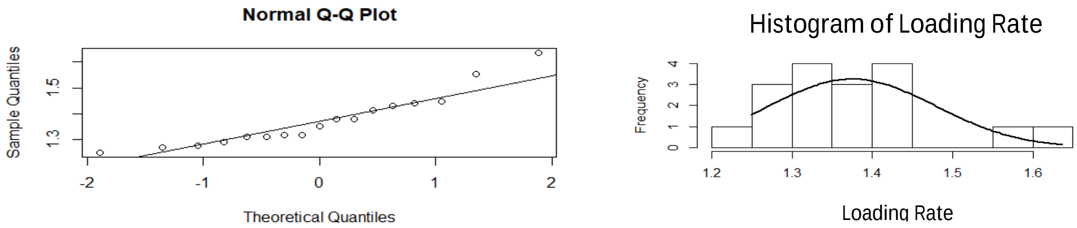

Figure 4.10: Cold Condition SAGR Load Testing – Jan.9, 2023–May16, 2023 – Demonstration of Normal Distribution of Load Rate

The One-Sample t-Test returned a t value of 22.76, which is greater than the critical t value of 1.746 (one tail, $\alpha = 0.05$, df = 16), indicating a statistically significant difference between the sample mean loading rate and the typical design loading rate of 0.8 lb-TKN/1000ft^3·day (*p-value* $= 6.449x10^{-14}$). The assumptions of these analyses are as follows:

- Full TAN removal would be at least as consistently achieved at the typical design loading rate of 12.8 g-TKN/m^3·day (0.8 lb-TKN/1000ft^3·day) as it was during the experiment
- The sample variance in loading rate approximates typical variance in the loading rate of the SAGR under normal operation.
- The sample data is normally distributed (proved above).
- The data are continuous and have been randomly sampled.

The Student's t-test compares two overlapping probability distribution curves. The overlapping portion of the curves must be small in order for the distributions to be considered significantly different. The One-Sample t-Test is designed to compare a sample distribution to a standard value (or population mean), which in this case is the typical SAGR design loading rate. No sample distribution is developed for the standard value, therefore, the variance of typical SAGR loading rates must be assumed to be similar to that of the experiment. This is a significant assumption, however, it is suspected to be sound because typical SAGR operation should have less variance than was measured during the experiment, resulting in less overlap between the distribution curves and greater significance. Typical SAGR operation should have less variance on account of having more experienced, well-trained operators managing the treatment process, and less complications related to ammonia dosing.

4.5. Conclusion

- The SAGR can be loaded at a rate of approximately 21.9g-TKN/$m^3 \cdot$day (1.38lb-TKN/1000$ft^3 \cdot$day), which is 1.7x the current typical design rate, and still provide nearly complete TAN removal in cold conditions with water temperature down to 3^oC, given sufficient aeration, and assuming low-$cBOD_5$ influent.
- While providing this TAN removal, the SAGR is also able to effectively polish TSS and $cBOD_5$ at this temperature range.
- It is important to maintain stable and controlled operation of the SAGR during the start-up and Step Feed stages of operation to ensure full TAN removal is achieved as the influent water temperature declines. Care should be taken to ensure sufficient biomass is grown in the secondary zone of each SAGR during Step Feed to counteract the effects of decreasing temperature, increasing BOD, and increasing TAN loads.
- The SAGR typically provides nearly full nitrification with very little NO_2^- in the effluent.

These results may help to improve the efficiency of the design of SAGRs, especially in climates with winter lagoon temperatures of 3-4^oC. A greater design loading rate corresponds to smaller cheaper reactors. This may translate into potential savings for rural municipalities that are struggling to meet regulatory TAN-related limits in their lagoon effluent, and are in need of treatment such as is provided by the SAGR.

4.6. References

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Appendix A: Confounding Factors and Operational Issues

Date	***Description***
Summer, 2022	Starvation of the SAGR occurred in the summer preceding this experiment as all flow and aeration was directed to the western SAGR train for the summer load rate experiment summarized in a separate report. Biomass is expected to have decreased to negligible levels.
Sept. 7 – Sept. 15, 2022	Onsite vehicle damage to the pilot building influent manhole caused the flow to the SAGR to cease. The pilot was temporarily shut down until the system was repaired on Sept. 15, 2022. Aeration of the SAGR continued during this period.
Sept. 7 – Nov. 16, 2022	From the beginning of the experiment through to November 16 the aeration of zone 2 of the SAGR was completed through only one of the two laterals in the zone (the upstream one). It was discovered on November 16 that a buried valve on the downstream lateral had been closed throughout. This had the effect of reducing the effective treatment volume of zone 2, but it is not known by how much. Effluent dissolved oxygen was always greater than 7mg/L, so the treatment is not expected to have been greatly impacted, however, this closed valve made control of the aeration system difficult for this period. This valve was opened on November 16 and aeration control improved throughout the remainder of the experiment.
Sept. 22 – Oct. 26, 2022	The Step Feed process started on September 22 and ended on November 7. As noted above, the process was intended to be completed at a loading rate of 14.3 g-TAN/m$^{3}\cdot$day (0.9lb-TAN/1000ft$^{3}\cdot$day). However, due to human error, the dosing was not actually increased until October 26. The Step Feed process was therefore not fully utilized to grow sufficient biomass in zone 2 to improve TAN removal when lagoon effluent temperature dropped rapidly from 8°C on November 3 to

	1.5°C on November 13 as noted below. The dosing rate was increased on October 26, however, the issue was not completely corrected until November 2 (see the entry for Sept. 22 – Nov. 2, 2022). Effluent TAN levels of up to 24.9mg/L were subsequently recorded. Upon discovering the mistake, a portion of the air flow rate was directed away from zone 1 and toward zone 2 to promote accelerated biomass growth rate from October 27 to November 4.
Sept. 22 – Nov. 2, 2022	An error in the spreadsheet used to calculate the dosing rate caused the required ammonium chloride addition to be calculated at 50% of what was needed to meet the required concentration. This error was discovered and corrected on November 2, 2022. The effect of this error was mitigated by frequent (on average 3 days) testing of the dosing solution concentration and subsequent addition of ammonium chloride to try to meet the required concentration. This did, however, have the effect of delaying complete correction of loading rate from 4.8 g-TAN/m^3·day to 14.3 g-TAN/m^3·day (see the entry for Sept. 22 – Oct. 26, 2022).
Nov. 3 – Nov. 13, 2022	The temperature dropped rapidly from 8°C on November 3 to 1.5°C on November 13. These conditions are not in themselves operational issues, however, because the Step Feed process was not fully utilized to grow biomass in zone 2 after the starvation period in the Summer of 2022 (see the entry for Sept. 22 – Oct. 26, 2022), these stresses were not mitigated to the full capability of the SAGR. The dosing rate was also increased just prior to this (see the entry for Sept. 22 – Nov. 2, 2022). The combined effect of the temperature decrease and TAN increase in the SAGR with insufficient excess biomass grown to overcome these stresses is that effluent TAN levels of up to 24.9mg/L were subsequently recorded on November 10.
Nov. 13 – Dec 1, 2022	The intent of the experiment was to keep the SAGR influent temperature between 3-4°C through the winter months. However, it was not until December 1 that bucket

	heaters were installed in the SAGR influent tank to maintain this temperature. SAGR influent temperatures between 1-2°C were recorded during this period, and recovery to full TAN removal was recorded within 7 days. Heaters were added late because until this point, the experiment was intended to use both SAGR trains with the west train influent heated and the east train influent unheated. The west train was shut down due to operational issues (see Section 4.3.2) in December and the east train influent began to be heated only after this.
Dec. 3 – Dec. 9, 2022	Flow ceased twice on the weekend of December 3 due to a faulty sensor and electrical receptacle at the SAGR effluent manhole and again on December 8 (see the entry below). During each cease in influent flow, the dosing flow continued, creating a very high TAN concentration in the SAGR influent tank system. The SAGR was not able to fully remove the high influent TAN and an effluent concentration of 35.7mg/L was recorded on December 8. The TAN concentration in the 1000L dosed splitter tank and 1000L SAGR influent tank reached equilibrium again in the subsequent week.
Dec. 8, 2022 – Jan. 9, 2023	On December 8, 2022 the SAGR influent tank was found to be backing-up, tripping high level alarms. The flow from the tank to the SAGR was in some way reduced. Flow during this period was decreased from 0.65L/s to 0.4L/s and the dosing rate increased to compensate for the reduced flow and maintain the design loading rate. On January 9, 2023, flow was increased again to 0.55L/s (and dosing rate adjusted, correspondingly, again). No further flow restriction issues were encountered.
April 14 – May 2, 2023	On April 14, the SAGR effluent manhole pump clogged and the manhole and SAGR flooded. The high-level alarm did not trip to stop the influent flow. When this was discovered, the influent flow, heaters, and dosing flow were temporarily turned off until the system was repaired, though aeration continued. The system

	was repaired and plant operation restarted the same day. It is expected that the flooded SAGR caused water infiltration into the aeration laterals, which were purged on April 17 to correct minor aeration issues (such as rapidly surging/fluctuating flow) noted during this period. The pump continued to operate poorly until it was replaced on May 2, 2023. Plant operation was again required to be shut down on the weekend of April 29-30, though aeration again continued.

Other general operational concerns and confounding factors can be summarized as follows:

Design Parameter	***Description***
Influent Flow	Throughout the experiment, it was noted that – between visits to the pilot – influent flow would sometimes be reduced. Upon opening the influent valve to increase the flow, large amounts of sediment would pass through the influent piping. It was concluded that sediment would settle in the piping system between site visits and that once the gate valve was opened, the sudden increase in the flow would scour the sediment and return the flow to the desired set point. On November 22, 2022, the influent flow was found to have stopped. It is suspected that a power outage at the pilot plant had occurred. The flow was restarted and it is estimated that the flow had only been stopped for a period of less than 12 hours.
Temperature	As flow would sometimes decrease between visits, the retention in the heated influent tank would increase and the SAGR influent would be warmer than intended until the flow was corrected. The bucket heaters used to heat the SAGR influent would periodically suffer lime and sediment build-up on the elements and heating efficiency would be decreased until the heaters were cleaned or replaced entirely. This had the effect of creating minor fluctuations in SAGR influent temperature throughout the experiment.

Aeration	On November 16, 2022, it was determined that one of the two air laterals in zone 2 (the one further downstream) had been turned off at a buried valve. This was determined to be a primary cause for the operational issues in achieving constant air flow to the zone and had the effect of reducing the aerated portion of the zone in use. As effluent dissolved oxygen concentration remained above 7mg/L it is not expected that treatment was significantly impacted. To maintain consistent aeration control, the system otherwise had to be intermittently purged at valves above grade to clear the laterals of water.
Ammonium Chloride Dosing	Various operational issues with the dosing pumps (including but not limited to the formation of air bubbles in the dosing tubes, restricting flow. The dosing rate) caused the dosing rate to not be consistent over time. The effect of this was mitigated by the use of the 1000L well-mixed splitter tank and 1000L SAGR influent tank. These provided dosing equalization to mitigate the immediate impacts of a decrease in dosing rate. As the dosing pumps changed slowly and site visits were completed every 3 days on average, the cumulative effect is likely to be minimal. As flow would sometimes decrease between site visits (see Influent Flow entry), the ratio of SAGR influent flow to dosing flow would decrease and the TAN concentration in the SAGR influent would increase slightly until the flow was corrected.
Third Party Laboratory Errors	During the monitoring period, some lab reports presented TKN<TAN. The issue was consistently reported to ALS, as none of the interferences listed in Standard Methods (APHA, 2021) (nitrate exceeding TKN, high concentration of organic matter and salts/solids) were applicable to lagoon effluent samples. The lab committed to run re-checks by senior analysist when they were available, but also mentioned post-pandemic struggles such as high turnover rates.

CHAPTER 5. CONCLUSION

5.1. Hypothesis 1

Hypothesis 1 was stated in Chapter 1 as follows:

> *A pilot SAGR receiving lagoon discharge wastewater at temperatures over 20°C will consistently remove over 99% of the influent TAN when operated at a loading rate of approximately 32g-TKN/m^3·day (2 lb-TKN/1000ft^3·day) rather than the modern typical design loading rate of 12.8 g-TKN/m^3·day (0.8 lb-TKN/1000ft^3·day).*

Chapter 3 showed that this hypothesis was confirmed. Though the mean loading rate through the experiment was 31.1g-TKN/m^3·day (1.96 lb-TKN/1000ft^3·day) and did not quite meet the hypothesis target of 32g-TKN/m^3·day, the difference is small and over 99% of influent TAN was consistently removed. The mean loading rate was shown to be significantly higher than the typical design value of 12.8 g-TKN/m^3·day. It is expected that SAGRs designed using a design loading rate of 32g-TKN/m^3·day in scenarios with lagoon effluent over 20°C (assuming sufficient aeration and low-cBOD influent) will provide consistent TAN removal to meet regulatory requirements. It is recommended that future research include further increases in design loading rates.

The SAGR can be expected to provide TSS and cBOD polishing and nearly full nitrification at these design parameters as well, leaving very little TSS, cBOD , or NO_2^- in the effluent.

5.2. Hypothesis 2

Hypothesis 2 was stated in Chapter 1 as follows:

> *A pilot SAGR receiving lagoon discharge wastewater at temperatures dropping to 3-4°C in the winter will consistently remove over 99% of the influent TAN when operated at a loading rate of approximately 19.0 g-TKN/m^3·day (1.2lb-TKN/1000ft^3·day) rather than the modern typical design loading rate of 12.8 g-TKN/m^3·day (0.8 lb-TKN/1000ft^3·day).*

Chapter 4 showed that this hypothesis was confirmed. In fact, the mean loading rate through the experiment exceeded the hypothesis target at 21.9g-TKN/m^3·day (1.38lb-TKN/1000ft^3·day), and still over 99% of influent TAN was consistently removed. The mean loading rate was shown to be significantly higher than the typical design value of 12.8 g-TKN/m$^{3}\cdot$day. It is expected that SAGRs designed using a design loading rate of 19.0g-TKN/m$^{3}\cdot$day in scenarios with lagoon effluent between 3-4°C (assuming sufficient aeration, adequate Step Feed implementation, and low-cBOD influent) will provide consistent TAN removal to meet regulatory requirements. It is recommended that future research include further increases in design loading rates.

The SAGR can be expected to provide TSS and cBOD polishing and nearly full nitrification at these design parameters as well, leaving very little TSS, cBOD , or NO_2^- in the effluent.

5.3. Engineering Significance

The result of this research is that SAGRs might be designed in the future with significant reductions in footprint and, therefore, significant reductions in cost to the end users. In the case of Hypothesis 1, the end users that may stand to benefit might include municipalities in warmer climates or industries with elevated wastewater temperature. In the case of Hypothesis 2, the end users might include municipalities with moderate winter temperatures (such as states in middle latitudes), or municipalities across Canada for whom lagoon discharge is only allowed in warm seasons. Due to these results, these end users may more readily implement TAN-reduction strategies, resulting in more cost-effective protection of the environment, surface water bodies, and downstream users.

This research has the potential to significantly benefit wastewater producers subject to regulatory requirements. They may – more cost-effectively – increase the security and health of surface water bodies to which they discharge. Though the users are expected to primarily consist of municipalities and some industry, recent research proves the SAGR is effective in alternate applications such as in gold mine wastewater treatment for cyanide-related compounds (di Biase et al., 2020), and in the cold weather removal of some contaminants of emerging concern (Anderson et al., 2020).

5.4. Future Research

For the experiment conducted in Chapter 3, because the SAGR was in this case operated below the minimum recommended DO concentration of 3 mg/L, and DO-limited kinetics was a concern, it is recommended that similar tests be completed in the future using greater aeration capacity. Should superfluous aeration be provided, perhaps an upper limit on the loading rate may be discovered at which TAN removal can no longer be achieved near 100%.

For the experiment conducted in Chapter 4, it is suspected that with proper control and TAN dosing during the early stages and Step Feed processes, a higher loading rate could have been targeted while still observing full TAN removal by the SAGR at the temperature range of 3-4^{o}C. Perhaps an upper limit on the loading rate may be discovered at which TAN removal can no longer be achieved near 100%. Similar tests in the future may include modifications such as:

- Increasing the target loading as high as 23.8g-TKN/m$^{3}\cdot$day (1.5lb-TKN/1000ft$^{3}\cdot$day);
- Decreasing the influent water temperature to between 0-1^{o}C;
- Operating the two SAGR trains in parallel with different operating parameters such that analysis of variance may be performed.

Should these experiments be completed in the future, care should be taken to ensure sufficient aeration is provided to the SAGR trains so that they do not become DO-limited in the nitrification reaction.