Industrial Electrical Engineering and Automation

Reject Water Treatment Models

Literature Review

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LITERATURE REVIEW

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Abstract

Reject water originates from the dewatering of digested sludge. It cannot be disposed in any arbitrary manner onto surface waters since it contains heavy metals, large amounts of nutrients, has highly variable pH, and usually has high temperatures. Traditionally, reject water is recycled back to the main flow line of the wastewater treatment plant; however, this may cause process instability in the whole plant. Separate reject water treatment is recommended for WWTPs handling huge amounts of reject water.

Different processes are used to treat the water from sludge and are mainly focused on nitrogen and phosphorus removal. These processes can be biological, chemical, or physical in nature. This report outlines several processes occurring during reject water treatment as well as the different technologies for the process. Reject water treatment models found in literature are also discussed and some examples are given on the experience and success of separate reject water treatment in plant-wide systems. And finally, different possibilities for control handles are discussed for reject water treatment processes.

1. Introduction

Due to strict environmental regulations, sludge from wastewater treatment plants (WWTPs) cannot be disposed of or reused in any arbitrary manner. Typical methods for sludge management are: reuse, disposal in landfill, and incineration. An important factor in sludge disposal is the cost. Since sludge from wastewater treatment plants contains more than 90% moisture content, it is very worthwhile to remove water from the sludge. The liquid part of the sludge, which is called "reject water", has very special characteristics which make it prohibited just to be discharged into surface waters as WWTP effluent. Even if the flow of reject water is very low, only about 2% of the total influent flow (Guo et al., 2010), its concentration of nutrients is very high that it accounts for 10-30% of Nitrogen (N) load (Dosta et al., 2007) and 10-80% of Phosphorus (P) load in the activated sludge tank (van Loosdrecht and Salem, 2006). It is quite common knowledge that these nutrients from WWTPs can cause eutrophication, deteriorating the quality of surface waters.

The natural response to reject water treatment is through recycling it back into the WWTP influent stream. This is logical; however, there are a number of disadvantages to this which is discussed further in this report. It is therefore suggested that a separate reject water treatment process be used.

This report discusses different reject water treatment processes. In addition, reject water treatment models are presented and discussed.

1.1. Definition of reject water

Reject water originates from the dewatering of digested sludge. In a wastewater treatment plant, settled sludge composed of 2-6% solids from the primary and secondary clarifiers are stabilized in a sludge digester. This anaerobic digestion process creates a stabilized sludge, about 70% of which is degradable, consequently reducing the total solids content by 50% (Chen et al., 2002). Sludge produced from the wastewater treatment process usually consists of suspended solids, chemicals used in coagulation process, and some biological materials. They undergo further treatment process, in this case anaerobic digestion, to reduce the volume and pathogens. This digestion converts organic materials into methane and/or carbon dioxide. Since raw sludge is more than 90% water, the volume of raw sludge is enormous. The treated sludge is needed to be dewatered before they can be used for other purposes such as for agricultural, land remediation, landfill cover, etc. Evidently, the use of the dewatered sludge depends on its chemical and biological content.

Knowing that a very large portion of the sludge is water, it is therefore important that reject water be recovered. The first step in the recovery process is done by dewatering. Dewatering process are usually physical methods. But they are also performed in combination with chemical methods to enhance the separation of trapped water in the sludge. Since the sludge is composed of heavy metals, large amounts of nutrients, and highly variable pH, this means that reject water, which also has a similar composition, cannot be directly discharged into surface waters. They need further treatment to pass effluent quality standards before they can be deemed fit for discharge.

Ordinarily, reject water can be treated in the same way as the influent wastewater, that is, reject water from sludge digestion is recycled back to the front of the biological treatment plant combined with the wastewater influent. However, this may be costly due to increase in load in the plant influent since reject water contains up to 25% of the total nitrogen load in a flow but is only about 2% of the total influent flow (Guo et al., 2010). Therefore, having a separate reject water treatment process in the WWTP is more advantageous.

1.2. Characteristics of reject water

As mentioned previously, sludge contains solids, water, pathogens, heavy metals, and nutrients. Table 1 presents the typical characteristics of reject water from a municipal WWTP.

Table 1. Typical composition of reject water (Ocansey, 2005)

	Value	Reference
N-Kj	690-1700 mg/l	Throndahl (1993); Wett et al. (1998)
N-NH$_4^+$	750-1500 mg/l	Berends et al. (2005)
P$_{tot}$	up to 130 mg/l	Pitman et al. (1991)
SS	< 800 mg/l	
COD	700-1400 mg/l	Thorndahl (1993)
Temperature	25-40 °C	
pH	7-13	Wett et al. (1998)
Alkalinity	53-150 mmol/l	Wett et al. (1998)

Important characteristics of the reject water are its high ammonium concentration, highly variable pH, and high temperatures. For WWTPs employing biological phosphorus removal, the phosphate content in the reject water is also significant (Phillips et al., 2006). This high-strength flow needs to be treated before discharged from the WWTP.

1.3. Motivation for reject water treatment

Effluent quality standards. Due to the more concentrated amounts of pathogens, heavy metals, and nutrients (N and P) in the reject water, there is a large need to treat the stream before discharging into surface waters. Large amounts of nutrients will lead to eutrophication of rivers and lakes. In addition, high temperatures should be reduced prior to discharge. The high temperatures and ammonium concentrations could be harnessed to aid the growth of bacteria in the activated sludge stream during winter (Wett et al., 1998).

Nutrient recovery. Treatment of the reject water will also lead to recovery of nutrients, N and P. Recovery of resources is sustainable. We consider not only wastewater as a resource but also the nutrients that can be recovered in the process. In this way, the cost for treating reject water is balanced by the nutrient recovery (Verstraete et al., 2009).

2. Reject water treatment methods

Reject water has specific characteristics, in terms of pH, temperature, NH_3 and NH_4 concentration, and COD/N ratio. This allows the application of special methods (physical, chemical, and/or biological). The biological methods are always preferred over the physical and chemical methods since the latter entails higher costs due to associated energy requirement and high cost of chemicals (Jenicek et al., 2007).

The conventional approach to treating reject water is to recycle it back into the plant combined with the wastewater influent. Although this method seems to be simple, it also has its drawbacks. First of which is the increase in the load of the plant as the reject water characteristics is very much different from the normal wastewater treatment plant influent.

Nitrogen is removed biologically from wastewater by nitrification of ammonia under aerobic conditions and denitrification of nitrite and nitrate under anoxic conditions. Phosphorus, on the other hand, is removed by phosphorus release during anaerobic conditions, and a surplus uptake using the polyhydroxybutyrate (PHB) stored during anaerobic conditions in the aerobic and anoxic conditions. It is clear that these nutrients may be removed from the wastewater using cyclic conditions of aerobic and anoxic/anaerobic conditions (Salem et al., 2004).

New methods have been developed which are targeted to treat wastewaters with low COD/N ratio. This new methods are based on the partial oxidation of ammonia to nitrite, followed by nitrite reduction. These methods fall on the category of nitritation/denitritation and nitritation/deammonification.

2.1. Methods for N-removal

Several biological processes have been developed to reduce the N (in the form of ammonia) concentration from the recycle stream before recycling it back or combining it back into the influent stream at the head of the plant (Jones et al., 2007). It is said that treating this N concentrated reject water in a separate process is more efficient than diluting it by recycling it directly with the influent stream.

Several combinations of nitrification, denitrification, and anaerobic oxidation of ammonium have been studied for N removal. These reactions are presented in more detail below. Examples of methods employing combinations of these reactions are: bio-augmentation batch enhanced technology (BABE) (Salem et al., 2004), single reactor system high activity ammonium removal over nitrite process (SHARON) (Hellinga et al., 1998), anaerobic ammonium oxidation process (ANAMMOX) (Strous et al., 1997), SHARON-ANAMMOX (Van Dongen et al., 2001), CANON (Szatkowska et al., 2007), OLAND

(Kuai and Verstraete, 1998), and aerobic/anoxic deammonification process (Gut et al., 2006).
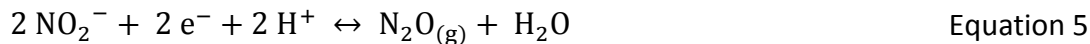
Nitrification-Denitrification

Nitrification is a two-step process:

$$NH_4^+ + 1.5\ O_2 \leftrightarrow NO_2^- + 2\ H^+ + H_2O \qquad\qquad \text{Equation 1}$$

$$NO_2^- + 0.5\ O_2 \leftrightarrow NO_3^- \qquad\qquad \text{Equation 2}$$

These processes are mediated by the ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB), respectively (Dosta et al., 2007; Guo et al., 2010).

Anoxic denitrification, on the other hand, is described by the following equation:

$$NO_3^- + 2\ e^- + 2\ H^+ \leftrightarrow NO_2^- + H_2O \qquad\qquad \text{Equation 3}$$

$$NO_2^- + e^- + 2\ H^+ \leftrightarrow NO_{(g)}^- + H_2O \qquad\qquad \text{Equation 4}$$

$$2\ NO_2^- + 2\ e^- + 2\ H^+ \leftrightarrow N_2O_{(g)} + H_2O \qquad\qquad \text{Equation 5}$$

$$N_2O + 2\ e^- + 2\ H^+ = N_{2\ (g)}^- + H_2O \qquad\qquad \text{Equation 6}$$

Nitritation-Denitritation

Nitritation is defined as partial nitrification wherein ammonia is converted until nitrite only, corresponding to Equation 1. Similarly, denitritation is partial denitrification wherein nitrite, and not nitrate, is converted to nitrogen gas, corresponding to Equations 4 to 6 (Dosta et al., 2007).

An example of a system employing nitritation is the SHARON (Single reactor system for High Ammonia Removal Over Nitrite) reactor. Savings of 25% in aeration costs and 40% in external carbon source are reported when using these methods. (Abeling and Seyfried, 1992; Hellinga et al., 1999; and Wett and Rauch, 2003)

Nitritation-Anammox

Anammox (Anaerobic Ammonia Oxidation) is used to convert the produced nitrite (50%) and ammonia (50%) from the partial nitrification process to nitrogen gas (90%) and nitrate (10%).

The anammox process is described by Equation 7 (Guo et al., 2010).

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O \qquad\qquad \text{Equation 7}$$

The above reactions are all biologically mediated but there are other existing methods, chemical and physical in nature, which removes N from sidestreams such as gas/steam stripping, ion exchange, and precipitation.

Since N in reject water is in the form of ammonium. Ammonium is converted to ammonia as pH is increased. Ammonia is water soluble but when in contact with a gaseous phase, will be in gaseous phase. *Gas or stream stripping* is therefore used to remove ammonium while high pH conditions are met (Janus and van der Roest, 1997).

Ammonium is also removed from reject water using *ion exchange* where MesoLite is used as the ion exchange medium [10]. Experiments have indicated that MesoLite is selective for ammonium ions and more than 95% of ammonium is removed from the reject water (Thornton et al., 2007).

Magnesium-ammonium-phosphate (MAP) or struvite precipitation is a chemical method by which N can be removed from reject water. This method is discussed in detail in Section 2.3.

2.2.   Methods for P-removal

Struvite precipitation can also remove P from reject water. This method is discussed in detail in Section 2.3.

Hydroxyapatite (HAP) precipitation (Momberg and Oellermann, 1992) is another method for precipitating and removing P from reject water and it follows the reaction shown in Equation 8. This mechanism is governed by the concentration of calcium ions and a ratio of Ca:P of 2:1 is found to be efficient for crystallization (Guo et al., 2010).

$$3PO_4{}^{3-} + 5Ca^{2+} + OH^- \rightarrow Ca_5(PO_4)_3OH \qquad\qquad \text{Equation 8}$$
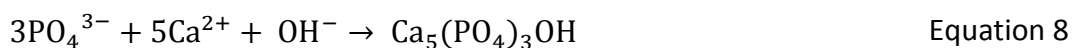
Chemical precipitation methods require the addition of alkalinity to reach a pH value of 8-9.5 and the right ratio of magnesium and calcium for MAP and HAP precipitation, respectively. Ferric and ferrous salts are also used for precipitation. But this has disadvantages: it requires lime addition since the salts are hydrolyzed at high pH, stainless steel equipment are needed, and entails high (Guo et al., 2010). As alternative to this, ferrous ions produced from microbial reduction of iron ore can be used. Iron obtained from the ore is seven times cheaper than the salts (Ivanov et al., 2009).

Two strategies for phosphorus removal from reject water make use of alum sludge. Alum sludge is a by-product of the drinking water treatment plant process when aluminium salt is added as coagulant. It is obtained from the sludge treatment process of drinking water treatment plants. It has been found to have very small reuse applications and is just usually disposed of in landfills. However, recent studies have found that alum sludge has high P adsorption capacities (37 g P/kg alum sludge) (Yang et al., 2009).

Figure 1 shows the process flow in the two strategies. In the first method, the liquid form of the alum sludge is combined to the anaerobically digested sludge in a correct ratio. It is expected that P will be reduced since P immobilization is enhanced.

In the second method, the reject water is filtered through a fixed bed filled with dewatered alum sludge. It is expected that P will be reduced as P is adsorbed to the alum sludge.

P removal in reject water has not gained as much progress and focus as N removal. This is due to the fact that the main mechanism for P removal is by precipitation. This involves chemicals and the process will then be complex and costly. Pipes may be clogged, dewatering and drying of precipitate entails additional costs, and the chemicals are expensive.
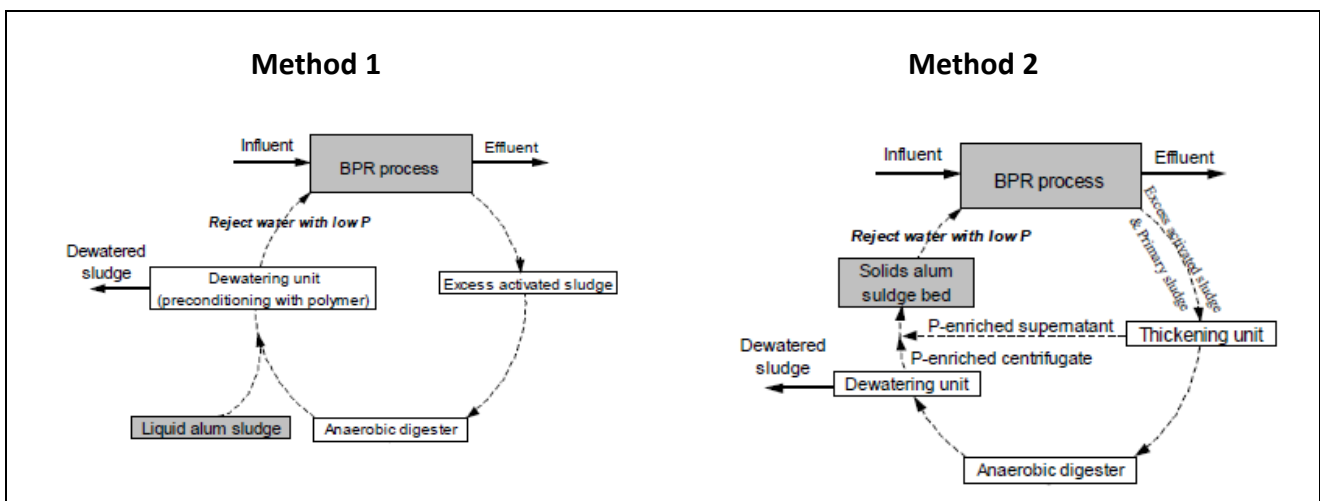

Figure 1. Two methods for P removal using alum sludge (Yang et al., 2009).

2.3. Combined N and P removal in reject water

Ammonium and phosphate can also be removed by *chemical precipitation of struvite*, also called magnesium-ammonium-phosphate (MAP) (Battistoni et al., 2006), however, the formation rate of struvite is low and it needs big reactors and it only occurs within a specific pH range (high) (Guo et al., 2010). Precipitation of struvite occurs according to Equation 9. In this process, both ammonia and phosphate can be removed. However this can only occur if there is enough magnesium and phosphate in the wastewater. pH is very important in this process as maximum struvite precipitation can be achieved at a pH of around 11. This process should be taken advantage of in plants designed for bio-P removal.
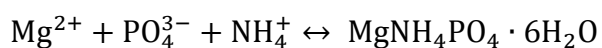
$$Mg^{2+} + PO_4^{3-} + NH_4^+ \leftrightarrow MgNH_4PO_4 \cdot 6H_2O \qquad\qquad \text{Equation 9}$$

The removal of nitrogen and phosphorus from reject water of municipal wastewater treatment plant can also be achieved *using ferric and nitrate bioreductions*. The removal of N using the sequential bio-oxidation of NH_4^+ and bioreduction of NO_3^- with removal of phosphate by precipitation using Fe^{2+} ions produced during the bioreduction of Fe^{3+}(Guo et al., 2010).

3. Reject water treatment models

Three key reject water treatment models have been found in literature: Wett and Rauch (2003) provided a two-step nitritation-denitritation model based on operation in a Sequential Batch reactor (SBR), Van Hulle (2005) presented a two-step nitrification/denitrification Anammox reactions, and Volcke (2006) presented a two-step nitrification and denitrification model for the SHARON process. In these models, key processes as listed in Table 2 are included.

Table 2. Important processes that must be included in a reject water treatment model (Jones et al., 2007)

Process Aspect	Model Process	Important Considerations
Nitrification	• AOB growth and decay • NOB growth and decay	Different growth rates, temperature dependencies and inhibition effects.
Heterotrophic Denitrification	• Growth on substrate through denitritation (using nitrite as an electron acceptor) • Growth on substrate through denitratation (using nitrate as an electron acceptor)	Differences in yield must be accounted for.
Deammonification (Anammox)	• Growth and decay of Anammox bacteria	Appropriate inhibitions (i.e. nitrite toxicity) and limitations must be included.
pH	• All significant equilibrium relationships (i.e. nitric and nitrous acid, ammonia and carbonate system)	pH modeling is essential because, for example, some inhibition effects are caused by unionized species concentrations.
Gas-liquid interactions	• Stripping of certain model components such as ammonia and carbon dioxide	Gas-liquid interactions are essential to represent pH and in some cases, to properly represent growth-limiting conditions.

Two-step nitritation-denitritation model by Wett Rauch (2003)

In this model, the N elimination that can be found in the Activated Sludge Models (ASMs) are expanded to include the four oxidation and reduction processes and the decay processes for Nitrosomonas (NS) and Nitrobacter (NB). Inhibitions by NH_3 and HNO_2 are also accounted for (see Table 3 for the kinetic equations).

Table 3. Kinetic equations used in the model by Wett and Rauch (2003).

PROCESS	PROCESS RATE EQUATION
Nitrozation	$\mu_{ns}X_{ns}\,\dfrac{S_{NH}}{k_{NH\,ns}+S_{NH}}\,\dfrac{S_{O_2}}{k_{O_2\,ns}+S_{O_2}}\,\dfrac{\exp\left(\frac{S_{HCO_3}-k_{HCO_3}}{a}\right)}{\exp\left(\frac{S_{HCO_3}-k_{HCO_3}}{a}\right)+1}\,\dfrac{k_{NH_3ns}}{k_{NH_3ns}+S_{NH_3}}\,\dfrac{k_{HNO_2}}{k_{HNO_2}+S_{HNO_2}}$
Decay of Nitrosomonas (NS)	$b_{ns}X_{ns}0.5\left(1+\dfrac{S_{O_2}}{0.1+S_{O_2}}\right)$
Nitration	$\mu_{nb}X_{nb}\,\dfrac{S_{NO}}{k_{NO\,nb}+S_{NO}}\,\dfrac{S_{O_2}}{k_{O_2\,nb}+S_{O_2}}\,\dfrac{\exp\left(\frac{S_{HCO_3}-k_{HCO_3}}{a}\right)}{\exp\left(\frac{S_{HCO_3}-k_{HCO_3}}{a}\right)+1}\,\dfrac{k_{NH_3nb}}{k_{NH_3nb}+S_{NH_3}}\,\dfrac{k_{HNO_2}}{k_{HNO_2}+S_{HNO_2}}$
Decay of Nitrobacter (NB)	$b_{nb}X_{nb}0.5\left(1+\dfrac{S_{O_2}}{k_{O_2\,nb}+S_{O_2}}\right)$
NO$_2$ reduction	$1.77\,\mu_h X_h\,\eta\,\dfrac{S_S}{k_{S\,h}+S_S}\,\dfrac{S_{NH}}{k_{NH\,h}+S_{NH}}\,\dfrac{S_{NO_2}}{k_{NO\,h}+S_{NO_2}}\,\dfrac{k_{O_2}}{k_{O_2\,h}+S_{O_2}}$
NO$_3$ reduction	$\mu_h X_h\,\eta\,\dfrac{S_S}{k_{S\,h}+S_S}\,\dfrac{S_{NH}}{k_{NH\,h}+S_{NH}}\,\dfrac{S_{NO_3}}{k_{NO\,h}+S_{NO_3}}\,\dfrac{k_{O_2}}{k_{O_2\,h}+S_{O_2}}\,\dfrac{\frac{S_{NO_3}}{S_{NO_2}}}{\frac{S_{NO_3}}{S_{NO_2}}+1}$
CO$_2$ stripping	$Q_{air}=R^{(1-x)}\,\dfrac{\frac{V_{fluid}}{k_{strip\,O_2}}}{\frac{H_{O_2}}{\rho_{O_2}}O_{2\,air}-O_{2\,fluid}}$ $\dfrac{dCO_{2\,fluid}}{dt}=\left(CO_{2\,air}\dfrac{H_{CO_2}}{\rho_{CO_2}}-CO_{2\,fluid}\right)k_{strip\,CO_2}\,R_{O_2}^{x}\,\dfrac{Q_{air}}{V_{fluid}}$

Two-step nitrification/denitrification Anammox reactions by Van Hulle (2005)

This model is based on ASM1 by Henze et al. (1987) and is extended to include Anammox reaction and two-step nitrification and denitrification. The stoichiometric matrix for this model is given in Table 4.

Table 4a. Petersen matrix for ASM1 extended with two-step nitrification/denitrification Anammox reactions Van Hulle (2005)

	S_O	S_S	S_{TAN}	S_{NO2}	S_{NO3}	S_{N2}	X_H	X_{NH}	X_{NO}	X_{AN}	X_S	X_I
Hydrolysis of entrapped organics	$-\left(\frac{1-Y_H}{Y_H}\right)$	1									-1	
Growth of X_H		$-\left(\frac{1}{Y_H}\right)$	$-i_{nbm}$				1					
Decay of X_H			$i_{nbm}-f_p i_{nxi}$				-1				$1-f_i$	f_i
Growth of X_H on NO_3^-		$-\left(\frac{1}{Y_{H,NO3}}\right)$	$-i_{nbm}$	$\left(\frac{1-Y_{H,NO3}}{1.14\,Y_{H,NO3}}\right)$	$-\left(\frac{1-Y_{H,NO3}}{1.14\,Y_{H,NO3}}\right)$		1					
Growth of X_H on TNO_2		$-\left(\frac{1}{Y_{H,NO2}}\right)$	$-i_{nbm}$	$-\left(\frac{1-Y_{H,NO2}}{1.71\,Y_{H,NO2}}\right)$		$\left(\frac{1-Y_{H,NO2}}{1.71\,Y_{H,NO2}}\right)$	1					
Growth of X_{NH}	$-\left(\frac{3.43-Y_{NH}}{Y_{NH}}\right)$		$-\left(\frac{1}{Y_H}\right)-i_{nbm}$	$\left(\frac{1}{Y_{NH}}\right)$				1				
Decay of X_{NH}			$i_{nbm}-f_p i_{nxi}$					-1			$1-f_i$	f_i
Growth of X_{NO}	$-\left(\frac{1.14-Y_{NH}}{Y_{NH}}\right)$		$-i_{nbm}$	$-\left(\frac{1}{Y_{NO}}\right)$	$\left(\frac{1}{Y_{NO}}\right)$				1			
Decay of X_{NO}			$i_{nbm}-f_p i_{nxi}$						-1		$1-f_i$	f_i
Growth of X_{AN}			$-\left(\frac{1}{Y_{AN}}\right)-i_{nbm}$	$-1.52-\left(\frac{1}{Y_{AN}}\right)$	1.52	$\left(\frac{2}{Y_{NO}}\right)$				1		
Decay of X_{AN}			$i_{nbm}-f_p i_{nxi}$							-1	$1-f_i$	f_i

Table 4b. Kinetic expressions for the two-step nitrification/denitrification Anammox model by Van Hulle (2005).

PROCESS	PROCESS RATE EQUATION
Hydrolysis of entrapped organics	$k_n \dfrac{\frac{X_S}{X_H}}{K_X + \frac{X_S}{X_H}} X_H$
Growth of X_H	$\mu_H^{max}\, e^{\theta_H^{growth}(T-Tr)} \dfrac{S_O}{K_{O,H}+S_O} \dfrac{S_S}{K_{S,H}+S_S} X_H$
Decay of X_H	$b_H\, e^{\theta_H^{decay}(T-Tr)} X_H$
Growth of X_H on NO_3^-	$\mu_H^{max}\, e^{\theta_H^{growth}(T-Tr)} \eta_{NO3} \dfrac{K_{O,H}}{K_{O,H}+S_O} \dfrac{S_{NO3}}{K_{NO3,H}+S_{NO3}} \dfrac{S_{NO3}}{K_{TNO2}+S_{NO3}} \dfrac{S_S}{K_{S,H}+S_S} X_H$
Growth of X_H on TNO_2	$\mu_H^{max}\, e^{\theta_H^{growth}(T-Tr)} \eta_{NO3} \dfrac{K_{O,H}}{K_{O,H}+S_O} \dfrac{S_{TNO2}}{K_{TNO2}+S_{TNO2}} \dfrac{S_{NO2}}{S_{NO2}+S_{NO3}} \dfrac{S_S}{K_{S,H}+S_S} X_H$
Growth of X_{NH}	$\mu_{NH}^{max}\, e^{\theta_{NH}(T-Tr)} \dfrac{S_O}{K_{O,NH}+S_O} \dfrac{S_{NH3}}{K_{NH3,NH}+S_{NH3}} X_{NH}$
Decay of X_{NH}	$b_{NH}\, e^{\theta_{NH}(T-Tr)} X_{NH}$
Growth of X_{NO}	$\mu_{NO}^{max}\, e^{\theta_{NO}(T-Tr)} \dfrac{S_O}{K_{O,NO}+S_O} \dfrac{S_{HNO2}}{K_{HNO2,NO}+S_{HNO2}} X_{NO}$
Decay of X_{NO}	$b_{NO}\, e^{\theta_{NO}(T-Tr)} X_{NO}$
Growth of X_{AN}	$\mu_{AN}^{max}\, e^{\theta_{AN}(T-Tr)} \dfrac{S_{TAN}}{K_{TAN,AN}+S_{TAN}} \dfrac{S_{TNO2}}{K_{TNO2,AN}+S_{TNO2}} \dfrac{K_{O,AN}}{K_{O,AN}+S_O} X_{AN}$
Decay of X_{AN}	$b_{AN}\, e^{\theta_{AN}(T-Tr)} X_{AN}$

Two-step nitrification and denitrification model for the SHARON process by Volcke (2006)

Volcke developed a four-step nitrogen removal model. This is again a modification to the most common IWA Activated Sludge Models (ASMs) (Henze et al., 1987; Henze et al., 2000). See Table 5. for the model matrix and kinetic equations used in this model.

Table 5a. Model matrix and kinetic equations for the four-step nitrogen removal model (Volcke, 2006).

	S_S	S_I	S_O	S_{NH}	S_{NO2}	S_{NO3}	S_{N2}	S_{ALK}	X_I	X_{BH}	X_{AOB}	X_{NOB}
Aerobic growth of heterotrophs on readily biodegradable COD	$-\left(\frac{1}{Y_H}\right)$		$-\left(\frac{1-Y_H}{Y_H}\right)$	$-i_{XB}$				*		1		
Nitrate reduction to nitrite	$-\left(\frac{1}{Y_H}\right)$			$-i_{XB}$	$\left(\frac{1-Y_H}{1.14\,Y_H}\right)$	$-\left(\frac{1-Y_H}{1.14\,Y_H}\right)$		*		1		
Nitrite reduction to nitrogen gas	$-\left(\frac{1}{Y_H}\right)$			$-i_{XB}$	$-\left(\frac{1-Y_H}{1.71\,Y_H}\right)$		$\left(\frac{1-Y_H}{1.71\,Y_H}\right)$	*		1		
Decay of heterotrophs			$-(1-f_{XI})$					*	f_{XI}	-1		
Aerobic growth of AOB			$-\left(\frac{3.43-Y_{AOB}}{Y_{AOB}}\right)$	$-i_{XB}-\left(\frac{1}{Y_{AOB}}\right)$	$\left(\frac{1}{Y_{AOB}}\right)$			*			1	
Aerobic growth of NOB			$-\left(\frac{1.14-Y_{NOB}}{Y_{NOB}}\right)$		$-i_{XB}-\left(\frac{1}{Y_{NOB}}\right)$	$\left(\frac{1}{Y_{NOB}}\right)$		*				1
Decay of AOB			$-(1-f_{XI})$					*	f_{XI}		-1	
Decay of NOB			$-(1-f_{XI})$					*	f_{XI}			-1
Oxygen supply			1					*				

Table 5b. Kinetic equations for the four-step nitrogen removal model (Volcke, 2006).

PROCESS	PROCESS RATE EQUATION
Aerobic growth of heterotrophs on readily biodegradable COD	$\mu_{mH} \dfrac{S_S}{K_S + S_S} \dfrac{S_O}{K_{O,H} + S_O} X_{BH}$
Nitrate reduction to nitrite	$\mu_{mH} \dfrac{S_S}{K_S + S_S} \dfrac{K_{O,H}}{K_{O,H} + S_O} \dfrac{S_{NO3}}{K_{NO3} + S_{NO3}} \eta_{NO3 \rightarrow NO2} X_{BH}$
Nitrite reduction to nitrogen gas	$\mu_{mH} \dfrac{S_S}{K_S + S_S} \dfrac{K_{O,H}}{K_{O,H} + S_O} \dfrac{S_{NO2}}{K_{NO2} + S_{NO2}} \eta_{NO2 \rightarrow N2} X_{BH}$
Decay of heterotrophs	$b_H X_{BH}$
Aerobic growth of AOB	$\mu_{mAOB} \dfrac{S_{NH}}{K_{NH} + S_{NH}} \dfrac{S_{ALK}}{K_{ALK} + S_{ALK}} \dfrac{S_O}{K_{O,A} + S_O} \dfrac{K_{NH3}^{AOB}}{K_{NH3}^{AOB} + S_{NH3}} \dfrac{K_{HNO2}}{K_{HNO2} + S_{HNO2}} X_{AOB}$
Aerobic growth of NOB	$\mu_{mNOB} \dfrac{S_{NO2}}{K_{NO2} + S_{NO2}} \dfrac{S_{ALK}}{K_{ALK} + S_{ALK}} \dfrac{S_O}{K_{O,N} + S_O} \dfrac{K_{NH3}^{NOB}}{K_{NH3}^{NOB} + S_{NH3}} \dfrac{K_{HNO2}}{K_{HNO2} + S_{HNO2}} X_{NOB}$
Decay of AOB	$b_A X_{AOB}$
Decay of NOB	$b_A X_{NOB}$
Oxygen supply	$k_L a (S_O^* - S_O)$

The tables above show the 2-step nitrification [(5) & (6)] and 2-step denitrification [(2) & (3)] processes. Non-competitive inhibition terms for NH_3 and HNO_2 were included for the nitrification kinetic expressions. Correction factors for heterotrophic growth under anoxic conditions were also included.

4. Reject water treatment in a plant-wide context (Case-studies)

Volcke et al. (2006) studied the effects of reject water treatment in the performance of a WWTP. Ammonium concentrations were found to be significantly higher (28%) when reject water is recycled to the main flow of the plant. A SHARON-Anammox process was modeled as a separate reject water treatment and the effluent quality of the main WWTP was found to improve.

In the Netherlands, to reach the stricter requirements for N removal, the conventional biological treatment is extended by using additional aeration tanks. However, it was shown to be more advantageous to increase nutrient removing capacity by installing complementary techniques or a separate reject water treatment reactor. The STP at Utrecht was found to produce reject water which has low ammonium concentrations thus a bioreactor without sludge retention was suggested. The STP at Beverwijk was suggested to perform steam stripping where the residual ammonia solution can be sold to a chemical company (Janus and van der Roest, 1997).

WWTP in Strass employs a two-stage biological treatment. A plant-wide model is done which includes a sludge digestion model based on Siegrist model. The efficiency of N removal was compared between a system with a separate reject water treatment and one with a nitrogen return load (Wett et al., 1998). The study has shown that a separate reject water treatment process improved the N removal by 7-11%. In addition, the process was found to be more stable unlike without, wherein N/COD ratios was high causing a decrease in denitrification rate, thereby reducing alkalinity, and further causing a decrease in the denitrification rate.

5. Control strategies

The BSM2 platform (Jeppsson et al., 2007) is used to study different control strategies that can be implemented in a WWTP. Different plant configurations can be used and different reject water treatment processes can also be modeled and compared. Figure 2 shows a reject water treatment process (SHARON-Anammox) model integrated in the BSM2 as an example of control strategy development and comparison (Volcke et al., 2006).

Various control strategies can be implemented in reject water treatment process. In Strass WWTP, the pH value is kept within a desired range by aeration control (Wett et al., 1998).

The Alexandria Sanitation Authority pilot plant using SBR for reject water treatment implemented control strategy in the nitritation/denitritation process using a DO on/off control based on pH (Wett et al., 2007). In the nitritation/deammonification process, a narrow pH control band was set to prevent NO_2 accumulation which is toxic to anammox bacteria.

In case where there is no separate reject water treatment but only a recycle to the main line of the WWTP, flow equalization of the reject water stream can be implemented (Phillips et al., 2006).
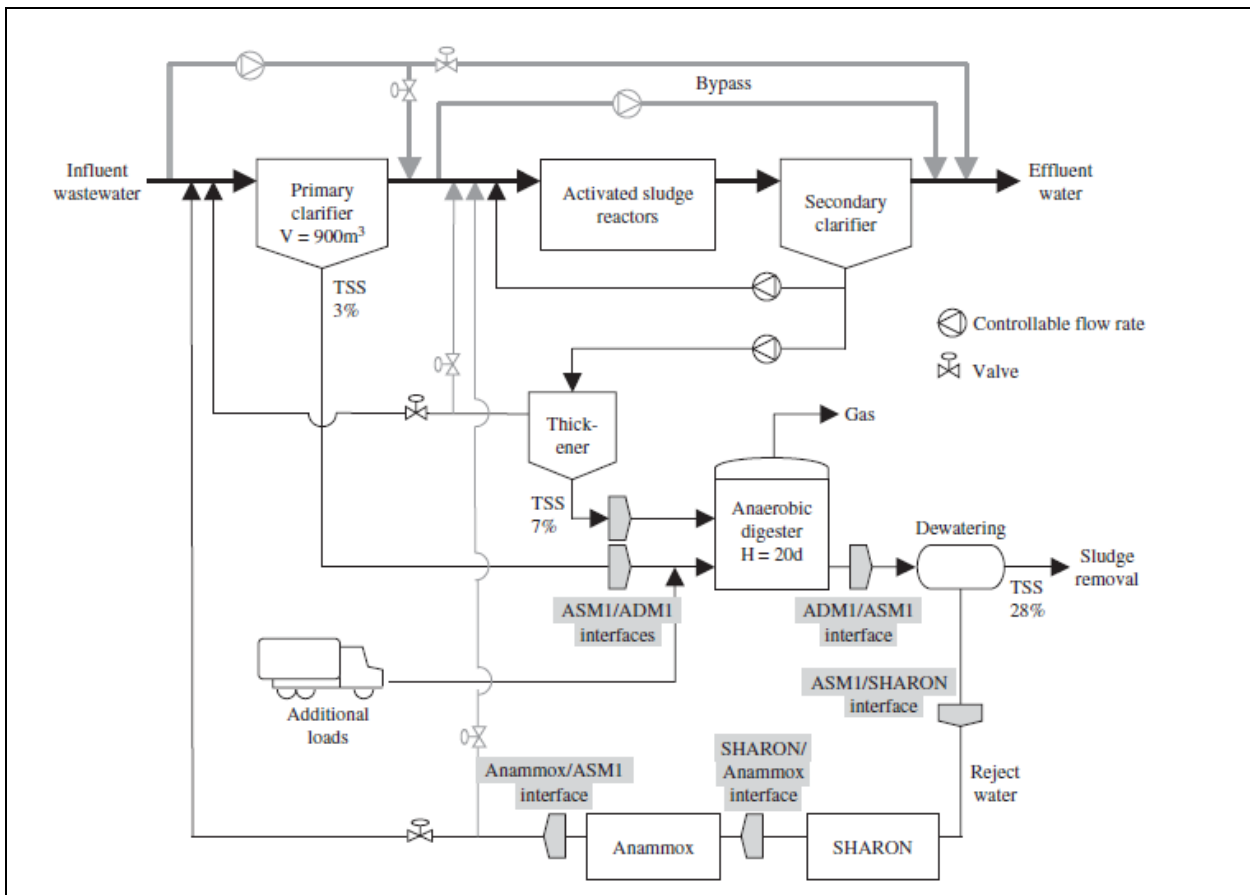
Figure 2. BSM2 with reject water treatment process (adapted from Jeppsson et al., 2006)

Optimization of the nitrification process to remove ammonia can be done by limiting the temperature between 30-35°C. It was reported that at temperatures below 30°C, nitrification goes at a slow rate while at above 35°C, nitrification rate becomes inhibited (Phillips et al., 2006).

As reject water treatment is different from the treatment occurring in the main WWTP, Jones et al. (2007) presented several ideas to consider when deciding for control and operation or reject water treatment process:

• Temperature dependencies and difference in the growth rates of AOBs and NOBs determine when to stop nitrification to prevent nitrate formation.
• Ammonia and nitrous acid concentrations can inhibit AOB and NOB growth.
• pH should be carefully controlled
• Anammox organisms require long SRTs and process start-up times.

6. Summary and conclusion

Reject water treatment becomes important as legislations become more stringent with regards to WWTP effluent qualities. In addition, separate reject water treatment becomes more advantageous in preventing WWTP instability when high-strength reject water is instead recycled to the main line of the WWTP.

This report outlined several processes occurring during reject water treatment as well as the different technologies for the process. In addition, models were also presented to show how such technologies can be implemented mathematically which benefits modelers and WWTP practitioners. Some examples were also given on the experience and success of separate reject water treatment in a plant-wide system. And finally, different possibilities for control handles are discussed for reject water treatment processes.

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