"Implementation of state of the Art Modelling and Novel Microbial Processes in the Nitrogen Cycle. Can such a program be implemented in Cyprus!"

S. Xanthos[1,2], J. Fillos[1], K. Ramalingam[1], M. Gong[1], R. Jezek[1], A. Rosenthal[1], A. Deur[3], K. Beckmann[3]
[1.] Department of Civil and Environmental Engineering, The City College of CUNY, 137[th] and Convent Avenue, New York City, New York, 10031, [2.] Fulbright Scholar, University of Cyprus, Department of Civil and Environmental Engineering, NIREAS International Water Research Center, 1678 Nicosia, Cyprus, 3. New York City Department of Environmental Protection, 1 Lefrak City Plaza, 59-17 Junction Blvd. Flushing, NY. (E-mail: *xanthos@ccny.cuny.edu)*

Abstract

The New York City Department of Environmental Pollution (NYCDEP) is implementing step feed biological nitrogen removal (BNR) process to meet the recent nitrogen discharge permit regulations at its Waste Water Treatment Plants (WWTPs). This kind of a process change leads to an increase in the mixed liquor suspended solids (MLSS) concentration in the aeration tanks which results in an increased hydraulic and solids loading to the final settling tanks (FSTs). To assess performance and evaluate alternatives to improve the efficiency of the FSTs, a computer model was developed depicting the actual structural configuration of the tanks and the current and proposed hydraulic and solids loading rates. The goal of this paper is to discuss some of the steps of the development of this integrated numerical tool for effluent quality prediction and control. Additionally, the demand for energy reduction and sustainable WWTP operations has also lead to the implementation of novel technologies in nitrogen removal such as the SHARON (Stable and High activity Ammonia Removal Over Nitrite) and Anammox (**An**aerobic **AMM**onium **Ox**idation) microbial processes. A brief introduction of the implementation of the anammox process along with the challenges that have to be considered in implementing this in the New York City WWTPs is detailed.

Keywords: Final Settling Tank Modelling, CFD, ANNAMOX.

Background and Introduction

The New York City Department of Environmental Protection (NYCDEP) is performing a comprehensive update of its Waste Water Treatment Plants (WWTPs). The Wards Island WWTP was designed to provide secondary treatment for an average dry weather flow of 275 MGD (million gallons per day) or 12.0 m^3/s. Recognizing the critical nature of FST's in upgrading plant performance to the BNR mode, a three dimensional (3D) computer model was developed to assess proposed low cost enhancement alternatives to sustain the additional solids and hydraulic loadings and still achieve discharge permit limits. The model was specifically developed for the Gould II type rectangular tanks for which a detailed description is given by Ramalingam et al. (2009), Gong et al. (2010) and Xanthos et al. (2011). This paper will address some of the major steps taken in developing such a 3D CFD model. These steps identify and address many issues some of which are outlined below:

1. Geometric characterization of final settling tanks,
2. MLSS settling characteristics and their importance in model predictions,
3. Turbulence models utilized in the numerical solutions,
4. Incorporation of different flocculation sub-models and effect of the velocity gradient (G),
5. Tracer studies and their use in calibration and model validation,
6. Hydrodynamic versus Solid-Coupled models,
7. Verification with in-tank experimental measurements which were carried out after the tank modifications which were primarily baffle additions (inlet and in-tank baffle), baffle sensitivity, and the impact of these on the quality of the effluent suspended solid (ESS) prediction.

In this short white paper details will be given on the following items 1) i.e. Geometry construction for the CFD Model, 2) MLSS settling characteristics focusing on discrete settling, 3) inlet and in-tank baffle sensitivity and their influence on ESS prediction and 4) the anammox process.

Geometry Construction

Modelling the large Gould II type rectangular tanks posed many geometrical challenges due to their complex structural components. For example, **Figure 1**a shows the actual upstream view of the existing tank with all its features, while **Figure 1b** demonstrates the discretized domain that was developed for the CFD model. **Figure 2** illustrates the original inlet baffle which consisted of a solid wood wall with rectangular and circular openings for flow distribution. As part of the modelling effort, in order to have a well-defined entrance to the tank, one bottom plank was removed. This configuration was subsequently used for all the initial field testing which included SS profiles and dye studies using Rhodamine WT and for domain development in the CFD model. .

(a) **(b)**

Figure 1: a) Actual image of influent side of the FST,
b) Perspective upstream view of CFD model of the FST".

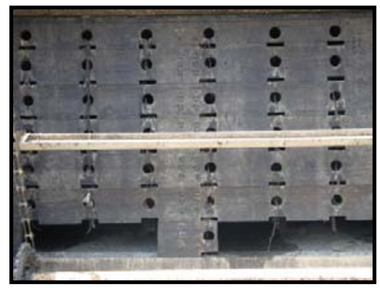

Figure 2: Actual perforated inlet baffle configuration.

MLSS Settling Characteristics

Sedimentation or settling is intrinsic to final settling tanks found in WWTPs. Liquid-solid separation occurs under different conditions. The concentration of the MLSS entering the FST is generally in the range of 1000 - 3000 mg/L. The settling process begins almost immediately after the flow enters the inlet region of the FST and because of the concentrations in different zones, different types of settling can be observed ranging from the clarified effluent to the compressed blanket region. As indicated in **Figure 3**, five types of settling can be experienced in the FSTs, namely compression settling, zone or hindered settling, flocculent settling, discrete settling and non-settling. Discrete settling of the flocs has been shown to be a dominant removal process in FSTs. The procedure to determine the solids fraction in the discrete settling process is relatively new and the description within builds upon the initial work carried out by A. Griborio and J.A. McCorquodale (2004). Discrete settling occurs at low concentrations of SS and in the absence of interference from hydrodynamic flow field of other particles in the suspension. The SS threshold at which discrete settling occurs was first determined by preparing successive dilutions of MLSS using plant effluent until particle interaction was not observed visually. In a series of dilutions undertaken, discrete settling became evident when the MLSS concentration was between 550 and 400 mg/L. Therefore discrete settling experiments were conducted at concentrations below 550 mg/L and sometimes as low as 150 mg/L. The particles in the mixed liquor comprising SS are biological flocs of irregular shape and composition. Consequently it is difficult to classify them in terms of size and shape. However, since the main interest in this effort was to determine their capture efficiency in the FSTs, it was convenient to classify them in terms of their settling velocity. Therefore, the MLSS were separated into three groups, Large, Medium, and Small size flocs based only on their apparent settling velocities: **Large Size Flocs -** flocs that exhibit a settling velocity, $V_s > 6$ m/hr, **Medium Size Flocs -** flocs with 1.5 m/hr < V_s < 6 m/hr and **Small Size Flocs -** flocs with V_s < 1.5

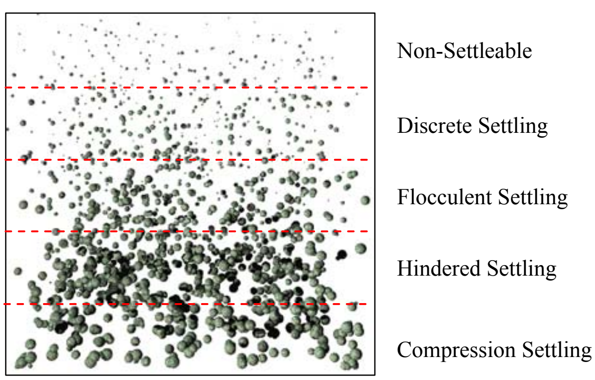

Figure 3: Different Settling Regions in typical FST.

m/hr. It should be noted that the basis of classification of SS among the three groups though arbitrary, has shown to be useful in developing a method to compute the capture efficiency of SS in the FSTs. Three separate columns with a total volume of approximately four litres were constructed from Plexiglas as shown in Figure 4. Each column was attached to an Imhoff cone to facilitate sampling of the SS transiting a referenced cross-section area at the junction between the column and the Imhoff cone. Valves for sampling were located at the bottom of the cone and just above the cone-column junction. Though the three columns are identical, the settling times provided during the tests were different so that column 1 measured the large flocs, column 2 measured the combined large and medium sized flocs, and column 3 measured the concentration of SS that remained in the supernatant after a settling time of 60 minutes. These "non-settleable" SS would be included in the class of small size flocs. The tri-column method was repeated several times using different settling velocity criteria for defining particle size distribution from data collected in the field while carrying out the experiment by the first method. These data were then applied to the tri-column test and tested for validation. The combined total data showed that the large size particles are predominantly composed of particles with a settling velocity greater than 6.0 m/hr. and at times as high as 9.0 m/hr, i.e., greater than the value used in the definition at the start of this discussion. This indicates that large size flocs should be easily removed in FSTs which are typically designed for an average overflow rate of 1 m/hr. Similarly the medium size flocs were measured using average settling velocities between 2.3 - 6.9 m/hr and account for 10 - 25 % of the MLSS. In order to confirm the definitions selected in the beginning, the experiments were repeated for this criteria. Table 1 shows that particles with velocities greater than 6 m/hr comprised approximately 73% of the MLSS at a specific time period and are denoted as large size flocs. Small particles with velocities less than 1.5 m/hr comprised 14% and consequently medium size particles comprise 13%. This size distribution exercise was performed multiple times especially when there was a large variability on the SVI (sludge volume index) values of the MLSS and was used as in input parameter to the CFD model for the FSTs.

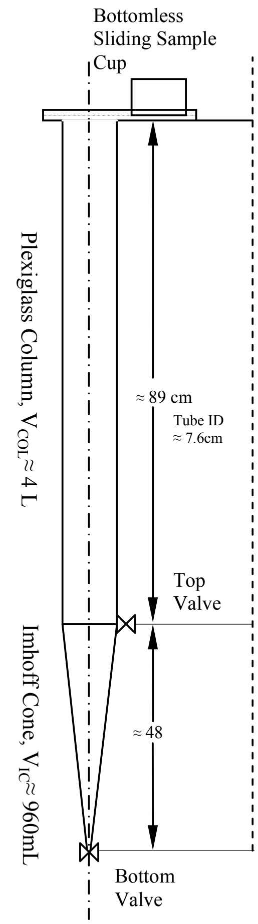

Figure 4: Apparatus Used to measure Discrete Settling Velocities

Table 1: Typical Tri-Column Classification Results

Experiment #	Average Large V_s (m/hr)	Average Medium V_s (m/hr)	Average Small V_s (m/hr)	MLSS (mg/L)	Temp °C	Large Floc Fraction	Medium Floc Fraction	Small Floc Fraction
1	-	-	-	1183	26.3	0.77	0.12	0.11
2	-	-	-	1196	26.3	0.68	0.14	0.18
Average	> 6	~ 3.75	~ 1.13	-	-	**0.73**	**0.13**	**0.14**

CFD Results – Inlet and In-Tank Baffles Addition to NYCDEP WWTP's

In addition to the experiments mentioned in the previous section, extensive data was collected in-situ on sludge blankets and the concentration gradient within the blanket. Table 2 gives a summary of some of the data used as input parameters to the model. Figure 5.d shows the final inlet (4H7V) and in-tank baffle configuration that was selected after many iterative simulations on the calibrated and validated CFD model. It also points out the quantitative prediction on the value of G (Velocity shear) of the CFD model as a function of depth along the length of the tank for the 4H7V configuration (figure 5.b).

Table 2: Data used as input parameters to the model

Description	Variable	Value	Units
Large Floc Settling Velocity	V_1	9.19	m/hr
Medium Floc Settling Velocity	V_2	4.8	m/hr
Small Floc Settling Velocity	V_3	0.77	m/hr
Large Floc Fraction	F_1	0.75	NA
Medium Floc Fraction	F_2	0.15	NA
Small Floc Fraction	F_3	0.1	NA
Non-Settleable Solids Threshold	X FSS	4	mg/L
Discrete Threshold	X_d	600	mg/L
Hindered Threshold	X_h	120	mg/L
Initial Settling Velocity for Zone/Compression Settling	V_0	12.2	mg/L
Decay Rate for Zone/Compression Settling	K_1	0.43	L/g
Floc - aggregation coefficient	K_A	8.50 E-04	L/g
Floc - breakup coefficient	K_B	7.80 E-08	s

Large shear rates $G>30s^{-1}$ were observed where floc breakup was likely to occur along with a probable reduction in the average particle size within the first 1.5 meters. Immediately beyond the inlet baffle, the value of G falls within the range of 20 to 30 s^{-1} which is considered to be of intermediate shear rate magnitude with maximum flocculation rates, Serra (2008). Values of this magnitude tend to produce large flocs with higher settling velocities and overall better suspension sedimentation.

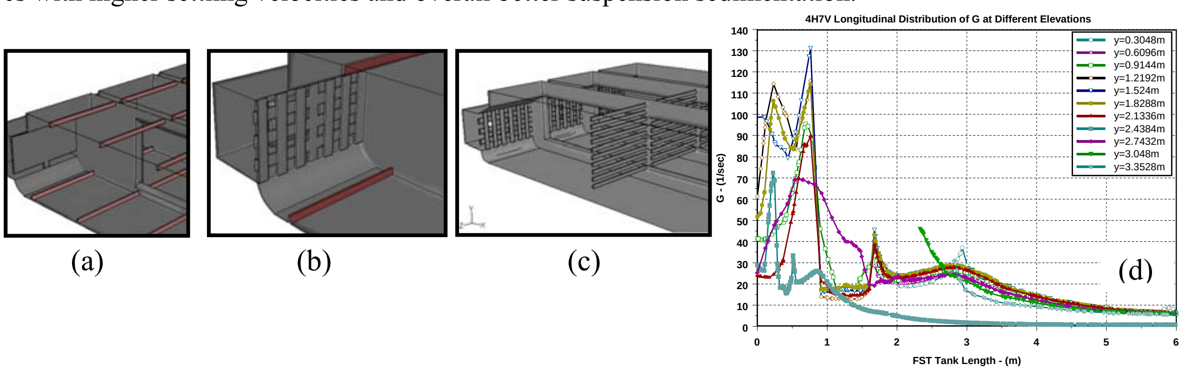

Figure 5: Inlet Slotted baffle configurations: a) Old Configuration (1H1V) b) 4 horizontal and 7 vertical beam configuration, (4H7V) c) 4H7V with in-tank slotted baffle arrangement at 12m, d) Distribution of G at different elevations as a function of tank length with the 4H7V baffle configuration seen in figure 5.b.

Results - Tank Baffle Addition

Different influent baffle arrangements can have a significant influence in the dynamics of the flow in the first half of the FST, (see figure 6.a). Inlets should be designed to dissipate the influent flow energy and allow for the even distribution of flow in all directions in the tank and should promote flocculation by harnessing energy, eliminate scouring of solids off the blanket and thus have minimal disturbance on the blanket and reduce short circuiting and minimize density current effects. Energy dissipating inlets as well as in-tank structures such as baffle plates if correctly positioned can promote re-flocculation and provide uniform flow distribution. Using the 4H7V inlet baffle configuration and an in-tank baffle at 12 m (see figure 5.c and 6.a) the effect on the flow characteristics and SS settling efficiency is shown. To explore the validity of the hypothesis of the increased flocculation in the region between the inlet and in-tank baffles, plots of the solids fraction profiles predicted by the CFD model are plotted at two elevations along the tank. Figure 6.b and 7 show quantitatively the prediction on the large fraction solids for the 4H7V case with and without the baffle. It is evident that the high values of G seen in the first 10 meters of the tank as shown in figure 5.d produce a higher distribution of large particles in that region which would settle by gravity due to their higher weight. This further substantiates that the addition of the inlet baffle reduces the solids volume fraction beyond the in-tank baffle and illustrates how such a geometrical addition would improve the efficiency of an FST.

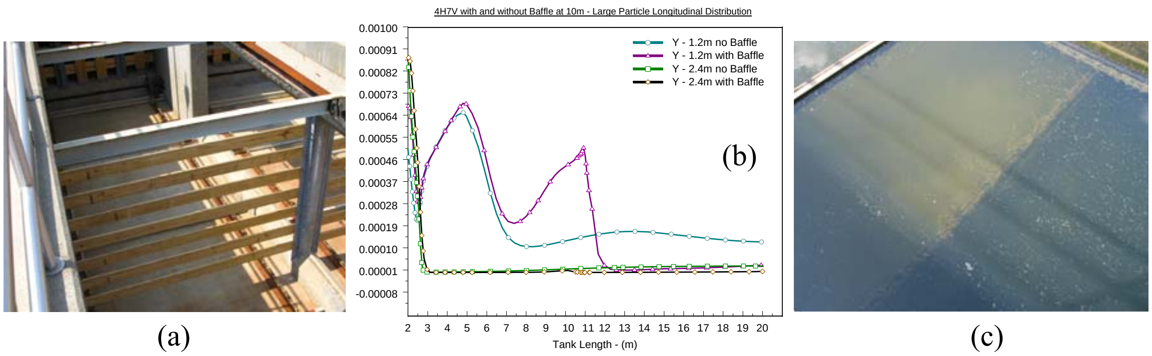

Figure 6: a) In-tank baffle addition at a distance of 12m from influent sluice gate, b) Large solids fraction effect of baffle with and without baffle shown in 5.c, Observation of region of high flocculation prior to in-tank baffle with distinct difference in the value of suspended solids, SS.

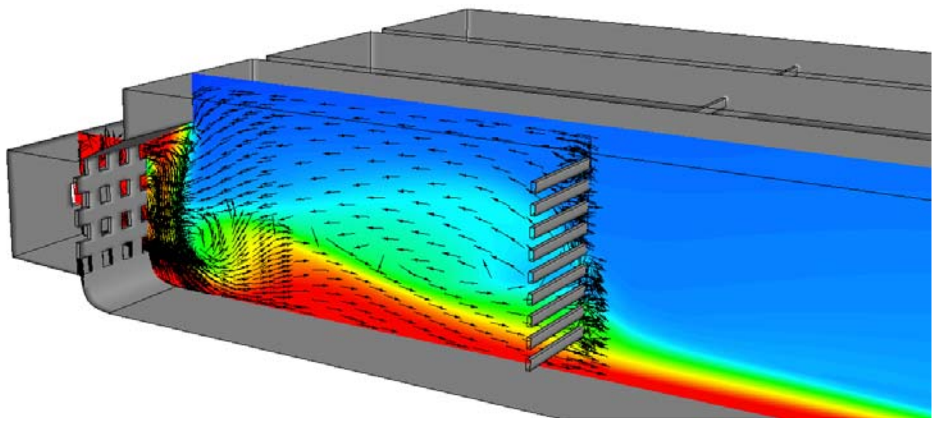

Figure 7: Velocity vectors and small solid fraction distribution in the region behind the inlet baffle of the simulated FST. Recirculation is present due to the strong density current with small particle entrapment within the flocculation zone between inlet and in tank baffles. Quantitative results are discussed in figure 6b.

Annamox Process - A novel nitrogen removal process especially from ammonium rich side streams

Anaerobic ammonium oxidation (anammox) is a recently discovered microbiological process that converts ammonia (NH_3) and nitrite (NO_2^-) directly to nitrogen gas (N_2). The application of anammox in wastewater treatment results in the lowest operating cost and carbon footprint of any currently applied biological nitrogen removal process. Over the past decade over thirty full scale anammox reactors have been built and successfully operated in Europe for the removal of nitrogen from anaerobic digester reject water, or as it is commonly known, centrate. However, there are no full scale Annamox process installations in the United States although there have been bench and pilot studies that demonstrated its effectiveness. As a result of this, there are several installations in the design and construction phase. Anammox was first discovered in 1990 when unexplained removal of ammonia was documented in an anaerobic wastewater purification system in the Netherlands (van de Graaf, 1990). The organisms responsible for the process are anaerobic autotrophic members of the bacterial phylum Planctomycetes (Strous, 1999) and exhibit a stoichiometry described by **Equation 1** (Strous, 1998). Equation 1 shows that the anammox reaction requires a stoichiometric ratio of approximately 55% nitrite to 45% ammonia. Therefore implementation of the anammox process requires an aerobic phase where approximately 55% of the ammonia is first oxidized to nitrite followed by an anoxic phase where the ammonia remaining is oxidized to molecular nitrogen in accordance to Equation 1.

$$1\ NH_4^+ + 1.32\ NO_2^- + .066\ HCO_3^- + .13\ H^+ \rightarrow$$
$$1.02\ N_2 + .26\ NO_3^- + .066\ CH_2O_{0.5}N_{0.15} + 2.03\ H_2O \qquad (1)$$

When applied to centrate for the removal of nitrogen, ammonia is partially nitrified to nitrite either in a separate reactor upstream of an anammox reactor or in a single reactor enriched with both ammonium oxidizing bacteria (AOB) and anammox bacteria.

The anammox process is superior to other BNR processes especially in streams with high concentrations of ammonia, insufficient amount of alkalinity, and limited amount of biodegradable organics. These characteristics are typically present in centrate generated during the dewatering of anaerobically digested sludge. New York City Department of Environmental Protection, (DEP), owns and operates 14 wastewater treatment plants, (WWTPs), some of which are or in the process of being upgraded to achieve BNR. Anaerobic digestion is practiced in all WWTPs though dewatering is available in only eight centralized facilities. Centrate generated in such facilities can contribute up to 40% of a plant's total nitrogen load. Assessment of BNR treatment alternatives has indicated that separate side stream treatment of the centrate is a cost effective alternative for several of the WWTPs. Table 3 provides a comparison between conventional BNR and an anammox processes in terms of energy, methanol, sludge production, carbon emission, and total costs. When the values of Table 3 are used as the basis for a full scale anammox facility at the 26th Ward WWTP in Brooklyn, NY and a 70% nitrogen removal efficiency is assumed, then the savings translate to over 1100 megawatt hours of electricity, 1900 metric tons of methanol, 2600 metric tons of CO_2 emissions, which is approximately $2.2 million in annual saving. These savings become more than 5-fold higher if anammox process is adopted at all centralized dewatering facilities.

Table 3: Comparison between conventional BNR and partial nitritation/anammox

	Conventional BNR	Partial Nitritation/Anammox
Power (kWh/kgN)	2.8	1
Methanol (kg/kgN)	3	0
Sludge Production (kgVSS/kgN)	0.5-1.0	0.1
CO_2 emission (kg/kgN)	>4.7	0.7
Total costs ($US/kgN)	4.1-6.9	1.4-2.8

Source: Data reprinted from *Biological Wastewater Treatment: Principles, Modelling and Design* with permission from the copyright holders, IWA publishing.

Annamox Challenges

The implementation of the process and the potential of realizing the stated benefits depends on the ability of the reactor to retain sufficient biomass to overcome anammox' s primary shortcoming namely its extreme slow growth rate, a doubling time of approximately 10 days. The two approaches that have been used to maximize biomass retention are that of a moving bed biofilm bioreactor, (MBBR), and sequencing batch reactors, (SBRs), operated to promote granular sludge solids, (Abma, 2007; Wett, 2007). A multiyear study was initiated at (CCNY), to enrich both types of reactors with anammox bacteria and demonstrate the nitrogen removal potential from centrate generated at the New York City WWTPs. **Figure 8** shows some initial results obtained from the MBBR reactor with removal rates reaching the maximum value of 70% removal based on alkalinity values observed at NYC WWTPs. The encouraging results of the bench scale study resulted in additional funding from DEP and the New York State Energy Research and Development Authority, (NYSERDA), for further demonstration of the performance of the anammox process in a pilot facility located at the 26th Ward WWTP in New York City.

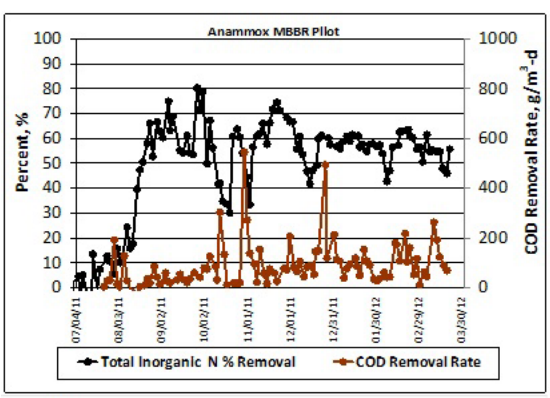

Figure 8: % Total Inorganic N removal and COD removal rate at a MBBR.

Conclusions

The CFD modelling domain for the first time has been extended into the 3D arena with the development of the CCNY 3D CFD model which can address real life 3D issues that arise out of flow and geometrical asymmetries. The effort highlighted the importance of collecting data at site specific locations where the model needs to be applied to capture all the local and biological intricacies peculiar to that site especially when dealing with the biology of activated sludge. The modified configuration with the 4H7V configuration inlet baffle and an in-tank baffle at 12 meters was found to be optimal for the FSTs at Battery ”E” at the Wards Island WWTP and highlighted the critical role played by flocculation which was clearly discernible in the model predictions. Additionally, in terms of sustainable development and achieving substantial savings in WWTP operations, the new ANNAMOX process demonstrated the cost effectiveness in treating centrate and was a superior alternative to other side stream treatment technologies. As illustrated in Table 3 the savings in terms of energy, methanol, sludge production and carbon emissions are very significant between conventional BNR and the anammox process. Thus realistic modelling and adoption of innovative technologies can be used as effective tools if applied within the right frame work as shown in this white paper and could be harnessed to yield sustainable and substantial savings in the long run. It behoves each country and its municipalities to analyse, research and implement appropriate technologies as demonstrated by several European entities and municipalities in the United States. It is my sincere hope that Cyprus will similarly explore and delineate its needs and focus on appropriate technologies that can lead to sustainable development and improvement in the quality of its environment.

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