Aerobic Granular Biomass Technology: recent performance data, lessons learnt and retrofitting conventional treatment infrastructure

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Abstract
Aerobic granular sludge is seen as the future standard for industrial and municipal wastewater treatment. Through a Dutch research and development program, a full-scale aerobic granular biomass technology has been developed – the Nereda® technology – which has been implemented to treat municipal and industrial wastewater. The Nereda® system is considered to be the first aerobic granular sludge technology applied at full-scale and more than 30 municipal and industrial plants are now in operation or under construction worldwide. Further plants are in the planning and design phase, including plants with capacities exceeding 1 million PE. Data from operational plants confirm the system's advantages with regard to treatment performance, energy-efficiency and cost-effectiveness. In addition, a new possibility for extracting alginate-like exopolysaccharides (ALE) from aerobic granular sludge has emerged which could provide sustainable reuse opportunities. The case is therefore made for a shift away from the 'activated sludge approach' towards an 'aerobic granular approach', which would assist in addressing the challenges facing the wastewater treatment industry in Asia and beyond.

Keywords
Aerobic granular sludge, Nereda®, Alginate recovery, sustainable wastewater treatment

INTRODUCTION

Aerobic granular sludge has been extensively researched over the last two decades as a part of the search for more sustainable wastewater treatment solutions. Conventional activated sludge (CAS) systems have key disadvantages such as slow settling flocculent biomass necessitating large clarifiers and low reactor biomass concentrations (typically 3-5 kgMLSS/m^3), large treatment system footprints and relatively high system energy usage. It has been shown at the lab, pilot and the full scale that aerobic granular sludge has distinct advantages, when compared to CAS systems, including improved settling characteristics, which in turn allows for higher biomass concentrations and hence more compact treatment systems.

A co-ordinated research partnership in the Netherlands led to the development of the Nereda® technology – a full-scale application of aerobic granular sludge. Currently, over 30 full scale Nereda® plants are operational or under design/construction across 5 continents. The operational full-scale plants have met effluent requirements whilst achieving more sustainable wastewater treatment with key advantages outlined below (compared to similarly loaded activated sludge systems):

- 25-75% reduction in treatment system footprints as a result of higher reactor biomass concentrations and the non-use of secondary settling tanks;
- 20-50% energy usage reduction and;
- Associated capital and operational cost savings.

This paper highlights the different Nereda® design configurations which have been developed to meet requirements at different sites across the world. Furthermore, results from several full-scale treatment plants are presented and the potential to extract a high-value reuse product (alginate) from Nereda® excess/waste sludge is discussed.

AEROBIC GRANULAR BIOMASS AND THE NEREDA® TECHNOLOGY

Starting with activated sludge, aerobic granular sludge can be formed by applying specific process conditions such as selectively wasting slow settling biomass and retaining faster settling sludge (de Kreuk et al, 2005). Furthermore, favouring slow growing bacteria such as Poly-phosphate Accumulating Organisms (PAOs) has been shown to enhance granulation (de Kreuk et al, 2006). Aerobic granular sludge consists of bio-granules, without carrier material, of sizes typically larger than 0.2 mm. The granular biomass can be used to biologically treat wastewater using similar processes to activated sludge system, however the granular sludge has a distinct advantage of faster settling velocities when compared to activated sludge, which allows for higher reactor biomass concentrations (e.g. 8-15 g/ℓ) (de Kreuk et al, 2007).

When aerated, an oxygen gradient forms within aerobic granules whereby the outer layers are aerobic and the inner core is anoxic or anaerobic (de Kreuk et al, 2007). Nitrifiers and heterotrophic bacteria proliferate in the aerobic outer layer of the granules, enabling the degradation of organics (COD removal) and nitrification (conversion of ammonia to nitrite/nitrate) respectively (de Kreuk et al, 2007). A simultaneous nitrification-denitrification process occurs whereby the formed nitrates (from nitrification) are denitrified (conversion of nitrate to nitrogen gas) in the anoxic core of the granules (Pronk et al, 2015). PAOs in the aerobic granules enable enhanced biological phosphorus removal whereby phosphate uptake occurs during aeration and phosphate rich waste sludge is subsequently removed from the system (de Kreuk et al, 2005). Aerobic granular sludge can therefore achieve biological nutrient removal in a single tank without the need for separate anaerobic and anoxic compartments or tanks. Comparatively, activated sludge systems capable of biological nitrogen and phosphorus removal require at least 3 tanks or zones (anaerobic, anoxic and anaerobic) and multiple recycles between the zones or tanks (Wentzel et al, 2008).

In the early 2000's, lab-scale research at the Delft University of Technology (TU Delft), showed that aerobic granular sludge could be formed under a variety of conditions and that granular sludge could be used to achieve stable biological COD, phosphorus and nitrogen (de Kreuk et al, 2007). A collaborative public-private partnership was set up involving TU Delft, Royal HaskoningDHV, several Dutch District Water Authorities, STOWA (the Dutch Foundation for Applied Water Research). This partnership led to the development of the Nereda® wastewater treatment system, which is a full scale application of the aerobic granular sludge technology. Following initial pilot-scale research, the first full-scale Nereda® wastewater treatment plant was commissioned in 2006 at a cheese factory in the Netherlands (van der Roest et al, 2011). Subsequently, 16 full-scale Nereda® treatment plants have entered operation. Table 1 provides details of the operational plants as well as the full-scale plants under construction (8 plants) and in the final stages of design (7 plants).

Nereda® operates a cyclical process with three cycle components or stages: simultaneous influent fill and effluent withdrawal; aeration/reaction and settling – all of which occur in a single reactor without partitions (Giesen et al, 2013). Granulation can be achieved via an incremental start-up process using activated sludge for seeding or alternatively granular seed sludge from other Nereda® plants can be used. The enhanced sludge settleability of aerobic granular sludge is evident from a comparison of typical full scale SVI (sludge volume index) values – for aerobic granular sludge the SVI_5 (5 minutes) tends towards the SVI_{30} (30 minutes), with typical values at operational Nereda® plants around 30-60 mℓ/g (Giesen et al, 2013), whereas for activated sludge the SVI_{30} is typically in the range of 110-160 mℓ/g and the SVI_5 is not measured because activated sludge exhibits minimal settling 5 minutes (Tchnobanoglous et al, 2004).

Nereda® systems are preceded by conventional pre-treatment consisting of screening, grit removal and, depending on the application, FOG (fats, oils and greases) removal; whilst primary sedimentation is optional. Typical reactor depths range from 5.5 to 9 m, with lower and deeper depths possible; whilst secondary settling tanks and major sludge recycles are not required for the Nereda® system.

Table 1. List of full scale Nereda® treatment plants in operation, under construction and in the final phases of design.

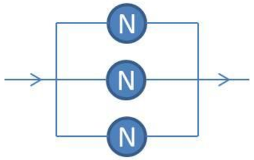
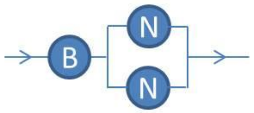
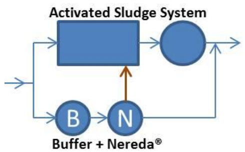
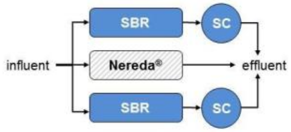
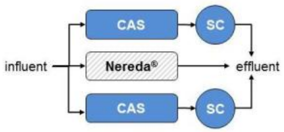
Operational plants	**Daily average flow (m^3/day)**	**Peak flow (m^3/h)**	**Person Equivalent (For p.e. a 54 g. BOD)**	**Start-up**
Vika, Ede (NL)	50-250		1,500-5,000	2005
Cargill, Rotterdam (NL)	700		10,000-30,000	2006
Fano Fine Foods, Oldenzaal (NL)	360		5,000-10,000	2006
Smilde, Oosterwolde (NL)	500		5,000	2009
STP Gansbaai (RSA)	5,000	400	63,000	2009
STP Epe (NL)	8,000	1,500	54,000	2011
STP Garmerwolde (NL)	30,000	4,200	140,000	2013
STP Vroomshoop (NL)	1,500	400	12,000	2013
STP Dinxperlo (NL)	3,100	570	11,111	2013
STP Wemmershoek (RSA)	5,000	625	39,000	2013
STP Frielas, Lisbon (PT)	12,000		44,444	2014
STP Ryki (PL)	5,300	430	42,889	2015
Westfort Meatproducts, IJsselstein (NL)	1,400		43,000	2015
STP Clonakilty (IRL)	4,896	626	23,278	2015
STP Carrigtwohill (IRL)	6,750	844	41,204	2015
STP Deodoro, Rio de Janeiro (BR)	86,400	6,120	480,000	2016
Plants under construction				
STP Jardim Novo, Rio Claro (BR)	23,500	1,764	152,315	2016
STP Hartebeestfontein (RSA)	5,000	1,250	52,185	2016
STP Kingaroy (AUS)	2,700	450	11,000	2016
STP Ringsend SBR Retrofit 1 Cell, Dublin (IRL)	21,700	6,750	94,000	2016
STP Highworth (UK)			10.111	
STP Cork Lower Harbour (IRL)	18,280	1,830	65,000	2016
STP Simpelveld (NL)	3,668	945	11,880	2016
STP Ringsend Capacity Upgrade, Dublin (IRL)	117,000	9,240	400,000 (part of the upgrade project to 2,4 million p.e.)	2019
Plants under design				
STP Alpnach (CH)	14,000	1845	49,000	2017
STP Österröd, Strömstad (S)	3,730	360	10,400	2017
STP Tatu, Limeira (BR)	57,024	3,492	517,000	2016
STP São Lourenço, Recife (BR)	19,093 (1st fase); 25,123 (2nd fase)	1,674	139,574	2016 2024
STP Jaboatão, Recife (BR)	109,683 (1st fase) 154,483 (2nd fase)	11,588	858,333	2017 2025
STP Jardim São Paulo, Recife (BR)	19,529 (1st fase) 78,117 (2nd fase)	5,859	325,315	2017 2025
STP Utrecht (NL)	55,000	13,200	430,000	2018
STP Faro – Olhão (PT)	28,149	3,942	113,200	2018
Pilots and demo's				
Nereda Research Program (NL)				2003-2010

Bavaria, Lieshout (NL)				2007
Tata Steel, IJmuiden (NL)				2011
Anonymous Petrochemical (NL)				2011
Peka Kroef, Odiliapeel (NL)				2012
STP Frielas, Lisbon (PT)	3,000			2012
STP Utrecht (NL)	1,500			2013
Anonymous Chemicals (FR)				2014
STP Kloten Opfikon (CH)	1.5 – 5.0			2014
STP Davyhulme (UK)	1.5 – 5.0			2014
STP Daldowie (UK)	1.5 – 5.0			2014
STP Dalmarnock (UK)	1.5 – 5.0			2014
STP Crewe (UK)	1.5 – 5.0			2015
STP Werribee (AUS)	100-300			2015
STP Ringsend, Process Proving Unit 1, Dublin (IRL)	13,5			2015
STP Sha Tin (HK)	800 –1,000			2016

RESULTS FROM NEREDA® TREATMENT PLANTS

New insights have emerged since implementing the first full-scale Nereda® installations allowing for further innovation, system development and design optimisation. Several system configurations have been developed to suit a variety of scenarios experienced from site to site. Two ‘greenfield’ or parallel extension approaches have been used, whilst two ‘brownfield’ approaches have also been developed – these configurations are detailed in Table 2 below. For ‘brown field’ Nereda applications, it is often possible to reuse existing infrastructure and implement a significant increase in biological treatment capacity against low investments. Examples of such applications in Table 1 are the retrofit of the existing SBR’s of Cargill’s wastewater treatment facility in Rotterdam (The Netherlands) and Irish Water’s Ringsend STP. The Nereda at Lisbon’s Frielas STP is an example that also conventional continuous activated sludge tanks can be retrofitted.

Table 2. Nereda® configurations

Nereda® Configuration		Typical Layout		Configuration characteristic	Advantages	Reference examples	Potential Applications
1	Continuous feed, 3+ reactors	3 reactors		At least 1 reactor in feed phase at any given time	Scalable for application to large (>100 Mℓ/d) and mega (>500 Mℓ/d) treatment plants	Epe WWTP (Netherlands) 	‘Greenfield sites’; or extension to existing plants with parallel Nereda® system
2	Influent buffer followed by X reactors	1 buffer + 2 reactors		Buffer stores influent between feeds to reactors	Optimised investments (2 versus 3 reactors)	Wemmershoek WWTP (South Africa) 	‘Greenfield sites’; or extension to existing plants with parallel Nereda® system
3	Hybrid	1 or more Nereda® reactors with excess sludge connection to activated sludge system		Waste Nereda® sludge to activated sludge system	Enhance activated sludge system performance; Optimal use of existing infrastructure	Vroomshoop WWTP (Netherlands) 	‘Brownfield sites’; Extension / optimisation scenarios, utilising existing infrastructure
4a	SBR Reftrofit	Convert existing SBR		Upgrade existing SBR	Cost-effective capacity and performance enhancement using existing infrastructure	Ringsend WWTP (Ireland) 	‘Brownfield sites’. Enhanced capacity and/or performance
4b	CAS Retrofit	Convert existing continuous activated sludge reactor or any suitable tank		Use existing tanks or CAS reactors	Cost-effective capacity and performance enhancement using existing infrastructure	Frielas WWTP (Portugal) 	‘Brownfield sites’. Limited space or budget but require enhanced capacity and/or performance

Detailed treatment performance of various industrial and municipal Nereda plants has been reported before (e.g. Giesen 2013, Pronk 2015) and below operation results of Ryki WWTP, Prototype Utrecht and hybrid Vroomshoop will be presented.

Ryki WWTP - Poland

In the city of Ryki (Lublin Province, Poland) a new Nereda® wastewater treatment plants entered operation in February 2015. This is the first Nereda® installation located in the eastern part of Central Europe and also the first Nereda® plant that has to contend with low process temperatures during the winter period. The Ryki Nereda® plant is designed to treat 5,320 m^3/d (dry weather), corresponding to 38,600 PE. In addition to the challenging winter temperatures, the plant has to treat a range of different incoming sewages (domestic, septic tanks and industrial) and has to handle extended industrial peak load periods. The combined pre-treated influent is fed to an influent buffer tank (500 m^3) from where two Nereda® reactors (2 500 m^3 each) are separately fed by three submersible pumps ('1 buffer + 2 reactors configuration'). Biological treated wastewater is discharged to surface water via an existing pond. Table 3 shows the design loads for the plant, Figure 1 the wastewater temperatures experienced at the plant and lastly Table 4 shows the effluent performance compared to the effluent requirements.

Table 3. Design loads for the Ryki Nereda® plant

Parameter	**Design values**			
	Domestic	**Septic tankers**	**Industrial**	**Total**
Daily dry weather flow (m^3/d)	2,400	120	2,800	5,320
Daily wet weather flow (m^3/d)	3,418	120	2,800	6,338
COD (kg/d)	1,680	384	2,500	4,564
BOD_5 (kg/d)	960	156	1,200	2,316
TSS (kg/d)	1,200	144	400	1,744
Total N (kg/d)	192	22	112	326
Total P (kg/d)	48	4	28	80

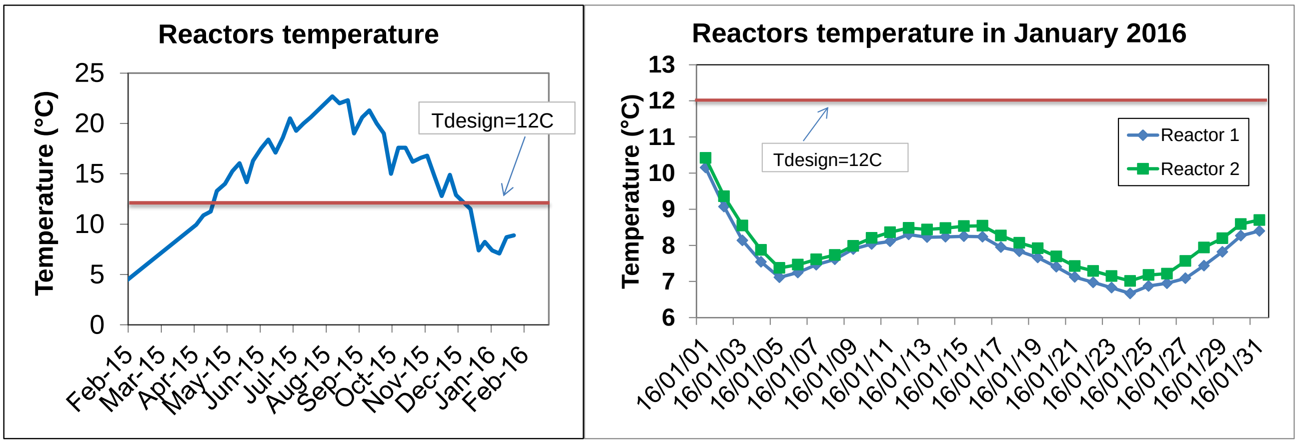


Figure 1. Temperatures at the Ryki WWTP

Table 4. Effluent performance at the Ryki Nereda® plant

Parameter	**Effluent requirements**	**Effluent quality (average from April 2015 to February 2016)**		
		Reactor 1	**Reactor 2**	**Pond Outlet**
COD (mg/ℓ)	125	43	46	39
BOD_5 (mg/ℓ)	15	5.5	6.3	4.4

TSS (mg/ℓ)	35	13	13	4.5
Total N (mg/ℓ)	15	5.7	5.5	5.0
Total P (mg/ℓ)	2	0.9	0.8	0.8

The Nereda® installation at Ryki has been operational for more than two years and continues to achieve effluent compliance, despite the low winter temperatures and highly variable seasonal loading.

Vroomshoop WWTP – the Netherlands
A hybrid Nereda® configuration was selected for the upgrade of the Vroomshoop WWTP (the Netherlands) and the new plant entered operation in 2013. The main feature of the hybrid configuration (see Figure 2) is that the Nereda® waste sludge is fed into a parallel activated sludge system. The plant is designed with a dry weather hydraulic capacity of 156 m^3/h and rain flow of 1,000 m^3/h, whilst the design pollution load is 22 600 PE (population equivalents at 150 gTOD/PE).

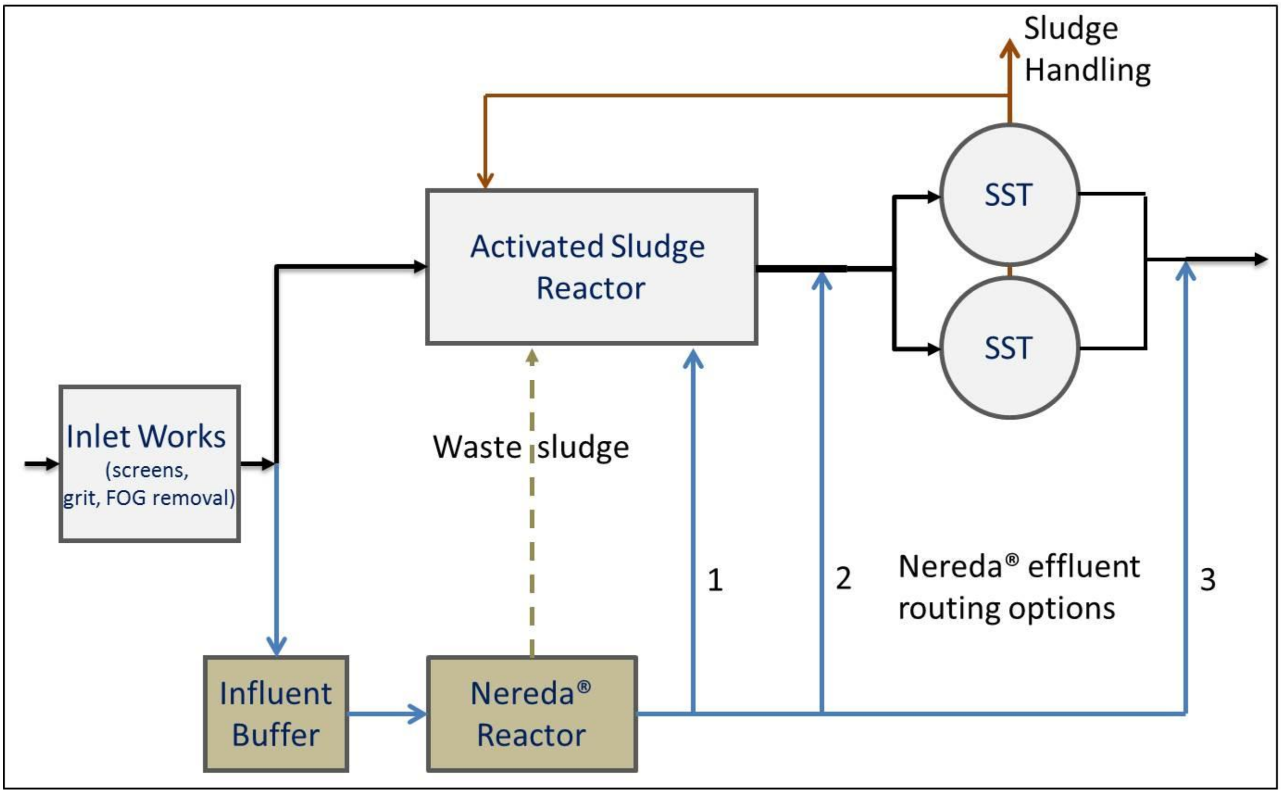


Figure 2: Schematic depiction of the Vroomshoop WWTP

The discharge of the Nereda® waste or excess sludge into the activated sludge system has been found to significantly improve the sludge settleability of the activated sludge. Figure 3 shows how the SVI (sludge volume index) in the activated sludge system steadily decreased as a result of the addition of the Nereda® waste sludge, indicating improved sludge settleability.

Improved settleability in an activated sludge system could allow for an increase in MLSS (mixed liquor suspended solids) concentrations in the activated sludge system and therefore increase the biological treatment capacity and/or; the possibility to allow higher hydraulic loading on the secondary settling tanks since the sludge settling rates are improved. Another potential advantage of this hybrid configuration is an improvement in biological phosphorus removal in the activated sludge system, since Nereda® waste sludge contains higher concentrations of PAOs (polyphosphate accumulating organisms) when compared to activated sludge.

Between June and November 2014, energy usage monitoring at the Vroomshoop WWTP showed that the Nereda® side of the plant used on average 35% less energy than the activated sludge side.

Furthermore, effluent performance monitoring in 2014 showed the compliance of the plant under full loading conditions (see Table 5).

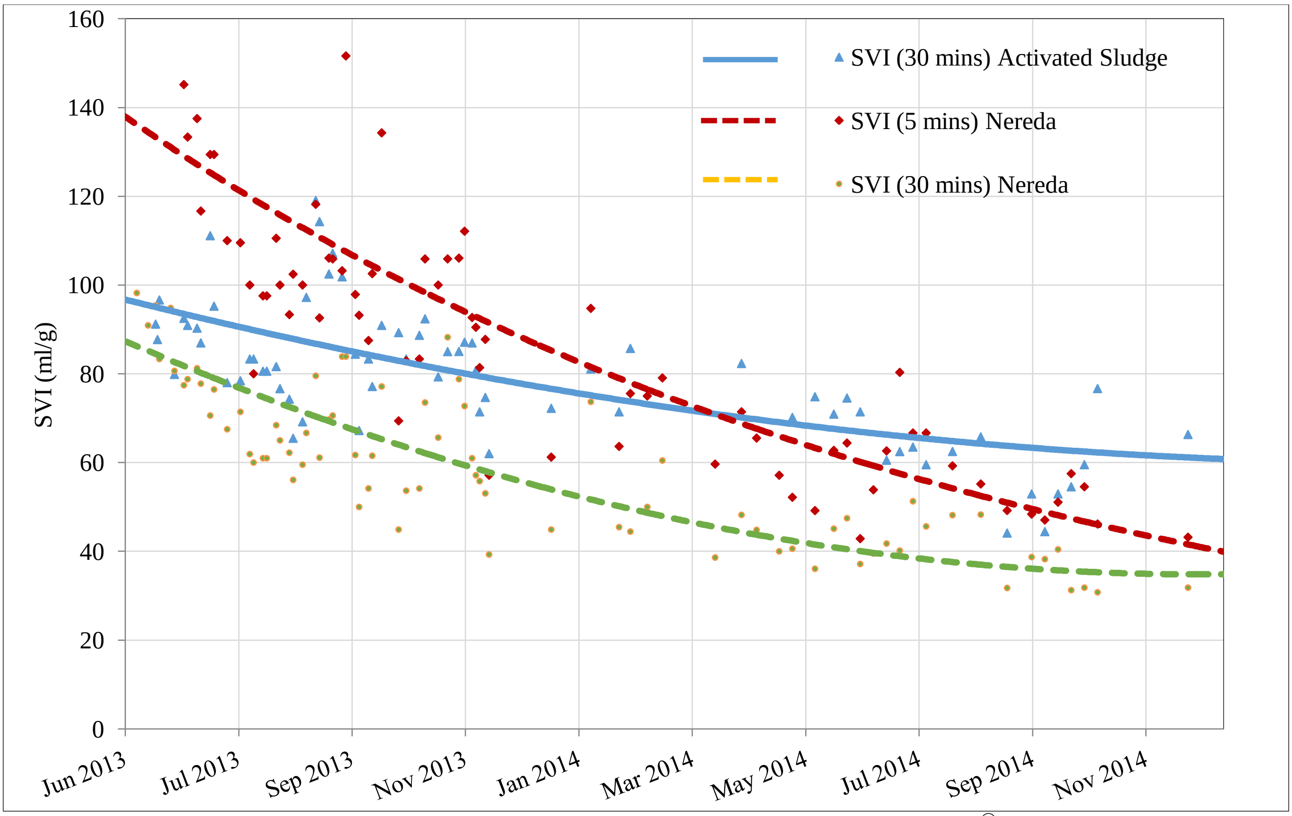


Figure 3. Comparison of SVI (sludge volume indexes) of the Nereda® and activated sludge systems at Vroomshoop WWTP (data from end-user: Waterschap Vechtstromen)

Table 5. 2014 effluent performance at the Vroomshoop WWTP (data from end-user: *Waterschap Vechtstromen*)

Parameters		**Average Influent (mg/ℓ)**	**Average Effluent (mg/ℓ)**	**Requirement (mg/ℓ)**	**Regulatory Compliance Criteria**
Organics	COD	720	55	125	Limit (3 x per year up to 250)
	BOD_5	263	4	10	Limit (3 x per year up to 20)
Nitrogen	TN	-	7.2	10	Yearly Average
	TKN	66	5.2	-	-
	NH_4-N	-	Summer=1.4; Winter = 3.0	Summer = 2 Winter = 4	Average (1 May - 1 Nov.) Average (1 Nov. - 1 May)
	NO_2/NO_3-N	-	2.0	-	-
Phosphorus	TP	8.9	0.9	2	Moving average of 10 successive samples
	PO_4-P	-	0.6	-	-
Suspended Solids	TSS	317	10	30	Limit

Prototype Nereda® Utrecht (PNU)

In 2013 a project specific Nereda® prototype (PNU) was installed at the existing Utrecht WWTP in order to investigate the potential of utilising Nereda® for the replacement of the existing 430 000 PE plant which is aging and utilises the non-optimal AB type activated sludge process. The prototype consist of a single 1 000 m^3 reactor which is designed to treat an average flow of 1 500 m^3/day (9 000 PE), however the plant can be fed up to 600 m^3/hr for test purposes. After successful demonstration and optimization of the design parameters for the Utrecht STP specific conditions, the PNU is operated by Royal HaskoningDHV as test and training facility. Whereas testing full-scale plant performance beyond the plant design condition is often not possible because at operational plants effluent quality is a priority and the plant receives influent defined by the incoming sewer system, at the PNU facility it is possible for test purposes to operate well beyond the normal conditions.. PNU is also used to validate usability and reliability of instrumentation and equipment design optimizations.

Treated wastewater is decanted from Nereda using a fixed overflow weir, similar to a conventional clarifier. In the design of the first municipal Nereda plants, it was decided to discharge any particulars that might lead to scum with the treated effluent as the obtained water quality fully meet the discharge requirements. To investigate the achievable effluent quality when – like in many clarifiers – scum forming particulars are withhold in the reactor, baffles were added to the PNU effluent launders in 2015. Figure 4 shows how the effluent suspended solids were reduced to well below 10 mgTSS/l.. Based on these results the optional use of scum baffles has been introduced in various full-scale designs where stringent requirement apply for suspended solids or total-P.

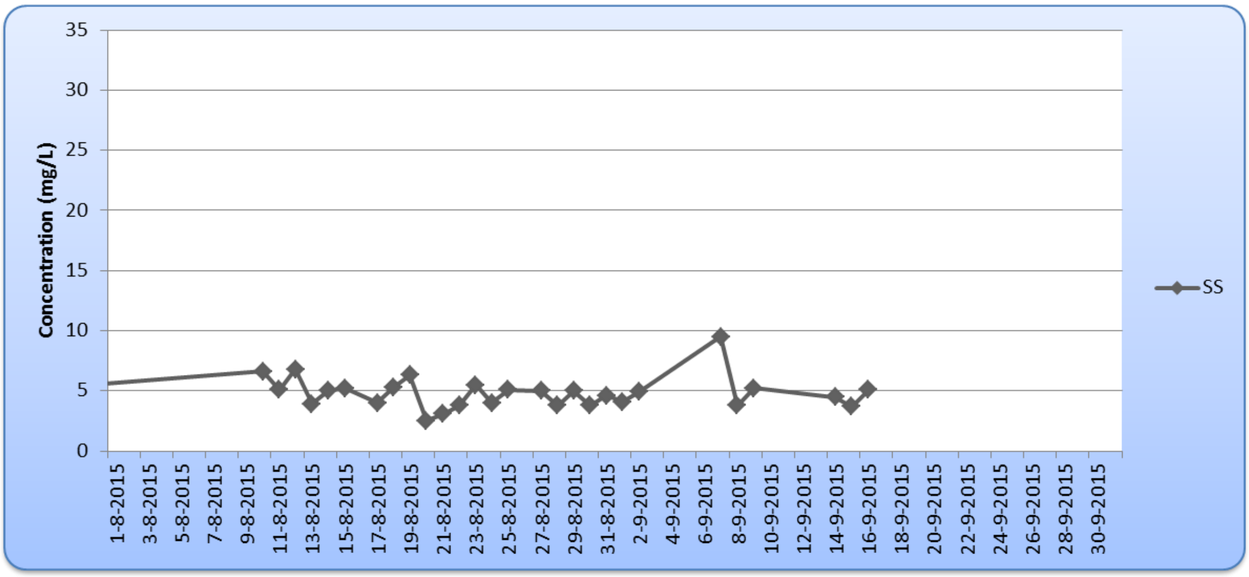


Figure 4. Effluent suspended solids performance at the PNU facility with baffles (no primary clarification)

FURTHER DEVLOPEMENTS – ALGINATE RECOVERY

Research at TU Delft uncovered the ability to extract alginate-like exopolysaccharides (ALE) from aerobic granular sludge (Lin et al, 2010). Alginate is currently produced from seaweed at relatively high costs and is used in a variety of industries as a thickener or gel and as a basis for coatings. Aerobic granular sludge has been found to contain between 15 to 25% of ALE (alginate-like exopolysaccharides). Extracted ALE could potentially be used in the chemical sector, textile and paper industries, as a soil enhancer to improve water retention in semi-arid areas or as a brick additive (van der Roest et al, 2015). The recovery of ALE from Nereda® excess sludge (aerobic granular sludge) is a potential re-use opportunity, whereby a waste stream could be converted into a product with a high resale value. Combining alginate extraction with the existing excess sludge treatment processes at wastewater treatment plants could also improve sludge treatment efficiency because alginate extraction reduces sludge volumes and the remaining (non-extracted) sludge has a higher digestibility and better dewaterability. The National Alginate Research Programme (NAOP) has been set up in the Netherlands to further research and develop this promising sustainable re-use concept. The NAOP is a public-private sector collaborative research initiative with the goal of developing sustainable and commercially viable ALE-extraction from Nereda® excess sludge (van der Roest et al, 2015). The NAOP is similar to the public-private collaborative partnership that successfully developed Nereda®. Currently a pilot study is planned to test the different aliginate extraction processes. Depending on the results two demo installations will be realized in 2017.

DISCUSSION AND CONCLUSIONS

Results from full-scale Nereda® treatment plants over the last decade have shown that Nereda® has numerous advantages when compared to similarly loaded activated sludge systems, including:

- 25-75% reduction in treatment system footprints as a result of higher reactor biomass concentrations and the non-use of secondary settling tanks;
- 20-50% energy usage reduction and;
- Associated capital and operational cost savings.

Nereda® treatment plants have been shown to achieve similar or improved enhanced biological nutrient (nitrogen and phosphorus) removal when compared to similarly loaded activated sludge systems. Furthermore, the possibility to recover alginate-like exopolysaccharides (ALE) from Nereda® waste sludge has the potential to generate a reuse product with high commercial value.

Four main Nereda® configurations have been developed for a wide range wastewater treatment scenarios ranging from 'green-field' systems to retrofits at 'brown-field' sites. The hybrid configuration (e.g. Vroomshoop WWTP) whereby Nereda® waste sludge is fed into a parallel activated sludge system has the potential to increase the loading capacity of the activated sludge system through improved sludge settleability. This configuration could therefore be applied advantageously for the extension of existing plants with an activated sludge line.

The results achieved at full-scale Nereda® treatment plants show that aerobic granular sludge has clear and significant advantages over conventional activated sludge systems. Currently sustainability requirements (including cost-effectiveness) are driving technological advancement and innovation. The advantages of Nereda® in comparison to activated sludge systems ultimately translate into more sustainable and cost-effective wastewater treatment. A shift away from the 'activated sludge approach' towards an 'aerobic granular approach' would assist in addressing the challenges facing the wastewater treatment industry in Asia and beyond.

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