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987

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Aerobic granular biomass technology: advancements in design, applications and further developments

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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 40 municipal and industrial plants are now in operation or under construction world-wide. 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.

Key words: aerobic granular sludge, biopolymer recovery, Nereda®, 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 40 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):

Water Practice & Technology Vol 12 No 4
doi: 10.2166/wpt.2017.101

- 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 & van Loosdrecht 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 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, 18 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 11 plants) and in the final stages of design (11 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®

Water Practice & Technology Vol 12 No 4
doi: 10.2166/wpt.2017.101

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 (Calculated for p.e. a 54 g. BOD)	Start-up	Greenfield/Retrofit CAS or SBR/Hybrid
Vika, Ede (NL)	50–250		1,500–5,000	2005	Retrofit
Cargill, Rotterdam (NL)	700		10,000–30,000	2006	Retrofit
Smilde, Oosterwolde (NL)	500		5,000	2009	Retrofit
STP Gansbaai (RSA)	5,000	400	63,000	2009	Greenfield
STP Epe (NL)	8,000	1,500	41,000	2011	Greenfield
STP Garmerwolde (NL)	30,000	4,200	140,000	2013	Greenfield
STP Vroomshoop (NL)	1,500	200	12,000	2013	Greenfield
STP Dinxperlo (NL)	3,100	570	11,000	2013	Greenfield
STP Wemmershoek (RSA)	5,000	468	39,000	2013	Greenfield
STP Frielas, Lisbon (PT)	12,000	1,850	44,000	2015	Retrofit
STP Ryki (PL)	5,320	465	38,600	2015	Greenfield
Westfort Meatproducts, IJsselstein (NL)	1,250	330	43,000	2015	Greenfield
STP Clonakilty (IRL)	4,896	622	23,000	2015	Greenfield
STP Carrigtwohill (IRL)	6,750	844	41,000	2015	Greenfield
STP Deodoro, Rio de Janeiro (BR)	Phase I - 64,800 Phase II - 86,400	4,590 6,120	360,000 480,000	2016 2025	Greenfield
STP Kingaroy (AUS)	2,625	450	11,000	2016	Greenfield
STP Simpelveld (NL)	3,668	945	10,000	2016	Greenfield
STP Cork Lower Harbour (IRL)	18,280	1,830	72,000	2017	Greenfield
Plants under construction					
STP Highworth (UK)	1,719	197	10,000	2017	Greenfield
STP Jardim Novo, Rio Claro (BR)	24,166	1,806	152,000	2018	Greenfield
STP Hartebeestfontein (RSA)	5,000	208	52,000	2018	Greenfield
STP Alpnach (CH)	14,000	1,872	48,000	2018	Greenfield
STP Zutphen (NL)	10,128	550	237,000	2018	Greenfield
STP Utrecht (NL)	55,000	13,200	343,000	2018	Greenfield
STP Inverurie (UK)	10,871	544	47,204	2018	Retrofit
STP Kendal (UK)	26,000	1,749	103,000	2019	Greenfield
STP Österröd, Strömstad (S)	3,730	360	13,000	2019	Greenfield
STP Faro – Olhão (PT)	20,582	1,908	149,000	2019	Greenfield
STP Ringsend, Dublin (IRL)	600,000	50,000	2,670,000	2021	Retrofit
Plants under design					
STP Morecambe (UK)	17,000	2,088	33,000	2018	Greenfield
STP Tatu, Limeira (BR)	57,024	3,492	322,000	2019	Greenfield
STP Tijuco Preto, Sumaré (BR)	19.900	1.492	110.000	2019	Greenfield
STP Breskens (NL)	3,500	1,000	31,300	2019	Greenfield
STP Jardim São Paulo, Recife (BR)	Phase I – 22,792 Phase II – 67,764	1,871 5,577	109,000 325,000	2019 2025	Greenfield
STP São Lourenço, Recife (BR)	Phase I – 18,842 Phase II - 25,123	1,287 1,715	105,000 140,000	2020 2024	Greenfield
STP Jaboatão, Recife (BR)	Phase I - 109,683 Phase II - 154,483	8,536 12,037	609,000 858,000	2020 2025	Greenfield
STP Kloten (CH)	26,000	2,850	125,000	2023	Retrofit
STP Barston (UK)	21,784	1,424	86,000	Tbd	Greenfield
STP Walsall Wood (UK)	7,176	646	29,166	Tbd	Greenfield
STP Radcliffe (UK)	5,324	463	24,722	Tbd	Greenfield

Water Practice & Technology Vol 12 No 4
doi: 10.2166/wpt.2017.101

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 after 5 minutes (Tchobanoglous *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.

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 where conventional continuous activated sludge tanks were retrofitted.

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

Ryki STP – Poland

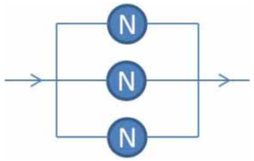
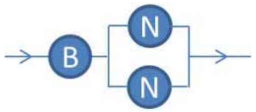
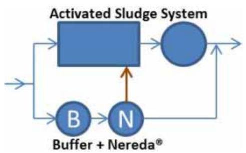
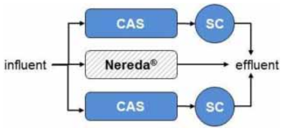
In the city of Ryki (Lublin Province, Poland) a new Nereda® wastewater treatment plants entered operation in February 2015. This is the first Nereda® installation located in the eastern part of Central Europe and also the first Nereda® plant that has to contend with low process temperatures during the 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.

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 STP – the Netherlands

A hybrid Nereda® configuration was selected for the upgrade of the Vroomshoop STP (the Netherlands) and the new plant entered operation in 2013. The main feature of the hybrid configuration

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 STP (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 STP (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 STP (Netherlands) 	‘Brownfield sites’; Extension/ optimisation scenarios, utilising existing infrastructure
4 Retrofit	Convert existing continuous activated sludge reactor, SBR or any suitable tank 	Use existing tanks or CAS reactors	Cost-effective capacity and performance enhancement using existing infrastructure	Frielas STP (Portugal) 	‘Brownfield sites’; Limited space or budget but require enhanced capacity and/or performance

Water Practice & Technology Vol 12 No 4
doi: 10.2166/wpt.2017.101

Table 3 | Design loads for the Ryki Nereda® plant

	Design values			
Parameter	**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

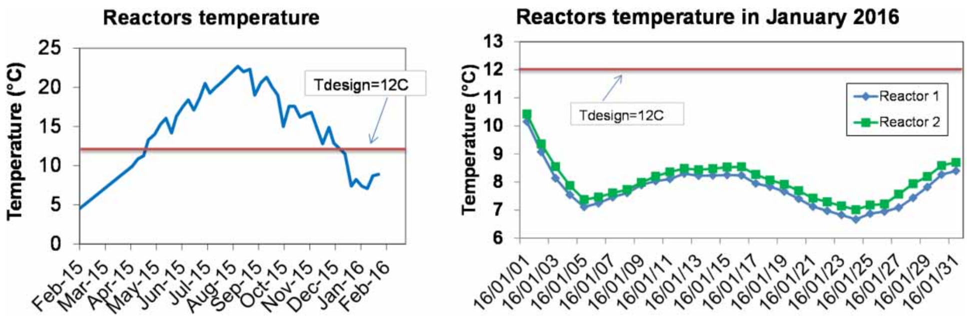


Figure 1 | Temperatures at the Ryki WWTP.

Table 4 | Effluent performance at the Ryki Nereda® plant

		Effluent quality (average from April 2015 to February 2016)		
Parameter	**Effluent requirements**	**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

(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).

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 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 when compared to activated sludge.

Water Practice & Technology Vol 12 No 4
doi: 10.2166/wpt.2017.101

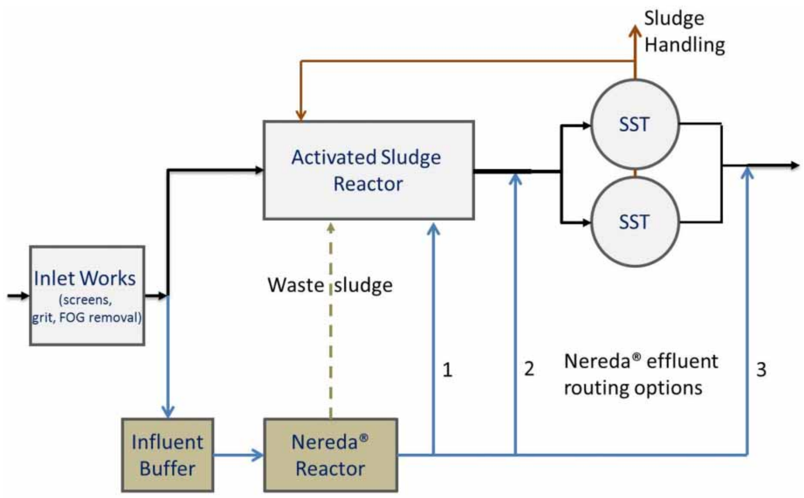


Figure 2 | Schematic depiction of the Vroomshoop STP.

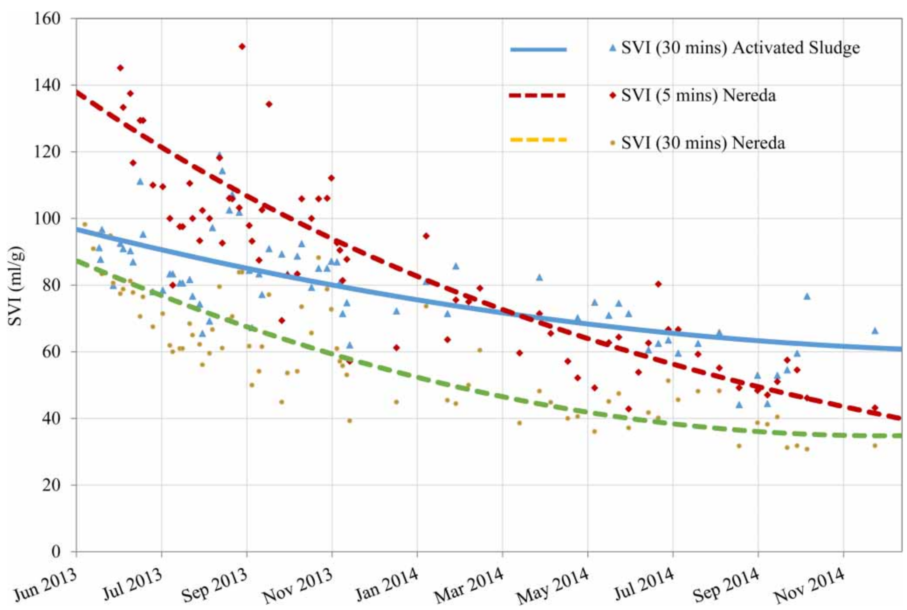


Figure 3 | Comparison of SVIs of the Nereda® and activated sludge systems at Vroomshoop STP (data from end-user: Waterschap Vechtstromen).

Between June and November 2014, energy usage monitoring at the Vroomshoop STP 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).

Prototype Nereda® Utrecht (PNU)

In 2013 a project specific Nereda® prototype (PNU) was installed at the existing Utrecht STP 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

Water Practice & Technology Vol 12 No 4
doi: 10.2166/wpt.2017.101

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× per year up to 250)
	BOD_5	263	4	10	Limit (3× 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

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 conditions 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 particles 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 particules are kept in the reactor, baffles were added to the PNU effluent launders in 2015. Figure 4 shows how the effluent suspended solids were reduced to below 10 mgTSS/l. Based on these results the optional use of scum baffles has been introduced in various full-scale designs where stringent requirements apply for suspended solids or total-P.

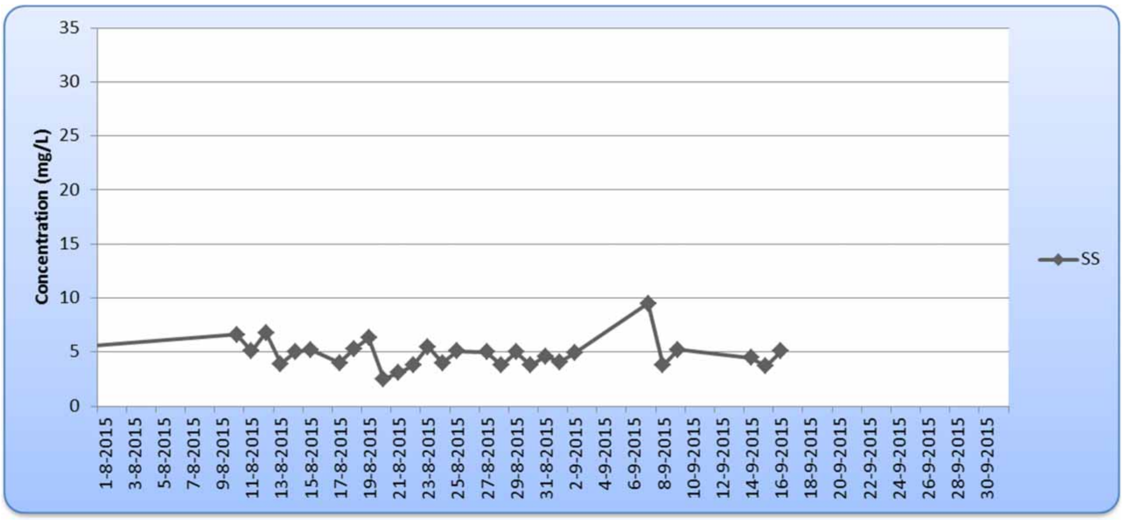


Figure 4 | Effluent suspended solids performance at the PNU facility with baffles (no primary clarification).

Water Practice & Technology Vol 12 No 4
doi: 10.2166/wpt.2017.101

FURTHER DEVLOPEMENTS – ALE 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 20 to 30% of ALE. Extracted ALE could potentially be used in the chemical sector, as a soil enhancer in agriculture 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 ALE extraction with the existing excess sludge treatment processes at wastewater treatment plants could also improve sludge treatment efficiency because ALE extraction reduces sludge volumes and the remaining (non-extracted) sludge has a higher digestibility and an improved 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®. During the summer of 2017 a pilot study was carried out and based on the results two demo installations will be designed and realized in 2019.

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 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 STP) 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 CAS 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.

Water Practice & Technology Vol 12 No 4
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