Aerobic Granular Biomass Technology: further innovation, system development and design optimisation

Andreas Giesen[1]*, Mark van Loosdrecht[2], Struan Robertson[3], Bart de Buin[1]

[1] Royal HaskoningDHV, the Netherlands
[2] Delft University of Technology, the Netherlands
[3] Royal HaskoningDHV, South Africa
* E-mail: andreas.giesen@rhdhv.com

ABSTRACT
Aerobic granulation is seen as the future standard for industrial and municipal wastewater treatment and subsequently research efforts are quickly developing in this field. As an outcome of a Dutch research and development program, an aerobic granular biomass technology has been scaled-up and implemented to treat urban and industrial wastewater. This Nereda® technology is considered being the first aerobic granular sludge technology applied at full-scale and more than 20 municipal and industrial plants are in operation or under construction worldwide. Further plants are in the planning and design phase, including plants with capacities exceeding 1 million PE. Operating data confirm the projected advantages with regard to treatment performance, energy-efficiency and cost-effectiveness. In addition, a new possibility for extracting alginate like polymers from aerobic granular sludge has emerged which could provide sustainable reuse opportunities.

KEYWORDS: Aerobic granular biomass, *Nereda*®, cost-effective, energy efficient, sustainable, small footprint, biotechnology, innovation, wastewater treatment, sanitation

INTRODUCTION

Since the development of BNR systems for activated sludge, the research on biological wastewater treatment processes has focused on improved separation techniques for activated sludge by improving settling properties and physical separation techniques (i.e. MBR systems). The fundamental requirements to improve settlability are compact, dense, large particles with higher specific gravity. This became the foundation for the research and development of aerobic granules by Delft University of Technology (DUT). Discovered by Professor Mark van Loosdrecht from DUT, the process has been engineered to suit commercial applications by Royal HaskoningDHV and has been commercially branded as Nereda® Technology.

Aerobic granular biomass has several advantages over conventional activated sludge flocs that have been well-documented. These include good settling ability that leads to better biomass retention and higher biomass concentrations, provision of a structured matrix for biomass growth, and ability to withstand high load variations. These all lead to a compact reactor design that can reduce plant footprints significantly.

The research and development of aerobic granules commenced at DUT in 1993. In 2002 aerobic granular sludge is discovered and stable laboratory scale granulation was achieved. This was followed by the pilot scale research at Ede WWTP and several pilot plants have been in operation for both industrial and municipal influent since 2003, in and outside the Netherlands. The first industrial full scale Nereda® prototype was implemented in 2005 by retrofitting an existing tank and was followed by several greenfields and industrial plant upgrade applications.

In 2007, DUT, STOWA (Dutch Foundation for Applied Water Research), Royal HaskoningDHV and six Dutch Water Boards joined forces in the Dutch National Nereda® Development Program (NNOP) to scale-up and implement aerobic granular biomass technology for municipal applications. In parallel two Nereda® demonstration plants (Gansbaai, South Africa and Frielas, Portugal) were instrumental in the further scale-up. Epe WWTP was designed and built in 2010/2011 and has been in operation for more than two years. Following the successful design, construction and operation of Epe WWTP, various other municipal Nereda® plants were projected (see Table 1).

Currently, more than 20 full scale plants in 7 different countries are operational or under construction. A further 5 are in the design stage, a lot more in the lead phase. The technology grows-out from an innovation into a proven new standard for urban and industrial biological wastewater treatment. Royal HaskoningDHV is widely implementing Nereda® technology for about two years now together with partners in Australia (Aquatec Maxcon), the UK (Imtech), Ireland (EPS Group), Brazil (Odebrecht), Switzerland and India (WABAG).

Table 1. Nereda® References, July 2015.

Operational plants	Daily average flow (m^3/day)	Peak flow (m^3/h)	Person Equivalent	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	15,730	2013
STP Frielas, Lisbon (PT)	12,000		40,000	2014
STP Ryki (PL)	5,300	430	41,000	2015
STP Wemmershoek (RSA)	5,000	625	39,000	2013
STP Clonakilty (IRL)	4,896	626	20,500	2015
Plants under construction				
Westfort Meatproducts, IJsselstein (NL)	1,400	1,400	43,000	2015
STP Carrigtohill (IRL)	6,750	844	30,000	2015
STP São Lourenço, Recife (BR)	19,093 (1st fase); 25,123 (2nd fase)	1,674	139,600	2015 2024

STP Jardim Novo, Rio Claro (BR)	23,500	1,764	133,000	2015
STP Deodoro, Rio de Janeiro (BR)	86,400	6,120	480,000	2016
STP Jardim São Paulo, Recife (BR)	19,529 (1st fase) 78,117 (2nd fase)	5,859	434,000	2016 2025
STP Tatu, Limeira (BR)	57,024	3,492	517,000	2016
STP Hartebeestfontein (RSA)	5,000	1,250	44,000	2015
STP Kingaroy (AUS)	2,700	450	16,000	2016
Plants under design				
STP Jaboatão, Recife (BR)	109,683 (1st fase) 154,483 (2nd fase)	11,588	858,330	2016 2025
STP Breskens (NL)	5,400	1,100	37,000	2016
STP Simpelveld (NL)	3,668	945	11,880	2016
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		10,000	2012
STP Utrecht (NL)	1,500	600	9,000	2013
Anonymous Chemicals (FR)				2014
STP Kloten Opfikon (CH)	1.5 – 5.0	1.0	10-30	2014
STP Davyhulme (UK)	1.5 – 5.0	1.0	10-30	2014
STP Daldowie (UK)	1.5 – 5.0	1.0	10-30	2014
STP Dalmarnock (UK)	1.5 – 5.0	1.0	10-30	2014
STP Crewe (UK)	1.5 – 5.0	1.0	10-30	2015
STP Werribee (AUS)	100-300	50	500-1,500	2015

METHODOLOGY: AEROBIC GRANULAR BIOMASS

Aerobic granules were defined at the First Aerobic Granule Workshop 2004, Munich, Germany which stated "Granules making up aerobic granular activated sludge are to be understood as aggregates of microbial origin, which do not coagulate under reduced hydrodynamic shear, and which subsequently settle significantly faster than activated sludge flocs."

The main features in defining aerobic granules are minimum diameter of 0.2 mm and SVI5 of aerobic granules being comparable to SVI30 of activated sludge. Figure 1 illustrates the settling properties of aerobic granular sludge compared to activated sludge after 5 minutes of settling.

Figure 1. Settling Properties of the Aerobic Granular Biomass (left) compared to Activated Sludge (right).

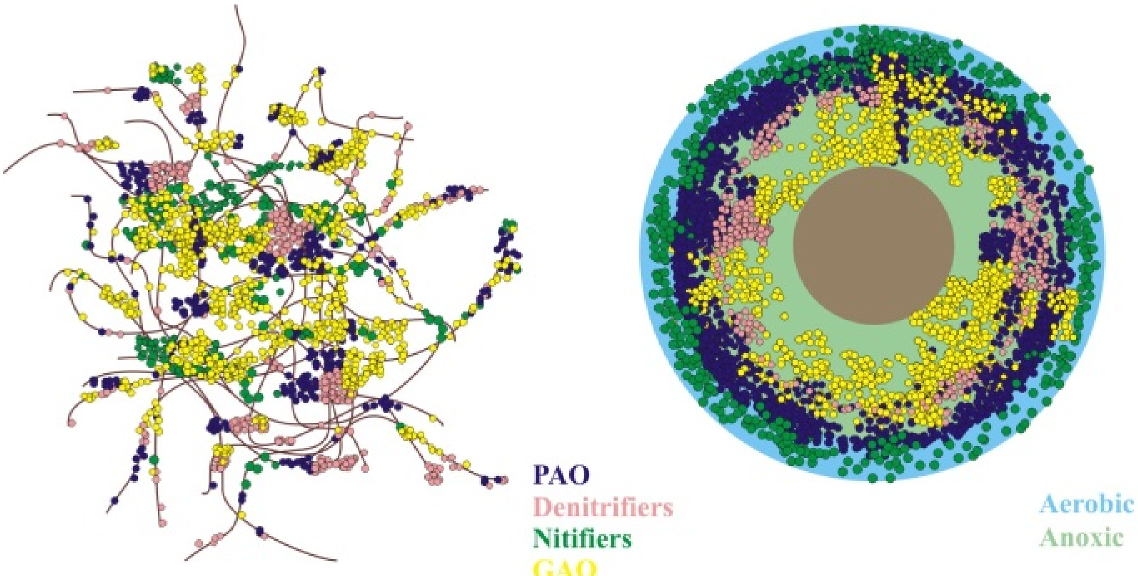


Figure 2. Difference between Activated Sludge (left) and Granular Biomass (right).

In the Nereda Technology, design and control mechanisms are utilized to encourage biomass to form granules with efficient settling properties. In granular sludge the three reaction zones are present in different layers inside the granular particles, with diffusion connecting the reaction zones, thus allowing simultaneous anaerobic,

aerobic and anoxic conditions to exist in the granules. Hence, this technology reduces the need for multiple tanks and recirculation for the different processes. Figure 2 shows a pictorial representation of the distribution of biological organisms within aerobic granules compared to activated sludge, including phosphate accumulating organisms (PAO), nitrifiers, denitrifiers and glycogen accumulating organisms (GAO).

The process operates intermittently, with the fill and decant phase occurring simultaneously (Figure 3 illustrates the basic Nereda® process cycle). Due to good settling capacity of the aerobic granules, the process does not require mechanical decanters to ensure low solids in the effluent.

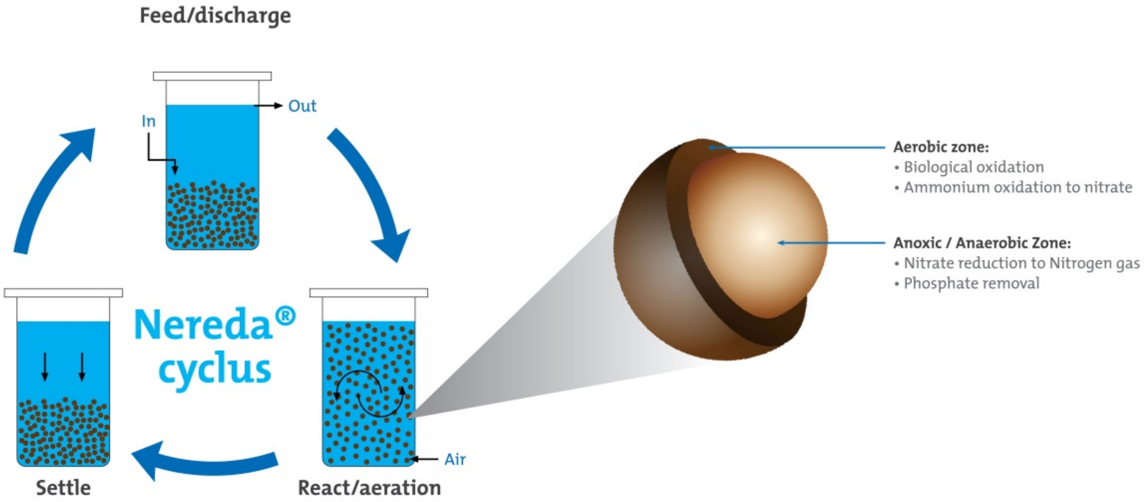


Figure 3. Nereda® Process Cycle.

Nereda technology enables efficient water treatment in compact and uncomplicated designs. The amount of mechanical equipment is much less compared to the conventional processes (reduction in investment by approximately 25%). For example, separate clarifiers, return sludge pumping stations or moving decanters are not necessary. Investment in imported goods is even stronger reduced , which is an important extra benefit for developing countries. The simple process scheme makes that it is easy to operate and, therefore, reliable. What's more, the concentrated biomass substantially reduces tank volume and easily makes the required area a factor 4 smaller (Figure 7). This lowers the direct plant costs for green field, brown field, retrofit or hybrid capacity extension application and often enables that existing treatment sites are utilized rather than acquiring new land. Operation and maintenance costs are much lower thanks to the reduction in mechanical equipment, chemical-free operation and the remarkably high energy efficiency of the process. On average, a Nereda plant uses 30-40% less energy than conventional wastewater treatment plants, while delivering better water quality.

Nereda® Controller

Each Nereda installation consists of an AquaSuite® Nereda® Controller, a tailor made process controller – integrated with the plants PLC/SCADA – to ensure fully automated plant operation, reliable performance, ease-of-operation and optimized and energy-efficient treatment.

The Nereda® technology is based on optimized sequencing batch cycles. Duration and process parameters in the various cycle steps must be adjusted to assure optimal and efficient performance while for example water flow, water composition and temperature fluctuate. The Nereda® Controller automates these adjustments and makes effective use of the extensive experience of the Nereda® process specialists.

Furthermore the Nereda® Controller provides large flexibility for future extensions or upgrades. For example, if in future the number of Nereda® reactors must be increased to cope with increased water flows, only a simple reconfiguration of the controller will be required.

In addition, the PC-based controller enables logging of process parameters. These parameters are transformed into smart process performance information, providing detailed insights into process fundamentals and kinetics. This way the Nereda® Controller is an important instrument in plant performance evaluation enabling extensive optimization and early-warnings.

Extracting alginate from Nereda® sludge

Recent research at the Delft University of Technology showed that the substance responsible for the granular growth of microorganisms in aerobic granular sludge (used for wastewater treatment) is a polymer termed 'alginate-like exopolysaccharides' (ALE). This polymer binds strongly with water, can thicken or gel liquids and can be used as a basis for coatings. These properties make ALE a valuable raw material with many potential applications. Seaweed derived alginate is currently used extensively in the medical and food industries; however the price for alginate is high due to the limited availability of seaweed. Wastewater derived alginate (with lower costs) could potentially be used in the chemical sector, paper and textile industries or as a soil enhancer in the agricultural sector to improve water retention in semi-arid areas.

As with all biological wastewater treatment systems, Nereda® treatment plants generate a constant stream of excess sludge that requires further treatment. Given the discovery of ALE in aerobic granular sludge, the question that arises is: Can the waste/excess sludge from Nereda® systems be used for cost-effective ALE-extraction, enabling the sustainable bio-based reuse of a waste product? The success of the NNOP in the development of the Nereda® system provided an example of the ideal structure and 'already interested' partners for research into and development of ALE-extraction from Nereda® sludge – therefore in 2013 the NAOP (National Alginate Research Programme) commenced with the goal of realizing commercially viable and sustainable ALE-extraction from aerobic granular Nereda® excess sludge.

Aerobic granular sludge contains 15-25 percent of ALE which, in principle, can be recovered with existing technologies used for alginate extraction of seaweed.

Combining alginate extraction with the existing excess sludge treatment processes at wastewater treatment plants would not only yield a valuable raw material but 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 Dutch Water Authorities (responsible for municipal wastewater treatment in the Netherlands), are committed to striving for the transformation of wastewater treatment plants into “Energy and Resource Factories” i.e. sustainable recovery of all valuable resources in wastewater – the extraction of ALE from Nereda® excess sludge would be an important step towards achieving the sustainable “Energy and Resource Factories” concept. The extraction of ALE from excess granular wastewater sludge is seen as an innovative and sustainable development in the direction of a bio-based economy and therefore warrants further research.

In 2013 the private-public NAOP (National Alginate Research Programme) was started by the following partners: Royal HaskoningDHV, Delft University of Technology, STOWA and three Dutch Water Authorities (Rijn & IJssel, Vallei & Veluwe and Vechtstromen). From the outset, it was obvious that the partners should first focus on the interest of market parties in the ALE product(s). Further technological development towards full-scale ALE-extraction from excess granular wastewater sludge would not be tenable without commercial parties showing serious interest in the product(s). An exploratory market study showed promising interest from (large) companies across various industrial sectors. Furthermore, various government entities have also shown interest in the sustainability linked concept of a circular economy involving ALE-production from wastewater and subsequent reuse for industrial processes.

Selected companies, some acting as representatives for certain industrial sectors, others as direct consumers and intermediaries, are currently being consulted again. The participating companies receive an amount of dried alginate or granulate (dried granules with 20% ALE), to further explore the substances’ properties and potential use. At the same time a research project is underway to further develop and test the ALE-extraction methods. The promising developments and results achieved to date, have not gone unnoticed and on 10 December 2013 the NAOP partners, were awarded the prestigious Dutch Water Innovation Award 2013 for “the recovery and reuse of alginate from granular sludge” – an exciting new development resulting from the revolutionary Nereda® wastewater treatment technology.

The NAOP has plans for two full-scale demonstration installations for ALE extraction. One extraction installation will treat the granular excess sludge from municipal Dutch Nereda® installations at Epe, Dinxperlo and Vroomshoop, while the other demo-installation will extract alginate from excess sludge from a planned industrial Nereda® installation in The Netherlands. The cost for the research program, including the demo-installations has been estimated at €14 million and therefore careful planning and significant funding is required. Partners are currently discussing the best way forward to realize these demo-installations including the exploration of various revenue models.

RESULTS - NEREDA VERSATILITY

Since implementing the first full-scale Nereda installations new insights have emerged allowing for further innovation, system development and design optimisation. New system configurations have been developed to suit a variety of scenarios experienced from site to site and from country to country. Two ‘greenfield’ or parallel extension approaches have been used and are detailed below (see Figure 4):

1. 3+ Nereda® reactors
   - At least one Nereda® reactor is fed at any given time
   - E.g. applied at Epe WWTP (the Netherlands)

2. Buffer(s) followed by Nereda® reactor(s)
   - Typically 1 buffer followed by 2 Nereda® reactors.
   - Often results in overall lower tank volumes and capital cost savings (case dependent).
   - E.g. applied at Wemmershoek WWTP (South Africa), Ryki WWTP (Poland), Garmerwolde WWTP (The Netherlands)

In addition two ‘brownfield’ options have been developed:

3. Nereda® and CAS hybrid
   - Waste sludge from Nereda® system is fed into CAS system.
   - Improves CAS treatment efficiency and / or capacity in addition to the expanded capacity achieved via the Nereda® system.
   - E.g. applied at Vroomshoop WWTP (the Netherlands)

4. Nereda® retrofit
   - Convert existing tank(s) into a Nereda® reactor (SBR, CAS aeration basin or any other suitable tank)
   - Make use of existing infrastructure whilst increasing system capacity and reducing energy, chemical use.
   - E.g. applied at Frielas WWTP (Portugal) (in combination with the hybrid approach)

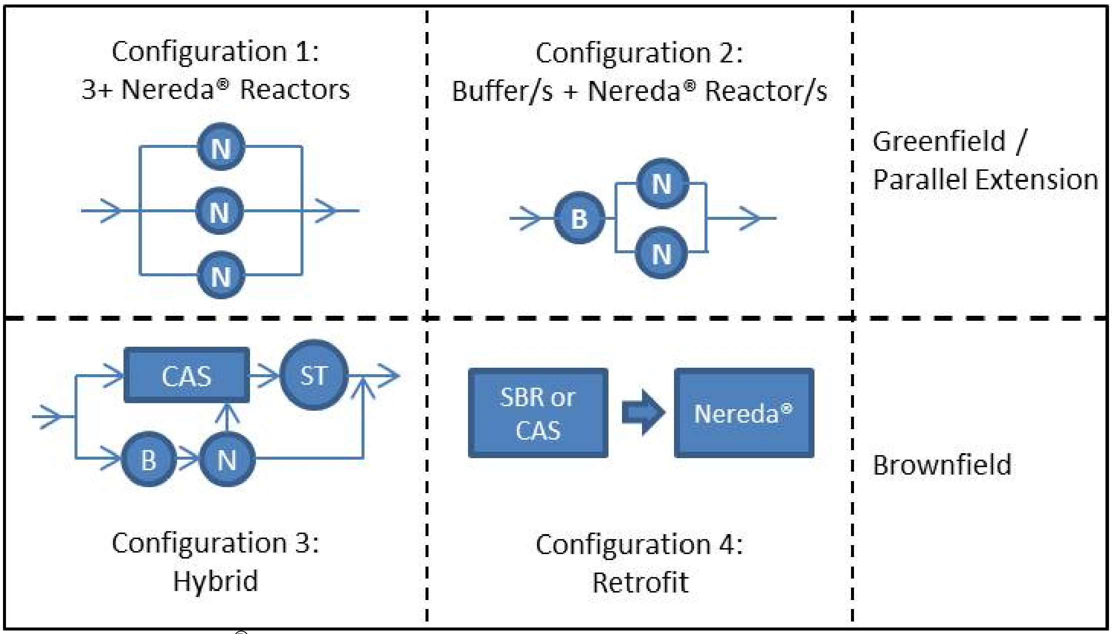
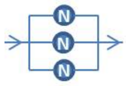
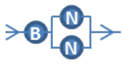
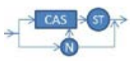
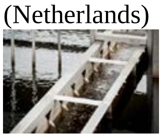


Figure 4. Nereda® configurations/approaches.

Table 1. Nereda® configurations

	Nereda Configuration	Typical Layout		Attributes	Advantages	Reference examples	Potential Applications
1	3*X reac-tors	3 reac-tors		At least 1 reactor fed at all times	Scalable for application to the world's largest treatment challenges	Epe WWTP (Netherlands) 	Greenfield sites; extension to existing plants with parallel Nereda line
2	Buffer followed by X reac-tors	1 buffer + 2 reac-tors		Buffer stores between feeds to reactors	Optimized investments (2 reactors vs 3).	Wemmers-hoek WWTP (South Africa) 	Greenfield sites; extension to existing plants with parallel Nereda line
3	Hy-brid	1 or more Nere-da reactor – con-nected to acti-vated sludge system		Waste Nereda sludge to activated sludge system	Improve activated sludge system performance / optimise existing infrastructure	Vroomshoop WWTP (Netherlands) 	Brownfield sites Extension / optimisation scenarios with optimal use of existing infrastructure
4	Retro-fit	Con-vert exis-ting SBR/ acti-vated sludge reactor or any suit-able exis-ting tank		Use existing infrastructure	Cost-effective way to increase capacity and improve performance whilst using existing infrastruc-ture	Frielas WWTP (Portugal) 	Brownfield sites. Space or budget constraints / capacity increase or improved performance required

The four basic configurations or approach options outlined above have covered all of the treatment scenarios experienced to date at full-scale. Details of the Epe WWTP (configuration 1), Garmerwolde WWTP and Wemmershoek WWTP (configuration 2), Vroomshoop WWTP (configuration 3) and Frielas WWTP (configuration 4) are presented below.

RESULTS AND DISCUSSION: SOME PROJECT DATA

Epe WWTP

Client: Water Board Vallei & Veluwe
Wastewater type: Municipal & Industrial
Location & start-up: Epe, The Netherlands, 2011
Average capacity: 8,000 m^3/day; 54,000 p.e. inclusive 13,750 p.e. from industrial discharges
Peak flow: 1,500 m^3/hour

The first Dutch municipal full-scale plant was constructed at Epe WWTP. The Epe WWTP was designed and constructed in 2010-2011 and is operational since September 2011. Prior to design, a pilot trial was carried out for four years and the data was used to design the full scale plant. The plant consists of the following main processes; inlet works with screens and grit removal, followed by three Nereda® reactors and effluent polishing via gravity sand filters. The waste sludge is thickened via a gravity belt thickener and transported off-site.

The performance of the Epe plant shows that Nereda® even exceeds expectations. The energy consumption of the WWTP is significant less than any type of similar-sized conventional treatment plant in the Netherlands. Furthermore the effluent quality meets the highest standards in The Netherlands, i.e. total Nitrogen and Phosphorous concentrations lower than 5 and 0.3
mg/l.

Garmerwolde WWTP

Client: Construction consortium GMB/Imtech for Water Board Noorderzijlvest
Wastewater type: Municipal
Location & start-upr: Garmerwolde, The Netherlands, 2013
Average capacity: 30,000 m^3/day; 140,000 p.e.
Peak flow: 4,200 m^3/hour

The Garmerwolde WWTP was retrofitted into an AB activated sludge system in 2005 and was subsequently not able to meet the required nutrient removal targets, which necessitated a plant upgrade. Nereda® was selected as the preferred solution to extend the capacity and improve the biological nutrient removal capabilities of the plant. The solution, which commenced operation in 2013, involved the addition of two 9,500 m^3 Nereda® reactors – tank sizes similar to the world's largest SBR-tanks – preceded by a 4,000 m^3 buffer in parallel to the existing plant. The extension was designed for 140,000 P.E. (150 gTOD) of pollution load and hydraulically for 20,000 m^3/d (average flow) and 4,200 m^3/hr (peak flow).
The use of 1 buffer and 2 Nereda® reactors (configuration 2) enabled an overall tank volume saving of approximately 35% when compared to the 3 Nereda® reactor option (configuration 1, e.g. Epe WWTP) for this specific case.
The extension (Nereda®) performance requirement for nutrient removal (without any downstream filtration step) is a Total-N of 7 mg/l (yearly average) and Total-P of 1 mg/l (average of ten successive samples). After a year-long monitoring period (2014)

the Garmerwolde WWTP was found to fully comply with the overall effluent requirements, despite receiving on average 28,500m^3/d (designed for 20,000m^3/d). The Garmerwolde WWTP offers the possibility to directly compare the performance of the Nereda® and activated sludge technologies. The energy consumption of the Nereda® installation (including intermediate pumping) was consistently more than 40% lower than the energy consumption of the parallel AB system in 2014. Furthermore, the AB system requires chemical dosing, including C-source (denitrification), coagulants (sludge properties) and iron salts (phosphorous removal). Apart from the high chemical costs incurred, the dosing also results in a sludge production almost double that of the parallel Nereda® extension. Consequently the overall operational costs (energy, chemicals, sludge treatment) of the activated sludge plant are significantly higher than the Nereda® extension.
Considering that the Nereda® installation treats 41% of the daily influent flow and the original installation (AB-system) 59%, Figure 7 shows Nereda®'s advantage in terms of system footprint.

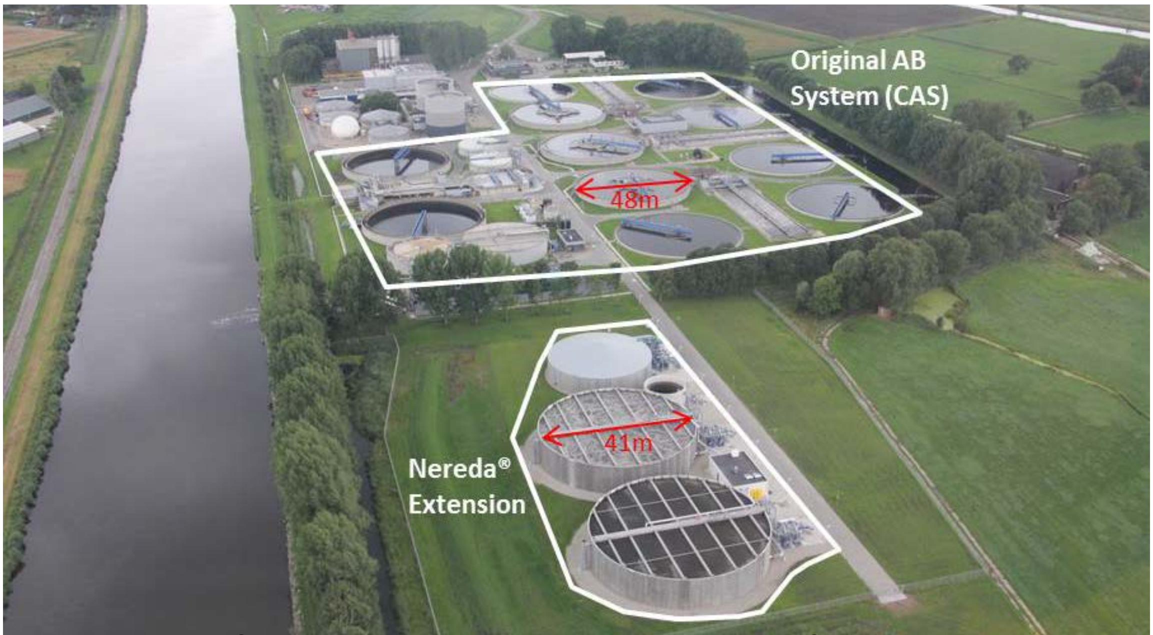


Figure 7. Nereda® Garmerwolde WWTP. (The two Nereda® tanks in front treat approx. 40% of the sewage. The existing AB-system in the back 60%).

Ryki WWTP

Client: Przedsiebiorstwo Gospodarki Komunalnej i Mieszkaniowej
Wastewater type: Municipal & industrial
Location & year: Ryki, Poland, 2015
Average capacity: 5,300 m^3/day; 41,000 p.e. , high portion of tanked-in septic and industrial discharges which can go up to 60% of the total COD load
Peak flow: 430 m^3/hour

Based on the outcome of a public tender process, the municipal-owned utility company selected Nereda® technology-based offer for the design and engineering of their new wastewater treatment. Important criteria in the tender evaluation process were capital expenditure and total costs of operation. The wastewater is a mixture of sewage, tanked-in septic and industrial discharges from primarily vegetables.

Start-up of this plant was mid-February. The effluent of the two reactors is discharged into a pond and poured over the surface waters. When the pond is overflowing the effluent is measured. Discharge standards are amply achieved.

Table 4. Nereda® Ryki data from the end of March 2015.

parameter	Concentrations (mg/l)				
	influent	Effluent R1	Effluent R2	Outlet effluent pond	Effluent standard
COD	623	39	42	50	125
BOD	227	5.6	6.3	8.2	15
TN	72	4.8	4.8	6.6	15
TP	7.7	0.5	0.5	1.0	2
TSS	238	15	17	10	30

Wemmershoek WWTP

Client: Stellenbosch Municipality
Wastewater type: Municipal
Location & start-up: Wemmershoek, South Africa, 2015
Average capacity: 5,000 m^3/day; 39,000 p.e.
Peak flow: 625 m^3/hour

In 2010 the Stellenbosch Municipality decided to centralise wastewater treatment for the Franschhoek area by decommissioning two existing treatment plants (Franschhoek and La Motte WWTPs) and treating all wastewater at the Wemmershoek WWTP. To realise a cost-effective centralisation of treatment capacity a new 5Mℓ/d treatment system was required at the Wemmershoek works. The Franshhoek area falls within the sensitive Berg River catchment which meant stringent effluent requirements (special limits). Royal HaskoningDHV proposed the Nereda® technology and effluent reuse as a cost-effective and sustainable means to meet the project requirements. By utilising effluent reuse (irrigation) the need for extensive tertiary treatment to meet expected future (even more stringent) standards was not required. Details of the treatment plant are provided in Table 5.

Figure 8. Nereda® reactor at Wemmershoek discharging effluent.

Table 5. Wemmershoek WWTP design details.

Design Component	**Unit**	**Wemmershoek Design**
Primary Treatment	-	Screening and grit removal
Secondary treatment	-	1 x 600m^3 Nereda® Influent Buffer; 2 x 1 800m³ Nereda® reactors
Tertiary treatment	-	Chlorine disinfection, maturation pond
Sludge treatment	-	Mechanical thickening and dewatering
Average Dry Weather Flow	Mℓ/d	5
Peak Wet Weather Flow	Mℓ/d	14.4
Effluent discharge	-	Discharge to Berg River and re-use for irrigation (pumped to Franschhoek)
Influent Characteristics	-	Design (actual)
COD	mgCOD/ℓ	870 (796)
Total Kjeldahl Nitrogen	mgTKN-N/ℓ	60
Ammonium	$mgNH_4$-N/ℓ	45 (79)
Nitrate	$mgNO_3$-N/ℓ	-
Total Phosphorus	mgP/ℓ	12 (11,7)
Ortho-phosphate	$mgPO_4$-P/ℓ	- (8,6)
Suspended Solids	mgTSS/ℓ	- (381)

( )_The data in parenthesis are averages over the last 4 independently analysed samples (24 March to 1 April)

The new 5 Mℓ/d system was commissioned in August 2014 and following the development of granular sludge the treatment plant is producing excellent effluent quality (well below requirements) – see Table 6 with recent effluent results.

Table 6. Effluent quality at Wemmershoek WWTP.

Parameter	Unit	Average CSIR Lab Results – Final Effluent	Effluent Requirement (General Limit)
COD	mgCOD/l	48	<75
Ammonium	mgNH_4-N/l	0.3	<6
Nitrate	mgNO_3-N/l	0.1	<15
Nitrite	mgNO_2-N/l	0.1	-
Total phosphorus	mgP/l	2.6	-
Ortho-phosphate	mgPO_4-P/l	2.3	<10

The data presented in Table 6 is based on average effluent results from March to April independently verified by an external laboratory (CSIR). The Wemmershoek treatment plant has a discharge limit of 10 mgPO4-P/ℓ. Although the phosphorus concentrations in the final effluent are well below this limit, the process control has not yet been fully optimised for biological phosphorus removal. If optimal Nereda® biological phosphorus removal is implemented, effluent ortho-phosphate concentrations below 0.9 mgPO4-P/ℓ could be achieved without chemical dosing (concentrations of 1,5 mg/ℓ, 0,6 mg/ℓ and 1,2 mg/ℓ were achieved during March 2015, giving a clear indication of the potential).

The Berg River Improvement Plan (BRIP) was developed in 2012 by the Western Cape provincial government, the Department of Water Affairs and local stakeholders. The main aims of the BRIP are the sound management of this sensitive catchment and to improve water quality. The Wemmershoek WWTP project is positively contributing to achieving the BRIP's goals by limiting pollution loads from the Franschhoek area. This is an example of how innovative wastewater treatment solutions (Nereda®) in conjunction with exceptional municipal operations and management (Stellenbosch Municipality) can fit into broader integrated water resource management as envisaged by South Africa's National Water Act (2008).

Vroomshoop WWTP

Client: Water Board Vechtstromen
Wastewater type: Municipal
Location & start-up: Vroomshoop, The Netherlands, 2013
Average capacity: 1,500 m^3/day; 12,000 p.e.
Peak flow: 400 m^3/hour

In 2008, the Dutch Waterboard Vechtstromen became interested in helping with the development of the Nereda® technology as a part of their strategic commitment to advancing the wastewater treatment technology field. At the Vroomshoop WWTP an opportunity emerged to use Nereda® for the expansion and replacement of the existing treatment plant, which consisted of an ageing oxidation ditch system that would not be able to meet future effluent requirements, especially with regard to nutrient (nitrogen and phosphorus) removal.

A hybrid configuration (configuration 3) was selected because it was found to be an effective means of making use of an existing settling tank at the site, an optimal way to deal with the high rain weather to dry weather flow ratio at the plant and this option provided an opportunity to meet innovation and sustainability targets such as reducing energy usage. The hybrid arrangement of the treatment plant is schematically shown in Figure 9 below.

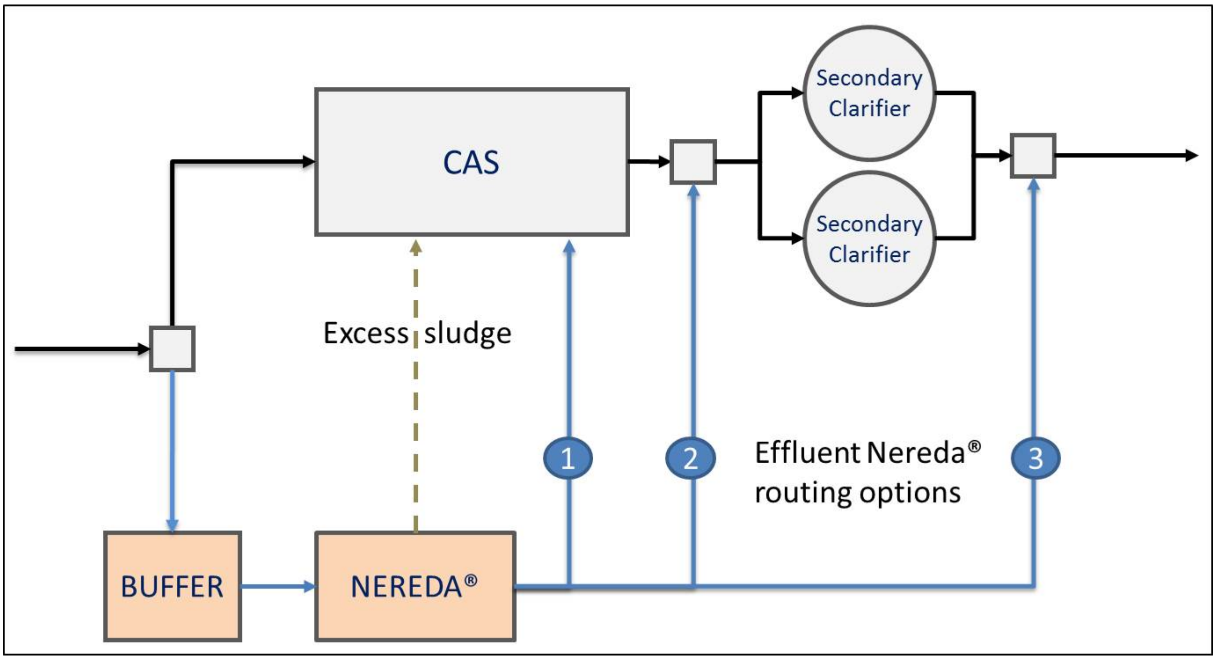


Figure 9. Flow scheme at Vroomshoop WWTP with full hydraulic routing options (1, 2 and 3)

The new Vroomshoop WWTP entered operation in mid-2013. The plant is designed for a pollution load of 22,600 P.E. (150 gTOD) and hydraulically to receive 156 m3/hr of wastewater during dry weather conditions and 1,000 m3/hr during rain weather conditions. The introduction of Nereda® excess/waste sludge into the CAS system has proven to be an effective way to improve the performance of the CAS system. The settleability of the CAS sludge showed a marked improvement (lower SVI) as can be seen in Figure 10 below.

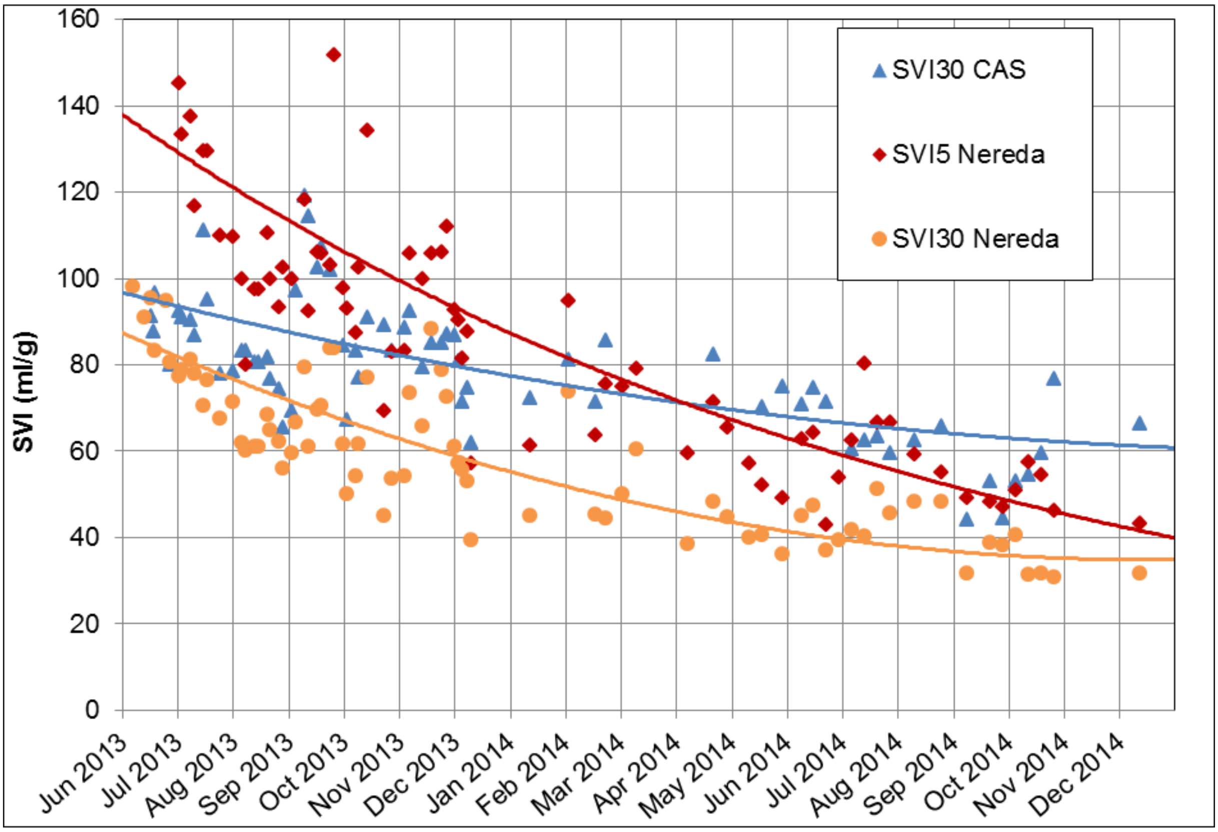


Figure 10. SVI comparison of the Nereda® and CAS systems at Vroomshoop from start-up in June 2013 until the end of 2014.

Using Nereda® waste sludge to improve settleability in CAS systems (hybrid – configuration 3) offers numerous advantageous possibilities, such as:

- the potential to increase biomass concentrations in the CAS system, thereby increasing biological treatment capacity and;
- enabling higher hydraulic loading through the CAS system.

Furthermore, Nereda® waste sludge contains a high fraction of PAOs (which drive bio-P removal) and therefore improvement in biological phosphorus removal in the CAS side of a hybrid system is possible. With the plant at full loading, the performance in terms of effluent quality has met all requirements (see Table 7). Furthermore, energy consumption monitoring at Vroomshoop (June-November 2014) showed the Nereda® side of the treatment plant used approximately 35% less energy than the CAS side.

Table 7. Vroomshoop WWTP - overall treatment performance in 2014 (data from Waterboard *Vechtstromen*).

Parameter (mg/l)	Influent	Effluent	Requirement	Compliance Conditions
COD	720	55	125	Limit (3 x per year up to 250)
BOD5	263	4	10	Limit (3 x per year up to

				20)
TN		7,2	10	Yearly Average
TKN	66	5,2	-	-
NH_4-N	-	2,2	Summer = 2 Winter = 4	Average (1 May - 1 Nov.) Average (1 Nov. - 1 May)
NO_x-N	-	2,0	-	-
TP	8,9	0,9	2	Moving average of 10 successive samples
PO_4-P	-	0,6		-
TSS	317	10	10	Limit (3 x per year up to 30)

Frielas WWTP

Client: Agua de Portugal – Simtejo
Wastewater type: Municipal & Industrial
Place & year: Lisbon, Portugal, 2012 + 2014
Average capacity demo: 3,000 m^3/day; 10,000 p.e.
Average capacity full scale retrofit: 12,000 m^3/day; 40,000 p.e.

The Frielas WWTP is a 70,000 m^3/d plant currently at 70% of its biological design capacity and receives, mainly, domestic wastewater from 250,000 inhabitants, in the Greater Lisbon area. Regarding effluent quality, the WWTP has carbon removal and disinfection requirements (i.e., COD < 125 mg/l and TSS < 35 mg/l) and no specific discharge limits for nitrogen and phosphorous. Since start-up in 1997, the Frielas WWTP suffered from several operational constraints related to some technological decision made at the design phase but also because the wastewater characteristics became quite different from those used for the original plant design. To validate if Nereda could improve the plant performance under realistic field conditions, one of the six continuous activated sludge reactors was retrofitted into a Nereda® reactor (Figure 11) with a volume of approximately 1,000 m3, which was then run in parallel to the remaining five activated sludge reactors. This was the first continuous Activated Sludge Nereda® retrofit application.

Figure 11. Conversion of reactor nº6 of Frielas WWTP to Nereda® technology.

Besides providing a robust and efficient operation during all influent conditions, a driver for the retrofit was to evaluate the possibility to substantially lower the electricity demand of a conventional WWTP. Another important motivation for the implementation of Nereda® was the possibility of working at higher hydraulic loads and achieving nutrient removal without the (eventual) future need for increasing reactor volume.

The demonstration reactor start-up was made with normal activated sludge from one of the other aeration streams. Operation reached a steady state SVI30 around 40 ml/g, a SVI5 as low as 60 ml/g, a granulation fraction above 80% and an increasing biomass concentration in the range of 6 to 8 g/l. It is important to note that the start-up was made partially during winter time with diluted wastewater (i.e. COD levels below 300 mg/l) contributing to a slower biomass growth and transformation rate.

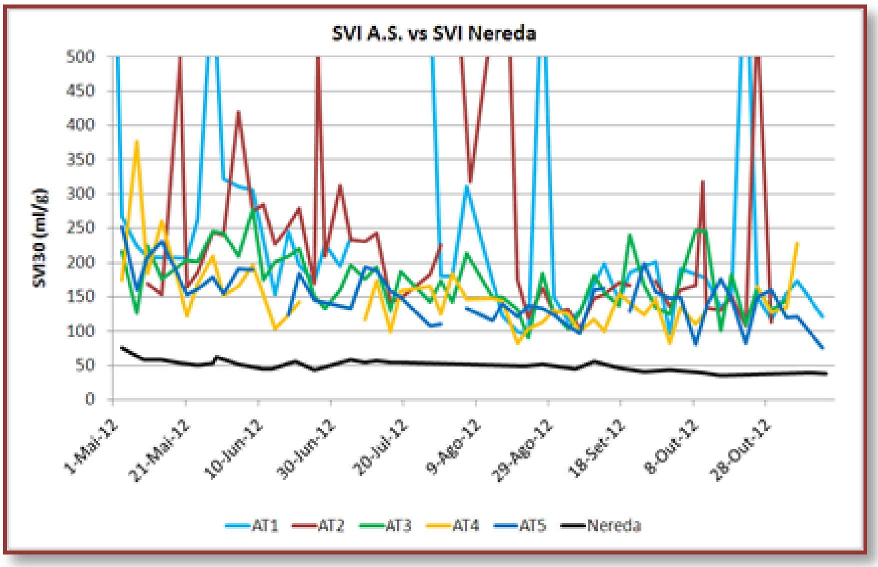


Figure 12. Comparison between the settleability of the biomasses from the Nereda reactor and the activated sludge (AS) from the other five biological reactors (AT) in the Frielas WWTP.

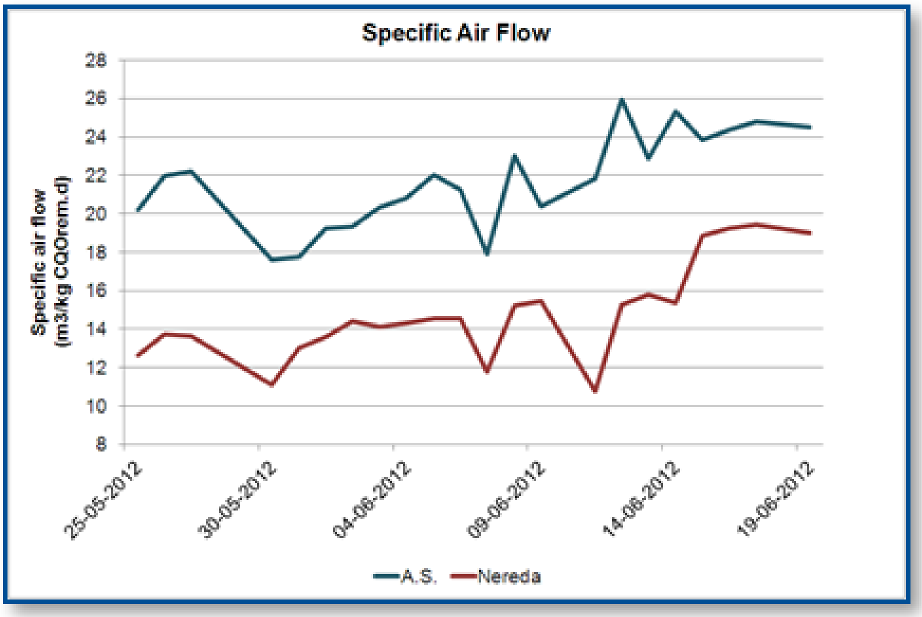


Figure 13. Comparison between the airflow rates to activated sludge and Nereda plants.

After more than one year of plant operation the effluent quality was shown to be significantly better and far more consistent than the quality obtained in the original continuous AS system. This plant also gave a unique opportunity to observe the power consumption of Nereda® in parallel to an AS system. Airflow rates are shown in figure 13. A significant decrease in energy consumption was observed. Since Nereda® is operated in parallel with the conventional aeration tanks using the same water depth, existing and common air supply equipment, the comparison between the two technologies is reliable and representative. During a two month monitoring period the air consumption of both systems was measured with the dissolved oxygen (DO) levels similar and nitrification in Nereda® fully suppressed to mimic the biological performance of the AS reactors.
Taking into account the efficiency of the air blowers, the measured air flow consumed in each system per mass of chemical oxygen demand (COD) removed was translated into the specific electricity consumption. It was observed that the average specific consumption for the Nereda amounts to 0.35 kWh/kg COD removed, representing approximately 30% electricity savings compared to aeration for the AS system. Combining this with the energy saving that granules bring by not using settling tanks, sludge recirculation pumps and post-filtration units, the overall electricity saving potential for the plant was computed to 50%.

Following the positive results obtained with the Nereda® demonstration reactor, Simtejo has implemented an extension of the demo to a full-scale reactor (4,000 m^3) operated parallel to the existing continuous activated sludge reactors. The reactor has a treatment capacity of 12,000m^3/d and 40,000 inhabitants with a start-up in the summer of 2014. Although using only 9% of the total biological volume of the plant, the Nereda® technology will treat 25% of the total flow and will produce an effluent with a better quality.

During two months the air flows were compared. Taking into account the efficiency of the air blowers, specific electricity requirements were computed and savings of about 30% were calculated, with a specific average consumption of 0,35 kWh/kgCOD. Combined with savings regarding the fact that Nereda® does not need separate settlers, sludge recirculation and post-filtration, the potential savings on the plant are 50%.

DISCUSSION AND CONCLUSIONS

Like activated sludge a century ago, its innovative offspring aerobic granular biomass is a game-changer in the biological treatment arena and considered to become the new aerobic treatment standard. The last two decades, the Nereda® aerobic granular biomass technology has been developed, scaled-up and matured from laboratory, pilot and prototype into a dozen full scale applications. The data from these industrial and municipal applications demonstrate that biological nutrient removal in combination with high energy-efficiency and cost-effective plant construction are obtained.

The steadily growing number of international Nereda® applications and tank sizes close to the largest sequencing batch reactor tanks worldwide, mark that the innovation has matured into an applied technology that is now ready for implementation for even the largest-scale wastewater treatment applications.

The development of this innovative technology is a perfect role model for the delivery power of the golden triangle of private parties, government and knowledge institutes. And what is more, an exciting new development resulted from the Nereda® technology: the biopolymer alginate can be extracted from the Nereda® sludge. The possibility of recovering a valuable raw material from granular sludge contributes to the transformation of a wastewater treatment plant into a factory for raw materials and the development of a bio-based economy.

REFERENCES

Giesen, A., Niermans, R., Van Loosdrecht, M. (2012) Aerobic granular biomass: the new standard for domestic and industrial waste water treatment?, *Water21* April, 28-30

Inocêncio, P., Coelho, F., Van Loosdrecht, M. and Giesen, A. (2013) The future of sewage treatment: Nereda technology exceeds high expectations, *Water21* April, 28-29

De Kreuk, M.K. (2006) *Aerobic Granular Sludge - Scaling-up a new technology* [Dissertation], Delft University of Technology, The Netherlands, ISBN 90-9020767-8

De Kreuk, M.K., Kishida, N. and Van Loosdrecht, M.C.M. (2007) Aerobic granular sludge - state of the art. *Water Science and Technology*, 55(8-9), 75-81.

De Kreuk, M.K., ea. (2010). Behavior of polymeric substrates in an aerobic granular sludge system. *Water Research* **44**, 5929-5938

Lin Y, De Kreuk, M., Van Loosdrecht, M.C.M. and Adin, A. (2010) Characterization of alginate-like exopolysaccharides isolated from aerobic granular sludge in pilot-plant. *Water Research* **44**, 3355-3364

Morgenroth, E., Van Loosdrecht, M. C. M., ea. (1997) Aerobic granular sludge in a sequencing batch reactor, *Water Research* **31** (12), 3191-3194

Oosterhuis, M., Eekhof, M., Van Bentem, A., Van der Roest, H. (2015) Hybride Nereda: anderhalf jaar ervaring met verrassend resultaat, *H2O* **4**

Struan Robertson, S., Van der Roest, H., and Van Bentem A., (2015) Achieving sustainable wastewater treatment through innovation, *Water21* April, 39-41

Van der Roest, H., Van Loosdrecht, M., Langkamp, E., Uijterlinde, C. (2015) Recovery and reuse of alginate from granular Nereda sludge, *Water21* April, 48

Winkler, M.-K.H., ea. (2011). Selective sludge removal in a segregated aerobic granular biomass system as a strategy to control PAO-GAO competition at high temperatures. *Water Research* **45**, 3291-3299