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The limits and ultimate possibilities of technology of the activated sludge process

A. F. van Nieuwenhuijzen, A. G. N. van Bentem, A. Buunnen, B. A. Reitsma and C. A. Uijterlinde

ABSTRACT

The (low loaded) biological nutrient removing activated sludge process is the generally accepted and applied municipal wastewater treatment method in the Netherlands. The hydraulical and biological flexibility, robustness and cost efficiency of the process for advanced removal of nutrients like nitrogen and phosphorus without (too much) chemicals results in a wide application of the activated sludge process within Dutch waterboards.

Presumably, wastewater treatment plants will have to contribute to the improvement of the quality of the receiving surface waters by producing cleaner effluent. In this perspective, the Dutch research organisation STOWA initiated a research project entitled "The Boundaries of the Activated Sludge Process" to investigate the possibilities and limitations of activated sludge processes to improve the effluent quality.

It is concluded that the activated sludge process as applied and operated at WWTP's in the Netherlands has the potential to perform even better than the current effluent discharge standards (10 mg N_{total}/l and 1 mg Ptotal/l). Reaching the B-quality effluent (< 5mg N_{total}/l and < 0.3 mg P_{total}/l) will be possible at almost all WWTPs without major adjustments under the conditions that:

the sludge load is below 0.06 kg BOD/kg TSS.d

the internal recirculation is above 20

the BOD/N ratio of the influent is above 3.

Complying with the A-quality effluent (< 2.2 N_{total}/l and < 0.15 mg P_{total}/l) seems to be difficult (but not impossible) and requires more attention and insight into the activated sludge process. Optimisation measures to reach the A-quality effluent are more thorough and are mostly only achievable by additional construction works (addition of activated sludge volume, increasing recirculation capacity, etc.).

It is furthermore concluded that the static HSA-results are comparable to the dynamic ASM-results. So, for fast determinations of the limits of technology of different activated sludge processes static modelling seems to by sufficient.

Key words | activated sludge, advanced biological nutrient removal, limits of technology, nitrogen removal, phosphorus removal

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INTRODUCTION

The (low loaded) biological nutrient removing activated sludge process is the generally accepted and applied municipal wastewater treatment method in the Netherlands. The hydraulical and biological flexibility, robustness and cost efficiency of the process for advanced removal of nutrients like nitrogen and phosphorus without (too much) chemicals

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results in a wide application of the activated sludge process within Dutch waterboards (STOWA 2007).

Presumably, wastewater treatment plants will have to contribute to the improvement of the quality of the receiving surface waters by producing cleaner effluent. In this perspective, the Dutch research organisation STOWA initiated a research project entitled "The Boundaries of the Activated Sludge Process" to investigate the possibilities and limitations of activated sludge processes to improve the effluent quality (STOWA 2007).

The study aims to determine the limits of the activated sludge process technology and to define the technological possibilities and measures to improve effluent quality to be able to comply to possible future yearly average effluent requirements, like:

- B-quality: nitrogen = 5.0 mg N_{total}/l and phosphorus = 0.3 mg P_{total}/l;
- A-quality: nitrogen = 2.2 mg N_{total}/l and phosphorus = 0.15 mg P_{total}/l.

This concerns yearly average concentrations in feed-water and effluent baring in mind possible future seasonal average effluent discharge standards within the European Water Framework Directive.

METHODS

Statistic analysis

The research was conducted by a combination of practical investigations, statistical database analysis and modelling with a static and a dynamic activated sludge model.

Firstly, the performances of all 387 municipal waste-water treatment plants (WWTPs) operated by Dutch Waterboards in 2005 were analysed. Based on the performance investigation, the research focussed on trends and relationships between operational factors and effluent quality.

The available process configurations have been defined on forehand into four systems (IAWQ 1997; STOWA 2007; Takacs *et al.* 2007):

- aeration ditch type (entitled PhoSim in this report);
- aeration ditch type with pre-denitrification (entitled PhoRedox);
- the modified University of Cape Town Process (mUCT);
- the modified aeration ditch type with Bio-P in anaerobic zone and pre-denitrificication (entitled as the Hoogvliet type WWTP).

Model based calculations

Additionally, process operations and wastewater characteristics influencing the effluent quality were analysed by applying the activated sludge models: the static HSA-model (HochSchulGruppenAnsatz, IAWQ 1997; STOWA 2007) and the dynamic ASM (Activated Sludge Model, SIMBA, STOWA 2007) Both models were calibrated with practical data of WWTP Hoogvliet (Waterboard Hollandse Delta, see Figure 1).

Table 1 presents the average assumable composition of municipal WWTP-influent related to nitrogen and phosphorus distributions that were taken as basic influent distribution. These distributions are divided over bound and soluble fractions as well as on organic and inorganic fractions (Debarbadillo *et al.* 2007; Meltem *et al.* 2007; Neethling *et al.* 2007; Rosenwinkel *et al.* 2007).

With both calibrated models sensitivity analysis were carried out for MLSS concentration, influent BOD/N ratio, process temperature and the internal recirculation ratio. Additionally, both models were tested by simulating the two previously identified best performing process configurations (PhoSim and PhoRedox) and the prevailing modified University of Cape Town (UCT) process configuration.

RESULTS

Statistics

Anno 2006–2007 389 municipal WWTPs were in operation in the Netherlands (STOWA 2007). 58 WWTPs were found reaching a yearly average total nitrogen concentration lower than 5.0 mg/l, of which four were operated with primary sedimentation. Seven installations were found with a yearly average P_{total} concentration of 0.3 mg/l or lower, of which one applied with primary sedimentation (see frequency distributions in Tables 2 and 3).

Figure 1 | WWTP Hoogvliet (Waterschap Hollandse Delta). Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

Generally, it was found that more WWTP's than expected already produce a high quality effluent and possibly are able to perform even better. More than 50 WWTPs are capable of producing the B-quality standard for nitrogen ($N_{total} < 5.0$ mg/l). Concerning phosphorus 7 WWTPs produce the B-quality of $P_{total} < 0.3$ mg/l.

WWTPs that are complying for nitrogen and phosphorus to the B-quality effluent are rare. Only the WWTP's Leidsche Rijn, Barendrecht, Burgum and Zwaanshoek comply to this aim. WWTP Leidsche Rijn was identified to score the best with yearly average effluent composition of $N_{total} = 2.0$ mg/l and $P_{total} = 0.2$ mg/l; this is almost complying with the A-quality effluent (see Figures 2 and 3).

The following treatment configurations are predominantly present in the list of best performing WWTPs:

- PhoSim;
- PhoRedox;
- Hoogvliet type WWTP;
- mUCT.

Next to the top-3 WWTPs, 5 treatment plants with primary sedimentation tanks comply abundantly to the B-quality for nitrogen. These five plants perform very well for nitrogen and phosphorus removal even with comparable low BOD/N-ratios at fully loaded treatment capacities.

Based on the performance investigation, the research focussed on trends and relationships between operational

Table 1 | Assumable influent composition of nitrogen distribution and phosphorus distribution

Nitrogen fractions	Phosphorus fractions
$N_{total} = 4.0–10.0$ mg/l	$P_{total} = 0.3–2.0$ mg/l
	$P_{ortho} = 0.1–1.8$ mg/l
NH_4-N = 0.5–2.0 mg/l	$P_{organicsoluble} = 0.05–0.3$ mg/l
NO_3-N = 2.0–5.0 mg/l	$P_{organicbound} = 0.05–0.5$ mg/l
$N_{organicsoluble} = 0.5–1.5$ mg/l	
$N_{organicbound} = 0.5–1.5$ mg/l	

Table 2 | Frequency distribution of WWTP's based on effluent N_{total}

	N_{total} concentration (mg/l)	Number of rwzi's	% all WWTP's
Group 1	2–3	10	2.5
Group 2	3–4	21	5.4
Group 3	4–5	27	6.9
Total	<5	58	15

Table 3 | Frequency distribution of WWTP's based on effluent P_{total}

	P_{total} concentration (mg/l)	Number of WWTP's	% of all WWTP
Group 1	0.1–0.15	0	0
Group 2	0.15–0.2	3	0.8
Group 3	0.2–0.3	4	1.0
Total	<0.3	7	1.8

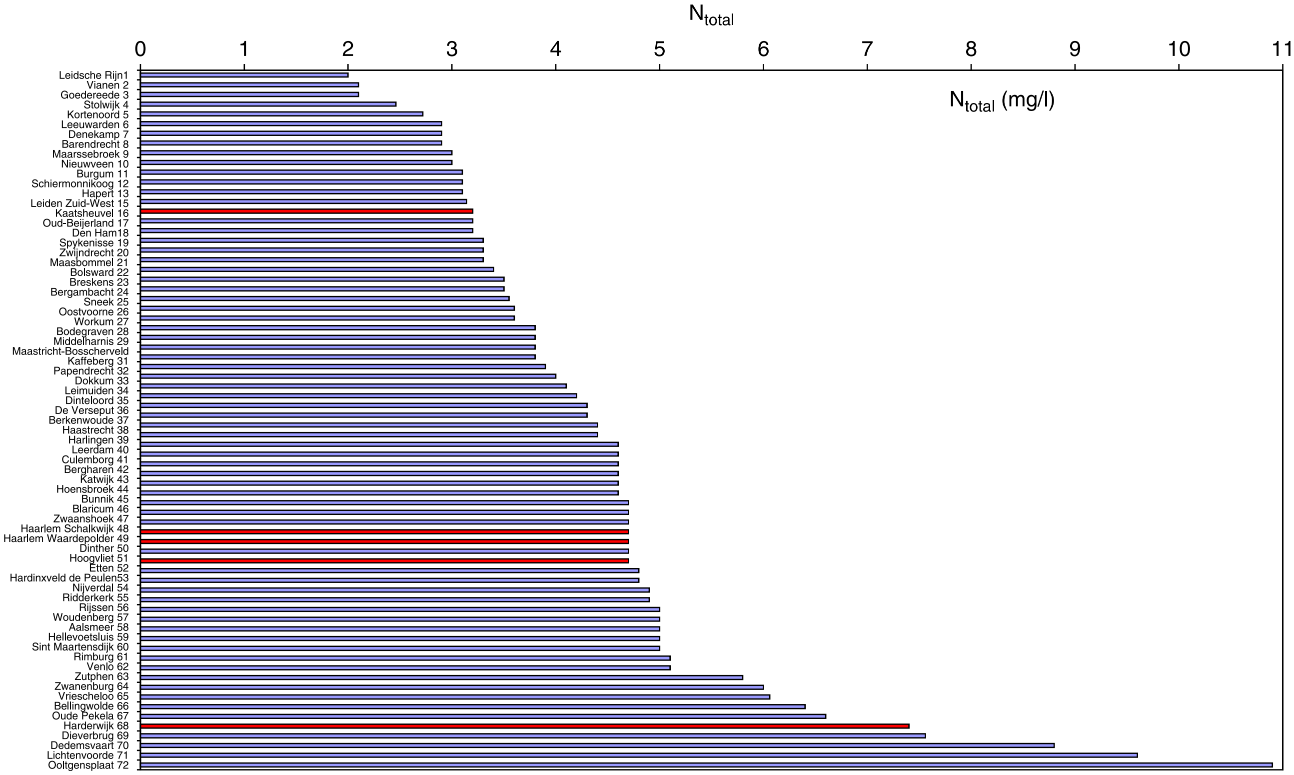

Figure 2 | Yearly average N_{total}-concentration in effluent of indentified WWTP's (year 2005). Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

factors and effluent quality. However, it seemed not possible to find proper relations and conclusions since the operational factors influence the effluent quality randomly and multi-regressional. Additionally, safety factors in design and operation compensate negative effects from the operational factors.

Modelling the limits of technology

The differences between the four tested process configuration, as modelled with the ASM(TUD) model in SIMBA, are presented in Table 4. It is concluded that primarily the internal recirculation ratio is predominantly influencing the effluent quality for nitrogen. Systems with relative low recirculation ratios (like the (m)UCT process) produce relative high total nitrogen concentrations in the effluent. The other modelled process configurations, all using high circulating oxidation ditches, perform equally. The differences for phosphorus removal efficiency are negligible, since the applied models only anticipate on biological P-removal without calculating a proper P-balance over the process configuration. The modified UCT process performs best since the internal recirculation into the anaerobic tank is fed by the oxygen and nitrate free return sludge stream from the (pre)denitrification zone instead of from an oxic nitrification zone.

The model calculations show that at very low N_{total} and P_{total} concentrations (soluble and particulate) organic bound fractions (of N and P) contribute substantially to the final achievable concentrations. The activated sludge process is not able to remove these organic fractions sufficiently. Additional tertiary treatment units like effluent filtration (rapid sand filtration or membrane filtration) or MBR-technology in combination with chemical precipitation may remove the organic fractions partially.

Related to the MLSS-concentration and the influent BOD/N-ration the results of the model based calculations are compared to the results of the statistical inventory (see Figures 4 and 5). From this comparison it seems that the model based results are an indication for the lower boundary or limit of the practical results. This is explainable

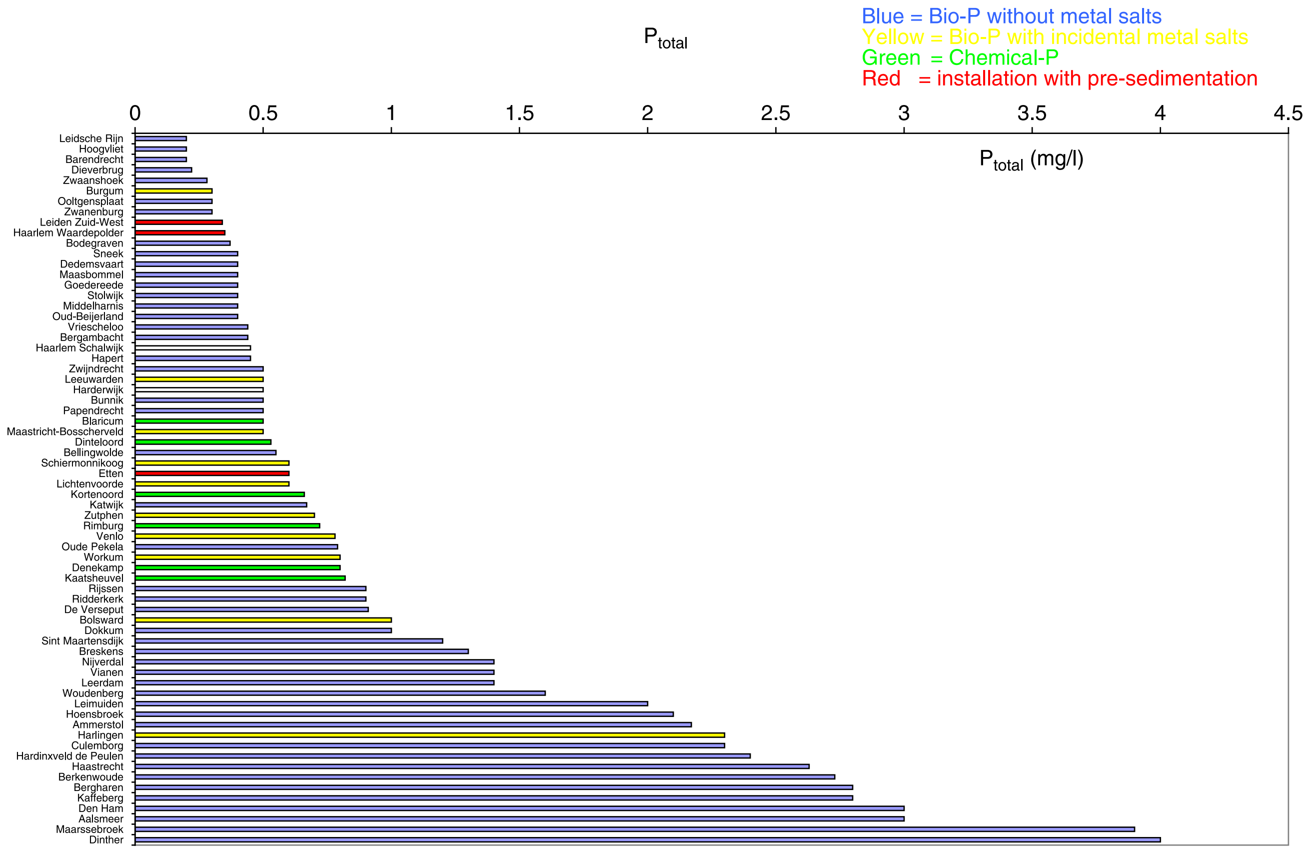

Figure 3 | Yearly average P_{total} concentration in effluent of identified WWTPs (year 2005). Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

since the models reflect the results of a advanced and optimised treatment process, where disturbing effects (as in practice occur) like for example large fluctuations in influent concentrations, temperature effects, non-optimal process configurations, and set points as well as technical malfunctioning of devices and machines do not occur. So the models predict the lower limit of the practical functioning of the activated sludge processes.

Table 4 | Overview of achievable effluent concentrations of different treatment configurations (based on results of ASM-modelling)

Parameter	Unit	Hoogvliet	PhoSim	PhoRedox	(m)UCT
NH_4-N	mg/l	1.0	1.0	1.0	1.0
NO_3-N	mg/l	1.1	0.6	0.9	1.9
$N_{organic}$	mg/l	1.2	1.2	1.2	1.2
$N_{kjeldahl}$	mg/l	2.2	2.2	2.2	2.2
N_{total}	mg/l	3.3	2.8	3.1	4.1
P_{ortho}	mg/l	0.02	0.03	0.02	0.01
P_{total}	mg/l	0.13	0.15	0.14	0.12

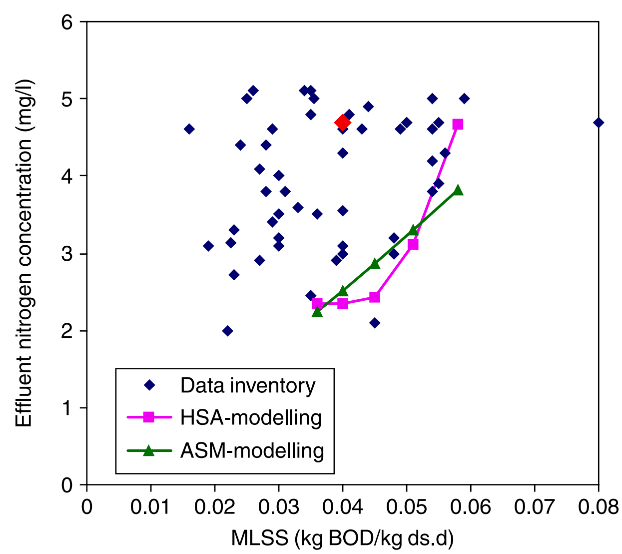

Figure 4 | Comparison of practical results (◇ = WWTP Hoogvliet) and model based results—MLSS-concentration. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

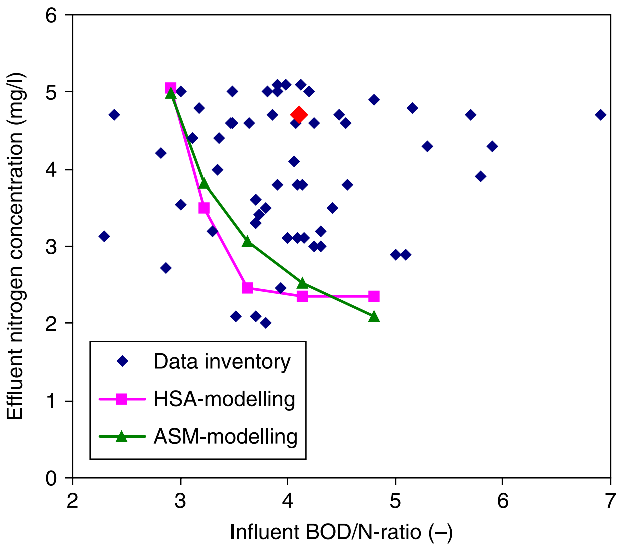

Figure 5 | Comparison of practical results and (◇ = WWTP Hoogvliet) and model based results—BOD/N-ratio. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

It is concluded that the activated sludge process as applied and operated at WWTPs in the Netherlands has the potential to perform even better than the current effluent discharge standards (10 mg N_{total}/l and 1 mg P_{total}/l). Reaching the B-quality effluent (<5 mg N_{total}/l and <0.3 mg P_{total}/l) will be possible at almost all WWTPs without major adjustments under the conditions that:

- the sludge load is below 0.06 kg BOD/kg TSS.d
- the internal recirculation is above 20
- the BOD/N ratio of the influent is above 3.

Another result is that the static HSA-results are comparable to the dynamic ASM-results. So, for fast determinations of the limits of technology of different activated sludge processes static modelling seems to be sufficient.

CONCLUSIONS

It is concluded that the activated sludge process as applied and operated at WWTPs in the Netherlands has the potential to perform even better than the current effluent discharge standards (10 mg N_{total}/l and 1 mg P_{total}/l). Reaching the B-quality effluent (<5 mg N_{total}/l and <0.3 mg P_{total}/l) will be possible at almost all WWTPs without major adjustments under the conditions that:

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Based on the investigation results an action list was prepared with which it is possible to improve the current effluent quality of an existing WWTP. The suggested actions in this list intend to create and maintain the ideal process conditions to improve the effluent quality (oxygen concentration, recirculation, sludge concentration, organic load). In practice the process conditions have to be monitored and controlled properly to be able to guarantee a high effluent quality over the year. To do this, adequate measurements and process control systems are required to monitor and steer the activated sludge process (pumps, recirculations, oxygen). The application and optimisation of the monitoring and process control strategy to be implemented at a specific WWTP is always a tailor made solution.

REFERENCES

Debarbadillo, J. B. & Rectanus, R. 2007 Focus On Total Inorganic Nitrogen: Operating Considerations At Plants Meeting Very Low Effluent Nitrogen Limits. Proceedings IWA WEF Conference Nutrient Removal 2007, Baltimore, USA.

GWRC 2005 Membrane Bioreactors for Municipal Wastewater treatment; State of Science Report. Global Water Research Coalition GWRC; STOWA/GWRC report 2005-24, Utrecht/ London.

IAWQ 1997 (ed, Ekama, G. A., et al.), *Report Secondary Settling Tanks: Theory, Modelling Design and Operation*, Richmond, UK.

Neethling, B. W., Harmon, D. & Benisch, M. 2007 Phased Nitrification-Denitrification Provides Flexible Nitrogen

Removal. Proceedings IWA WEF Conference Nutrient Removal 2007, Baltimore, USA.
Rosenwinkel, J. M. & Pabst, M. 2007 Experimental And Model-Based Evaluation Of The Maximum Allowable Flows In Activated Sludge Systems Under Storm Conditions. Proceedings IWA WEF Conference Nutrient Removal 2007, Baltimore, USA.
Smolders, G. J. F. 1995 A metabolic model of the biological phosphorus removal: Stoichiometry, kinetics and dynamic behaviour. Proefschrift TU Delft.
STOWA 2007 The Limits of the Activated Sludge Process–limits and possibilities (in Dutch). STOWA report 2007-24, ISBN 978.90.5773.373.4, Utrecht, The Netherlands.
Takács, M. O'shaugnessy, S. Murthy, K. Brian, N., Shirodkar, & Katehis, D. 2007 Design Of Denitrification Systems Using Methanol. Proceedings IWA WEF Conference Nutrient Removal 2007, Baltimore, USA.Urgun-Demirtas, M., Sattayatewa, C. & Pagilla, K.R. 2007 Bioavailability Of Dissolved Organic Nitrogen In Treated Effluents. Proceedings IWA WEF Conference Nutrient Removal 2007, Baltimore, USA.
Yu-Min Su, Jacek Makinia & Krishna R. Pagilla 2007 Estimation Of The Maximum Specific Growth Rate Constant For Autotrophs–Experience From The Longterm Operation Of A Lab-Scale SBR System. Proceedings IWA WEF Conference Nutrient Removal 2007, Baltimore, USA.