

Impact of separate urine collection on wastewater treatment systems

J. Wilsenach and M. van Loosdrecht

Department of Biochemical Engineering, Delft University of technology, Julianalaan 67, 2628 BC, The Netherlands (E-mail: J.A.Wilsenach@tnw.tudelft.nl)

Abstract Wastewater treatment should not only be concerned with urban hygiene and environmental protection, but development of a sustainable society must also be considered. This implies a minimisation of the energy demand and potential recovery of finite minerals. Urine contains 80% of the nitrogen (N) and 45% of the phosphorus (P) in wastewater. Separate collection and treatment would improve effluent quality and save energy in centralised biological nutrient removal (BNR). BNR processes are not optimal to treat water with very low N concentration resulting from separate urine collection. Relying on nutrient removal through sludge production, methanation of the sludge, subsequent nutrient removal from the digestion effluent results in optimised and more sustainable wastewater treatment. This paper quantitatively evaluates this option and discusses the potential.

Keywords Energy; nutrients; Sharon/Anammox; struvite; urine; wastewater

Introduction

Wastewater treatment has slowly changed over the last century from a system for prevention of diseases in urban society towards a system for protecting the natural environment. In recent years, society started to demand that technical systems contribute to the “sustainability” of the same society. Although “sustainability” can not be quantified easily, it is generally accepted that recovery of resources from waste contributes to an increased sustainability.

Nutrients (ammonium and phosphate) and organic carbon can potentially be recovered from municipal wastewater. However, the dilute nature of wastewater makes recovery economically and energetically expensive. Several studies have shown that up to 80% of the total N load and around 45% of the total P load in municipal wastewater originate from urine (Larsen and Gujer, 1996; Hanæus *et al.*, 1997). Experience from ecological villages in Sweden showed that separate urine collection can be done efficiently (Hanæus *et al.*, 1997; Jönsson *et al.*, 1997). Separate urine collection largely improves the potential for nutrient recovery, because the concentrations of N and P are a hundred times higher than in wastewater. On the other hand, in e.g. The Netherlands, the nutrients in human waste amount to less than 20% of the amount in animal manure. From a societal point of view, nutrient recovery from animal manure should get prime attention, because manure can be collected more easily and can be treated locally on a large scale.

The importance of urine separation is recognised but the effect on central treatment processes has not yet been quantified. Separate urine collection would not be worthwhile if it only had a marginal impact on central wastewater treatment systems. Improvement of the overall wastewater management system should be a stronger driving force than nutrient recovery alone. If it can be shown that advanced treatment processes would benefit from separate urine collection, then wastewater treatment in general would benefit from urine separation. Most advanced wastewater treatment works operate according to variants of the modified UCT process. For this study we chose the BCFS[®] process (Biological/Chemical Phosphorus and Nitrogen removal) as a conventional reference process. The treatment

plant at Hardenberg in The Netherlands is taken as an example, because a calibrated model was available (Meijer *et al.*, 2001). The system as such is already fully optimised for biological N and P removal and produces good effluent quality (current annual average: $3.5 \text{ gN}_{\text{tot}}/\text{m}^3$, $0.5 \text{ gNH}_4\text{-N}/\text{m}^3$, $0.15 \text{ gP}/\text{m}^3$).

The N content of bacteria is between 9% and 12% and the P content is between 1% and 3% of the volatile suspended solids (Ekama and Marais, 1984). This means that for wastewater with an influent COD:N:P ratio of approximately 100:5:1 almost all the N and P will be used for cell growth (with the yield factor $Y_H = 0.63 \text{ gCOD/gCOD}$). If urine were collected separately, the influent nutrient load could then be reduced to match this cell growth requirement. The N and P normally removed through nitrification/denitrification and dephosphatation, e.g. in a BCFS[®] process, could then be removed by collecting a large percentage of urine separately. The N and P remaining in the influent could be removed through waste activated sludge production at short solid retention times. A major decrease in the influent N and P load would allow for simple treatment processes that will not be effective if all urine remains diluted in wastewater. This paper evaluates quantitatively the advantages of separate urine collection for the design, operation and sustainability aspects of a centralised wastewater treatment system. Hereto we made use of sub-systems already applied at large scale.

Methodology

Influent characteristics

Average Dutch influent flow rates and concentrations were used for this study (CBS, 2000; STOWA, 2002). Influent concentrations for chemical oxygen demand, total nitrogen, ammonium and total phosphorus were $\text{COD}_{\text{tot}} = 537 \text{ gCOD}/\text{m}^3$, $\text{N}_{\text{tot}} = 50 \text{ gN}/\text{m}^3$, $\text{NH}_4^+ = 40 \text{ gN}/\text{m}^3$ and $\text{P}_{\text{tot}} = 8 \text{ gP}_{\text{tot}}/\text{m}^3$. The COD, N and P fractions in influent wastewater were divided into different model components, similar to Hao *et al.* (2001). The current wastewater influent at Hardenberg (8,500 m^3/d) is still less than the design flow rate. At the current flow rate, the total N effluent concentration is much lower than the effluent standard of $10 \text{ gN}/\text{m}^3$. The flow rate was maximised to the extent that the system just complied with the effluent demand and was determined by iteration to be $13,500 \text{ m}^3/\text{d}$. Effects of changing influent nutrient loads were compared to this reference (zero scenario).

Modelling urine separation

Urine contributes only a small volume to the total wastewater volume. However, the water currently used to flush urine is a significant fraction of the total. Urine flush water was assumed to be 35 l/p.d (Jönsson *et al.*, 1997). Therefore, if 100% urine separation could be achieved, wastewater discharge to the treatment works could be reduced by 36.25 l/p.d (including 1.25 l/p.d urine). Modern source separation toilets use a small amount of flush water. The production of urine (including flush water) was assumed 2 l/p.d.

From the influent nitrogen concentration, $40 \text{ gN}/\text{m}^3$ can be attributed to urine. Nitrogen in urine is mainly present as urea, $\text{CO}(\text{NH}_2)_2$. This soluble compound rapidly hydrolyses to NH_4^+ and HCO_3^- . The N-load contributed by urine was assumed to consist of soluble ammonium (S_{NH4}) only (Helström *et al.*, 1999 and Hellström and Johansson, 1999). At 100% urine separation, the total N influent concentration would drop from $50 \text{ gN}/\text{m}^3$ to $11.4 \text{ gN}/\text{m}^3$ (including the effect of the decreased flow rate). The ammonium concentration at different urine separation efficiencies was determined according to Eq. (1):

$$\text{NH}_{4_25} = (\text{NH}_{4_00} \times V_{00} - 0.25 \times \text{NH}_{4_urine} \times I) / V_{25} \quad (1)$$

Where, NH_{4_25} = ammonium concentration in wastewater with 25% urine collected

separately (gN/m^3), NH_{4_00} = ammonium concentration in wastewater without urine separation (gN/m^3), V_{00} = wastewater flow rate without urine separation (m^3), NH_{4_urine} = ammonium load in urine (12 gN/p.d), I = number of individuals connected to treatment plant (45,000, at flow rate = 13,500 m^3/d) and V_{25} = wastewater flow rate with 25% urine collected separately.

The phosphorus and COD concentration due to separate urine collection was determined in the same way. The inflow concentration of P_{tot} was 8 gP/m^3 in wastewater without urine separation. The phosphorus load from urine was assumed 1 gP/p.d . At 100% urine separation, the total influent phosphorus concentration would then be 5.3 gP/m^3 . Separate urine collection will lead to a small decrease in the COD load discharged to wastewater treatment works (12 gCOD/p.d @ 100% urine separation).

Modelling the BCFS® process

Hao *et al.* (2001) modelled the BCFS® process at Hardenberg. We used the computer software package AQUASIM 2.0 (Reichert, 1998) to implement the dynamic simulation of the BCFS® process model, which is schematically represented in Figure 1.

The total volume of the five compartments is 10,000 m^3 . A secondary settling tank (2,800 m^3) is downstream of the final aeration basin. Mixed liquor is returned to different reactors and the settled sludge return rate was equal to the inflow. Waste activated sludge was withdrawn from the clarifier’s sludge compartment. In all simulations of the BCFS® process the total suspended solids concentration (TSS) was kept constant at 5,000 g/m^3 . In practice, solids retention time (SRT) controls the TSS. In the simulations a TSS equal to 5,000 g/m^3 was maintained by adjusting the SRT. The sludge volume index of existing BCFS® processes is below 120 ml/g . It was assumed that the sludge will separate and settle well in the secondary settling tank. A conservative temperature, common for the colder half of the year in north-west Europe, of 12°C was used for all simulations.

Treatment optimisation and model integration

A second set of simulations was done to evaluate a proposed system for treatment of separately collected urine and wastewater. Figure 2 presents a flow diagram for the integration of existing processes. Effluent concentrations and removal efficiencies for different process units were based on literature information. The aerobic reactor was simulated as described above. The sum of influent wastewater (Q_1), the pre-thickener overflow (Q_4) and effluent from the Sharon/Anammox process (Q_{10}) gives the influent flow rate and concentrations (Q_3) as shown in Figure 2. The aerobic reactor had a volume of 1000 m^3 (hydraulic retention time of two hours). The volume of the clarifier’s sludge compartment was assumed 10% of the volume of the aerobic reactor.

Based on the substrate ratio required for bacterial growth (COD:N:P = 100:5:1) it is clear that nutrients are present in excess of the requirement; $N_{\text{exc}} = 24 \text{ g/m}^3$ and $P_{\text{exc}} = 1.5 \text{ g/m}^3$. According to these figures, nutrients remaining in wastewater after 60% urine

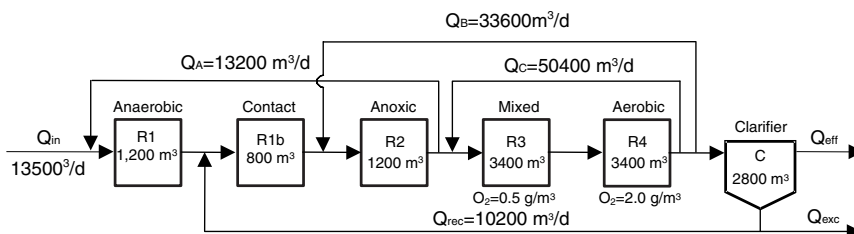


Figure 1 Schematic process diagram of the Hardenberg wastewater treatment works

separation could be removed with waste sludge. Waste sludge should be gravity thickened ($TSS = 25 \text{ kg/m}^3$, Tchobanoglous, 1991) before entering anaerobic digestion (Q_5). We assumed that 100% of slowly biodegradable COD (X_{S}) and 90% of the COD of bio-mass (X_{H} and X_{I}) can be transformed into bio-gas (Q_{12}). The $CH_4:CO_2$ ratio was assumed 65:35 for this study (Malina and Pohland, 1992). Digested sludge (Q_6) can be thickened (80 kg/m^3) and dewatered (200 kg/m^3) before incineration. Supernatant and centrate (Q_7) are mixed with the separately collected urine stream. The COD concentration in anaerobic digester supernatant is normally around $1,200 \text{ g/m}^3$ (Stowa, 2000, 25). It could be assumed that no gaseous nitrogen escapes the digester and that at steady state, all nitrogen entering the digester leaves as either NH_4^+ , or nitrogen in dewatered sludge (Q_{13}).

Struvite ($MgNH_4PO_4 \cdot 6H_2O$) precipitates naturally in urine or in anaerobic sludge digesters and downstream piping. Relatively low phosphate concentrations can be expected from anaerobic digester supernatant; $P_{tot} = 50 \text{ g/m}^3$. In this case, supernatant and filtrate is combined with urine; $P_{tot} = 800 \text{ gP/m}^3$. Addition of MgO would increase pH sufficiently to precipitate struvite from the combined stream (Q_8) and yield a constant effluent concentration of 18 gP/m^3 (Schuiling, 1999). Recovered struvite could be used as fertiliser (Q_{15}).

The mixture of urine ($9,000 \text{ gNH}_4^+ \text{-N/m}^3$) and supernatant ($1,200 \text{ gNH}_4^+ \text{-N/m}^3$) leaving the struvite crystalliser (Q_9) would still contain around $2,400 \text{ gNH}_4^+ \text{-N/m}^3$. Recent development of the Sharon/Anammox technology made removal of highly concentrated NH_4^+ from wastewater more sustainable. Up to 95% of the influent ammonium is removed as nitrogen gas (Q_{14}) and only 5% of the influent total nitrogen leaves the combined process (STOWA, 2000–25). The effluent from these processes would be returned to the aerobic reactor (Q_{10}). A combination of computer simulation and mass balance calculations was used to evaluate the performance of this integrated process.

Assessment of energy demand

The energy consumption of integrated separate urine and wastewater treatment was evaluated. The energy consumption of a BCFS[®] process without urine separation or pre-settling was used as a reference. Energy consumption of the two processes was determined theoret-

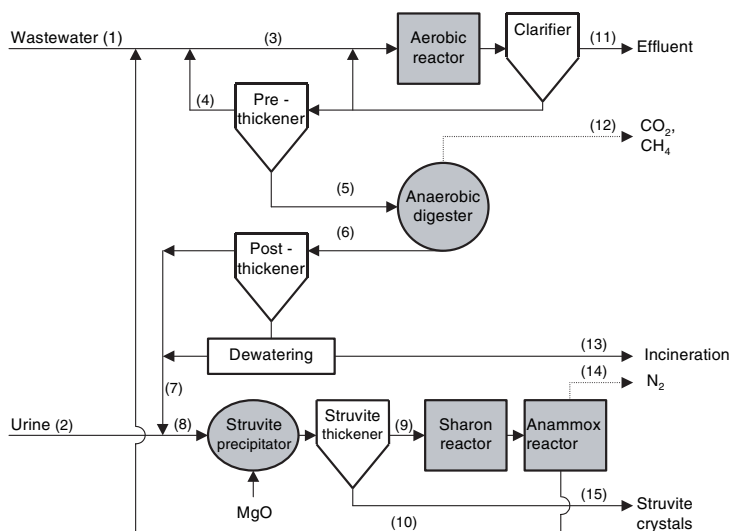


Figure 2 Proposed process flow diagram to treat wastewater and urine separately (Flow numbers refer to subscripts in the text, Q_1, Q_2, Q_3 , etc.)

ically, based on aeration (E_{aer}), sludge dewatering (E_{dew}), sludge incineration (E_{inci}), pumping (E_{pump}), mixing of tank reactors (E_{mix}) and methane gas (E_{CH_4}) produced by the anaerobic sludge digestion. The total net energy requirement (E_{net}) can be expressed as:

$$E_{net} = E_{aer} + E_{dew} + E_{inci} + E_{pump} + E_{mix} + E_{heat} - E_{CH_4} \quad (2)$$

The total oxygen requirement is the sum of oxygen required for sludge production in the aerobic reactor and the oxygen required in the Sharon process. The oxygen requirement for the aerobic reactor was simulated with a full activated sludge model in AQUASIM. Oxygen requirement for the Sharon process was based on the stoichiometric ratio, 1.82 g O_2/gNH_4-N influent (STOWA, 2000).

The calculation of energy involved in incineration, dewatering and methane combustion was described by van Loosdrecht *et al.* (1997). Energy required for pumping and mixing is usually neglected in estimations. The total recirculation flow of the BCFS[®] process is almost tenfold the simple aerobic reactor and becomes significant when processes are compared. Pump rates were based on average daily flows. The mixing of anaerobic and anoxic compartments in the BCFS[®] process has to be compared to mixing in the struvite precipitator and Sharon/Anammox reactor. Furthermore, the anaerobic digester requires a considerable amount of mixing. The power requirement of mixing was based on an average figure of 10 W/m³ mixed volume (Grady and Lim, 1980).

Results and discussion

Effect of urine separation on nutrient removal in a BCFS process

The effects of separate urine collection on an existing BCFS process with raw wastewater were simulated. The main results are shown in Figure 3.

Due to a decrease in the number of autotrophic bacteria (nitrifiers), effluent ammonium concentration ($NH_4^+_{eff}$) increases slightly with increasing urine separation. Effluent nitrate concentration ($NO_{3,eff}$) decreases with increasing urine separation. The COD/TKN ratio increases with increasing urine separation and therefore the denitrification potential increases. Less nitrate is produced (less ammonium oxidation) while the capacity to reduce nitrate increases. While $NO_{3,eff}$ decreases non-linearly, the amount of nitrogen gas produced decreases linearly with increasing urine separation. Total N in the effluent ($N_{tot,eff}$) is the sum of ammonium, nitrate and nitrogen contained in suspended solids (not settled in the clarifier). The model predicts $N_{tot,eff} = 3.2 \text{ g/m}^3$ at 50% urine separation, which is the current effluent concentration at Hardenberg, at influent flow rate of 8,500 m³/d compared

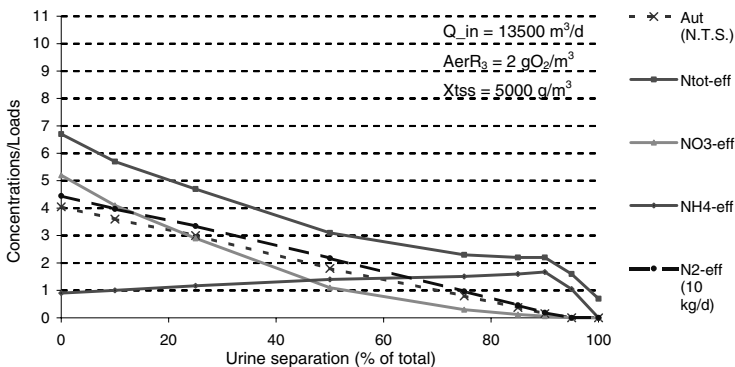


Figure 3 Effects of urine separation on N removal in advanced UCT-type (Figure 1) wastewater treatment processes

to 13,500 m³/d in the model simulations. The N removal capacity of a BCFS process can be increased by 60% with 50% urine separation. One observes a substantial decrease in N_{tot_eff} with urine separation up to 50%. The decrease is less obvious above 50% urine separation.

Virtually all phosphate had already been removed in the case of zero urine separation and urine separation therefore had little effect on the P-removal efficiency.

Effect of urine separation on nutrient removal through increased sludge production

In the second set of simulations, the effect of urine separation on nutrient removal through sludge production was evaluated. Hereto a short SRT is preferable. At too high sludge withdrawal rates (short SRTs), sludge growth rate limits the process. The relation between SRT and sludge production in an aerobic zone integrated with other processes (Figure 2), with 75% of urine collected separately, is shown in Figure 4(a). The figure shows a drastic increase in effluent nutrient concentrations (little sludge produced, but much COD in effluent) at SRT < 0.5 days. The oxygen consumption is also an indication of the sludge activity at low SRT. Higher SRT and resulting lower waste sludge removal results in higher effluent nutrient concentrations. The optimum SRT is around one day. Nitrification starts at SRT ≅ 5 d for a temperature of 12°C.

Temperature of wastewater also determines the growth rate of bacteria and sludge formation. Figure 4(b) shows that the effluent concentrations of N and phosphorus vary relatively little because of changing temperature. Temperature variations are not too important at SRT = 0.8 d. The figure also shows that working with 12°C gives a conservative estimate of the sludge production and related nutrient removal.

Figure 5 illustrates the effect of increased urine separation efficiency. This leads to a lower nutrient load in the final effluent (Q₁₁, Figure 2). Higher urine separation also results in more nitrogen gas (Q₁₄, Figure 2) and struvite production (Q₁₅, Figure 2). However, at urine separation efficiencies > 75%, the unavailability of ammonium limits sludge production, as can be seen from the increased COD load in the effluent. Limiting sludge production also leads to higher effluent N_{tot} and P_{tot} concentrations.

Energy balance

Table 1 gives a brief summary of energy requirements for different scenarios. The total energy requirement of separate urine and wastewater treatment is shown for urine separation efficiencies of 50%, 65%, 75% and 85%. The energy demand of the reference system is also shown.

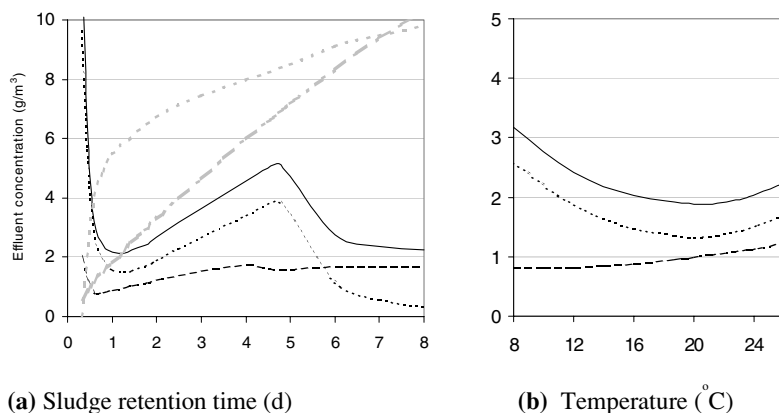


Figure 4 Effects of (a) Sludge retention time, with T = 12°C, and (b) Temperature, with SRT = 0.8 d, on nutrient removal at 75% urine separation N_{tot} — NH₄ - - - P_{tot} - - - X_{TSS} (1:2500) —·—·— O_{2_net} (1:20) ·····

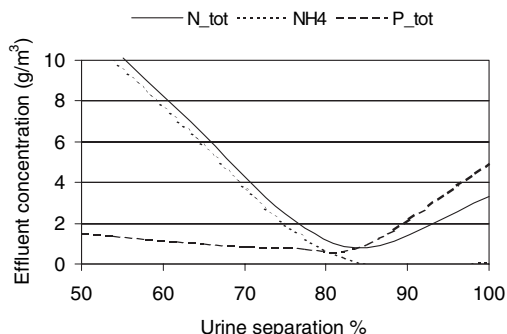


Figure 5 Effluent concentrations as a function of urine separation efficiencies for the flow scheme of Figure 2, with $T = 12^{\circ}\text{C}$ and $\text{SRT} = 0.8 \text{ d}$

Table 1 Summary of energy requirements for urine separation system and reference systems. (Negative number for total energy indicate net production)

Urine separation	0	50	65	75	85	%
Digested sludge mass	2,111	1,917	1,888	1,881	1,760	kg/d
Urine mass	0	45,000	58,500	67,500	76,500	kg/d
Total energy	15,302	-6,204	-5,671	-5,467	-4,666	MJ/d
	6.25	-1.60	-1.46	-1.41	-1.20	W/pers

The energy requirement for sludge handling (in the integrated processes) is still less than the reference system (where less of the produced sludge is transformed to methane, due to a higher sludge age and lower degradable fraction). The amount of energy generated via methane combustion in the integrated processes is more than three times the potential of the reference system. The energy requirement for aeration in the reference system is four times as high as the combined energy requirement for aeration of urine and activated sludge production. The model shows that a net energy production is possible with separate treatment of urine and wastewater. The continuous power demand for treatment of normal wastewater (including dilute urine) in the reference process is around 6 W/p. The potential net power generation (resulting from methane combustion and low aeration) is more than 1 W/p.

Conclusions

1. Advanced biological nutrient removal processes would benefit from separate collection and treatment of urine. Total nitrogen effluent concentrations could be reduced from 7.5–2.5 gN/m^3 at around 60% urine separation. Separation efficiencies over 60% show little further improvement, because the process is not optimal for low ammonium influent concentrations.
2. Existing processes can be integrated and optimised to treat urine and wastewater on central scale, with more than 60–70% urine separation. Effluent with very low ammonium, nitrate and phosphate concentrations can be produced (all less than 1 g/m^3).
3. The actual nutrient content of particulate influent COD and nutrient content of sludge strongly influence the nutrient removal efficiency. Default values of N and P content in sludge suggest that complete nutrient removal is possible with 75% urine separation.
4. Urine separation decreases the energy requirement for wastewater treatment radically. Where advanced BNR processes require around 6 W/p, an integrated process to treat urine and wastewater separately could produce more than 1 W/p. The energy available for separate collection and transport of urine may therefore not exceed 7 W/p.

References

- Ekama, G.A. and Marais, G.v.R. (1984). *Theory, design and operation of nutrient removal activated sludge processes*, South-African Water Research Commission report.
- Grady, C.P.L. and Lim, H.C. (1980). *Biological Wastewater Treatment – Theory and Applications*, Marcel Dekker Inc. ISBN 0-8247-1000-2.
- Hanæus, J., Hellström, D. and Johansson, E. (1997). A study of a urine separation system in an ecological village in northern Sweden, *Water Science and Technology*, **35**(9), 153–160.
- Hao, X. Heijnen, J.J., Qian, Y. and van Loosdrecht, M.C.M. (2001). Contribution of P-bacteria in BNR processes to overall effects on the environment, *Water Science and Technology*, **44**(1), 67–76.
- Hellström, D. and Johansson, E. (1999). Swedish experience with urine separating systems, *Wasser & Boden*, **51**(12), 26–29.
- Hellström, D., Johansson, E. and Grennberg, K. (1999). Storage of human urine: acidification as a method to inhibit decomposition of urea, *Ecological Engineering*, **12**, 253–269.
- Jönsson, H., Stenström, T.-A., Svensson, J. and Sundin, A. (1997). Source separated urine-nutrient and heavy metal content, water savings and faecal contamination, *Water Science and Technology*, **35**(9), 145–152.
- Larsen, T.A. and Gujer, W. (1996). Separate management of anthropogenic nutrient solutions (human urine), *Water Science and Technology*, **34**(3–4), 87–94.
- Malina, J.F. and Pohland, F.G. (1992). Design of anaerobic processes for the treatment of industrial and municipal wastes, *Water Quality Management Library*, Volume 7, Technomic Publishing Company Inc.
- Meijer, S.C.F., van Loosdrecht, M.C.M. and Heijnen, J.J. (2001). Metabolic modelling of a full-scale enhanced biological phosphorus removing WWTP, *Water Research*, **35**(11), 2711–2723.
- Reichert, P. (1998). AQUASIM 2.0 – *Computer Program for the Identification and Simulation of Aquatic Systems*, EAWAG, ISBN 3 906484-16-5.
- STOWA (2000). *Het gecombineerde Sharon/Anammoxproces: Een duurzame methode voor N-verwijdering uit slibgistingwater*, STOWA report 2000–25.
- Van Loosdrecht, M.C.M., Kuba, T., Van Veldhuizen, H.M., Brandse, F.A. and Heijnen, J.J. (1997). Environmental impacts of nutrient removal processes: Case study, *Journal of Environmental Engineering*, **123**(1), 33–40.