How does greywater separation impact the operation of conventional wastewater treatment plants?

Carlo Morandi and Heidrun Steinmetz

ABSTRACT

Source separation has thus far been addressed mainly within the context of decentralization in new development areas; centralized approaches for resource-oriented sanitation remained, however, largely disregarded. By means of inhabitant-specific load and volume flow balances, based on typical reference values for municipal wastewater in Germany, a stepwise transition towards on-site greywater recycling was investigated for a model wastewater treatment plant (WWTP). Up to 17% transition (separation of greywater from 17% of the total inhabitants), greywater separation was proven to benefit plant operation by reducing energy consumption for aeration. From 17% transition onwards, however, unfavorable carbon to nitrogen ratios (C/N) were reported, as less biodegradable carbon reaches denitrification, thus shifting C/N ratios negatively. Therefore, nitrogen recovery/removal from N-rich sludge sidestreams would be required. At 35% transition, a 50% N recovery from sludge liquor was proven to be sufficient in order to ensure full denitrification; combined with greywater separation, nutrient recovery yielded 14% reduction in power demand for aeration (on the actual state). Additionally, extensive mainstream process changeovers could be avoided by separating N-rich urine alongside greywater from the main wastewater stream. Urine separation was proven to maintain denitrification stability as well as reduce power demand for aeration. The calculations show that, under consideration of specific boundary conditions, existing WWTP can be successfully integrated in transition concepts for resource-oriented sanitation.

Key words | greywater recycling, mass and volume flow balances, nutrient recovery, transition, urine separation, wastewater treatment plant

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INTRODUCTION

Among water and wastewater infrastructures, municipal wastewater treatment plants (WWTP) account for most of the total environmental impact (Slagstad & Brattebø 2013), as the wastewater treatment sector consumes large amounts of energy (e.g. pumping, aeration) and materials (e.g. metal salts, polymers) to remove carbon (C), nitrogen (N) and phosphorus (P) and so on as well as to comply with discharge standards (Mo & Zhang 2013; Tchobanoglous *et al.* 2014). In fact, the amounts of total N and P in municipal wastewater are typically much higher than required for cell synthesis of the bacteria in activated sludge; only around 20% of the influent nutrient loads are eliminated through excess sludge removal (Henze *et al.* 2008). Moreover, municipal wastewater has thus far been regarded as a residue/energy sink rather than a source for water, nutrients and energy (Nowak *et al.* 2015). Indeed, domestic wastewater streams differ significantly with respect to composition and volume flows, so fractionating domestic wastewater, for example into greywater, brownwater and urine, can significantly improve treatment and generate added value through energy production, recycling of nutrients and/or water reclamation (Frijns *et al.* 2013; Zeeman & Kujawa-Roeleveld 2013). Eventually, source separation could extensively contribute to closing energy, nutrient and water cycles (DWA 2016; Skambraks *et al.* 2017).

Source separation of wastewater and utilization of the resources contained therein are an essential prerequisite for

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sustainable long-term wastewater treatment. On-site greywater recycling can help to cope with high water consumption patterns and water scarcity worldwide. Greywater generally accounts for approximately 40% of the total chemical oxygen demand (COD) and approximately 70% of the total volume flow in domestic wastewater, but only 8% of all N (DWA 2016). However, scientific literature also indicates wide fluctuation ranges for greywater (e.g. Gross *et al.* 2015); this can be further aggravated by cross-contaminations between greywater and blackwater collection systems, particularly in developing countries (see Tolksdorf & Cornel 2017). It is still, however, necessary to assess the impacts of greywater separation (from the main wastewater stream) upon the operation of existing WWTP. Some previous studies have investigated urine and blackwater separation from the main wastewater stream and how this affects conventional WWTP. Larsen *et al.* (2009) reported that urine separation could significantly reduce nutrient loads to WWTP, as urine contains approximately 80% of all N and 40 to 50% of the total P in municipal wastewater, thus reducing treatment requirements at the plant. The combined treatment of urine and sludge liquor (e.g. Wilsenach & van Loosdrecht 2006) has also been previously suggested, as has blackwater co-digestion in municipal WWTP (see Gottardo Morandi *et al.* 2018). Larsen *et al.* (2009) reported that separating urine from the main wastewater stream allows an easier nutrient recovery by using technologies such as struvite precipitation. To what extent greywater separation impacts the operation of conventional WWTP is still unclear. Additionally, on the premise that most WWTP have long service lives and many will probably still function to a satisfactory extent in the mid-term, it is imperative to integrate conventional wastewater infrastructures in transition concepts for resource-oriented sanitation, so that synergistic effects can be achieved both at the WWTP and on site. To the best of the authors' knowledge, the integration of existing WWTP in transition concepts for resource-oriented sanitation as well as the impacts of source separation upon WWTP have thus far not been widely described or well investigated in the scientific community. Indeed, many studies have thus far addressed concepts and technologies for source separation of wastewater (Larsen *et al.* 2013; Lema & Suarez Martinez 2017), particularly greywater recycling (Boyjoo *et al.* 2013; Ghaitidak & Yadav 2013) and urine treatment (Maurer *et al.* 2006; Ronteltap *et al.* 2007; Udert & Wächter 2012). Moreover, pilot projects with source separation have been implemented in Europe (Nowak *et al.* 2015) and elsewhere, however most notably – and almost exclusively – within the context of new development areas.

On the premise that transition of existing centralized WWTP to sustainable urban water systems is only possible by closing water, energy and material flows, the present study elaborates on possible operating shortcomings at the plant. These may be triggered by the partial separation of greywater from the main wastewater stream. In areas with existing wastewater infrastructures, transition states would arise, during which a safe operation of WWTP undergoing transition would have to be ensured. The present study also weighs the pros and cons of urine and/or blackwater segregation – alongside greywater separation – upon the operation of conventional WWTP. Different scenarios were assessed and discussed, while correcting measures were proposed. Furthermore, under the assumed specific boundary conditions for a model WWTP, energy utilization, biogas production and nutrient recovery potentials were correspondingly quantified. A simplified mass-flow based algorithm, first introduced in Gottardo Morandi *et al.* (2018) – a previous study from the same research group – was adopted for this paper and further adapted for greywater separation in order to assess critical transition states as well as probable impacts upon plant operation.

METHODS

The present study investigates the stepwise transition towards on-site greywater recycling of a model activated sludge WWTP that operates an upstream denitrification, simultaneous chemical phosphorus elimination and anaerobic sludge stabilization, typical for industrialized countries such as Germany, Denmark and so on and, to a lesser extent, the USA, UK, Australia, etc. (Edwards *et al.* 2015). The model WWTP, depicted in Figure 1, was generated by means of an Excel-based algorithm that comprises iterative calculations for load and flow rate balances. The algorithm was developed by the authors of the present study and first introduced in Gottardo Morandi *et al.* (2018) with the original aim of investigating blackwater co-digestion in WWTP digesters. In Figure 1, inhabitant-specific COD, total nitrogen (N_{tot}) and total phosphorus (P_{tot}) loads and flow rates are shown for the actual state of the model WWTP. Bar heights provide different scales for different parameters, whereas absolute values allow any quantitative analysis. The 85th percentile values used are characteristic for Germany. Table 1 gives assumptions and calculations for the mass and volume flow balances, which precisely define the boundary conditions assumed in this study and allow a more comprehensive understanding of the balances shown in Figure 1 as well as the relationships among the different

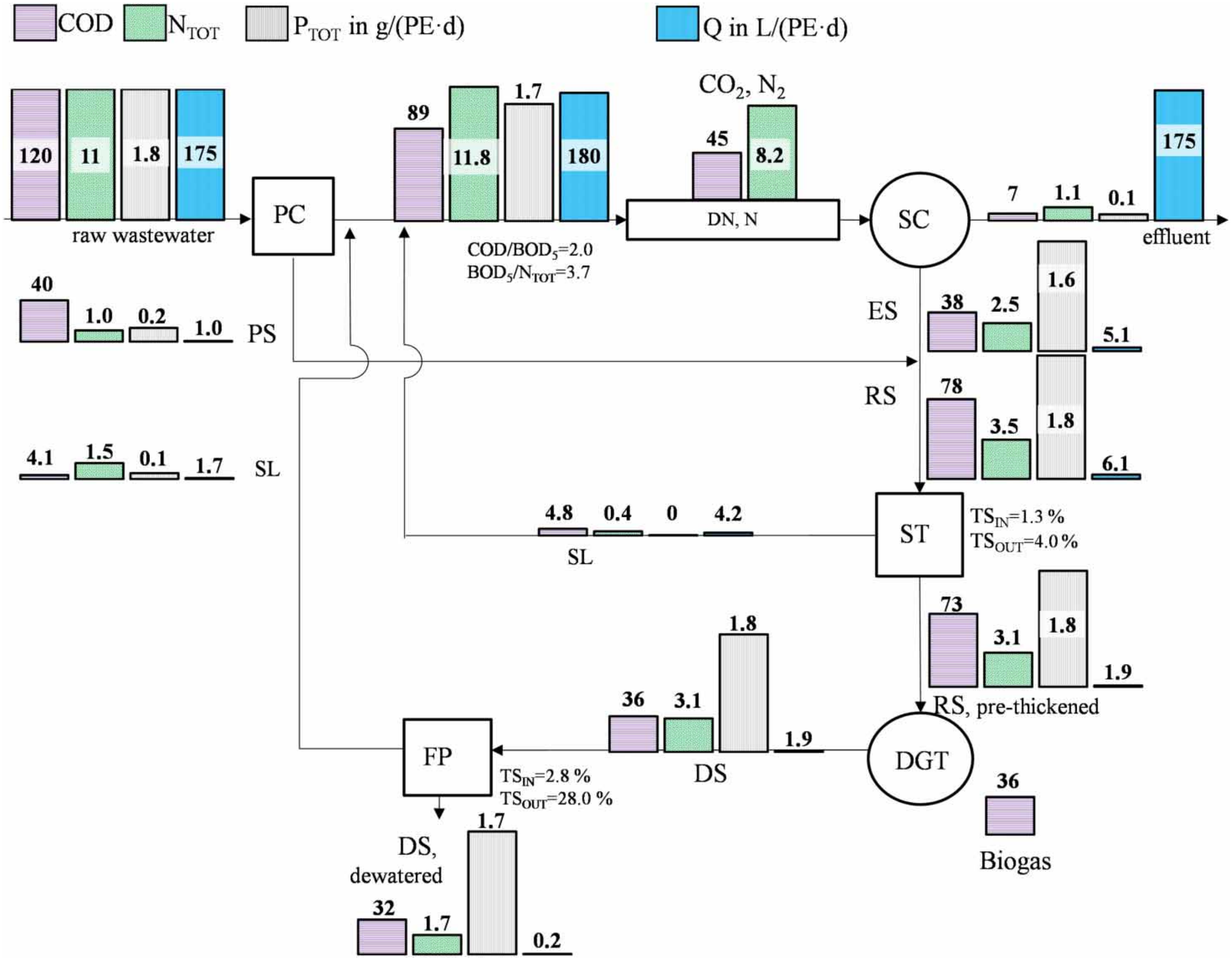

Figure 1 | Mass and volume flow balances for the actual state (0% transition) of the model WWTP, with: Q, volume flow; PC, primary clarifier; *N*, nitrogen removal; D*N*, denitrification; SC, secondary clarifier; ST, sludge thickener; DGT, digester; FP, filter press; PS, primary sludge; ES, excess sludge; RS, raw sludge; DS, digested sludge; SL, sludge liquor.

parameters stated. For instance, raw greywater was assumed to be low in nutrients ($N_{tot} = 25$ mg/l, $P_{tot} = 2$ mg/l), but to have a considerable COD concentration in the order of 545 mg/l, typical for Germany. Cross-contamination issues were considered negligible for the boundary conditions proposed. Most notably, however, the absolute values proposed in Table 1 and Figure 1 play merely a subordinate role due to intrinsic wastewater fluctuations, as these are directly tied to the boundary conditions assumed and are thus only valid for the model WWTP proposed.

In this study, the term 'transition' was defined as the fraction of inhabitants within a definite catchment area using source-separation to collect greywater separately, so that mass and volume flows of separated greywater increase with increasing transition; this leads to changes in volume and composition of further WWTP streams, such as influent, excess and primary sludge, influent to the digester, sludge liquor, effluent and so on, as greywater is incrementally separated from the plant. Special emphasis was laid on transition states, immediately after which operating shortcomings would occur. These tipping points were identified and corrective measures were proposed with the intent of ensuring a safe and stable long-term plant operation as well as satisfactory cleaning efficiencies (the main objective of WWTP). Additionally, power generation/consumption as well as nitrogen and phosphorus recovery potentials for different transition states were assessed correspondingly.

RESULTS AND DISCUSSION

Figure 2 shows mass and volume flow balances for 17% transition of the model WWTP. 17% transition means that the greywater of 17% of all the population equivalents

Table 1 | Assumptions and calculations for mass and volume balances in the actual state (0% transition) if not otherwise stated, based on Gottardo Morandi *et al.* (2018)

Wastewater stream	**Loads, volume flows (85th percentiles) and further parameters**
Raw wastewater (WWTP influent)	$BOD_5 = 60$; $COD = 120$; $N_{tot} = 11$; $P_{tot} = 1.8$ g/(PE·d) (ATV-DVWK A 131 2000) Dry weather flow Q = 175 L/(PE·d) (DWA M 368 2014): 121 L/(PE·d) domestic wastewater +54 L/(PE·d) infiltration water
Primary sludge	Q = 1 L/(PE·d) with 2.0 h flow time in primary clarifier; TSS = 4% (typical range: $TSS_{PS} = 3–6\%$ (DWA M 368 2014) $BOD_5 = 20$; $COD = 40$; $N_{tot} = 1$; $P_{tot} = 0.2$ g/(PE·d) (ATV-DVWK A 131 2000)
Excess sludge	Q = 5.1 L/(PE·d); VS = 25.1 g/(PE·d); TS = 0.7% (DWA M 368 2014) with T = 15 °C, 15 d sludge retention time and $T_{designn} = 12$ °C in the activated sludge process With COD/VS = 1.5; $N_{tot}/VS = 0.1$ in g/g (ATV-DVWK A 131 2000) COD = 38; $N_{tot} = 2.5$ g/(PE·d); P = dependent on P elimination extent
Treated wastewater (WWTP effluent)	Compliance with 50% of the emissions standards stated in AbwV. (2004) for WWTP > 6.000 kg BOD_5/d COD = 37.5; $N_{tot} = 6.5$; $P_{tot} = 0.5$ mg/l; effluent concentrations were assumed 50% of permissible emission standards in Germany
Greywater (100% transition)	Calculated after 121 L/(PE·d) water consumption (UBA 2015) and average usage of 33 L/(PE·d) flush water (BDEW 2011): Q = 121–33 = 88 L/(PE·d) COD = 48 g/(PE·d): assumed to entail 40% (e.g. DWA 2016) of the total COD load in domestic wastewater; $N_{tot} = 2.2$ g/(PE·d): assumed to entail 20% of the total N load in domestic wastewater; $P = 0.2$ g/(PE·d): assumed to entail 10% (e.g. Otterpohl 2001) of the total P load in domestic wastewater; cross-connections between greywater and blackwater collection systems were considered negligible for Germany
Blackwater (100% blackwater separation)	Q = 33 L/(PE·d) flush water (BDEW 2011) COD = 72; N = 8.8; $P = 1.6$ g/(PE·d), calculated after $load_{blackwater} = load_{domestic\ wastewater} - load_{greywater}$
Urine (100% urine separation)	Q = 1.37 L/(PE·d) (DWA 2016) COD = 10.3 g/(PE·d): assumed to entail 14.3% (DWA 2016) of the total COD load in blackwater; $N_{tot} = 7.7$ g/(PE·d): assumed to entail 87.4% (DWA 2016) of the total N load in blackwater; $P = 1.1$ g/(PE·d): assumed to entail 2/3 (DWA 2016) of the total P load in blackwater

For assumptions and calculations regarding thickened sludge, sludge liquor (after thickening), sludge liquor (after dewatering), the activated sludge process, the digester, digested sludge (after dewatering), digester gas, please see Gottardo Morandi *et al.* (2018).

connected to the plant was assumed to be decoupled from the conventional wastewater drainage system, collected separately and treated onsite. When compared to the actual state (see Figure 1), it can be inferred that, up to 17% transition, only minor changes in the average wastewater composition apply, although incrementally separating greywater from the main wastewater stream slowly alters wastewater composition at the inlet as well as reduces loads and volume flows to the plant. Up to 17% transition, the reference average COD concentration in the WWTP influent was proven to increase about 15 mg/l (2%), whereas nutrient concentrations have gone up from 63 to 69 mg/l for N and from 10 to 11 mg/l for P, respectively (approximately 10% increase on the actual state). Even though greywater is generally low in nutrients, it is also characterized by high volume flows, so its separation from the main wastewater stream merely leads to a slight concentration increase of several wastewater constituents at the inlet. These concentration values are generally within typical fluctuations in wastewater; however, neither the influent flow nor COD, N and P loads follow the same pattern as the concentrations. Gradually separating greywater from the main wastewater evidently decreases the loads and volume flow to the plant, as can be observed in Figure 2. Segregating greywater, however, brings about a more expressive COD withdrawal in terms of g/(PE·d) than it does for N or P. At 17% greywater separation, the COD load to the WWTP decreases by 8 g/(PE·d), if compared to the actual state, whereas the N load only drops by 0.4 g/(PE·d). The P load remains practically unchanged. However, changes in carbon to nutrient ratios may arise in different wastewater and sludge streams and could, for instance, negatively interfere with biological processes. Nonetheless, the load and volume flow balances carried out for 17% transition (depicted in Figure 2) indicate that separating greywater is favorable for plant operation up to 17% transition, as sufficient biodegradable carbon (expressed as the biochemical oxygen demand during five days of incubation, i.e. BOD_5) ensures a stable denitrification due to favorable C to N ratios (i.e. BOD_5 to N ratios higher than 3.5). Most notably, this finding is only valid for the

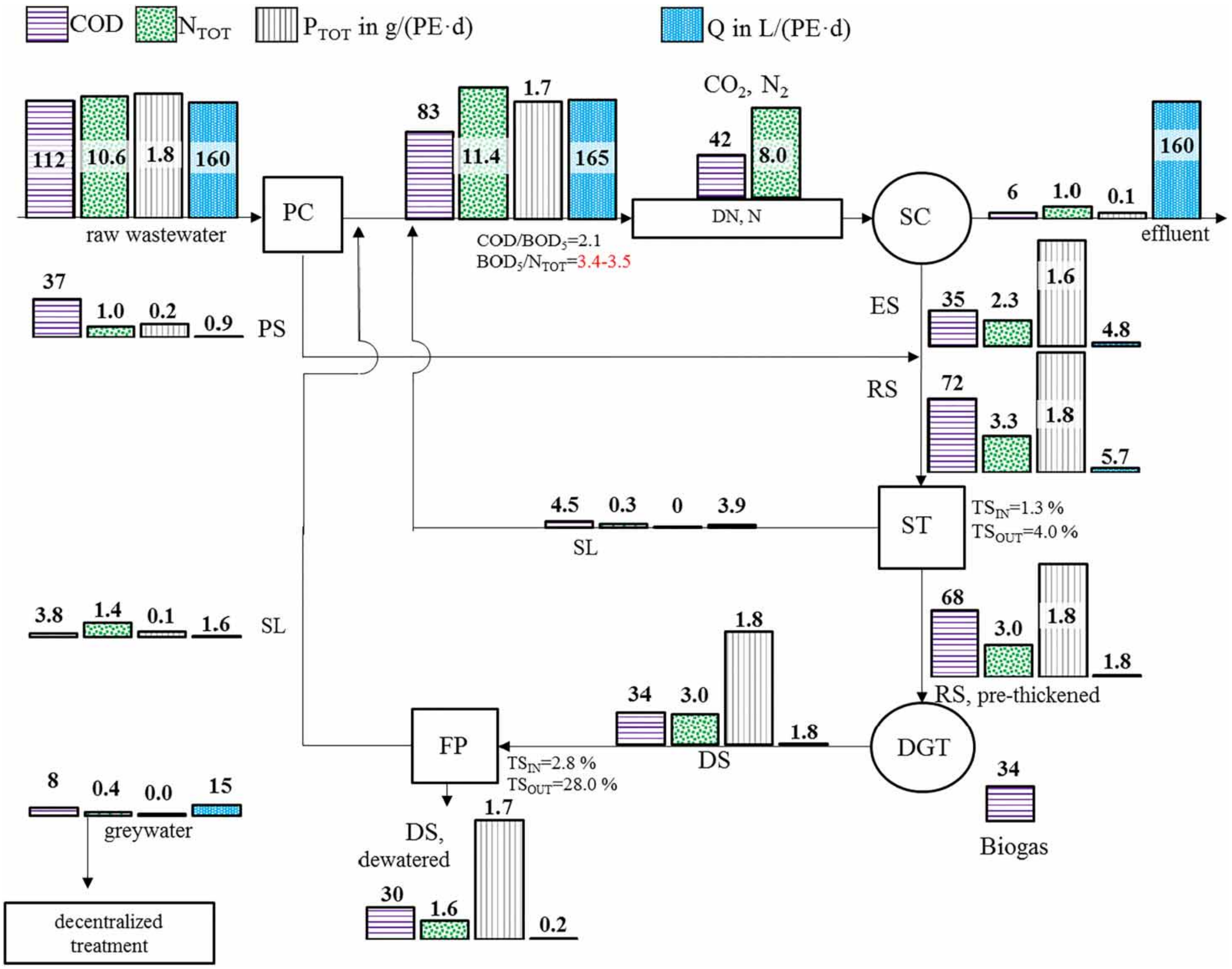

Figure 2 | Mass and volume flow balances for 17% transition of the model WWTP. with: Q, volume flow; PC, primary clarifier; *N*, nitrogen removal; D*N*, denitrification; SC, secondary clarifier; ST, sludge thickener; DGT, digester; FP, filter press; PS, primary sludge; ES, excess sludge; RS, raw sludge; DS, digested sludge; SL, sludge liquor.

boundary conditions assumed in this work (see Figure 1 and Table 1). At 17% transition (17% greywater separation), a decrease of 1.4 kWh/(PE·a) in aeration requirements was reported. It has to be noted, however, that withdrawing carbon from the main wastewater stream also reduces the removal of excess sludge and, to a lesser extent, primary sludge (particularly suspended solids contained in kitchen greywater), so that a reduced power generation in the digester of – 1.1 kWh/(E·a) can be expected at 17% transition. Thus, the actual net electric energy gained by greywater separation amounts to roughly 0.3 kWh/(PE·a) for 17% transition. In order to increase biogas production and as a result enhance power generation, co-digestion strategies at the plant could be implemented – for instance the co-treatment of sewage sludge and blackwater in municipal digesters (see Gottardo Morandi *et al.* 2018). With regards to nutrient recovery potentials at the plant, higher nutrient concentrations usually favor recovery processes, wherefore particularly the sludge liquor stream (small volume flow and high concentrations) provides a promising starting point for the implementation of nutrient recovery processes. Up to 17% transition, maximum recovery rates of 1.4 to 1.5 g N/(PE·d) and 0.1 g P/(PE·d) from the sludge liquor are theoretically achievable (see Figures 1 and 2), which merely represent approximately 15% of the total N and 5% of the total P influent loads to the model WWTP. However, an enhancement of these low recovery potentials could possibly be attained by blackwater co-digestion at the plant, as suggested in Gottardo Morandi *et al.* (2018); the displacement of blackwater nutrients to sludge processing lines would substantially increase N and P recovery potentials in the sludge liquor. Alternatively, the combined treatment of urine and sludge liquor has also been previously proposed (Wilsenach & van Loosdrecht 2006).

From 17% transition onwards, the BOD_5:N ratio in denitrification for the model WWTP is expected to shift negatively, if no corrective operating measures are provided. $BOD_5:N_{tot} < 3.5$ would be expected hereafter for the model WWTP, as greywater entails approximately 40% of the COD load in raw wastewater and is low in nutrients (see Table 1). An incomplete denitrification would promptly result in increasing nitrate effluent concentrations, so that for the model plant corrective operating measures would have to be undertaken, for example: (1) addition of external carbon (yet, resource-inefficient), (2) reduced primary sludge removal (i.e. partial BOD_5 by-pass to denitrification, yet energy-inefficient) or (3) sidestream N removal/recovery from sludge processing lines. Evidently, the ratio of biodegradable COD to nitrogen in the sludge liquor is too low (approximately 1 g BOD_5/g N) for complete nitrogen removal via heterotrophic denitrification or even nitritation/denitritation. Possible sidestream N recovery processes comprise biological and physicochemical processes, such as (1) autotrophic nitritation followed by anammox (no C required), (2) autotrophic nitrification to stabilize ammonia followed by distillation to concentrate nearly all nutrients in a solid/fertilizer (yet energy costs are high and heavy metals as well as iron or alum salts could pose risk to humans and the environment), (3) ammonia stripping (yet large-scale experience is rather available in the industrial wastewater treatment), (4) use of zeolites (yet substantial amounts of (costly) adsorbent are required), (5) struvite precipitation (yet extensive N recovery is only possible by addition of phosphorus (and magnesium)).

As previously mentioned, from 17% transition onwards, unfavorable C/N ratios are expected in the denitrification stage, if no corrective measure is provided. Thus, mass and volume flow balances for 35% transition of the model WWTP (see Figure 3) took into account the implementation of a sidestream N removal/recovery within the sludge processing lines. At 35% transition (35% greywater separation), the inlet characteristics are further changed by source separation of greywater, as can be inferred from the bar heights at the inlet. When compared to the actual state (see Figure 1), it is also true that only minor changes in the composition of raw wastewater apply (e.g. the COD concentration drops by 30 mg/l on the actual state), yet concentrations are much less relevant than loads for assessing and correcting possible operating shortcomings or, correspondingly, re-designing WWTP undergoing transition. Particularly the COD load and the volume flow to the plant decreased considerably (Figure 3), when compared to the actual state. By implementing a sidestream N removal/recovery within the sludge processing lines, a minimum of 50% N removal/recovery rate from sludge liquor was proven to be required at 35% greywater separation to uphold a favorable $BOD_5:N_{tot}$ ratio in denitrification, as can be inferred from Figure 3. In addition, increasing the N removal/recovery rate to 90% would enable the WWTP to work effectively up to 48% transition. The need for relatively high recovery efficiencies from the sludge liquor at higher transition states can be ascribed to relatively low maximum recovery potential of 1.3 g N/(PE·d) and 0.1 g P/(PE·d) in the sludge liquor, as can be inferred from Figure 3. At 35% transition, N removal from sludge processing lines along with greywater separation yields an energy reduction in aeration of 14% or, correspondingly, 3.3 kWh/(PE·a). However, at 35% transition a counterproductive reduction in power generation in the digester/combined heat and power (CHP) unit of 2.3 kWh/(E·a) can be expected due to lower sewage sludge production.

From 35% transition onwards, nitrogen removal from N-rich sludge lines does not alone offset the withdrawal of carbon in greywater, so an irreversible increase in nitrate effluent concentrations would pose risk to the environment due to insufficient denitrification ($BOD_5:N < 3.5:1$). Therefore, the plant would have to undergo substantial process and structural alterations to compensate for the considerable carbon withdrawal at the inlet, for example: (1) mainstream process changeovers (e.g. nitritation/denitritation; nitritation/anammox; dismantling of primary sedimentation/aerobic sludge stabilization (yet, energy-inefficient)), (2) partial separate collection of blackwater and co-digestion in municipal digesters followed by N recovery from sludge liquor (see Gottardo Morandi *et al.* 2017), or (3) partial separate urine collection. Human urine contributes to approximately 80% of the total nitrogen and 50% of the total phosphorus load to municipal wastewater plants (DWA 2016), so that a separate urine collection and specific treatment (on-site, in semicentralized urine treatment centers or at the plant; for example, combined with sludge liquor treatment processes) could help to uphold a stable denitrification in the anoxic zone. Moreover, Wilsenach & van Loosdrecht (2006) showed that an integrated centralized treatment of municipal wastewater and urine enables the achievement of very good effluent qualities with a substantial saving in resources for most types of WWTP. Considering all this, urine separation has been introduced as a corrective operating measure in Figure 4.

Figure 4 depicts mass and volume flow balances for 50% greywater separation of the model WWTP. Decoupling urine from the main wastewater stream at an adequate rate allows the renouncement of an additional nutrient

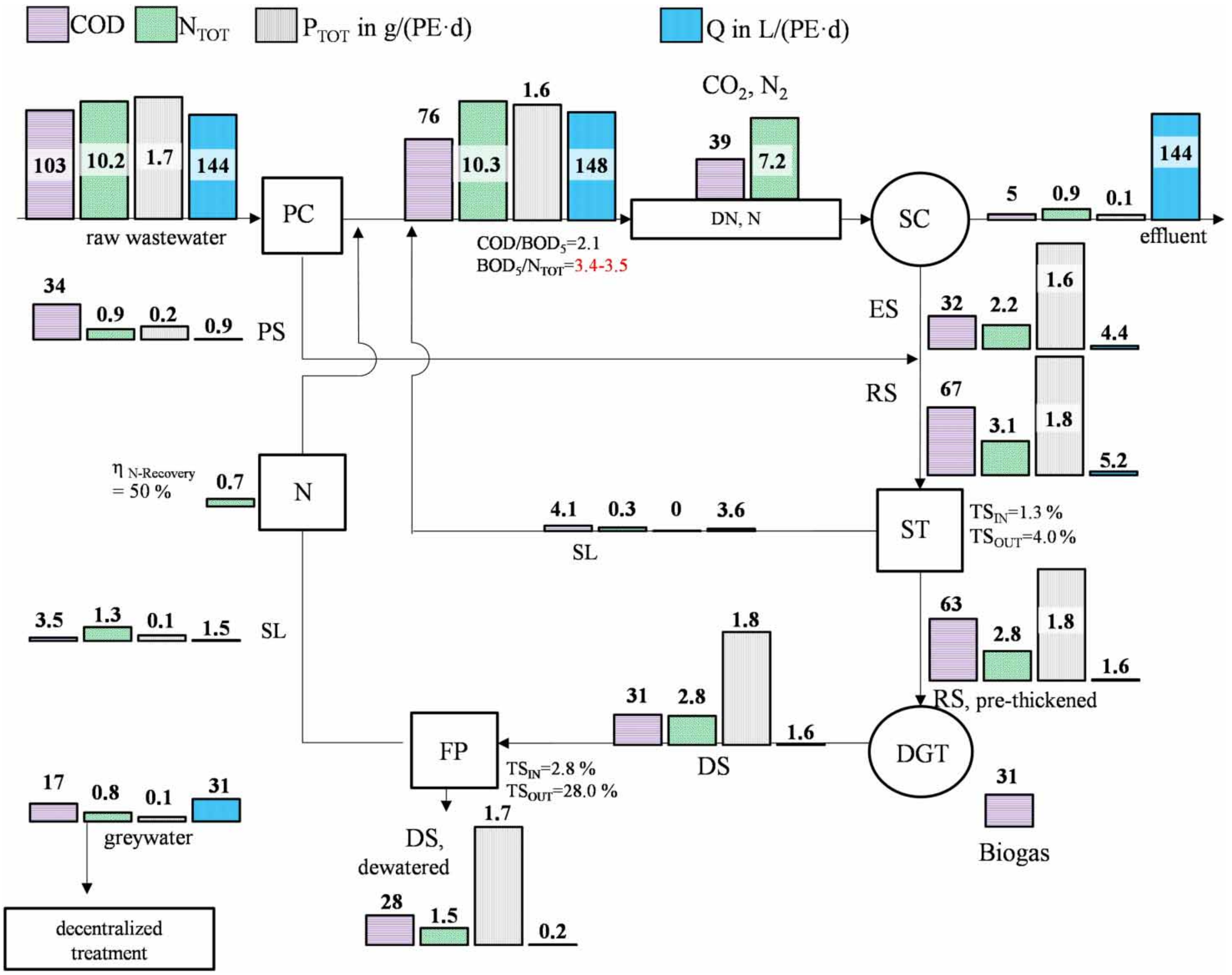

Figure 3 | Mass and volume flow balances for 35% transition of the model WWTP with an implemented sidestream N removal/recovery from sludge processing lines, with: Q, volume flow; PC, primary clarifier; N, nitrogen removal; DN, denitrification; SC, secondary clarifier; ST, sludge thickener; DGT, digester; FP, filter press; PS, primary sludge; ES, excess sludge; RS, raw sludge; DS, digested sludge; SL, sludge liquor.

recovery unit within the sludge processing lines. At 50% transition, source-separation of greywater further changes the composition of the influent, but especially alterations in loads and the volume flow at the inlet are noticeable, as can be seen in Figure 4. When compared to the actual state (see Figure 1), it is evident that the fate of the different wastewater constituents considerably varies within the various wastewater and sludge streams. Furthermore, it can be deduced from Figure 4 that partially separating urine from domestic wastewater (e.g. by deriving it from public buildings via no-flush urinals or urine-diverting toilets and, to a lesser extent, from domestic residences) would significantly benefit denitrification at the plant; else, the BOD$_5$/N ratio in the denitrification would reach 3.1 at 50% transition, meaning that nitrate effluent concentrations would possibly pose risk to the environment. At 50% transition, power demand for aeration amounted to 70% on the actual state, which was calculated to be 23.4 kWh/(PE·a) (Gottardo Morandi *et al.* 2018), while urine separation alone accounted for approximately 13% of the total savings in energy for aeration; the reminiscent 17% were ascribed to carbon withdrawal due to greywater separation. At 50% transition, the reduction in power demand was found to be 7 kWh/(PE·a) for the boundary conditions assumed, which corresponds to 30% reduction on the actual state, as mentioned previously. Nevertheless, by gradually removing greywater from the main wastewater stream or, correspondingly, reducing the load of organic solids to the plant, less energy can be retrieved from sewage sludge – 12.3 kWh/(PE·a) instead of 16.3 kWh/(PE·a)

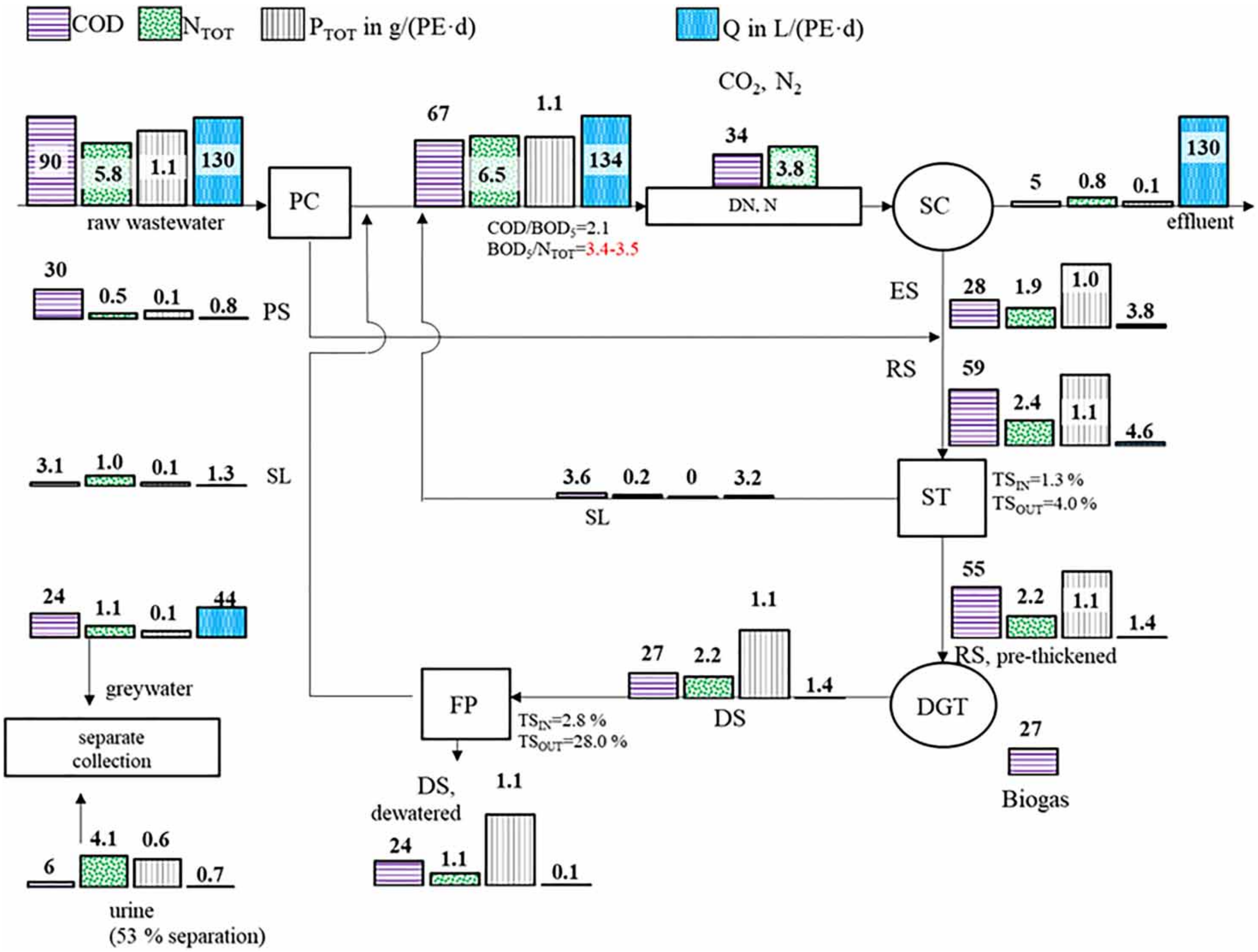

Figure 4 | Mass and volume flow balances for 50% transition (50% greywater separation) of the model WWTP with urine separation as a means to uphold a favorable C/N ratio in the anoxic stage to ensure full denitrification, with: Q, volume flow; PC, primary clarifier; N, nitrogen removal; DN, denitrification; SC, secondary clarifier; ST, sludge thickener; DGT, digester; FP, filter press; PS, primary sludge; ES, excess sludge; RS, raw sludge; DS, digested sludge; SL, sludge liquor.

in the actual state. This relativizes the earlier finding to some extent.

Table 2 summarizes the investigated tipping points for plant operation during transition and provides respective operating measures to overcome those points. The separation of greywater from the main wastewater stream favors plant operation in the short term, mainly under energy aspects. Additionally, this study found that the separation of greywater or, correspondingly, the carbon contained therein would lead to a reduction in power demand for aeration at a rate of 0.8 kWh/(PE·a) per 10% transition. However, a parallel reduced power generation in the digester in the order of –0.65 kWh/(E·a) per 10% transition was reported as well due to lower sewage sludge production with increasing greywater separation. In sum, the actual net electric energy gained by greywater separation amounts to roughly 0.15 kWh/(PE·a) per 10% transition. Process implementations, for example, within sludge processing lines (e.g. N recovery from N-rich sludge side streams) are required in the mid-term to offset unfavorable carbon to nitrogen ratios in the anoxic stage and enable full denitrification. Additionally, extensive mainstream process changeovers (e.g. nitritation/anammox) can be avoided in the mid-term, if alongside greywater separation urine is collected separately and decoupled from the main wastewater stream, so less N load would reach the denitrification stage. From 17% transition onwards, if no N removal/recovery were implemented, an incremental urine separation from the main wastewater stream (alongside greywater separation) would be necessary. The required extent of urine separation was proven to be tied to the separation of greywater and can be found in Equation 1. This correlation was obtained by using the Excel-based algorithm introduced in this study to determine, for several

Table 2 | Proposed transition scenarios with respective drawbacks and benefits for conventional WWTP as well as corrective measures to overcome operating problems

Transition scenario	Drawbacks (-) and benefits (+)	Corrective operating measures
0–17% transition: 0–17% greywater separation from the main wastewater stream (WWTP inflow), on-site greywater treatment for water reuse	(+) reduction in power demand for aeration at a rate of 0.8 kWh/(PE·a) per 10% transition due to greywater separation (−) reduction in power generation by sludge digestion at a rate of 0.65 kWh/(E·a) per 10% transition due to lower sludge production • Net reduction in power demand of 0.15 kWh/(PE·a) per 10% transition	• Co-digestion of sewage sludge with e.g. blackwater (see Gottardo Morandi *et al.* 2018) to enhance power generation
17–35% transition: 17–35% greywater separation from the main wastewater stream (WWTP inflow), on-site greywater treatment for water reuse	(−) Increase in nitrate effluent concentrations due to insufficient denitrification ($BOD_5:N < 3.5:1$) (+) Possibility of recovering N and P from sludge liquor at max. rates of 1.3–1.4 g N/(PE·d) and 0.1 g P/(PE·d), respectively	• Nitrogen recovery from N-rich sidestreams within sewage sludge processing line (50% N recovery efficiency required at 35% transition) or • Reduction of primary sludge removal and partial BOD_5 by-pass to denitrification or • External carbon source for denitrification
35–85% transition 35–85% greywater separation from the main wastewater stream (WWTP inflow), on-site greywater treatment for water reuse	(−) Increase in nitrate effluent concentrations due to insufficient denitrification ($BOD_5:N < 3.5:1$) and extensive greywater separation from the plant (+) reduction in power demand for aeration at a rate of 1.4 kWh/(PE·a) per 10% transition by combined separation of greywater and urine (+) Possibility of recovering N and P from sludge liquor and urine at max. rates of $0.087{\cdot}x + 0.800$ g N/(PE·d) and $0.013{\cdot}x - 0.005$ g P/(PE·d) x [% greywater separation]	• Urine separation from the main wastewater stream at a rate y [% urine separation], where $y = 1.26{\cdot}x - 9.3x$ [% greywater separation] • Separate collection and treatment of blackwater (see Gottardo Morandi *et al.* 2018) or • Need for major mainstream process alternations, such as nitritation/denitritation, nitritation/anammox, aerobic sludge stabilization, etc.

'Transition' was defined as the fraction of inhabitants within a definite catchment area using source separation to collect greywater separately. WWTP, wastewater treatment plant; BOD_5, biochemical oxygen demand after five days; N, nitrogen; P, phosphorus; PE, population equivalent.

percentages of greywater separation, the respective amount of urine necessary to uphold a BOD_5/N ratio of 3.5. Subsequently, a linear regression was used to fit a predictive equation to the observed data set. Equation (1) is valid up to 87% greywater separation and its use ensures, for a definite percentage of greywater separation, favorable C/N ratios in the anoxic zone. Most notably, the absolute values are only valid for the model WWTP under the specific boundary conditions assumed. According to Equation (1), 50% greywater separation requires approximately 53% urine separation (collection of the urine of 53% of the inhabitants) for full denitrification.

$$y[\%\,\text{urine separation}] = 1.26 \cdot x[\%\,\text{greywater separation}] - 9.3 \tag{1}$$

For instance, at 60% transition (separation of greywater from 60% of all inhabitants), 66% urine separation would be required to allow a satisfactory denitrification. At 75% greywater separation, for instance, the urine of 85% of the inhabitants would have to be separated from the main wastewater stream to stabilize denitrification and avoid higher nitrate concentrations in the effluent. Transition states higher than 50% represent very unlikely scenarios for the next decades, as the long-term wastewater management, particularly in urban areas, will certainly be determined not exclusively by on-site treatment strategies, but rather a mix of centralized and decentralized approaches. Considering both effects of greywater and urine separation, the reduction in power demand for aeration was proven to follow a rate of 1.4 kWh/(PE·a) per 10% transition. Whereas the separation of greywater from the main wastewater stream has hardly any effect on nutrient recovery potentials at the plant, as greywater is generally low in nutrients, urine separation could help to promote overall resource efficiency and sustainability, particularly by benefiting nutrient recovery and considerably reducing the nitrogen load to the denitrification stage.

Assuming a combined nutrient recovery from the sludge liquor and urine, N and P recovery potentials at the plant were correlated with the percentage of greywater separation using Equations (2) and (3), which are both valid from 17% to 87% greywater separation. For the determination of these equations, the same procedure as for Equation (1) was applied; a data set was generated with the algorithm by increasing the percentage of greywater separation, while the nutrient recovery potentials were plotted as a function of greywater separation. For the model WWTP, under the assumed specific boundary conditions, both equations were obtained for the total N and total P recovery potentials in both sludge liquor and urine, whereas the correlation between greywater separation and urine separation was previously given in Equation (1).

$$N[\mathrm{g\,N/(PE\cdot d)}] = 0.087 \cdot x[\%\,\mathrm{greywater\,separation}] + 0.800 \tag{2}$$

$$P[\mathrm{g\,P/(PE\cdot d)}] = 0.013 \cdot x[\%\,\mathrm{greywater\,separation}] - 0.005 \tag{3}$$

Considering 175 L/(PE·d) dry weather flow (see Table 1), N load and volume flow balances showed that by fictively separating approximately 95% of all urine in the catchment area, there would be no need for nitrogen elimination at the plant to comply with typical N_{tot} discharge standards of 13 mg/l for WWTP with >6.000 kg/d BOD_5 in Germany; that is, plants connected to more than 100,000 PE (see AbwV. 2004). Assuming 200 L/(PE·d) dry weather flow and a less stringent N_{tot} discharge standard of 18 mg/l, which applies, for instance, for German WWTP with 600 to 6,000 kg/d BOD_5 (AbwV. 2004) with a typical connection size between 10,000 to 100,000 PE, the urine of 80% of all inhabitants would have to be collected separately to fully forgo the need for an N elimination. With 300 L/(PE·d) and maximum 18 mg/l N_{tot} in the effluent, 55% urine separation would already suffice to do without nitrification/denitrification. Hence, depending on the plant size, the amount of infiltration water in the WWTP inflow and cultural habits regarding water consumption as well as according to different discharge regulations for N_{tot}, partial urine separation could vastly contribute to a reduction of the amounts of materials and energy required for plant operation and could help to revert the drawbacks of separating greywater from the plant. In the mid-term, urine separation could help to increase resource efficiency and sustainability at the plant, while globally reducing the total environmental impact in the wastewater treatment sector.

CONCLUSIONS

Source-separation/decentralization is of foremost importance for the long-term wastewater management, in which both decentralized and centralized WWTP will play an important role. This study revealed that WWTP can be successfully integrated in transition concepts for resource-oriented sanitation and that transition of existing centralized wastewater infrastructures represents a prerequisite for the mitigation of the total environmental impact in the wastewater sector. Only by looking upon the overall system can synergistic effects possibly be achieved in both decentralized and centralized approaches and thus significantly contribute to sustainability in the future of the wastewater engineering.

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