Research article

Ex-ante quantification of nutrient, total solids, and water flows in sanitation systems

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ABSTRACT

To prioritise sustainable sanitation systems in strategic sanitation planning, indicators such as local appropriateness or resource recovery have to be known at the pre-planning phase. The quantification of resource recovery remains a challenge because existing substance flow models require large amounts of input data and can therefore only be applied for a few options at a time for which implementation examples exist. This paper aims to answer two questions: How can we predict resource recovery and losses of sanitation systems ex-ante at the pre-planning phase? And how can we do this efficiently to consider the entire sanitation system option space? The approach builds on an existing model to create all valid sanitation systems from a set of conventional and emerging technologies and to evaluate their appropriateness for a given application case. It complements the previous model with a Substance Flow Model (SFM) and with transfer coefficients from a technology library to quantify nutrients (phosphorus and nitrogen), total solids (as an indicator for energy and organics), and water flows in sanitation systems ex ante. The transfer coefficients are based on literature data and expert judgement. Uncertainties resulting from the variability of literature data or ignorance of experts are explicitly considered, allowing to assess the robustness of the model output. Any (future) technologies or additional products can easily be added to the library. The model is illustrated with a small didactic example showing how 12 valid system configurations are generated from a few technologies, and how substance flows, recovery ratios, and losses to soil, air, and water are quantified considering uncertainties. The recovery ratios vary between 0 and 28\% for phosphorus, 0–10\% for nitrogen, 0–26\% for total solids, and 0–12\% for water. The uncertainties reflect the high variability of the literature data but are comparable to those obtained in studies using a conventional post-ante material flow analysis (generally about 30\% variability at the scale of an urban area). Because the model is fully automated and based on literature data, it can be applied ex-ante to a large and diverse set of possible sanitation systems as shown with a real application case. From the 41 technologies available in the library, 101,548 systems are generated and substance flows are modelled. The resulting recovery ratios range from nothing to almost 100\%. The two examples also show that recovery depend on technology interactions and has therefore to be assessed for all possible system configurations and not at the single technology level only. The examples also show that there exist trade-offs among different types of reuse (e.g. energy versus nutrients) or different sustainability indicators (e.g. local appropriateness versus resource recovery). These results show that there is a need for such an automated and generic approach that provides recovery data for all system configurations already at the pre-planning phase. The approach presented enables to integrate transparently the best available knowledge for a growing number of sanitation technologies into a planning process. The resulting resource recovery and loss ratios can be used to prioritise resource efficient systems in sanitation planning, either for the pre-selection or the detailed evaluation of options using e.g. MCDA. The results can also be used to guide future development of technology and system innovations. As resource recovery becomes more relevant and novel sanitation technologies and system options emerge, the approach presents itself as a useful tool for strategic sanitation planning in line with the Sustainable Development Goals (SDGs).
1. Introduction

If there is one thing important for health and environmental protection, and thus for social and economic development, it is good sanitation.

The importance of sanitation has been acknowledged in the human right to water and sanitation (UN, 2010). That sanitation should also be sustainable has been recognized by the Sustainable Development Goals SDG 6 (UN, 2015). In most of high-income countries, we benefit from great sanitation services and make great efforts to treat wastewaters and to prevent environmental pollution. However, at a global level considering rapidly growing urban centres in low-income areas, the situation has not been improving much recently. One reason for this is, that conventional sanitation solutions are not appropriate and thus not viable in fast growing urban areas, where most of the current population growth is taking place (Dodman et al., 2017; Isunju et al., 2011; Tremolet et al., 2016; UNDESA, 2014). This is due to their requirements for large amounts of water and energy, expensive infrastructure, and long planning horizons (Davis et al., 2019). Sustainable sanitation systems should be locally appropriate in terms of technology, institutions and social acceptance, and economically viable in order to protect the human health and the environment (SuSanA, 2008). But to be in line with SDG 6, they should also be designed to closing water and nutrient loops at the lowest possible level.

The definition of sustainable sanitation has triggered the development of many novel sanitation technologies and system configurations such as urine diversion toilets or container-based sanitation (Tilmans et al., 2015; Tobias et al., 2017). Many of these innovations are independent from sewers, water, and energy and therefore more appropriate for developing urban areas. They are also potentially more sustainable because they often allow for the recovery of resources such as nutrients, water, and energy (e.g. Andriessen et al., 2019; Chen and Beck, 1997; Cofie et al., 2009; Daigger, 2009; Davis et al., 2014; Evans et al., 2013; Harder et al., 2019; Langengerber and Masi, 2018; Rao et al., 2017; Trimmer et al., 2019; Udert and Wachter, 2012). Also, the flexibility to cope with changing environmental and socio-demographic conditions further enhance their sustainability (Hoffmann et al., 2020; Larsen et al., 2016).

While innovation potentially enhance sustainability, they certainly enhance planning complexity. The currently available portfolio of technologies leads to an overwhelming number of possible system configurations. To consider them all in a strategic planning process is extremely difficult. The two main challenges are (1) the lack of knowledge what options exists and how appropriate they might be in a given context; and (2) data about the performance of these options regarding the multiple sustainability criteria. The sustainability criteria are given by the five objectives for sustainable sanitation laid out by the Sustainable Sanitation Alliance (SuSanA, 2008): health and hygiene, economic viability, socio-cultural acceptance, technical and institutional appropriateness, and protection of the environment and natural resources. Because sustainability requires multiple dimensions to be considered, trade-offs are to be expected and a multi-criteria decision approach such as structured decision making is needed (Gregory et al., 2012). Spuhler et al. (2018) addressed the lack of knowledge about possible system configurations and local appropriateness. The here presented manuscript addresses the second point by presenting a model to quantify resource recovery and losses as one sustainability indicator and by providing a technology library containing international data and knowledge needed for this task.

Only if practitioners have the knowledge and data about the resource recovery and loss ratios of the various sanitation system they can consider environmental protection and circular economy when strategically planning for sustainable sanitation. Hence this knowledge and data are needed ex-ante, at the pre-planning phase. Unfortunately, in the absence of infrastructure in place and few full-scale implementation examples of novel technologies and systems, we cannot measure this data. Thus, a modelling approach is required. Resource recovery and loss ratios can be modelled using substance flow modelling (SFM) based on material flow analysis (MFA, e.g. Baccini and Brunner, 2012; Huang et al., 2012; Mehr et al., 2018). Unfortunately, existing models require detailed knowledge about the technology implementation and large amount of data (e.g. Espinoza and Otterpohl, 2014; Montangero and Belevi, 2008; van der Hoek et al., 2016; Yoshida et al., 2015). Therefore, they can only be applied post-ante for few options at a time (e.g. Dahlmann, 2009; Meinzinger et al., 2009; Montangero et al., 2007; Ormandzhieva et al., 2014; Schütze and Alex, 2014; Ushijima et al., 2012; Woltersdorf et al., 2016; Yiougo et al., 2011). Moreover, most of the existing models are designed for conventional systems and are not easily applicable for innovations. To our knowledge, there is currently a complete lack of generic methods to model substance flows of a large and diverse range of sanitation systems at the scale of an entire city.

1.1. Aim

To help solve this problem we will address two questions in this paper:

1. How can we predict resource recovery and loss ratios of sanitation systems ex-ante at the pre-planning phase?
2. And how can we do this efficiently to consider the entire sanitation system option space?

To answer these questions, we present two elements. First, we present a method to model substance flows that is generic to any system and can be applied automatically for many sanitation systems. Second, we provide the required a priori data to apply this model for four substances and a large and diverse set of conventional and emerging technologies ex-ante. The four substances cover nutrients (nitrogen and phosphorus), organics and energy (total solids), and water. Because the a priori data is highly variable depending on the technology implementation, the quality and quantity of flows, and the local context, we also calculate the uncertainties of the results. To exemplify the model and its outputs we present a didactic case and some snapshots of a full-scale application of 41 technologies resulting in 101,548 valid system configurations.

2. Methods

2.1. Overview

The quantification of recovery ratios of sanitation systems automatically, for many options simultaneously, and ex-ante, requires three elements: a generic description of the systems; a method to model the substance flows within these systems, and the data on transfer coefficients and inflowing masses. Additionally, we need a way to consider the uncertainties related to the data of transfer coefficients as those data are based on prediction and not on in-situ measurements.

Spuhler et al. (2018) provides an automated system builder that allows to find all valid system options from a set of technologies. We extended this model with a substance flow model and the technology library with the required data on transfer coefficients and their uncertainties. The only additional input is the masses entering a system which is defined by the number of users within a year. Fig. 1 provides an overview on the required model and data elements. The substance modelling aspects are described in this method section. The required a priori data (potential technologies, transfer coefficients and uncertainties, inflowing masses) are provided in the results section.

2.2. Sanitation technologies and system builder

The sanitation system builder defines a sanitation system (SanSys) as a set of compatible sanitation technologies (Techs) which in combination transport, transform, or separate sanitation products from their...
point of generation to the final point of reuse or disposal (Maurer et al., 2012; Spuhler et al., 2018; Tilley et al., 2014). This definition is generic and could be applied to any unit process, infrastructure, or service. Sanitation products are materials that are generated either directly by humans (e.g. urine, faeces, greywater), the urban environment (e.g. stormwater), or by some Techs (e.g. sludge, biogas). Each Tech is defined by the possible input and output products and the stage within a system (functional group) it can apply to (see Fig. 2). Sources could be toilets, handwashing stations, stormwater collection tanks, organic solid waste bins. In this paper, we focus on toilet sources only.

2.3. Substance flow modelling

The product connections between the technologies in each sanitation system define the flow paths of the substances (see also Fig. 2). Transfer coefficients (TCs) define how much of substance entering a technology is transferred to one of the output products, or lost to the environment. These TCs and the connections can be expressed in a matrix $P$, where $P_{ij}$ is the fraction of the substance leaving Tech $i$ that is transferred to Tech $j$. Additionally, we define a row vector $F^{\text{ext}}(t)$, where the $i$-th element represents the external inflow to Tech $i$ at time $t$ (e.g. the dry toilet Tech receives 0.548 kg/year of phosphorus per one person). Based on this information, we can calculate the total inflow into Tech $i$ at time $t$. We define a row vector $F(t)$ where the $i$-th element represents the sum of all inflows to Tech $i$ at time $t$ (e.g. the amount of phosphorus entering a single pit through excreta).

The mass flows at time $t + 1$ are obtained by

$$F_{i+1} = F_i \cdot P + F^{\text{ext}}_{i+1} \tag{1}$$

If we assume a constant inflow $F^{\text{ext}}(t) = F^{\text{ext}}$, we have a steady state flow $F$ that is calculated by

$$F = F \cdot P + F^{\text{ext}} \tag{2}$$

$$F = F^{\text{ext}} \cdot (1 - P)^{-1} \tag{3}$$

The flow at steady state from node $i$ to node $j$ is consequently defined as

$$\text{flow}_{ij} = F_i \cdot P_{ij} \tag{4}$$

The recovery ratios are defined only by the sinks. The total losses are obtained by summing all the losses from all Techs within a SanSys. Because we have different external inflows and transfer coefficients for each substance, the calculations are repeated separately for each substance that is to be modelled.

2.4. Transfer coefficients

Each technology needs to be characterised with a TC for each output flow and substance of interest. For a given substance, the TC for the $i$-th output flow of a technology (TC) is the fraction of the sum of the input flows that leave the technology through outflow $i$:

$$TC_i = \frac{\sum_{j=1}^{n} \text{flow}_{ij}}{\sum_{j=1}^{n} \text{flow}_{ij}} \tag{5}$$

where $n$ is the total number of inputs to this Tech. The output flows are the output products as well as the losses to the environment: to air, soil/groundwater, and surface water. Input flows are defined only by the input products as we assume a system with no biological fixation. Thus, the sum of all TCs of a technology must always be 1 and all TCs positive.

Three types of TCs can be distinguished:

(i) Input-output TCs. For every output a TC needs to be defined; the number of outputs depends on the Tech.

(ii) Input-loss TCs. Quantifying the fraction of substances transferred to air, soil or groundwater, and surface water. We only consider the losses (e.g. leaching of phosphorus from a single pit into the soil) and not the subsequent interactions (e.g. transfer of the same phosphorus from the soil to the surface water).

(iii) Recovery TCs. Besides losses, sink technologies also have a TC to quantify the fraction of a substance that can be recovered (e.g. over 90% of phosphorus is recovered through the sink ‘application of stored urine’).

Fig. 3 provides an example of the flows and the TCs for the technology single pit and the substance total phosphorus (TP). The example also shows the high variability of the data found in literature. Therefore, we need a systematic method to consider and model this uncertainty.

2.4.1. Estimation of transfer coefficients and their uncertainty

We use two different ways to determine transfer coefficients. If

$$F = F \cdot P + F^{\text{ext}} \tag{2}$$

$$F = F^{\text{ext}} \cdot (1 - P)^{-1} \tag{3}$$

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Confidence in substance: Low 1 2 5
Medium 2 5 25
High 5 25 100

Table 2

Experts’ knowledge about the technology and confidence in the substance are used to define the concentration factor k for transfer coefficients based on expert judgement. Confidence in the technology depends on different factors such as its development stage and the process used. Nitrogen and total solids have lower confidence, while phosphorus and water have medium and high confidence.

Table 3

Six standardized intervals are used to translate the variability of ranges observed in literature into the concentration factor k. The variability range of a transfer coefficient i (TCi) is defined by the range between the lowest and the highest value data points reported in literature.

Table 1

<table>
<thead>
<tr>
<th>Observed variability ranges in literature data</th>
<th>Concentration factor for the Dirichlet distribution (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 0.1] (0-10%)</td>
<td>100</td>
</tr>
<tr>
<td>[0.1, 0.2] (10-20%)</td>
<td>25</td>
</tr>
<tr>
<td>[0.2, 0.4] (20-40%)</td>
<td>5</td>
</tr>
<tr>
<td>[0.4, 0.6] (40-60%)</td>
<td>2</td>
</tr>
<tr>
<td>[0.6, 0.8] (60-80%)</td>
<td>1</td>
</tr>
<tr>
<td>[0.8, 1] (80-100%)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Fig. 3. Illustration of the approach used to quantify transfer coefficients (TCs) using the example of total phosphorus (TP) pathways in a single pit. The TCs are estimated based on literature values in mass and in percentage as mean values. In parenthesis we provide the variability range resulting from the literature data points. From the 100% of phosphorus entering the single pit via blackwater, 29% are transferred to sludge and 71% are lost to the soil. But the uncertainty resulting from the TC data results in a variability of 18-40 and 60-82% respectively.

Fig. 4. Three examples of concentration factors k for a set of four transfer coefficients (0%, 20%, 30% and 45%). For k = 100, the distributions are relatively narrow (small variability range of up to 10% expressed as standard deviation). For k = 5, the variability ranges are up to 40%.

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Concentration factors $k$ for TCs defined by expert judgement: We define the concentration factor $k$ as a statement of the experts’ confidence in two dimensions: (i) confidence in knowledge about the technology, and (ii) confidence in knowledge about the specific substance, as shown in Table 2. The knowledge about the technology is defined by the readiness level and its complexity. The knowledge in the substance is defined by a judgement how well the substance behaviour can be predicted.

2.5. Uncertainty propagation

Monte Carlo simulations are used to propagate the uncertainty of the TCs through the substance flow model and to quantify their effect on the resource recovery and loss ratios. The TCs for each Tech are sampled from their Dirichlet distribution and used to compute the mass flow of the entire SanSys in repeated runs. We used a total of 300 runs which proved to be sufficient for stable results (see SI-B).

2.6. Integration in the planning process

The approach from Spuhler et al. (2018) and the extension presented here are designed to provide input to strategic planning. As strategic planning framework, we use structured decision making (SDM) which covers six steps generic to any decision-making process (Gregory et al., 2012) as shown in Fig. 5. The integration of our methods into a regular SDM planning process happens at steps 2, 3 and 4. In Spuhler et al. (2020) we detailed the procedure and the requirements for this integration. Here we shortly explain how the appropriateness of sanitation system can be evaluated and how this can be used to pre-select a set of sanitation system planning options.

The main input are: (1) a set so screening criteria that can be used to evaluate the appropriateness of a given technology; (2) the data describing the local conditions; and (3) the number of options that should be pre-selected.

The screening criteria (appropriateness criteria) are obtained together with stakeholders and based on the definition of sustainable sanitation. They cover technical, legal, socio-cultural and institutional aspects (see also the SI of Spuhler et al., 2020; Spuhler et al., 2018). In

Fig. 5. Overview of the methods developed in Spuhler et al. (2018) and the expansion presented in this paper and how they are integrated into a structured decision-making (SDM) framework. Spuhler et al. (2018) provides the procedure to generate sanitation system options. In this paper we present an approach that supports step 4 consisting in the automatic evaluation and comparison of nutrient, solids and water recovery and loss ratios of the sanitation systems.
order not to bias the final decision, only criteria which are agreed on by all stakeholders and are not expected to involve trade-offs can be used for pre-selection. Typical screening criteria are groundwater table, water and energy availability, space availability, operation and maintenance skills availability, etc. Each technology is characterised for these criteria with data in the technology library. The data for the local conditions is provided by the SDM process. By matching the technology data to the local conditions, a technology appropriateness score (TAS) is calculated. By aggregating all TAS within a system, the system appropriateness scores (SAS) is obtained. The SAS varies between 0 and 100% and expresses the confidence in the suitability of the system for the local conditions (Spuhler et al., 2018).

The appropriateness assessment is not enough to limit the options to a manageable number (e.g. something between three and 50 options). Thus, an additional step is required. This step consists in selecting a set of options which is appropriate but also diverse in order to further avoid bias. The diversity is defined by system templates (Spuhler et al., 2018; Tilley et al., 2014). Using nine binary conditions, we define 19 templates as shown in Table 3. By selecting the most appropriate sanitation system from each template, a set of sanitation system planning options is obtained which is locally appropriate, of manageable size, and diverse.

2.7. Implementation

All algorithms used in this paper are implemented in Julia (Bezanson et al., 2017) and available for download as a package at https://github.

Fig. 6. Overview of the set of sanitation technologies currently available in the technology library for five functional groups. Each box represents a technology. The arrows represent the input and output products. So far only toilet sources are implemented, although greywater, stormwater, and organic waste sources can also be considered by the model.
Table 3
System templates (ST) used to characterize the sanitation system (SanSys) options. The STs are adapted from Spuhler et al. (2018). Each of the 19 STs has a unique profile defined by a value for the nine properties. ‘1’ means that the property applies; 0 means that the property does not apply; and ‘ND’ (not defined) means that the property does not apply to this ST.

<table>
<thead>
<tr>
<th>Group</th>
<th>Name</th>
<th>System template profiles</th>
<th>Dry material (pit humus, compost, dried or stored faeces)</th>
<th>Onsite sludge production</th>
<th>Urine</th>
<th>Blackwater</th>
<th>Transported black- or brown water</th>
<th>Effluent transport</th>
<th>Biogas, biochar or briquettes</th>
<th>Transported biogas, biochar, or briquettes</th>
<th>Onsite single pit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onsite simple</td>
<td>ST1 Dry onsite storage with sludge production without effluent transport</td>
<td>Onsite single pits with sludge production.</td>
<td>ND</td>
<td>1</td>
<td>0</td>
<td>ND</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>ST2 Dry onsite storage with sludge production with effluent transport</td>
<td>Onsite single pits with sludge production and with effluent transport.</td>
<td>ND</td>
<td>1</td>
<td>0</td>
<td>ND</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ST3 Dry onsite storage and treatment without sludge production</td>
<td>Onsite storage of excreta and transformation to either pit humus or compost.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>ND</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Urine</td>
<td>ST4 Dry onsite storage without treatment with urine diversion without effluent transport</td>
<td>Simple onsite storage of dry or wet toilet products with sludge production (e.g. single pits, double pits, twin pits) with onsite effluent management (e.g. soak pits).</td>
<td>ND</td>
<td>1</td>
<td>1</td>
<td>ND</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>ST5 Dry onsite storage without treatment with urine diversion with effluent transport</td>
<td>Simple onsite storage of dry or wet toilet products with sludge production (e.g. single pits, double pits, twin pits) with effluent transport to offsite management.</td>
<td>ND</td>
<td>1</td>
<td>1</td>
<td>ND</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ST6 Dry onsite storage and treatment with urine diversion</td>
<td>Urine diversion dry toilets (UDDTs) or dry composting systems with urine diversion.</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>ND</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ST7 Onsite blackwater without sludge and with urine diversion</td>
<td>Onsite composting systems with urine diversion.</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>ND</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ST8 Offsite blackwater treatment with urine diversion</td>
<td>Sewer systems with urine diversion.</td>
<td>ND</td>
<td>ND</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>ND</td>
<td>0</td>
<td>0</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Biofuel</td>
<td>ST9 Onsite biogas, biochar, or briquettes without effluent transport</td>
<td>Biogas reactors or other fuel producing technologies (e.g. ladep) with onsite effluent management (e.g. soak pit).</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>ND</td>
</tr>
<tr>
<td>ST10 Onsite biogas, biochar, or briquettes with effluent transport</td>
<td>Biogas reactors or other fuel producing technologies (e.g. ladep) where effluent goes to simplified sewer.</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>ST11 Offsite biogas, biochar, or briquettes without blackwater transport</td>
<td>Offsite production of biofuel from pit humus or sludge (e.g. from septic tanks).</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>0</td>
<td>ND</td>
<td>1</td>
<td>1</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>ST12 Offsite biogas, biochar, or briquettes with blackwater transport</td>
<td>Offsite co-digestion of blackwater collected through sewer lines.</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>1</td>
<td>1</td>
<td>ND</td>
<td>1</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Blackwater</td>
<td>ST13 Onsite blackwater without sludge and without effluent transport</td>
<td>Blackwater stored, dewatered, and transformed to compost or pit humus (e.g. twin-pits), onsite effluent management (e.g. soak pit).</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
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Table 3 (continued)

<table>
<thead>
<tr>
<th>Group</th>
<th>System template profiles</th>
<th>Dry material (pit, or stored faeces)</th>
<th>Effluent transport</th>
<th>Biogas, or briquettes</th>
<th>Biogas, or briquettes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST14</td>
<td>Onsite blackwater (e.g. twin-pits) with effluent transport</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>ST15</td>
<td>Blackwater stored, dewatered, and transformed to compost or pit humus or sludge</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>ST16</td>
<td>Onsite blackwater (e.g. septic tank) with effluent transport</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>ST17</td>
<td>Blackwater stored, dewatered, and transformed to compost or pit humus or sludge</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>ST18</td>
<td>Offsite blackwater treatment without effluent transport</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>ST19</td>
<td>Offsite blackwater treatment without effluent transport</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
</tbody>
</table>

Table 4

Overview of estimated inflow substance masses based on international literature per person and year. TP: total phosphorus, TN: total nitrogen, TS: total solids, H2O: water. The amount of TP, TN, and TS are the same for all sources; only water inflow masses depend on the flush volume. The assumed amount of flushing water is 2 L/day/person for the pour flush toilet and 60 L/day/person for the cistern flush toilet. Details on the assumptions and literature references are provided in SI-B.

<table>
<thead>
<tr>
<th>Substance</th>
<th>U1. cistern flush toilet</th>
<th>U2. pour flush toilet</th>
<th>U3. dry toilet</th>
<th>U4. urine diversion dry toilet (UDDT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflows in kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP year⁻¹ for 1 person</td>
<td>0.548</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS equivalent H2O</td>
<td>22447.1</td>
<td>1277.1</td>
<td>547.1</td>
<td></td>
</tr>
</tbody>
</table>

com/Eawag-SWW/SanitationSystemMassFlow.jl (v1.0). A newer version can be accessed at https://github.com/santiago-sanitation-systems/Santiago.jl. Case specific scripts are not included but can be shared upon request. The technology appropriateness model is separately implemented in R (R Development Core Team, 2018) and can be used independently. It is accessible at https://github.com/Eawag-SWW/TechAppA (v1.0).

Data and code used for the didactic application are available in the associated data package 1: https://doi.org/10.25678/0000HH (dataset Spuhler, 2020). The input data contains the definition of Techs including their transfer coefficients and appropriateness profiles. The output data contains plots of all systems, a table with the characteristics and mass flow results of all systems, and a Julia database to load and work with the data interactively.

The technology library including the TCs, a detailed description of each technology, and instructions how to add or modify technologies is provided in the associated data package 2: https://doi.org/10.25678/000000 (dataset Spuhler and Roller, 2020) and in Spuhler and Roller, 2020. The data package also contains a comma separated file for more convenient modification and which can be directly read by the models.

3. Results

Table 5

Characteristics of systems generated in the didactic application. Only the mass flow results for total phosphorus (TP) are shown and expressed in % of entered substances. The full results are provided in the associated data package 1 ERIC: https://doi.org/10.25678/0000HH (dataset Spuhler, 2020) and in SI-E. ID: unique identification number; Length: number of technologies contained in the system. The value in parentheses “(”) represents the standard deviation (SD) resulting from the Monte Carlo simulation.

<table>
<thead>
<tr>
<th>ID</th>
<th>Length</th>
<th>TP recovery ratio [%]</th>
<th>TP air loss [%]</th>
<th>TP soil loss [%]</th>
<th>TP water loss [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>10 (9)</td>
<td>0</td>
<td>89 (9)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>10 (8)</td>
<td>0</td>
<td>89 (9)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>6 (5)</td>
<td>0</td>
<td>93 (6)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>28 (17)</td>
<td>0</td>
<td>71 (18)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>99 (1)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>7 (7)</td>
<td>0</td>
<td>91 (7)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>10 (10)</td>
<td>0</td>
<td>89 (10)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>10 (9)</td>
<td>0</td>
<td>89 (9)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>28 (18)</td>
<td>0</td>
<td>71 (18)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>99 (2)</td>
<td>1 (2)</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>28 (18)</td>
<td>0</td>
<td>72 (18)</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>99 (1)</td>
<td>1 (1)</td>
</tr>
</tbody>
</table>

To use the developed substance flow model, we require the potential technologies, a priori data on the transfer coefficients and their
uncertainties, as well as the masses per person and year entering a system. To exemplify the use of the model and its outputs we present a didactic case. To illustrate the entire potential of the model we apply it to all 41 technologies resulting in 101,548 valid system configurations. To show the relevance for strategic planning and implications for practice we use the case of a rapidly growing small town in Nepal previously presented in Spuhler et al. (2018).

3.1. Technology library

The aim of the technology library is to cover a large and diverse set of conventional and emerging technologies. To compile the library we used as starting point the list of technologies provided by Spuhler et al. (2018) and Tilley et al. (2014). We complement this list here with five novel technologies: liquid urine fertilizer (aurin) production and application (Bonvin et al., 2015; Etter et al., 2015; Fumasoli et al., 2016), briquetting based on the process implemented by Sanivation in Naivasha (Jones, 2017), and latrine dehydration and pasteurization, ladepelletizing (Septien et al., 2018b). The resulting 41 technologies currently available in the technology library are shown in Fig. 6.

This technology library has two important features:

• First, it covers a set of technologies which is able to represent the entire system option space including different concepts (dry, wet, urine diversion, biofuel product) and degrees of centralisation (from onsite to decentralized, centralized, and hybrid systems). This is illustrated by the system templates described in section 2.6 and used in the full-scale example application (section 3.6).

• Second, using the generic definition of Techs and products, the library can easily be extended with any (future) technology.

3.2. Substances: total phosphorus, total nitrogen, total solids, and water

For every technology we added the transfer coefficients for four substances with different properties: Total Phosphorus (TP), Total Nitrogen (TN), Total Solids (TS) and water (H2O). TP and TN are both

![Fig. 7. Overview of losses, transfers, and recoveries for all four substances and 41 technologies. Each bar represents a technology, the colours indicate the fate of the substances which is either lost, transferred, or recovered. From top to bottom the technologies are grouped by functional group (rows). U: user interface, S: storage and treatment, C: conveyance, T: (Semi-)centralized treatment, D: reuse or disposal. The k is the concentration factor indicating the uncertainty. A low k means high uncertainty. See Fig. 6 for the technologies behind the labels (e.g. T9 = Co-composting). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)](image-url)
important macronutrients with significant environmental pollution potential and at the other hand predicted to deplete soon. TS can be used as a proxy for energy, for example in the form of briquettes or biochar (e.g. Andriessen et al., 2019; Motte et al., 2013), and for organic matter that can be used as soil amendment (e.g. Diener et al., 2014; Septien et al., 2018a). Water in many urban areas is under increasing pressure and has become a scarce commodity. For TN and TS, the behaviour is also more difficult to predict than for TP and water. Water is a special case because the inflowing masses vary significantly depending on the source (e.g. dry toilet versus cistern-flush toilet) and from a sustainability perspective, both the requirement and the recovered masses are interesting. A more detailed description of the four substances and their relevance can be found in the technology library ([dataset] Spuhler and Roller, 2020). In summary, the choice of substances allows to quantify resource recovery and losses in terms of nutrients, energy, and water and to demonstrate the approach for substances with different properties.

3.3. Transfer coefficients

The literature review and collection of expert knowledge resulted in the definition of transfer coefficients for the 41 technologies and the four substances. For the literature review, preference was given to peer-reviewed literature, but other literature such as project reports, fact-sheets, and books were also considered. In absence of literature data, we either made a best guess ourselves or contacted colleagues directly involved in the development of the technology. This was the case for aurin production, briquetting, and ladepa pelletizing. The detailed list of all TCs and corresponding literature references are available in the SI-D and in [dataset] Spuhler and Roller, 2020. Because this data is generic and could be used for any other application, we present an overview in Fig. 7. Each bar corresponds to a technology and the colours represent the fraction of a substance which is either transferred, lost to air, soil, or water, or recovered. This figure also indicates some pattern that are
confirmed by the analysis of recovery ratios from the full-scale application:

- The functional groups storage and treatment (FG S) and (semi-) centralized treatment (FG T) have a stronger contribution to losses.
- Recovery can only occur in the sink technologies (FG D) and many of the sink technologies provide either almost 100% recovery (recovery sinks) or 100% losses (disposal sinks).

3.4. System inflows

We used literature data to provide the inflowing masses for the four substances for one person and year (e.g. Lohri et al., 2010; Rose et al., 2015). Although the masses vary depending on the diet of people, the inflow masses presented in Table 4 provide an estimate that can be applied to any case in the absence of more detailed knowledge. Details on the underlying calculations are provided in SI-B. As the current version of the technology library only considers toilet sources, the inflowing mass is equal to the mass of substance contained in the urine, faeces, and flushing water. The values can be scaled using the number of inhabitants within an area or adapted if local data is available.

3.5. Didactic application

This simple didactic application helps to illustrate the substance flow model, the mass flow calculations, the estimations of resource recovery and loss ratios, and the consequences of the TC uncertainties. The results are fairly straightforward and intended to demonstrate that the fully automatic procedure is capable of producing reasonable outcomes. The example is based on only nine technologies: U2. pour flush toilet, S4. single pit, C4. human transport of dry material, T3. sludge drying bed, T9. co-composting, T12. horizontal subsurface flow constructed wetland, D4. application of compost and pit humus, D6. surface solids disposal, D10. Irrigation. The details on the transfer coefficients and their uncertainty is presented in SI-D and the associated data package 2 ([dataset] Spuhler and Roller, 2020).

3.5.1. Overview on results

The nine technologies can be combined into 12 systems listed in Table 5. All of them are valid according to our definition and very plausible from a practical point of view (see supplementary information SI-E). The mass flow calculations provide the flows in each technology, as well as the losses to air, soil, and surface water. These flows and losses allow to calculate the recovery and loss ratios for the four substances for the entire systems. The recovery and loss ratios can be calculated as mass or as ratio in percentage. Both results include the uncertainties of the transfer coefficients that can be expressed as standard deviation.

In Fig. 8, we present three SanSys in more detail:

- ID-12 is the simplest system possible with the nine technologies. But this system provides no phosphorus recovery, as it contains only a disposal sink.

![Figure 8](#)

Fig. 9. Recovery ratios of all sanitation system options for total phosphorus and accumulated for all four substances. The accumulated recovery corresponds to the sum of the ratio for phosphorus (TP), nitrogen (TN), total solids (TS), water (H2O). The y-axis shows the recovery ratio. The x-axis shows the system templates STs (no system from ST7 and ST8 was generated). Each dot represents a system. The color represents the source of the system which is either a cistern flush toilet, pour flush toilet, dry toilet, or urine diversion dry toilet. Because the results are shown in percentage and not in masses, the recovery ratios for the cistern flush and pour flush toilet are identical and therefore only light blue dots are visible. The grey box represents a boxplot of the same data with the line being the mean value. The figure shows that system templates are no indicator for the recovery ratio and that therefore it is important to know the recovery ratios of all possible systems. To optimise recovery, one of the systems at the upper edge of ST9 should be selected which combine urine diversion with biofuel production. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
• ID-6 is the most complex system which also integrates loops.
• ID-11 is similar to ID-12 but contains a recovery sink (‘the application of compost’) and is therefore the system with the highest resource recovery ratio for phosphorus.

For ID-11 we provide in details the flows for phosphorus. This is interesting, because it shows that the recovery ratio is mainly influenced by one technology: the single pit where 72% of phosphorus is lost to soil. For total nitrogen (TN) and total solids (TS), more important losses occur in the co-composting process to the air. Not only the losses, but also the uncertainties are dominated by the single pit where the standard deviation for the TP to soil is 18% (Table 5). Analysing the results of all 12 system we can identify three groups. Group 1 includes systems with recovery sinks (co-composting and application of compost, ID4, ID9, ID11) and high phosphorus recovery ratios. Group 2 includes systems with both loss sinks (sludge drying beds and surface solids disposal) and recovery sinks, ID1, ID2, ID3, ID6, ID7, and ID8) and low phosphorus recovery ratios. Group 3 includes systems with only loss sinks (ID5, ID10 and ID12) and no phosphorus recovery at all.

From this example we learn four things:

• The model is capable of creating reasonable system configurations and automatically calculating reasonable mass flows through the systems.
• Resource recovery depends on the technology interaction. For instance, the fraction of inflowing mass that can be recovered in a sink depends on how much losses occur on the way.
• There are some key technologies that have a major impact on the recovery ratios and the uncertainties (single pit in this example). Thus, in some instances, the recovery ratio can be significantly enhanced or reduced by exchange only one technology.
• Knowing uncertainties allows to assess the robustness of the results. The uncertainties obtained by the model are substantial, but comparable to those obtained in studies using a conventional post-ante material flow analysis (e.g. Montaner and Belevi, 2008).

3.6. Full-scale application

Using all the 41 technologies from the library, the system builder generated 101,548 valid SanSys of 17 system templates as defined in Table 3. The substance flows were modelled for 1000 people equivalent (corresponding to a larger neighbourhood) and for all 101,548 systems and four substances total phosphorus (TP), nitrogen (TN), total solids (TS), and water (H2O).

3.6.1. Resource recovery ratios

In Fig. 9 we show the results of the resource recovery ratios grouped by system template as defined in Table 3 which are indicated in the x-axis. Each dot represents one of the 101,548 systems. The colour represents the substance designating the source of this system which is either a cistern flush toilet, pour flush toilet, dry toilet, or urine diversion dry toilet. No system from ST7 and ST8 was formed because the urine diversion flush toilet was not considered. The y-axis shows the recovery ratio between 0 and 100%. Because the results are shown in percentage and not in masses, the recovery ratios for the cistern flush and pour flush toilet are identical and therefore overlap (only light blue dots visible).

As expected across the more than 100,000 systems, all four substances showed recovery ratios from nothing to almost 100% even within the same templates. The only exceptions are the simple onsite templates (ST1 and ST2) with exclusively low recovery ratios. This shows that system templates are not enough indicator for resource recovery. Fig. 9 provides additional information:

• For phosphorus recovery, the simple onsite blackwater systems (ST13 and ST14) have the highest mean recovery ratio. Thus, if you were interested in high phosphorus recovery, you would probably go for a system from one of these two templates.
• But for the accumulated recovery ratio, the results are different. Urine diversion templates (ST4 to ST6) show the highest mean accumulated recovery, followed by the biofuel templates (ST9 to ST12) and some blackwater templates (ST14, ST16). Thus, if the objective is resource recovery in general, you would prioritise the templates ST4 and ST5.
• However, if you are not interested in the templates, but are interested in the optimised recovery of phosphorus, then you would choose one of the systems at the upper edge of ST 3 (onsite composting) or ST14 (onsite blackwater systems). These systems include few treatment steps and are therefore particularly short. Urine diversion systems are generally longer (more products, more bifurcation) and losses are generally high for very long systems. Short systems reduce the risk for losses but can also result in very low effluent quality (e.g. direct irrigation after a septic tank).• If you are independently of the templates interested in optimising accumulated recovery (not only phosphorus), then the choice would be one of the systems at the upper edge of ST9 which combines urine diversion with the production of biofuel.

3.6.2. Dependencies with other sustainability criteria

To illustrate the integration with the planning process and the dependencies of resource recovery with other sustainability criteria we use the case of Katarniya, a rapidly growing small town in Nepal already used in Spuhler et al. (2018). 15 screening criteria from the library ([dataset] Spuhler and Roller, 2020) are used to calculate the sanitation system appropriateness scores SAS. In Fig. 10 we plot again all 101,548 systems comparing the resource recovery ratio with the SAS. For TP, TN, and TS we show the ratio in percentage. For water, we provide the absolute volume [m³ year⁻¹], as this is the more relevant information for comparing different systems. The coloured dots indicate the selected systems which are those with the highest SAS from each template. From this figure we learn two things:

• The selected systems are distributed over the entire range of recovery confirming that templates are no indicator for resource recovery (see previous Fig. 9).
• There exist no clear “winners” solutions. For some templates (for instance for ST3 or ST 19) there exists a high probability that systems could be found that are both, appropriate and enhancing recovery. But for others recovery ratio and appropriateness are diverging. Similar trade-offs would be expected for other sustainability indicators such as costs. Moreover, there exists also some systems that have a high recovery ratio for one substance but not for another implying that there exist also trade-offs among different types of reuse (e.g. energy versus nutrients).

These results highlight the need for an automated model that enables the consideration of resource recovery ratios already at the pre-selection phase in order to make trade-offs explicit and thus negotiable.

4. Discussion

4.1. Lessons from the model applications

The application of the model provided us with following insights:

• The amounts of resources potentially recovered in sinks designed for reuse is limited by the resources that are lost on the way. This is a simple example showing the importance of technology interactions on system level for resource recovery and cannot be evaluated based on single technology alone.
• Some system characteristics, like the integration of a specific technology or the length (number of technologies) can provide hints on the potential resource recovery, but no reliable guidance.

• There are trade-offs between different potentially recovered resources (e.g. phosphorus and water). Only some systems such as from ST9 manage to combine different reuse optimising the accumulated recovery ratios. There are similar trade-offs expected to arise in comparison with other sustainability criteria such as appropriateness or costs. Because there are no clear predefined winners or losers, it is important to know the resource recovery ratios of all systems options for the pre-selection and not only for some options during the detailed evaluation.

The relevance of technology interaction shows that an automated approach that can look at all possible systems instead of single technologies is useful. Because of the trade-offs, the model must be applicable ex-ante in order to support strategic planning.

4.2. Advantage and novelty of the approach

The presented approach integrates algorithms, literature data and expert knowledge into a systematic tool. This provides three main advantages:

• First, the model it is generic and thus can be easily extended to accommodate new technologies or products.

• Second, the model is automated. This allows an application to a diverse and large range of sanitation technologies and systems simultaneously with minimal manual labour.

• Third, all the data to apply the model ex-ante are available and uncertainties are systematically considered.

In the following, we discuss some of these aspect in more detail.

Generalisation and automation: the generic definition of technologies and systems enabled the automation. This generalisation brings however also a number of limitations which are discussed below.

Integration of literature data: A major strength of our approach is the quantitative integration of data from literature. The data in the associated data package 2 at ERIC: https://doi.org/10.25678/0000ss ([dataset] Spuhler and Roller, 2020) are based on an extensive literature research, are complemented with expert knowledge, and present a compact and accessible overview of the currently available knowledge on the performance of conventional and emerging technologies. Confidence in knowledge about the performance of a specific technology is reflected in the defined uncertainties. This large body of independent knowledge is integrated to the local planning process through the model results.

Fig. 10. Point plots of recovery ratios of all sanitation systems compared to the system appropriateness scores. For water, we provide the absolute volume \( \text{(m}^3/\text{year}^{-1}) \), as this is the more relevant information for comparing different systems. The selected systems (highest SAS) from each system template (ST) are shown as coloured dots and marked with the system ID. The templates are described in detail in Table 3. The figure shows that some of the appropriateness show low recovery ratio, confirming that templates are a good indicator for diversity. However, given that almost all templates also include systems with high recovery ratio, there exists a high probability that systems with both high recovery and high SAS could be found.
Uncertainty estimations: For each recovery and loss ratio, the model also quantifies the uncertainties arising from the transfer coefficients. For instance, in the didactic application the mean phosphorus recovery ratio is 0.154 kg per person and year (see Fig. 8) with a standard deviation of 0.099 kg (the uncertainty is relatively high due to the single pit). The detailed interpretation of these uncertainties is not trivial, as they aggregate different types of uncertainties: (i) related to local environmental conditions, (ii) specific to the implementation of a technology, (iii) related to the technology in general, and (iv) related to ignorance, particularly of novel technologies and their implementation at scale. However, this interwoven mix of uncertainty sources is certainly not unique for this model. Once the uncertainties are quantified, the robustness of each result can be evaluated (e.g. Scholten et al., 2015). Moreover, we observed overall uncertainties of maximally 28% (standard deviations for the recovery ratio of TN) in the full-scale application. This accuracy is comparable to other studies using classical ex-post material flow analysis (Keil et al., 2018; Meinzinger et al., 2009; Montangero et al., 2007).

Comparison with other approaches: Existing approaches to evaluate resource recovery from sanitation systems are either based on qualitative expert judgement (e.g. McConvile et al., 2014) or use material flow analysis and substance flow modelling (e.g. Espinosa and Otterpohl, 2014; Montangero and Belevi, 2008; van der Hoek et al., 2016; Yoshida et al., 2015). The first approach is limited in its transparency (e.g. what is the absolute scale and how do different expert interprets the various score). The second approach requires detailed knowledge about the technology implementation and large amount of data and can therefore only be applied post-ante for few options at a time (e.g. Dahlmann, 2009; Meinzinger et al., 2009; Montangero et al., 2007; Ormandzhieva et al., 2014; Schütze and Alex, 2014; Ushijima et al., 2012; Woltersdorf et al., 2016; Yiougo et al., 2011). To our knowledge, the here presented approach is the first one which is applicable for the entire sanitation system option space and ex ante.

4.3. Limitations

The approach presented here cannot replace a detailed mass flow analysis for existing systems (ex-post analysis). It is intended for automated ex-ante analysis to provide guidance based on the limited knowledge for strategic planning. Other limitations are due to a number of simplifications:

- How technologies are defined has an impact on the modelling results and should be carefully verified for a specific case. An example is the very generic definition of a single pit, which allows all sorts of input. As a consequence, this technology dominates the uncertainties and also in some cases the losses of a system (especially for phosphorus). However, local experience with specific implementations, which would provide additional data, can decrease the uncertainty and provide a better estimation of the transfer coefficient.
- Similarly, transfer coefficients are designed to be generic and therefore ignore many factors such as size of the technology or ambient temperature.
- The third simplification concerns the definition of ‘products’. The model uses a standardized set of products based on (Tilley et al., 2014). The purpose of which is to define the compatibility of two technologies (Maurer et al., 2012). It might be required to integrate context-specific information (e.g. quantity and quality of products, legal requirements) to validate systems from an engineering perspective (Spuhler et al., 2018).
- Another simplification is the requirement that the sum of all TCs for every substance of a Tech is equal one. This boundary condition enables the modelling of steady states but also means that biological fixation is ignored. But for many cases this is not very relevant and can therefore be neglected.

Importantly, these simplifications allow the automation and generalization of the model application. Consequences of the simplifications are captured in the uncertainty calculations. As the model is generic and flexible, the user is free to be more specific in the definitions of the input data for technologies, products, or transfer coefficients if more accuracy is needed.

4.4. Implications for practice

The main intention of the substance flow model is to provide information for the strategic planning in order to enable the prioritisation of resource efficient systems at an early planning phase. The approach complements the systematic generation of sanitation system options from Spuhler et al. (2018) by quantifying relevant indicators for resource efficiency and environmental protection in an ex-ante analysis. The information can be integrated at two levels of a structured decision-making process:

- The resource recovery and loss potentials can be used at the at the pre-selection stage if resource recovery or losses are part of the non-negotiable decision objectives. A possible example would be to make the low nutrient losses a precondition for appropriateness in the case of the presence of highly sensitive surface waters. Another example would be, to make optimised resource recovery as a precondition in line with SDG 6.
- The information can also be used together with other sustainability indicators during the detailed evaluation of pre-selected options using any multi-criteria decision analysis (MCDA) method. It is obvious that additional information, such as costs and value functions, would be required in the MCDA for different stakeholders (e.g. phosphorus recovery might have the same value for a given stakeholder as costs). If MCDA is not the preferred evaluation method, the results could also be fed into life cycle analysis (LCA).

The results could also be used for research. Either one could check the resource recovery ratio of newly developed technologies when integrated into entire systems. Or the full-scale application results could serve to identify system characteristics for resource recovery and guide future technology and system configurations.

It is also important to note, that in principle, our model could be applied for any substance. We have chosen the substances which are most relevant to the discourse on sustainable sanitation, water management, and resource recovery. Implementing the model for additional substances should be straightforward, as the substances already calculated exhibit very different properties.

4.5. Outlook

Generic results: The here presented full-scale application is, except for the appropriateness assessment based on generic information. As a result, the relative resource recovery ratios are independent of the inflow masses and therefore fully transferrable. Compiling these data into a catalogue would allow to make it available as a low-level planning support.

Detailed evaluation of the full-scale results: As the full-scale case is representative for many cases, a detailed analysis of the results could allow better understanding about how some system characteristics relate to resource recovery. System templates, for instance, proved to be insufficient predictors for resource recovery. On the other hand, the results showed, that some key technologies, mainly from the functional group S (storage) and T (treatment) have a mayor influence on losses. Moreover, the type of source, the type of sinks, or the length could have an effect. We also observed that the combination of different reuse pathways (e.g. urine diversion and biofuel production) allows to optimise recovery. An interesting next step would be the further analysis of these results in order to investigate how these characteristics could...
guide the development of future technology or system innovations.

Integration into an accessible tool: We also see an interest in making the algorithms and the data available as user-friendly software. This software would provide a much-needed complement to decision-making tools such as the Excreta Flow Diagrams (Peal et al., 2014), Sanipath (Robb et al., 2017), and Quantity and Quality of Faecal Sludge (Strande et al., 2018), and it would close an important gap for implementing SDM procedures such as CLUES (Lüthi et al., 2011) or Sanitation21 (Parkinson et al., 2014) in practice.

Technology library expansion: The technology library could also be adapted to capture future technology innovations and improved knowledge (local and international). A straightforward extension would be the addition of other technologies specific to a certain context (e.g. emergency sanitation) or other products such as organic solid waste and stormwater for a more holistic urban planning support.

5. Conclusions

Currently, we observe a development of novel sanitation technologies and system configurations and an increased attention to sustainability in the sanitation sector. We therefore provide an approach to systematically evaluate resource recovery and losses of the increasingly larger and more diverse range of sanitation systems early in the planning process.

- The approach allows to model substance flows and to quantify resource recovery and loss ratios for nutrients (phosphorus and nitrogen), total solids (as an indicator for energy and organics), and water. It builds on and complements the previously published tool that generates locally appropriate sanitation systems (Spuhler et al., 2018).
- The main advantages of the approach are that it is generic, automated, and considers uncertainties in order to be applied ex-ante for the entire option space build from a large set of conventional and emerging technologies.
- The resulting recovery ratio enable the prioritisation of resource efficient sanitation systems in strategic planning.
- At the core there is a technology library that provides a priori data for transfer coefficients for the four substances and 41 technologies that can be combined in 101,548 systems. This library is flexible and can be expanded with any (future) technology.
- Uncertainties are included as a means of capturing the diversity in knowledge and performance ranges. This enables the robustness of the results to be tested and used in formal decision support methodologies such as MCDA.
- Important limitations of the approach are the simplifications and generalization in the technology and product definitions and the linearity of transfer coefficients. These simplifications enable generalization and automation and their consequences are captured in the uncertainty. For a specific case study, the technologies and products can be adapted with available detailed specifications.
- The application to a didactic case shows that the model can generate plausible results, and that the resource recovery depends on technology interactions and therefore has to be evaluated for all possible systems and not on single technology level.
- The full-scale application provides substance flows and resource recovery ratios for over 101,548 valid system configurations. These results show that there exist trade-offs among different types of reuse (e.g. energy versus nutrients) or different sustainability indicators (e.g. local appropriateness versus resource recovery). This highlights the need for such an automated and generic approach that provides the recovery ratio data already ex-ante at the pre-planning phase.
- As resource recovery becomes more relevant and novel sanitation technologies and system options emerge, the approach presents itself as a useful tool for strategic sanitation planning in line with the SDGs.

Author contribution

Spuhler Dorothee, conceptualised this publication together and jointly managed reviewing and editing, was responsible for data curation, Formal analysis, Investigation, and validation, The methodology and software were developed jointly by, also wrote the original draft and visualized the results, were responsible for funding acquisition. Resources (primary literature data) were collected by Leandra Roller. Scheidegger Andreas, conceptualised this publication together and jointly managed reviewing and editing, supervised the process. Maurer Max, conceptualised this publication together and jointly managed reviewing and editing, supervised the process, were responsible for funding acquisition. Resources (primary literature data) were collected by Leandra Roller.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111785.

Terms and abbreviations

| EJ | Expert judgement |
| FG | Functional group of a sanitation system. Five FGs are used: |
| U | User interface |
| S | Collection and storage |
| C | Conveyance |
| T | Treatment |
| D | Reuse or Disposal |
References


