Review Paper

Review of frameworks and tools for urban strategic sanitation planning: considering technology innovations and sustainability

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ABSTRACT

To achieve citywide inclusive sanitation in developing countries, a strategic sanitation planning approach (SSA) needs to provide a variety of technical solutions that respond to different urban realities. Despite the development of various SSA frameworks, sanitation planning still often follows a 'one-size-fits-all' approach. Structured decision making (SDM) can help by balancing trade-offs among different solutions. But SDM requires a set of appropriate sanitation options to choose from. Because conventional sewer-based sanitation is often inappropriate, many novel technologies and systems have been developed (e.g. container-based sanitation). While these innovations enhance sustainability, they also increase planning complexity. In this review, we look at available frameworks and tools for SSA and discover a lack of systematic tools for the identification of planning options that are able to consider the growing portfolio of available solutions and multiple sustainability criteria. Therefore, we critically compare 15 tools from which we compile eight qualities that could help any future tool address the current sanitation challenge: it should be comprehensive, automated to deal with a large number of options, systematic, flexible towards future innovation and should consider all sustainability dimensions, make a contextualized evaluation, allow for participation, and consider uncertainties to be applicable ex-ante also for novel technologies.

Key words | appropriate technologies, developing countries, SDG 6, strategic sanitation planning approach (SSA), structured decision making (SDM), sustainable sanitation

HIGHLIGHTS

- Provides a historical review of frameworks for strategic sanitation planning.
- This reveals a lack of systematic tools to identify suitable planning options considering innovations.
- Compares how 15 tools for option selection address the current urban sanitation challenge.
- Compiles eight qualities from this analysis that could improve any future tool.
- Most important qualities are the ability to deal with the growing portfolio of novel technologies, multiple criteria, and uncertainties.
INTRODUCTION

Safe sanitation services are a precondition for healthy people and a healthy environment and thus also for social and economic development (WHO and UNICEF 2000, 2013; Hutton & Varughese 2016). Still in 2017, only 45% of the global population used safe sanitation, leaving the rest of the world at high risk for diseases and death (UN 2019). To reach the Sustainable Development Goal (SDG) 6 by 2030, each day an additional one million people have to get access to safe sanitation (Mara & Evans 2018). Half of those that need access live in urban areas of developing countries where most current population growth is taking place (Dodman et al. 2013; UNDESA 2014; WHO and UNICEF 2019). Even though there is less open defecation in urban than in rural areas (1% as compared to 18%, WHO and UNICEF 2019), safe collection and treatment downstream is more often lacking (47% as compared to 43%, WHO and UNICEF 2019). Only 18% of the products from domestic on-site sanitation facilities are treated worldwide (UN-WATER 2018). High-density and low-absorption capacity in the urban environment further increase the impact of unsafe sanitation. Climate change exacerbates the problem (World Resources Institute 2020). Unsafely managed urban sanitation creates hotspots of environmental degradation and public health hazards worldwide (Lüthi & Narayan 2018). Rapid unprecedented population growth, high density, and the lack of financial and human resources in many developing urban areas make it extremely difficult to address this problem (Tremolet et al. 2010; Isunju et al. 2011; UN-HABITAT 2012; Dodman et al. 2013, 2017; Ramoa et al. 2014).

Conventional approaches to urban sanitation are top down and technology driven and have often failed to address the current urban sanitation challenge. Already in the 80s, it was recognized that improving access to sanitation in urban areas of developing countries requires a strategic sanitation planning approach (SSA). Such an approach is multi-technology, multi-criteria, multi-professional and allows for incremental improvement by engaging with the community (Kalbermatten 1982; Kalbermatten et al. 1982; Middleton & Kalbermatten 1990; Wright 1997; Kalbermatten & Middleton 1999; Tayler et al. 2000, 2003; Lüthi et al. 2009a; Reymond et al. 2016; Scott et al. 2017). Since then, various SSA frameworks have been developed including, for instance, Household-centred Environmental Sanitation (HCES) or Sanitation21 (Eawag 2005; Parkinson et al. 2014). Despite these efforts, sanitation planning in urban settings of developing countries still tends to follow a ‘one-size-fits-all’ approach today. This leads to inappropriate technology choices, lack of ownership, and many failing projects worldwide (e.g. Jurga 2009; Montgomery et al. 2009; Lüthi et al. 2010; Kvarnström et al. 2011; Brunson et al. 2013; Starkl et al. 2013; Tilley et al. 2014). A main reason for failure is the lack of political will to invest time and human and financial resources for long-term strategic planning. Another reason is that planners lack the knowledge and experience concerning viable solutions for high-density low-income areas where water, energy, space, and land tenure are often lacking.

This has triggered the development of many novel sanitation technologies and system configurations and options for faecal sludge management (FSM) as alternatives to the sewered centralized solution. Examples include urine diversion dry toilets or container-based sanitation (e.g. Tilmans et al. 2015; Tobias et al. 2017). These options are often more appropriate for developing urban areas because they are independent of sewer, energy, and water supply. The innovations are also potentially more sustainable because they can adapt to changing environmental or socio-demographic conditions and allow for resource recovery and reuse opening up opportunities for private sector engagements (e.g. Evans 2013; Diener et al. 2014; Larsen et al. 2016; Russel et al. 2019; Hoffmann et al. 2020).

Current technological innovation provides a unique opportunity, especially for developing urban areas, to bypass the unsustainable conventional end-of-pipe approach to sanitation. This has also been recognized in the most recent urban strategic sanitation planning approach: City-wide Inclusive Sanitation (CWIS) (Lüthi & Narayan 2018; Gambrill et al. 2013; Schrecongost et al. 2020).
But while technology and system options potentially enhance appropriateness, sustainability, and inclusiveness, they also increase planning complexity. This can be illustrated by a simple mathematical example: considering 5 interchangeable technologies along the 5 functional groups of the sanitation chain, thus in total 25 technologies, results already in 3,125 possible system configurations. How can we consider them all and evaluate their suitability for a given planning context?

Structured decision making (SDM) is a generic planning framework that can help in such complex situations by systematically comparing several decision options regarding the decision objectives. It combines decision analysis with engineering methods in six steps that are generic to any decision-making process (Gregory et al. 2012): (1) understanding the decision context; (2) defining decision objectives and criteria; (3) identifying decision options/alternatives; (4) evaluating consequences of the options regarding the decision objectives; (5) discussing the trade-offs and selecting the preferred options, and (6) planning, implementation, and monitoring. SDM helps reveal trade-offs and balance opposing interests and differing stakeholder preferences. In recent years, a variety of tools have been developed to put strategic planning into practice following the SDM frameworks. Examples include Community-led Environmental Sanitation (CLUES, Lüthi et al. 2011), the five criteria for sustainable sanitation (SuSanA 2008), or Shit Flow Diagrams (SFDs) (Peal et al. 2014b). But most current research focuses on understanding the context or the selection of a preferred option, assuming that a set of appropriate sanitation planning options is already available. Still, every decision support is only as good as the options presented. The current sanitation challenge requires a tool that enables engineers and planners to consider the growing portfolio of technology options and the multiple sustainability criteria when providing suitable planning options.

**AIM OF THIS PAPER**

In this paper, we attempt to answer three questions:

1. What frameworks and tools for strategic sanitation planning in developing urban areas have been developed over the past 40 years and what can we learn from them by taking an SDM perspective?
2. What tools do we have for the identification of sanitation system planning options (step 3 of SDM) and to what extent do they help address the current sanitation challenge?
3. What are the qualities that a tool for option selection should embrace in order to address the current sanitation challenge?

To answer these questions, we start with a description of the current sanitation challenge. Secondly, we provide a review of SSA frameworks and tools that evolved over the past 40 years from an SDM perspective. Thirdly, we systematically compare 15 tools for the identification of sanitation system decision options (step 3 of SDM) in order to evaluate how they address the current sanitation challenge. For this, we are mainly interested in the capability to consider (i) the growing portfolio of available sanitation technologies and system configurations; (ii) multiple sustainability criteria; and (iii) uncertainties related to the local context or novel technologies.

**METHODS**

This publication is based on a review of a broad range of literature (academic publications, project reports, grey literature, and practice-oriented publications) collected and analysed within the GRASP project (GeneRation and Assessment of Sanitation options for Planning). GRASP was carried out at Eawag from 2015 to 2020 in collaboration with Arba Minch University (Ethiopia), University of Natural Resources and Life Sciences BOKU (Vienna, Austria), the Environmental and Public Health Organisation (ENPHO) and 500B Solutions (Nepal). The literature review covered two main topics:

1. Frameworks for strategic sanitation planning: Frameworks included ‘principles’ such as defined in the strategic sanitation approach (Middleton & Kalbermatten 1990); ‘frameworks’ such as Sanitation21 (Parkinson et al. 2014); detailed ‘guidelines’ such as CLUES (Lüthi et al. 2011); as well as ‘approaches’ such as CWIS (Schrecongost et al. 2020).
2. Tools to put these concepts into practice: Tools included any decision support for sanitation planning such as ‘decision trees’, ‘computer models’, and ‘information packages’. Particular attention was given to tools supporting the identification of sanitation system decision options (step 3 of SDM).

Literature was collected through (i) targeted research using databases such as Science Direct or Scopus, as well as through (ii) expert interviews for specific recommendations. To organize and compare the collected literature, the SDM approach (Gregory et al. 2012) was chosen, as it embraces all relevant steps for any generic decision-support process.

The literature review revealed a lack of systematic tools that allow for the consideration of the growing number of technology options and decision criteria when generating sanitation decision options (step 3 of SDM). Therefore, we systematically and critically compared 15 tools that can support step 3 of SDM and identified qualities that such a tool should embrace to address the current sanitation challenge.

THE CURRENT SANITATION CHALLENGE

The world has not achieved the Millennium Development Goals (MDG) for sanitation and is not on track to reach the SDG 6.2 (UN 2019), i.e. sanitation to all. While the MDGs aimed for improved access to toilets, the SDG extended the demand for toilets with a call for looking at entire systems, considering sustainable sanitation, and providing appropriate options for inclusive services.

The idea of appropriate technology initially evolved in the 1970s in order to promote an alternative to the capital-intensive technology of modern industry (Schumacher 1973). Appropriate sanitation services require a mixture of technologies that are adapted to (i) local skills and materials; (ii) capital resources; (iii) physical conditions, such as topography, soil type, water availability; (iv) and socio-demographic conditions, such as population density, user preferences, and affordability (Menck 1975; Iwugo 1979; Kalbermatten et al. 1980; Reymond et al. 2016; Spuhler et al. 2018).

The five criteria for sustainable sanitation have been laid out by the Sustainable Sanitation Alliance in 2008 (SuSanA 2008). To be sustainable sanitation systems must not only provide appropriate technologies that are socially acceptable and institutionally and financially viable – they must also protect the environment by saving/recovering natural resources. Social acceptance here not only refers to user preferences regarding e.g. squatting or sitting or the reuse of human waste but also integrates aspects related to gender issues and the inclusion of marginalized groups. The definition of sustainable sanitation challenged the sector to shift the focus from end-of-pipe treatment towards approaches that integrate resource recovery and reuse. As cities are responsible for the largest component of global energy, water, and food consumption, as well as related wastewater and organic waste production, this is a promising approach in regard to sustainable development (Schuetze et al. 2013; Lüthi & Narayan 2018). The need for resource efficiency was also reconfirmed by SDG 6 (UN 2014) and reflected in a new functional sanitation ladder that defines the quality of sanitation not by the technology of choice but by the functions that can be fulfilled (Kvarnström et al. 2011).

Moreover, for SDG 6.2, the focus is not only on toilet access but, for the first time, also on the management of the entire sanitation value chain or sanitation service chain. The sanitation service chain refers to the system approach introduced by the Compendium of Sanitation Systems and Technologies (Tilley et al. 2014b). A sanitation system is a set of compatible technologies, which in combination, safely manage human excreta and wastewater along five functional groups: user interface, containment and emptying, transport, treatment, and safe reuse or disposal (Tilley et al. 2014b; Maurer et al. 2012, Spuhler et al. 2018). The sanitation value chain refers to the technologies in place and to the quality of services. Service provision requires institutional arrangements that fit a given technology combination. Sewer systems are one type of sanitation system that is appropriate in well-planned central areas. These conventional solutions are, however, often not viable in fast-growing low-income areas because they rely on large quantities of water, costly sewer networks, stable institutions, and long planning horizons (Larsen et al. 2016).

The increasing recognition of a need for more appropriate and sustainable solutions has led to important investments in the development of innovations for non-sewered sanitation and FSM. These innovations consider both
novel technologies and system configurations. Examples include urine diversion dry toilets (Tobias et al. 2017), briquetting (Jones 2017; Septien et al. 2018), or container-based sanitation (Tilmans et al. 2015). The innovations are more appropriate for urban areas in developing countries because they are independent from energy, water, and sewer networks. They are potentially also more sustainable because they reduce water requirements, are more adaptable to demographic and environmental changes, and allow for resource recovery and reuse (e.g. phosphorus and nitrogen, biofuel, heat) (Drechsel et al. 2011; Tilmans et al. 2015; Larsen et al. 2016; Tobias et al. 2017). They also expand the possibilities for private sector involvement in the collection and safe reuse of resources in order to complement often lacking public services (Parkinson & Tayler 2003; Schertenleib 2005; Lüthi et al. 2009a; Murray & Ray 2010; Evans et al. 2013; Diener et al. 2014; Langergraber 2014). The ‘reinvent the toilet challenge’ (BMGF 2019) has significantly influenced the sanitation sector and the potential of novel sanitation solutions has also been recognized in high-income countries, where the focus is on optimizing aging infrastructure.

The current urban sanitation challenge can be described as a combination of challenging factors. These factors include rapidly changing demographics based on unprecedented growth, lack of political will, the paucity of human and financial capacities, failure of conventional sewer infrastructure, and high uncertainty related to local socio-demographic and environmental conditions, as well as novel technologies and systems.

To address the current urban sanitation challenge, the Manila Principles of CWIS are presently being framed (BMGF 2017; Lüthi & Narayan 2018; Gambrill et al. 2019; Narayan & Lüthi 2019; Schrecongost et al. 2020; Scott & Cotton 2020). These principles advocate an approach to urban sanitation, where all members of the city have equitable access to affordable sanitation services that incorporate a safe and complete sanitation service chain and consider effective resource use and diverse sanitation services (BMGF 2017; Narayan & Lüthi 2019). Many of the principles for which CWIS is advocating have been put forward previously, e.g. through the Bellagio Principles in Urban Environmental Sanitation Planning (Schertenleib 2005). The difference between the two approaches hinges on the term inclusive. This term encompasses several elements: all urban realities (e.g. centre, informal, peri-urban), different sanitation solutions appropriate to these different realities, multiple criteria, the entire sanitation value chain, all stakeholders, larger urban goals, and marginalized group (e.g. gender, disability, low-income level, etc.) (Narayan & Lüthi 2019).

Today, there is growing global agreement that sanitation innovations need to find their way into practice in order to achieve the SDGs and CWIS (e.g. Guest et al. 2009; Willetts et al. 2010; Davis et al. 2014; Larsen et al. 2016; Anderson et al. 2018; Drangert et al. 2018; Orner & Mihelcic 2018; Davis et al. 2019; Trimmer et al. 2019; Hoffmann et al. 2020). But while sanitation innovations potentially enhance appropriateness for difficult urban settings and sustainability in general, they also increase planning complexity. How compatible are technologies and how can they be assembled into entire systems? And, how appropriate and sustainable are those systems for a given urban area? These are questions that sanitation planners are increasingly struggling with.

**STRATEGIC SANITATION PLANNING FROM AN SDM PERSPECTIVE**

From a decision-making viewpoint, selecting locally appropriate and sustainable sanitation planning options is a complex multi-criteria decision-making problem involving a large and diverse range of technologies, multiple sustainability criteria, and often divergent stakeholder preferences (Kvarnström & Petersens 2004; Bracken et al. 2005; Zurbrügg et al. 2009; Lienert et al. 2013). SDM can help with such complex situations by combining engineering expertise with Multi-Criteria Decision Analysis (MCDA). This leads to enhanced transparency and more empirical decision making while taking stakeholder preferences into consideration. The aim is not only to elicit ‘better’ (more rational) decisions but also more accepted decisions.

Over the past 40 years, various frameworks have been developed for SSA in urban areas. All of them provide a more or less structured framework and/or methodology covering several steps of SDM. And each of them captures a current trend and provides an additional element based
on lessons learned from previous efforts (see Table 1 and supplementary information SI-A).

The basis for SSA was prepared in 1976 when John Kalbermatten set up the World Bank project looking at low-cost sanitation. SSA suggests that problems need to be addressed through (Kalbermatten 1982; Kalbermatten et al. 1982; Middleton & Kalbermatten 1990): (i) a multi-technology approach providing a mixture of on-site and centralized solutions appropriate for different urban realities; (ii) a multi-professional approach, including not only sanitary engineers but also economists, behavioural scientists, and health specialists; (iii) a multiple criteria approach including not only technical but also health, costs, socio-economic, socio-cultural, institutional, and environmental factors; and by (iv) allowing for flexible solutions and phase-wise incremental improvements. These key principles were the basis for moving away from a top-down, technology-centred approach towards engagement of the community and interactive planning processes that identify locally appropriate technologies considering multiple criteria. In 1997, ‘Towards a Strategic Sanitation Approach’ was published, operationalizing many of the ideas behind SSA. It advocates for (Wright 1997): (i) paying attention to the preferences of users and their willingness to pay; (ii) unbundling sanitation services into discrete parts (such as household services and trunk services) and providing these components in user preferred sequence; and (iii) involving the creative use of both formal and informal institutions to co-produce services. SSA was tested in several cities, including Kumasi, Ouagadougou, and Bharapur and was critically reviewed in the publication by Tayler et al. (2003). One of the main challenges in implementing the SSA was the significant technical and financial support required, due to the multi-sectoral complexity and scope. Many multilateral agencies were not prepared to invest the required time and resources for such an approach at that time.

The HCES (Eawag 2005) approach was formulated as guidelines for implementing the Bellagio Principles in Urban Environmental Sanitation Planning (Schertenleib

<table>
<thead>
<tr>
<th>Framework</th>
<th>Main innovation/contribution</th>
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<tr>
<td><strong>Strategic sanitation planning (SSP)</strong></td>
<td>Multi-professional; multi-criteria (not only technical and financial but also social and environmental); community participation, considering user preferences to provide appropriate technologies; unbundling services and allowing for incremental improvement; combining informal and formal institutions (co-creation)</td>
</tr>
<tr>
<td>Kalbermatten (1982), Kalbermatten et al. (1982), Kennedy-Walker et al. (2014), Middleton &amp; Kalbermatten (1990)</td>
<td></td>
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<tr>
<td><strong>Strategic sanitation approach (SSA)</strong></td>
<td>Community participation; willingness to pay; capacity development; market-based approach</td>
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<tr>
<td>Tayler et al. (2005), Wright (1997)</td>
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<tr>
<td><strong>Household-centred environmental sanitation (HCES)</strong></td>
<td>Combination of bottom-up and top-down approach using a multi-actor and multi-sector approach; prioritization of circular systems that consider waste as a resource and work within different city zones; focus on the enabling environment; not only a framework but a 10-step implementation methodology</td>
</tr>
<tr>
<td>Eawag (2005)</td>
<td></td>
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<tr>
<td><strong>City Sanitation Planning (CSP)</strong></td>
<td>Consideration of marginalized groups; comprehensive planning that considers all solid and liquid waste streams</td>
</tr>
<tr>
<td><strong>Community-led Urban Environmental Sanitation (CLUES)</strong></td>
<td>Further fostering enabling environment; empowering communities; 7-step methodology and a choice of tools that helps to put the methodology into practice</td>
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<tr>
<td>Lüthi et al. (2011)</td>
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<tr>
<td><strong>Sanitation21</strong></td>
<td>Pulls together key elements of good planning seen across the range of other planning tools/frameworks; focuses on objectives rather than technologies; citywide approach; emphasizes importance of institutional partnerships</td>
</tr>
<tr>
<td>Parkinson et al. (2014)</td>
<td></td>
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<tr>
<td><strong>Concerted municipal strategy (CMS)</strong></td>
<td>Specifically, for French-speaking areas; framework for inclusion of local actors; detailed guidance available; several case studies documented</td>
</tr>
<tr>
<td>Lefallé et al. (2012)</td>
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Source: authors; details provided in SI-A.

Table 1 | Historical overview of selected strategic sanitation planning frameworks and their contribution to address the current sanitation challenge
HCES was based on four core principles: (i) households should be at the centre of the planning process; (ii) bottom-up planning should be combined with a top-down approach considering multiple actors and multiple sectors; (iii) cities should be divided into spatial zones (household, neighbourhood, local government, etc.), with systems that emphasize reuse and recycling within these zones in order to solve the problems nearest to where they arise; and (iv) focus should be given to the enabling environment. The HCES approach was tested, piloted, and evaluated in seven cities (Lüthi et al. 2009b). The focus was mainly on community involvement within one zone independently, rather than looking at the zones jointly. Therefore, the scope of citywide sanitation was not achieved as initially intended.

In 2008, SuSanA laid out its vision in which five criteria for sustainable sanitation were defined: health and hygiene; environment and natural resources; technology and operation; financial and economic issues; social and institutional aspects (SuSanA 2008). SuSanA also introduced the systems approach and the sanitation value chain, acknowledging that providing toilet infrastructure alone does not improve public and environmental health conditions but may only help export problems to the next zone. The formulation of the five criteria as a directive allowed multi-criteria analysis to become operational (Kvarnström et al. 2004; Spuhler et al. 2008), as exemplified by Open Planning for Sanitation (Kvarnström & Petersens 2004).

In 2010, the Human Right to Water and Sanitation (HRWS) was declared, calling not only for increased participation but also for improved accountability and equity and consideration of marginalized groups (UN 2010). In parallel, various City Sanitation Planning (CSP) frameworks were developed (Gol 2008; MOUD 2008; WSP 2010; Walther 2016). A very similar approach was also developed for French-speaking areas, i.e. Concerted Municipal Strategy (CMS, LeJallé et al. 2012). The main three contributions of CSP are the detailed guidance provided for (i) the creation of a shared vision among all the actors; (ii) the consideration of all segments of the population including marginalized groups; and (iii) the joint consideration of liquid and solid waste streams.

In 2011, the Community-Led Urban Environmental Sanitation (CLUES) guidelines were presented as a follow-up concept to the HCES concept, making it more actionable (e.g. reducing the 10 steps to 7), and focusing on the community level instead of making the household level the centre of action (Lüthi et al. 2011). The main innovation of CLUES is the prominence given to the importance of the enabling environment. Furthermore, a set of tools was provided to put each planning step into practice. Several NGOs and institutions have validated and adopted the CLUES approach including among others WSUP (Water and Sanitation for the Urban Poor) and Helvetas Swiss Intercooperation.

The Sanitation21 framework (Parkinson et al. 2014) was intended to be complementary to CLUES addressing the challenge of citywide sanitation. Sanitation21 does not provide planning steps but highlights five features that should be covered: (1) build institutional commitment for planning; (2) understand the existing context and define priorities; (3) develop system options; (4) develop models for service delivery; and (5) prepare for implementation. The main contribution is the focus on planning objectives rather than technology options. However, there was a lack of funds for broad testing and it always remained an abstract framework. Nevertheless, the guidelines were instrumental in moving away from traditional, physically focused master plans to today’s more contemporary thinking on inclusive, multi-stakeholder sanitation planning.

In 2015, the World Health Organization published new guidelines for Sanitation Safety Planning (WHO 2015). Sanitation Safety Planning provides a step-by-step approach that assists risk assessment at the local level for each element of a sanitation system. Starting with the idea that all sanitation systems should protect human health, Sanitation Safety Planning focuses on the identification of hazardous events and risk exposure, as well as the assessment and prioritization of control measures. The main contribution of this risk assessment tool is that it links systematic health risk assessment at the local level with citywide hygiene conditions. The SaniPath Rapid Assessment Tool is a related example that helps assess exposure to faecal contamination in low-income urban settings (Robb et al. 2017).

Despite the efforts described above, the challenges for a citywide approach for sanitation are still not being addressed sufficiently. At the same time, the roles of on-site and non-sewered sanitation and FSM are recognized as part of urban sanitation solutions. Today, it is widely acknowledged that technical solutions exist that can be...
integrated into urban planning at scale to address areas which have been neglected so far and have relied on informally built and maintained on-site solutions. This together with the Sustainable Development Goals (SDG 6 and SDG 11), prepared the ground for the CWIS. This approach is still under development (see ‘current sanitation challenge’). But, there is broad agreement on a number of key principles, including safe and equitable service delivery, resource efficiency (water, nutrients, and energy), a mix of technologies and business models, and planning and accountability (Narayan & Lüthi 2019).

TOOLS TO MAKE PROCESS GUIDES OPERATIONAL

Despite the continuous development of theoretical foundations over the past decades, these theoretical well-planned participatory approaches are rarely used in practice (Kennedy-Walker et al. 2014; Ramôa et al. 2018). This is due to various practical challenges (Barnes & Ashbolt 2006; McConville 2010; Ramôa et al. 2018). One key constraint is that cities and development agencies are not prepared to invest time and resources in planning (Taylor & Parkinson 2005). And even when planning is undertaken, capacity and skill gaps persist (Lüthi & Kraemer 2012; Kennedy-Walker et al. 2014). One of these gaps consists of the lack of knowledge about new approaches and their potential to reply to local needs (McConville 2010; Lüthi & Kraemer 2012; Kennedy-Walker et al. 2014). And even if knowledge were available, planners are often confronted with an existing system that is overly constraining, making it difficult to think outside the box. To motivate and build capacity of the different stakeholders to productively participate in a structured planning process could be a first step towards improvement (Lüthi & Kraemer 2012). To go in this direction, recent research has focussed on the development of various methods and tools to put the different planning steps into practice.

In the table in SI-B, we provide an overview of tools that we know and believe to be useful for making SSA operational. As shown in this overview, tools exist for most of the SDM steps. Most recent and prominent examples include Sanitation Safety Planning (WHO 2013), excreta or SFDs (Peal et al. 2014a), SaniPath (Robb et al. 2017), and Quantity and Quality of Faecal Sludge (Strande et al. 2018). However, most current research focuses on understanding the current situation (e.g. diagnostic tools such as SFDs) and on selecting a preferred option (Schütze et al. 2019), assuming that an appropriate set of sanitation system decision options is already available. The identification of locally appropriate sanitation system planning options is most often left to engineering consultants. This leads to a number of shortcomings of such a knowledge bias. Consultants are often not familiar with novel options, lack data on their performance, and are overwhelmed when asked to consider a large and diverse range of sanitation technologies and systems. The situation is further complicated by the multiple criteria that should be looked at from a sustainability perspective, the preferences of different stakeholders regarding those criteria, and a high uncertainty regarding the future. Criteria that should be analysed include all dimension of sustainable sanitation: health, protection of the environment and natural resources, technical and institutional appropriateness, financial viability, and socio-cultural acceptance. Stakeholders should include all levels from the community to the city or regional government and civil society, as well as private and public sector actors. Uncertainties are due to the difficulty of predicting socio-demographic and environmental conditions in the future, as well as the performance of novel technologies.

IDENTIFYING APPROPRIATE SANITATION PLANNING OPTIONS (SDM STEP 3)

Option generation approaches that have been applied to sanitation include cause–effect analysis, creativity-based techniques, such as brainstorming, and mixed approaches, such as decision matrices and strategy tables (e.g. Keeney 1996; Mara et al. 2007; Eisenführ et al. 2010; Larsen et al. 2010; McConville et al. 2014; Tilley et al. 2014b; Gregory & Keeney 2017). Other popular and well-recognized support tools are a structured compilation of information (‘information packages’) such as the ‘Compendium of Sanitation Systems and Technologies’ or the ‘Philippines Sanitation Sourcebook and Decision Aid’ (e.g. WSP 2007; Tilley et al. 2014b). However, the results of these procedures rely heavily on available knowledge and are, therefore, also somewhat
arbitrary. The systematic identification of sanitation system options is currently one of the biggest weaknesses in SDM for water and sanitation (Hajkowicz & Collins 2007; Gregory et al. 2012; Spuhler et al. 2018).

To address the current sanitation challenge, tools for the identification of sanitation system options have to consider (i) the growing portfolio of available sanitation technologies and system configurations, (ii) multiple sustainability criteria; and (iii) uncertainties related to the local context or novel technologies. To better understand the extent to which existing tools cover these features, we critically compared 15 methods and tools that can be categorized into three types of approaches: decision trees, scoring or ranking using software support, and information packages (see Figure 1). For the evaluation, we only looked at the hardware aspect of ‘systems’ and did not include different institutional arrangements. We acknowledge that institutional arrangements depend on stakeholder preferences and involve trade-offs and therefore deserve to be dealt with once detailed planning is being undertaken (step 6 of SDM).

We compared the tools in relation to eight identified qualities. These eight qualities are based on our historical review of SSA frameworks: (1) the use of a systematic evaluation method; (2) comprehensiveness regarding the entire system, (3) comprehensiveness regarding the diversity of technical options; (4) appropriateness of technologies; (5) consideration of uncertainty related to technology performance or the context; (6) participation of local actors; (7) consideration of multiple criteria from all sustainability dimensions; and (8) flexibility towards future technology innovations. The detailed evaluation is available in SI-C. Table 2 provides a compact overview of the results. None of the analysed tools embrace all of the eight features. Three groups of tools could be distinguished:

1. Tools being systematic (transparent assessment), but not entirely comprehensive (both for all potential technologies and for entire systems), such as Kalbermatten (1982), Loetscher (1999), Nayono (2014), Olschewski (2013), leading to the risk of omitting valid options by not considering them (Keeney 1996; Siebert & Keeney 2015).
2. Tools being comprehensive, but not systematic, such as the information package ‘Compendium’ or the ‘Philippines Sourcebook’ (WSP 2007; Tilley et al. 2014b), leading to transparency issues (Olschewski et al. 2011; Ramôa et al. 2018).
3. A third group of tools was systematic and comprehensive but not flexible for novel technologies nor automated for comprehensive system generation (Langergraber et al. 2015; Ketema & Langergraber 2016).

Furthermore, while only two tools consider uncertainties, most of the tools allow for stakeholder participation and provide a contextualized appropriateness assessment. Nine of the 15 tools consider all sustainability dimensions and eight of them are flexible and can accommodate future technology innovation. A typical example of a flexible tool is the ‘Compendium of Sanitation Systems and Technologies’, which is an information package developed to support the informed creation of sanitation systems from a set of potential technology options (Tilley et al. 2014b). However, it results in an unmanageable number of system configurations that cannot be dealt with manually (typically

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**Figure 1** Types of decision-support tools and approaches currently available for the generation of sanitation system options as an input into structured decision making (SDM).

*Source: authors.*
<table>
<thead>
<tr>
<th>Name</th>
<th>Short description</th>
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<tr>
<td>Decision tree for the selection of sanitation technology (AST) Kalbermatten (2015)</td>
<td>Decision tree that allows the choice of a locally appropriate technology based on a fixed set of factors, using a fixed set of technology alternatives. The aim is to identify the most suitable technology or combination of technologies.</td>
</tr>
<tr>
<td>Algorithm for the selection of sustainable sanitation arrangement (ASSA) Mara et al. (2007)</td>
<td>Algorithm for the selection of sustainable sanitation arrangements, focusing on health, affordability, environmental sustainability, and institutional appropriateness.</td>
</tr>
<tr>
<td>A guide to sanitation selection (ASS) Franceys et al., Pickford (2014)</td>
<td>An algorithm based on the methods of anal cleansing, population density, affordability, demand for reuse, land availability, soil conditions, and user acceptance.</td>
</tr>
<tr>
<td>Scoring/ranking SANEX Loetscher (2013), Loetscher &amp; Keller (2015)</td>
<td>Software to assist (1) in the evaluation of a fixed set of technology alternatives using 20 mainly technical criteria; (2) the Multi-attribute Utility Technique (MAUT) to assess the feasibility; and (3) a model to quantify the costs of those.</td>
</tr>
<tr>
<td>Open planning Kvarnström &amp; Petersen (2007)</td>
<td>An overview of criteria for the evaluation of sanitation technologies, using function requirements and design for the Swedish context. The aim is to develop and evaluate different plans with the five sustainability criteria.</td>
</tr>
<tr>
<td>Water and Wastewater Treatment Technologies Appropriate for Reuse (WAWTTAR) Finney &amp; Gearheart (2007)</td>
<td>Similar to SANEX but covers water and wastewater treatment processes and designed for the Swedish context. The aim is to evaluate and select technologies that are feasible and sustainable.</td>
</tr>
</tbody>
</table>

**Systematic:** transparent and reproducible assessment

**Comprehensive:** novel and conventional technologies

**Comprehensive:** entire systems

**Contextualized:** considering specific local conditions

**Capable of handling uncertainty (related to technology and context)**

**Allows for stakeholder participation and an informed choice**

**Considers all sustainability dimensions**

**Score:** number of qualities out of the eight
<table>
<thead>
<tr>
<th>Name</th>
<th>Short description</th>
<th>Systematic, transparent and reproducible assessment</th>
<th>Comprehensive, novel and conventional technologies</th>
<th>Comprehensive, entire systems</th>
<th>Contextualized, considering specific local conditions</th>
<th>Capable of handling uncertainty (related to technology and context)</th>
<th>Allows for stakeholder participation and an informed choice</th>
<th>Considers all sustainability dimensions</th>
<th>Score: number of qualities out of the eight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainability-based Sanitation Planning Tool (SuStA) Nayono (2014)</td>
<td>A concept for a sustainability-based planning tools including the multi-criteria evaluation of technology appropriateness.</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>5/8</td>
</tr>
<tr>
<td>The CLARA simplified planning tool (CLARA STP) Ketema &amp; Langergraber (2016), Langergraber et al. (2015)</td>
<td>Excel spreadsheet to compare the costs of different system combinations in a given context.</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>5/8</td>
</tr>
<tr>
<td>Information packages</td>
<td></td>
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</tr>
<tr>
<td>WSP’s Philippines Sanitation Sourcebook and Decision Aid WSP (2007)</td>
<td>Reference collection of different sanitation and drainage technologies and data to compare them in terms of restricting variables (e.g. water supply) and influencing variables (technical and socio-cultural).</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>6/8</td>
</tr>
<tr>
<td>Compendium of Sanitation Systems and Technologies (The Compendium) Tilley et al. (2014b)</td>
<td>Contains: (1) an overview of the currently most common types of sanitation systems (system templates); and (2) an almost comprehensive collection of technology information sheets. The document helps to understand different technologies and know how to combine them into entire systems.</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>6/8</td>
</tr>
<tr>
<td>How to select? Monvois et al. (2012)</td>
<td>Describes a three-step procedure for the selection of an appropriate technology: characterizing the town, determining a sanitation chain (on-site, small-piped, or conventional), and selecting appropriate technologies. It also contains a compilation of factsheets on the treatment trains and technologies.</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

The tools are compared regarding eight features. Detailed results from the evaluation are available in the supplementary information.
more than 100,000 for 40 technologies). This underlines the need for an automated approach.

KEY FACTORS FOR IMPROVED OPTION SELECTION

To address the current urban sanitation challenge, there are three main features that need to be considered when developing planning options. First, we need to be able to consider the growing portfolio of available sanitation technologies and system configurations. Second, while selecting from all these options, we need to consider multiple criteria from all sustainability dimensions. And third, given the fast-changing socio-demographic and environmental conditions and the lack of knowledge specifically for novel options, we need to consider uncertainties. Based on the evaluation of the 15 tools, we define eight qualities that would provide an opportunity for significant improvement of any future tool:

1. **Comprehensive:** In order to avoid bias based on expert knowledge or opinion, there is a need to consider, if possible, the entire option space including novel options. Moreover, there is also a need to look at entire systems when comparing options because the performance of a system always depends on technology interactions. To be comprehensive requires that the needed information is available. This can be achieved by compiling international data and information in such a way, that it can easily be adapted to the local context.

2. **Automated:** Because the currently available portfolio of options is so large and diverse, it cannot be dealt with manually. For instance, a set of 40 technologies can lead to over 100,000 possible system configurations as shown in Spuhler et al. (2020). Obviously, not all of them are appropriate for a given setting, which confirms the need for a systematic approach for their evaluation (Spuhler et al. 2018). Automatization would allow unorthodox and innovative options to be generated that are said to be potentially more appropriate and sustainable and allow option generation to be more comprehensive.

3. **Flexible:** This quality is required to account for any future technology and system innovations. It could be achieved by providing a tool that can be easily extended by the users themselves.

4. **Systematic:** Providing a systematic approach would enhance transparency and reproducibility while being comprehensive. This could be achieved by using a clearly defined set of objective pre-selection criteria and by evaluating these in a given context for each and every technology with a quantitatively and qualitatively transparent method.

5. **Inclusive of all sustainability dimensions:** This is obviously required in order to be in line with the SDGs. It could be achieved by using a multi-criteria decision analysis (MCDA) approach that can deal with the very different scales and metrics of different criteria (e.g. socio-cultural acceptance and costs).

6. **Encourages participation of all relevant stakeholders:** Implementation and operation and maintenance of any technology or system will always depend on the stakeholder in charge of it. Participation should be well structured and specific in order to streamline the process and avoid endless discussion while enhancing accountability. This can be achieved by integrating the tool with an SDM framework and by including stakeholder preferences in the evaluation of options.

7. **Contextualized appropriateness assessment:** The performance of a technology or system highly depends on specific local conditions (centre, low-income dense, peri-urban). Contextualization could be achieved by providing a methodology for the appropriateness assessment that can be easily replicated for different areas within a city or for different cities all over the world.

8. **Considers uncertainties:** There is no single best solution but there might be an optimal solution given the currently available knowledge and data and local stakeholder preferences. The capacity to consider uncertainties would also allow the tool to be applied ex-ante and to produce useful input for strategic planning. Uncertainties that need to be considered are related to (i) local conditions (e.g. water availability, temperature, and population growth); (ii) knowledge about a technology (e.g. nitrogen degradation in a septic tank), and (ii) technology implementation (e.g. hydraulic retention time); or (iv) ignorance, particularly concerning novel technologies and their implementation at scale.

These qualities are not intended as a precondition but are intended to provide guidance to improve the capability of
future tools in addressing the current urban sanitation challenge. Moreover, it remains clear that even a tool with all these qualities will not provide the solution to the sanitation crisis but will only provide one piece of the puzzle. Any planning process depends first and foremost on political will and local leadership backed up with sufficient time and human and financial resources for strategic sanitation planning. The greatest challenge in sanitation planning lies in institutions laying out the responsibilities and resources for developing and implementing urban sanitation plans.

LIMITATIONS

This paper is based on the analysis of a broad range of literature that was collected over several years while paying attention to comprehensiveness. However, there is a strong risk for cognitive bias related to the GRASP project and the experts involved. There are, of course, other resources for supporting SSA. Because of this, there is a limitation in the empirical data, underlying the conclusions, giving it a speculative character. Nevertheless, despite these limitations, we feel that the identified research challenges are generalizable for the sanitation sector and can provide guidance for more effective strategic planning and SDM for urban sanitation in the future.

CONCLUSIONS

This paper provides an overview of the current sanitation challenge and existing strategic sanitation planning frameworks from a structured decision-making (SDM) perspective. It seeks to identify research needs for making strategic sanitation planning operational in practice.

The paper looks in detail at one need which is the availability of systematic tools, or lack thereof, for the identification of sanitation system planning options (step 3 of SDM). Existing tools do not fully address the current urban sanitation challenge. The growing portfolio of available sanitation technologies and system configurations is not sufficiently taken into account. Systematic evaluation of available options considering multiple sustainability criteria is also lacking. Existing tools are either: (i) systematic but not comprehensive (about all potential technologies, and about entire systems); (ii) comprehensive but not systematic; or are (iii) both systematic and comprehensive but not flexible enough to include future technologies and innovations, nor automated to deal with the very large number of existing system configurations.

Future decision-making support tools for the identification of sanitation options for strategic planning could be improved and better address the current urban sanitation challenge. Future tools would benefit from being comprehensive, systematic, and flexible. This could be achieved by using automatization for the consideration of a large and diverse portfolio of technologies and systems. Additionally, a method would be required that allows a systematic evaluation of all these options for multiple criteria, from all sustainability dimensions, and that considers uncertainties related to the local conditions and novel technologies. This would enhance transparency and reproducibility of the pre-selection of options. Integrating the tool in a participatory SDM framework would enhance accountability.

Better decision-making and planning approaches are urgently needed to achieve safely managed sanitation in the rapidly developing cities of the global South. Providing sanitation options that are appropriate for the different areas within a city that can deal with current challenges related to population growth, climate change, and resource depletion is an important step towards more citywide inclusive sanitation planning. However, it is only one piece of the puzzle and needs to come with political will and human and financial resources not only for planning but also for implementation and maintenance in the long term.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.
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