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Review

Contextualising urban sanitation solutions through complex systems thinking: A case study of the South African sanitation system

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A R T I C L E I N F O

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A B S T R A C T

South Africa's urban sanitation infrastructure is unfit-for-purpose and collapsing, leading to significant environmental and health risks. Many alternative sanitation solutions exist, but their implementation has not produced successful roll-out to scale in this context. These failures are likely due to many interactive, systemic factors. This research adopts a transdisciplinary knowledge synthesis approach to map the possible systemic factors to provide engineers and policymakers with relevant information to identify contextual risk factors for potential failure and emerging problems and novel approaches. Building from the narrative literature reviews and the joint fact-finding approach, the sustainable systems-of-systems framework is used as the analysis tool to identify important elements of the complex systemic context. The output is a set of nine interweaved contextual constraints. The value of the contextual constraints is illustrated by application to three commonly implemented sanitation solutions (chemical toilets, urine-diverting dry toilets, and decentralised wastewater treatment systems) where relevant contextual components of the success (or failure) of the solutions are highlighted. The framework is not intended to replace existing linear-thinking decision-making tools, but to provide important contextual information to augment existing decision-making.

1. Introduction

According to the Joint Monitoring Programme, South Africa is doing relatively well in the provision of sanitation services, with 73% of its urban population receiving improved, shared facilities or better (World Health Organization, 2023). However, these figures hide the parlous state of municipal sanitation services in South Africa due to a range of complex interlinked issues, as well as the enormous disparities in sanitation access between rich and poor inhabitants in one of the world's most unequal countries (Francis and Webster, 2019). Alternative interventions that augment existing water borne sewerage systems have been successfully implemented at scale in other low- and middle-income countries such as Indonesia (Eales et al., 2013) and India (Klinger et al., 2020). However, similar interventions, such as Urine-Diverting Dry Toilets in eThekwini (Mkhize et al., 2017) and Container-Based Sanitation in Cape Town (Dube et al., 2023), have been less successful, and decentralised wastewater treatment systems have not moved beyond demonstration units in South Africa (Arumugam et al., 2023). This often leaves shared, portable, and chemical toilets as the prominent "solution" for these underserved urban communities (Norvixoxo et al., 2023). Users are often dissatisfied with these "solutions", describing them as "apartheid-era bucket toilets in disguise" (Norvixoxo et al., 2023, p.

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1744). Gambrill et al. (2020) noted that for sanitation solutions to be successful they must also carefully consider the broader urban context and identified several systemic aspects that should be considered which include interactions with solid waste management, housing development, governance structures, the policy environment, and financial considerations. Naidoo et al. (2016) noted that ensuring water security in South Africa required considerations such as skills requirements, strong governance, infrastructure maintenance, and inter-departmental collaboration. A systematic analysis of the relevant systemic factors has yet to be conducted. This research applies a knowledge synthesis approach to frame these systemic factors in order to understand why various interventions fail in the South African context when they have been successful in other contexts. The approach adopted in this research aims to leverage transdisciplinary knowledge to characterise the various systemic factors that might reduce or enhance the effectiveness of city-wide inclusive sanitation interventions. Through a set of transdisciplinary narrative literature reviews analysed using the System of Systems analytic framework this paper aims to develop a systemic framework for *reasoning* about the range of systemic factors impacting on city-wide inclusive sanitation choices for a specific context (urban South Africa).

2. Literature review

2.1. Need for systemic views for problem solving

Evaluations of the "failures" in city-wide inclusive sanitation point to a range of possible root causes. Reymond et al. (2020) focused on the governance and financial issues that hampered scaling-up of sanitation interventions, but also identified inadequate operations and management, inappropriate standards and policies, and a lack of interdepartmental coordination. Similarly, Gambrill et al. (2020) identified issues such as a lack of technical expertise, inappropriate financial provisioning, developmental silos at government level, and a need to understand the context better. To improve the understanding of the context, Scott and Cotton (2020) suggested moving beyond linear thinking about interventions, by considering the enabling environment (i.e., the policies, budgeting/financial capacity, and institutional readiness), the living environment (i.e., people), and the service delivery environment (available service delivery infrastructure). These reflections imply that it is imperative to take both a more systemic approach to identify important implementation levers and to better understand the specific context of the implementation site. Apart from Scott and Cotton (2020) though, previous systemic evaluations do little to systematise the relevant factors. It is therefore unclear whether these reflections give a holistic account, while also acknowledging contextual factors.

It is evident that the complex challenges facing global sanitation needs such as global economic instability (Herrington, 2021), ecosystem disruptions and collapse (Pörtner et al., 2022), changing climatic conditions (Pörtner et al., 2022), emergent pollutants in wastewater (Aryal et al., 2020), and burgeoning unplanned urban settlements (World Cities Report, 2022) are unlikely to be met using solutions that prioritise the sewered, flush toilet and centralised, capital-intensive wastewater treatment facilities. Existing approaches, such as Shit Flow Diagrams (Peal et al., 2020), identify failures in the sanitation chain, but not why those failures occur, limiting possible solution sets to factors that engineers can control. There are also calls for a new global sanitation revolution to meet twenty-first century needs (Koottatep et al., 2019) which provides adaptable, context-specific, and reflexive solutions that recognise the complex interplay between the biophysical environment, technological innovation, and social and institutional transformation. Any analytical approach should be able to consider the reasons for existing failures as well as provide guidance for the possible effectiveness of the proposed solutions against novel challenges.

The complexity and scale of South Africa's urban sanitation challenge requires broader systemic thinking to identify relevant influences and to derive possible solutions. Transdisciplinary research aims to transcend disciplinary boundaries in order to obtain a systemic and integrative perspective aimed at addressing a societal problem (Darbellay, 2015). For Lang et al. (2012) transdisciplinary research is characterised by three interrelated components: (i) the research addresses a societally relevant problem within context (for example, this paper considers the problem of dignified sanitation solutions for the urban poor); (ii) knowledge is integrated (and differentiated) from across different disciplines, including actors outside academia (the transdisciplinary team includes someone from government, a practitioner in a local municipality, and an NGO representative); and (iii) the research produces solutions to a real-world problem. While some scholars stress the inclusion of actors from outside academia (Lang et al., 2012), Darbellay (2015) notes that transdisciplinary research also includes knowledge that emerges from a dialogue between academic disciplines. Of particular relevance to this research is that Barth et al. (2023) identified transdisciplinary learning as a key factor in addressing sustainability challenges, such as those presented by South Africa's urban sanitation problems.

2.2. Overview of South Africa's urban sanitation context

South Africa's racially oppressive Apartheid policy, which favoured piped, waterborne sanitation for the privileged white population and a variety of "degraded" solutions for the majority, disadvantaged black population was deeply unequal. The infamous "bucket system" prevailed in some disadvantaged communities even into the early 2000s (Amisi and Nojiyeza, 2008). The notorious Group Areas Act of 1950 made residential separation compulsory between racial groups, controlling the right of access to "white areas" and, thereby, the right of access to complete waterborne sanitation solutions (Tempelhoff, 2017). Despite efforts to provide sanitation services in rural areas and unplanned settlements, those services remained woefully inadequate (Tempelhoff, 2017).

Starting in 1994, the democratic era inherited a patchwork of differentiated sanitation services and thinking about sanitation services and access to dignified sanitation based along racial lines. Not only did the new, democratic government have to address a massive sanitation backlog, but also had to continue to maintain the existing waterborne, piped sanitation systems (and wastewater treatment plants) which were expensive and only served the rate-paying minority of the population. Three sanitation policies (in 1994, 2001 and 2016) sought to address sanitation inequality by entrenching the right of access to a basic water supply and sanitation. Other strategic frameworks, water and sanitation master plans, and audit processes (e.g., "Green Drop" Reports) developed and implemented in the 2000s and early 2010s have translated into numerical successes in the provision of basic sanitation solutions (World Health Organization, 2023). However, Nnadozie (2013) noted that this has resulted in a paradox with the low-income majority black population experiencing marked sanitation service improvements but were still deprived of the waterborne sanitation standard that wealthier households enjoyed.

The deployment of dry and on-site sanitation systems and services in areas mainly inhabited by the poor sometimes results in these systems and services being viewed with suspicion, often being rejected or even sabotaged (Norvixoxo et al., 2023). The idea of communities that do not have access to sanitation services rejecting or sabotaging the deployment of variants of these services may appear illogical. However, in the context of South Africa's apartheid history, such views are often born out of anger at the continuation of double standards of service provision in the democratic era. It does not help that dry and on-site sanitation systems are often portrayed and viewed as stop-gap measures, instead of alternatives with long-term potential. This can result in communities deciding that adopting these types of sanitation systems and services is akin to accepting an extension in "waiting" for equal services.

The Apartheid-era waterborne sanitation systems are also displaying failures on a significant scale. The 2022 Green Drop National Report (a national audit of wastewater treatment plant functioning) indicated that 39% of the country's wastewater treatment plants (WWTPs) were critically dysfunctional with a further 24% functioning at an unsatisfactory level. This was a deterioration from 2013, when the same audit found 29% critically dysfunctional and 19% unsatisfactory). These dysfunctional and overburdened WWTPs have contributed to severe environmental and public health impacts. Most recently a cholera outbreak in February 2023 in Hammanskraal resulted in 31 deaths (Mahlati, 2023). Vulnerability to such outbreaks are compounded by the continued prevalence of unplanned settlements, with the 2022 Census finding 12.3% of the population living in unplanned urban settlements (StatsSA, 2023a).

South Africa's urban sanitation challenge is composed of various aspects, including the deterioration of existing infrastructure, inadequate planning for the expansion of infrastructure, technology unsuited to unplanned settlements, legislation that is not implemented or enforced, dysfunctional institutions, and increasing pressure on environmental systems. Each of these aspects comprise multiple independent systems (i.e., systems-of-systems), contributing to the complexity and scale of the challenge, necessitating broader systemic thinking to help identify possible solutions.

3. Methods

3.1. Knowledge synthesis

Knowledge synthesis brings together information and knowledge from many sources and disciplines to help inform policy or debates (Donnelly et al., 2018). Integration and analysis across multiple disciplines and sources allows knowledge synthesis to produce novel insights while also increasing the scope and reach of research results. The challenge with transdisciplinary knowledge synthesis is integrating various specialised disciplinary knowledges into a coherent whole, while synthesising knowledge from academic and non-academic spheres (Tengö et al., 2014). Choosing a particular knowledge system may bias a particular discipline, while attempting to integrate interdisciplinary knowledges has the potential to create tensions and misunderstandings between participants. This study adopted Tengö et al.'s (2014) three phases of the Multiple Evidence Based approach: (i) co-development of the problem definition; (ii) all knowledge is treated on an equal basis; and (iii) a joint analysis to produce a multi-level synthesis. The knowledge synthesis technique adopted in this study was a Joint Fact-Finding approach (Schenk et al., 2016). Joint Fact-Finding attempts to recognise the various interests and knowledge areas of different stakeholders in situations where the facts are uncertain or contested in order to reach a shared understanding that will enable the identification of appropriate plans of action (Tengö et al., 2014). The Joint Fact-Finding approach was enacted in five steps and combined with the creation of expert narrative reviews that identified aspects of the problem. Transdisciplinary knowledge synthesis was chosen as the best way to obtain the broadest possible range of systemic considerations.

3.1.1. Step 1. Pre-kick-off consultations

The initial fourteen-member team was assembled to reflect a broad range of disciplinary expertise from across academia, government policymakers, and community-based non-governmental organisations. The broad demographic disciplinary constitution of the transdisciplinary knowledge team is presented in Table 1. Two pre-kick-off consultations were held to identify additional team participants and to co-define the problem. At this stage, five new participants were added to cover new areas of expertise (i.e., epidemiology, public health, urban design, an industry representative, and an additional non-governmental organisation). The knowledge synthesis team consisted of ten participants from academia, four from government departments, four from non-government organisations, and one from industry. The consultations identified the spatial and temporal focus of the sanitation problem requiring attention. The consultations also included a transect site visit by eight participants to witness urban sanitation issues first-hand, by visiting an unplanned urban settlement, an acid mine drainage discharge location, and a downstream agricultural and recreational dam experiencing high levels of eutrophication. It is a limitation that end-users from disadvantaged communities and stakeholders from across all the governance and/or operational hierarchy were not included in the transdisciplinary knowledge team. It is quite possible that having members representing these stakeholders may have provided novel insights not included in this synthesis and that the analysis may be biased by a participant (e.g., the extent of their knowledge, experience, standing in their respective community, and personality) or by the discussion dynamics.

Table 1
Demographic and disciplinary profile of the transdisciplinary knowledge team.

Gender	Frequency	Percentage
Female	10	52.6
Male	9	47.4
Other	0	0
Affiliation		
Academic institution	10	52.6
Non-governmental Organisation	4	21.1
Government organisation	4	21.1
Industrial company	1	5.2
Broad discipline		
Chemistry	3	15.8
Epidemiology/community health	3	15.8
Civil engineering	2	10.5
Chemical engineering	2	10.5
Freshwater ecology/environmental studies	2	10.5
Psychology	2	10.5
Urban studies/urban planning	2	10.5
Law	2	10.5
Economics	1	5.2

3.1.2. Step 2. Kick-off workshop (November 2021)

The three-day face-to-face kick-off workshop was used for participant introductions, trust-building, and to further co-define the problem. To help contextualise the sanitation problems the workshop included a site visit to a local, poor urban settlement. This enabled the stakeholders to further develop a shared understanding of sanitation problems and to informally interview sanitation end-users and service providers.

3.1.3. Step 3. Narrative reviews

Narrative reviews were used to collate and summarise research evidence using subject-area experts (Byrne, 2016). This type of descriptive or rapid literature review is flexible and pragmatic but is not as robust as a systematic literature review. They are useful in giving a broad overview of a topic for further in-depth analysis but may be biased by the preferences of the subject-matter experts and the literature that is accessible to them (Byrne, 2016). Narrative reviews were shared with the team. They covered the history of sanitation, sanitation technologies, local governance policies and legal frameworks on sanitation, behavioural approaches to sanitation, decision-making in sanitation solutions, health and sanitation, emerging sanitation technologies, and the environmental impacts of inadequate sanitation. Specific search terms depended on the topic being reviewed and were limited to the South African urban sanitation context, centred on publications found in the Scopus database. Reference lists were also checked for other relevant publications.

3.1.4. Step 4. Complex systems analysis workshop (August 2022)

The second face-to-face workshop took place over three days and incorporated a site visit to two WWTPs. The tool used to synthesise the narrative reviews and joint fact-finding discussions was a complex systems framework called the "sustainable systems of systems" (SSoS)

(Thatcher and Yeow, 2016). SSoS was chosen because it places humans, and human-technology interactions as central to the understanding and because it does not require pre-defined categories or systems. It was necessary that the relevant systems emerged from the joint fact-finding approach. Complex systems tools which have predetermined categories, indicators, or categories such as the Sustainable Livelihoods Framework (Mensah and Enu-Kwesi, 2019) or the Sanitation Sustainability Index (Hashemi, 2020) were therefore deemed inappropriate.

The theoretical underpinnings of the SSoS framework are Costanza and Patten's (1995) nested hierarchy of systems and Gunderson and Holling's (2002) complex adaptive cycles. Humans in this study were defined as the end-users of urban sanitation systems and the various engineers who design, implement, and manage technological solutions. SSoS consists of four components: (i) the nested hierarchy of systems; (ii) goal mapping; (iii) identifying the natural lifespans of relevant systems; and (iv) complex adaptive cycles (Thatcher and Yeow, 2016). For this study only the first two components were used. The nested hierarchy recognises that smaller, less complex systems are often nested within larger, more complex systems. This made it possible to identify and map the various related systems into a hierarchy of size, influence, and complexity, allowing the team to map out the different spheres of influence and impact of related systems on humans. Goal mapping considers how the goals of the target system match with the goals of stakeholders represented in the nested hierarchy. This enabled the team to identify overlapping and divergent goals. Further longitudinal analysis would be required to examine the other two components.

3.1.5. Step 5. Post-workshop consultations

Eight post-workshop consultations were held to finalise the relevant systems and to identify how to apply the outcomes to existing interventions.

3.2. SSoS analysis

During the complex systems analysis workshop, participants began by creating a stakeholder map (see Fig. 1). Next, the outcomes of the narrative reviews were mapped onto the different levels of the stakeholder map. At this stage, all outcomes were treated as equal in the mapping process. The team then worked to synthesise the outcomes into a single systemic representation through brainstorming and mapping. Through joint fact-finding dialogue and discussion new outcomes emerged (e.g., the need for skills development, job creation, and circularity), while other outcomes were consolidated (e.g., management and governance). The eight post-workshop consultations served to further consolidate this mapping, producing the systems map in Fig. 2.

At the national level the Department of Water and Sanitation (DWS) is responsible for providing policy, governance, and progress markers. Several other national Departments provide intersecting services such as the Department of Transport (responsibility for stormwater drains), the Department of Human Settlements (responsibility for housing including integrated sanitation systems), and the Department of Health (responsibility for health monitoring such as waterborne diseases, chemicals, and other pathogens). The DWS statutorily delegates responsibility for sanitation provision to Water Services Authorities (WSAs), usually metropolitan/district municipalities, who provide various bulk/on-site sanitation services through a network of contracted public, private, and municipal providers. Given the heavy reliance on water-borne sanitation there are obviously strategic links between water provision and sanitation services.

4. Results

The output of the SSoS analysis of South Africa's sanitation context is grouped into three layers: (1) complex constraints to future sanitation choices; (2) an analysis of stakeholder goals; and (3) evaluation of future sanitation choices through the lens of the complex constraints. The organising principle of the SSoS analysis is the contextual constraints relevant to sanitation choices at multiple scales of influence and across different social functions and knowledge domains.

4.1. Complex constraints to future sanitation choices

In conceptualising the complex interrelated challenges facing South Africa's sanitation situation, the output can be represented as a set of seven interweaving constraints: biophysical, population, financial, management and governance, energy, waste accumulation, and health constraints viewed through the lens of user and engineering-thinking constraints. The constraints have nested spheres of influence depending on the level of impact at either the global, regional, national, municipal, or local (WWTPs or on-site) level (see Fig. 2).

4.1.1. Biophysical constraints

The biophysical constraints include climate, weather, geochemical processes, biomes, ecosystems, and biodiversity. South Africa is a water-scarce country and the climate crisis is predicted to reduce rainfall, increase temperatures, degrade soil quality, and lead to biodiversity loss (Richardson et al., 2023). Flooding or reduced rainfall, in particular, pose a significant threat to existing water-borne sanitation systems.

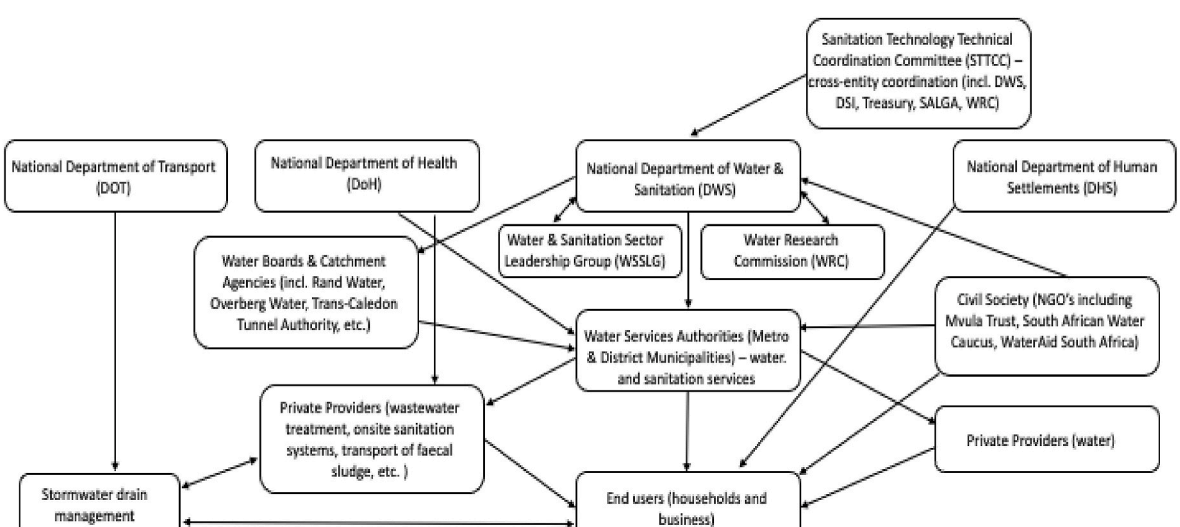

Fig. 1. A simplified map of the stakeholders involved in the provision of urban household sanitation services in South Africa.

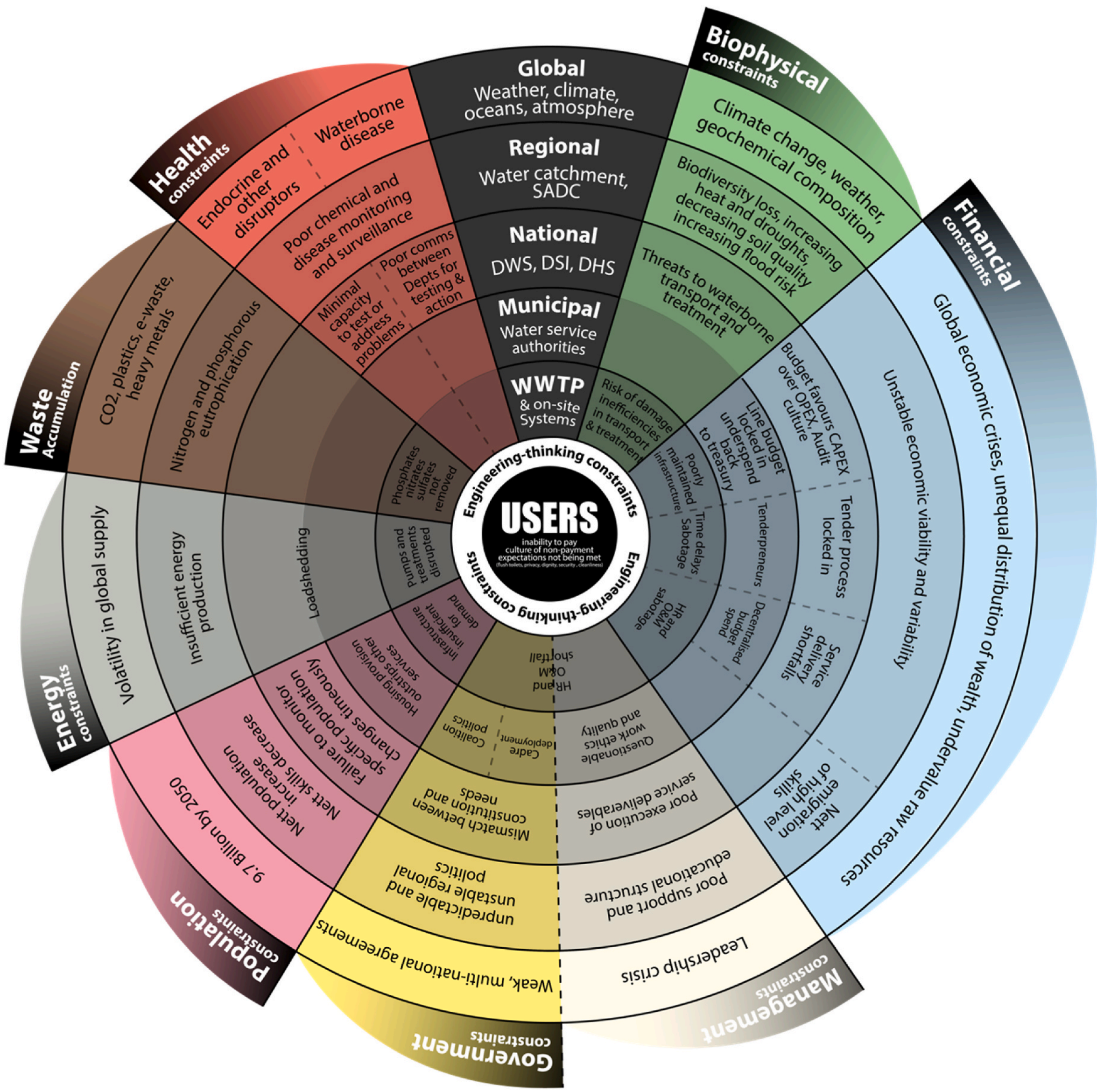

Fig. 2. A simplified systems map of the various systemic constraints impinging on the South African urban sanitation system.

Biophysical constraints have already contributed to the 2015–2018 Cape Town drought which led to the reduced efficacy of WWTPs (Bonthuys, 2018), and flooding in the eThekwini Municipality in 2022 (Soni, 2022) which caused significant damage to sanitation systems. As water security decreases, water is diverted to other essential-for-life services (e.g., drinking, food production, and cleaning). Consequently, there will be less water available to transport and treat wastewater. Under these conditions, using water to dilute and transport sewage is undesirable. In addition, offloading treated effluent into environmental water sources pollutes receiving water bodies, negatively impacting the environment while raising the costs and energy requirements to provide safe drinking water. South Africa's sanitation policies mention water scarcity and have acknowledged that it is more practical to implement non-water-borne systems than to provide flushing toilets for all.

4.1.2. Financial constraints

The inability to address many of other constraints is related to financial constraints. These stem from historical inequalities in the distribution of financial capital. While there are multiple financial constraints, three bear specific mention within this context. First, the budget system favours spending on large capital projects and social grants over spending on operational activities. The Municipal Finance Management Act produces an audit culture where line items are locked-in (Nkoana and Bokoda, 2009). This means that any under-spending on line items or capital expenditure must be returned to the national treasury rather than being re-purposed to spend on operational and maintenance needs. This may explain the chronic underspending on operations and maintenance until the systems catastrophically fail, necessitating capital expenditure. This leads to long repair and maintenance backlogs due to technical breakdowns of poorly maintained equipment. Furthermore, the Auditor-General views emergency deviations, under the Municipal Finance Management Act (e.g., to procure critical equipment) by municipalities as suspicious (Nzimakwe and Biyela, 2021), even when failing to replace or upgrade equipment may have severe environmental consequences.

Second, spending is largely dominated by tender processes which are intended to reduce costs and to give more equal opportunities to previously disadvantaged suppliers. In practice, despite the importance of Black Economic Empowerment for the national transformation agenda, the tender process has often resulted in a new class of "supplier" known as "tenderpreneurs" (Shava, 2016). The primary role of a "tenderpreneur" is to secure government tenders and contracts which are then "sold" to other contractors or preferred contacts. "Tenderpreneurs" are often people who have existing contacts in government institutions and/or have experience negotiating the tender process (Shava, 2016). Another consequence of the tender process is that appointment processes take place too slowly and are vulnerable to extended appeals on the part of unsuccessful applicants. Unscrupulous contractors may engage in sabotage of infrastructure in order to trigger further tenders. Moreover, "construction mafia" may extort contractors for an upfront fee, by intimidation, violence, or through site blockades.

Third, post-apartheid sanitation policies were clear that while the government would subsidise infrastructure costs, these could not cover operation and maintenance costs. WSAs are held responsible for cost-recovery for services above free basic sanitation from rate-paying customers. However, a combination of an underperforming economy (many households cannot afford to pay for services), inadequate revenue collection mechanisms, and the demographic profile of the user base (a high proportion of children and unemployed youth as well as increasing privatisation of these service by the wealthy) has resulted in under-recovery for these services. In addition, the extent of State-led corruption over recent decades (February, 2019), has hollowed out much of the funding earmarked for maintenance and capital expenditure on sanitation infrastructure. Billions of Rands were siphoned off the fiscus through corruption and to date little of these "lost" funds have been reclaimed, leaving less money for constructing, operating, and maintaining infrastructure and services (February, 2019).

4.1.3. Governance and management constraints

Two inter-related constraints emerge from this arrangement: governance constraints (usually found at the highest levels of a WSAs structure) and management constraints (usually found at the middle and lower levels of a WSAs structure). Eales (2011) noted that despite a rapid increase in service provision needs, there has been a concomitant decrease in critical skills. In many WSAs the ratio of WSA employees to consumers is one to tens of thousands. There are also transformation pressures to meet employment equity targets. While this alone is not an issue, it is often used as a cover to employ politically-connected rather than technically-experienced managers (known as "cadre-deployment"). In turn, these managers employ personnel who are often poorly-qualified or unqualified but politically-connected. As a result, leadership and management generally lack operational experience leading to the hollowing out of skills. One consequence of this lack of operational experience is that financial spending/underspending is based on immediate financial criteria (i.e., the cheapest) rather than the technical, operational, and maintenance needs. While auditing is performed, the lack of accountability by management to prosecute for malfeasance points to almost no consequence management. More recently immature coalition politics at the provincial and municipal level have resulted in unstable governance structures and uncertainty in policy formulation and service provision (Hanabe and Malinzi, 2019). These governance and managerial constraints directly impact sanitation and related infrastructural systems.

4.1.4. Population constraints

South Africa's urbanised population continues to grow not only due to the population's birth rate (2.34 births per woman), but also due to immigration from other African countries and internal migration from rural to urban areas (StatsSA, 2023a). Nearly 66% of South Africa's population resides in an urban area, with urbanisation expected to increase to 80% by 2050 (Parliamentary Monitoring Group, 2016). These changes have not been adequately monitored and the decadal population census was delayed in 2021 due to Covid-19. Moreover, 28.8% of the population is aged between 0 and 14 years old (StatsSA, 2023a), indicating the ever-increasing pressure on sanitation services. The provision of low-cost housing and burgeoning unplanned settlements have far outpaced the provision of sanitation services (Muanda et al., 2020) and the result is sewage-related contamination of cities' rivers, dams, estuaries, and coastlines (Adams et al., 2019). Rapid population growth and urbanisation has outpaced the policy provision of a minimum level of sanitation provision for State-subsidised housing. In the 2016 National Sanitation Policy there is a subtle shift of responsibility to the private sector, with the suggestion that the property development sector should be licensed and regulated to provide more appropriate sanitation systems.

4.1.5. Energy constraints

Since 2007 it is evident that the country's power production has not met the power demands (Naidoo, 2023). The shortfall has been managed through a process known as "loadshedding" which refers to the controlled reduction in power supply to match the shortfall, to prevent the total collapse of the electrical power grid. A combination of ageing infrastructure, poor maintenance, bad energy management planning, corruption, reliance on a single State-owned supplier using predominantly coal-fired power stations, and insufficient generation capacity means that the extent of loadshedding is highly variable and difficult for energy users to effectively manage. This creates disruptions for energy-driven treatments at WWTPs and pumping stations. None of South Africa's post-democratic sanitation policies acknowledge the energy constraint, making this a significant blind spot.

4.1.6. Waste accumulation constraints

Excessive nutrient accumulation in sanitation systems can be problematic with poor removal giving rise to major consequences such as eutrophication of water sources (Richardson et al., 2023). Moreover, problems are exacerbated by discharging untreated sewage through marine outfalls (Overy, 2020). Historically, human faecal waste was often considered a resource requiring careful husbandry to maximise resource recovery (Han and Hashemi, 2017). However, in contemporary society, a diverse range of chemical substances used in everyday routines find their way into sewage including medications, insecticides, fire-resistant compounds, and sanitizing agents. Together, these introduce new recalcitrant synthetic and organic chemical compounds, microplastics, endocrine disruptors, perfluoroalkyl and polyfluoroalkyl substances (PFAS), and other pharmaceutical substances into the body (Aryal et al., 2020) with many medications remaining unabsorbed or incompletely broken down during digestion or post-elimination treatment (Ojemaye and Petrik, 2019). While technologies exist for the treatment and remediation of wastewaters for many of these novel compounds (Badmus et al., 2018), some are costly to operate, require skilled operators, or are energy-intensive. The health and environmental risks from many of these compounds is unknown or poorly understood. These problematic compounds are present in effluents inevitably incorporated and concentrated in any feedstock extracted from sewage, thus complicating efforts towards water circularity while increasing costs for downstream WWTPs. The 2016 sanitation policy recognised the economic value of sanitation by-products, and called for a stronger focus on maximising recovery, reuse, and recycling of by-products to strengthen efficiency gains along the sanitation value chain.

4.1.7. Health constraints

The primary purpose of sanitation systems is to protect human health by facilitating clean environments, yet the most common route of exposure to waterborne disease agents is the oral-faecal route, associated with poor sanitation. This results in numerous diarrheal diseases which inordinately impact children and the poorest, most vulnerable in society (Johnstone et al., 2021). There are also risks of recombinatory viruses, bacteria, or parasites and evolutionary pressures for cross-species infections. In addition, undigested or un-metabolised antibiotics and other chemical compounds (such as antiretrovirals, endocrine disruptors, PFAS, and other pharmaceutical substances) may also produce significant health issues (e.g., antibiotic-resistant organisms) when circulating further in communities, producing health threats in recreational, agricultural, and domestic areas (Snyman et al., 2021).

While Environmental Health Practitioners are legally required to collect environmental water samples monthly at sites according to a sampling plan, there are very weak systems of monitoring and surveillance for water-borne diseases and almost no implementation strategies to deal with new chemical compounds (Hemson, 2016). Water quality monitoring and surveillance are limited to a few criteria including coliforms and selected bacteria (but not viruses and parasites) and the staggered testing process leads to delays in corrective action and disease prevention. There are few, if any, technological solutions in place to treat or remove emergent biological threats and chemical compounds. Rather than implementing improved monitoring and surveillance, South Africa's post-democratic sanitation officials have consistently dealt with the health impacts by calling for improved health and hygiene awareness and education, placing the onus of action upon the affected communities.

4.1.8. Engineer-thinking constraints

Central to these eight constraints are the engineers (and related professionals) who must design, implement, maintain, and upgrade sanitation systems. Engineers (and, in fact, most scientific disciplines) learn to solve clearly-defined problems on the basis of a clear set of assumptions. For example, for a specific population size and for known services the engineers and urban planners must make assumptions about population growth (or not) and the cost-sharing mechanisms to determine, according to a set of rules, how much water is (and will be) required or how large to make a WWTP to support the population. Implicit assumptions, like the availability of electricity, are rolled up in these decisions. What engineered systems do not plan for is large system changes, such as a change in government that may de-prioritise the maintenance budgets, or extending designs beyond their intended lifespans, or unexpected increases in the population which may require extensions or upgrades to the WWTP. The impacts of extremely dynamic societal pressures are not well suited to incorporation within the engineering design space and are normally incorporated as buffer capacity based on professional judgement (which is not always accurate or complete). The engineering design space is therefore often trapped into trying to solve problems which they have no control over. The levers of society are not the actual services supplied by engineered systems, but disciplines such as law, economics, governance, psychology, and politics.

4.1.9. User constraints

The primary user constraint is that some users are either unable or unwilling to pay for sanitation services. Given the high proportion of children and youth in the population (61.2% below 35 years old – StatsSA, 2023a), and the high rate of unemployment in the country (in excess of 32% - StatsSA, 2023b), many millions of people are unable to pay for sanitation services. Even where people are employed, income is quickly absorbed by other basic needs such as food, energy, and transport to places of employment. Generally, there is a culture of non-payment (Patji and Selepe, 2022) since constitutionally basic services (e.g., water, electricity, and sanitation) are be provided free-of-charge by the government. Users carry a set of minimum expectations about government-provided services related to equality of provision. The "flush" toilet provides a safe, secure, clean, private, and dignified solution (Muanda et al., 2020) for the serviced segment of the population and is therefore expected to be equally available for all. These expectations conflict with the government's policy position for systems that are less reliant on water. When expectations are not met, people are reluctant to pay for these services and service delivery protests and vandalism are considered as valid modes of resistance. Resistance may be individualised such as deliberately blocking a sanitation system to get authorities to attend to the matter faster (Norvixoxo et al., 2023) or collectively organised such as service delivery protests (Morudu, 2017).

Non-payment for services is not limited to the poor, but includes wealthier individuals, corporations, and even government departments. There are a complex array of reasons for non-payment including the legacy of boycotting service payments during the anti-apartheid struggle, mixed political messaging about who qualifies for free basic services, dissatisfaction with the quality of service provision, concerns that local government is corrupt and payments will be misappropriated, poor payment management systems, and a lack of enforcement for non-payers. Even if sanitation services are available, there are multiple factors that determine whether these services are accepted. Acceptance is centred around whether the service is perceived as dignified which includes attributes such as perceived privacy, safety, cleanliness, maintainability, and convenience (Muanda et al., 2020). Cultural belief systems also play a role in the acceptance of sanitation options. Muanda et al. (2020) refer to the belief that the faeces of children is harmless and therefore open defecation is not a problem for them. There is also the widespread belief that touching, or even carrying faeces, is considered bad luck (Norvixoxo et al., 2023) for both the handler and the producer.

4.1.10. Interconnectedness of constraints

Fig. 2 necessarily simplifies the relationships between the different constraints. These constraints interact in complex ways. There are obvious interactions between the financial constraints (e.g., tenderpreneurships and corruption) and the culture of non-payment by end-users. Climate change (a biophysical constraint) will have a major impact on water availability (for the "flush" toilet option) which will be exacerbated by population growth and urbanisation (a population constraint), which will lead to ever higher waste loads with more complex waste streams (waste accumulation constraints). There is no doubt that with population constraints, health constraints will increase particularly in vulnerable populations. South Africa is already facing energy constraints which has been exacerbated by the same governance/management and financial constraints facing sanitation. The scarcity of skilled human resources is a population constraint, financial constraint, and governance/management constraint. This interconnectedness means that the sanitation "problem" can't easily be "fixed" by tackling a single constraint, but must consider multiple, sometimes competing, constraints simultaneously.

4.2. Alignment/misalignment of goals

The second output was the goals of the important stakeholders to find gaps and overlaps. The goals of the DWS and WSAs are contained in the National Sanitation Policy (Department of Water and Sanitation, 2016). The goals of end-users were derived from the narrative reviews on South African users' behaviour with sanitation systems, and the goals of the transdisciplinary knowledge synthesis team were established at the kick-off workshop. The goals of the four primary stakeholders were mapped against economic, social, and environmental goals (see Fig. 3). This analysis suggests that the goals of DWS and WSAs are not always aligned with end-users, particularly around environmental goals. Understandably, end-users were more focused on meeting economic and social needs, and less focused on broader environmental needs such as CO_2 reduction, conserving water, or damage to rivers and estuaries. However, a core goal of comfort for end-users was not a goal of other stakeholders suggesting a likelihood that users may reject top-down interventions that ignore comfort. This analysis of goals also emphasises that there are important emerging aspects identified by the transdisciplinary knowledge synthesis team which were missed by DWS and WSAs. These include improved financial return opportunities through circularity in wastewater treatment, the creation of decent work opportunities, addressing novel compounds, and developing systems that reduce the release of CH_4. Given the degree of misalignment between the stakeholders apparent in Fig. 3, addressing the problem of sanitation in South Africa would be more complicated than in situations or countries where there is greater alignment of goals between the major stakeholders.

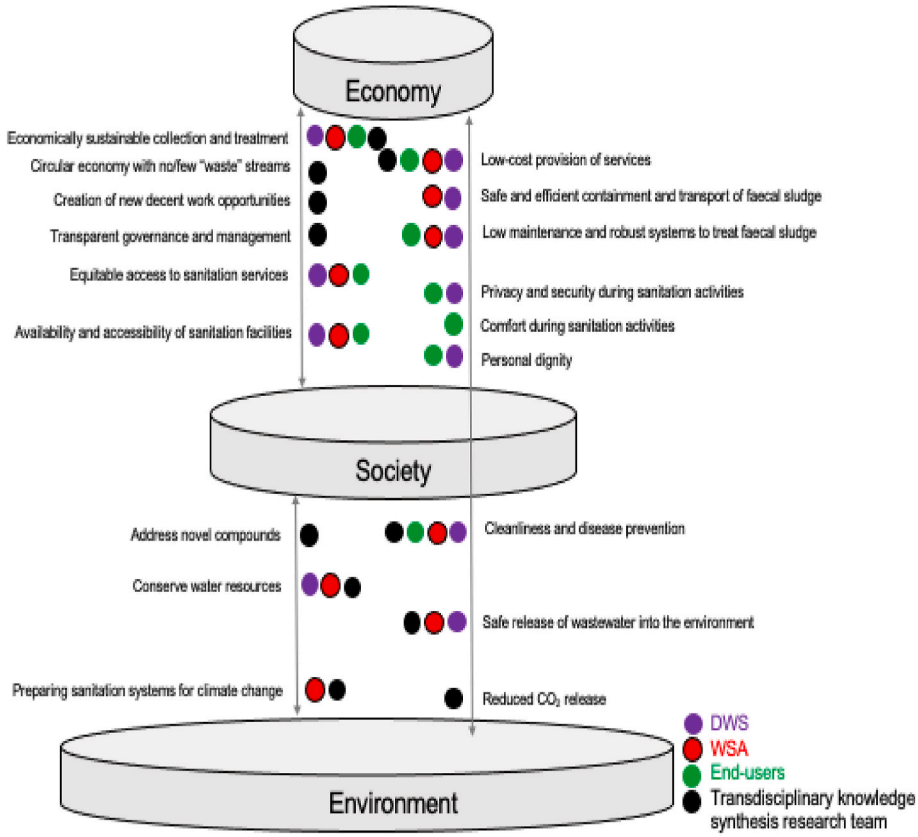

Fig. 3. Goal alignment between primary stakeholders.

4.3. Potential technologies of the future through the lens of complex system constraints

Taking these complex system constraints and stakeholder goals into account, it is possible to see how the constraints and goals impact on the implementation success of sanitation solutions. An example of this type of thinking is presented in this section which evaluates three common sanitation solutions for South Africa considering non-sewered contexts (see Table 2). There are a few points that bear noting from this analysis. First, the three examples are not meant to be exhaustive, but a demonstration of how the SSoS outputs can be applied to identify "best case" options in the context of multiple constraints and goals. There are many other decentralised (e.g., dehydration toilets, porta-potties) and centralised options (e.g., seawater sanitation and water reclamation plants) that could also be considered. Second, it should be evident from the constraints that no single solution will be appropriate for all contexts. Third, the analysis does not suggest that solutions can (or should) be implemented immediately. Fourth, the outputs should be used in conjunction with detailed cost-benefit analyses, technical competence evaluations, to identify the best solution for each context.

4.3.1. Chemical toilets

Chemical toilets are individual or shared on-site facilities, where faeces and urine are collected in a shallow container with chemicals added to treat the sludge and to reduce odours. Contractors must regularly remove the container contents to a WWTP, but otherwise require no technical expertise to maintain, and do not require water or energy sources to operate. They were originally intended to only be deployed in emergency situations for a limited period of time (Overy, 2013). However, due to their relatively low cost, ease of installation, and limited space requirements they have increasingly been permanently installed in a variety of high-density, underserviced urban contexts. They are expensive to maintain due to regular servicing for sludge removal and the addition of chemicals. Lucrative maintenance contracts are ripe for exploitation by tenderpreneurs. Cleaning and maintenance aspects of the units themselves are left to the community. Community members restrict access by locking units to assure "ownership", leaving some community members with no access to sanitation facilities. Chemical toilets are often located far from dwellings, creating security issues, especially for women and at night. They are susceptible to damage if non-effluent products (e.g., nappies, feminine hygiene products) are discarded. Collection for centralised sludge treatment might make it easier to remove emergent chemical compounds and to monitor pathogens. User acceptance of chemical toilets is low and their implementation is often resisted (Norvixoxo et al., 2022).

4.3.2. Urine diverting dry toilets (UDDTs)

UDDTs separate urine from faeces, ostensibly to enable the extraction of nutrients from urine and the drying of faeces for fertiliser, although this seldom occurs (Mkhize et al., 2017). They were originally intended for single-dwelling installation in rural areas to mitigate poor access to water supplies. However, UDDTs are increasingly being found in high-density urban areas (Silveti and Andersson, 2019). UDDTs are installed above-ground to enable the removal of faecal matter, meaning that there is less risk of contamination of/by groundwater (Mkhize et al., 2017). They do not require water (or electricity) to operate. After installation, it is expected that households would maintain the units and manage the effluent. For this reason, local governments consider UDDTs to be affordable because the ongoing maintenance costs are transferred to the user (Silveti and Andersson, 2019). However, increasingly urbanised contexts (and the high pathogen loads) means that users cannot dispose of dried faeces, and removal costs are growing for local governments. There are significant health risks when handling faeces, using faeces as fertiliser, and when cleaning composting units (Schönning et al., 2007). It is extremely difficult to remove or treat faeces for emergent chemical compounds or to monitor for pathogens.

Table 2
Examples of how the SSoS outputs links to sanitation solutions across non-sewered and sewered communities to constraints for future scenarios.

Type	Constraints (and goals) *	Would this be chosen based on SSoS outputs	Has it been implemented?	Was the implementation successful
Chemical toilets	+**tive**: Biophysical constraints. Does not require water in a water-scarce country. +**tive**: Energy constraints. Does not require energy source to operate. +**tive**: Financial constraints. Relatively inexpensive to purchase and install. +**tive**: Waste accumulation constraints. Possible treatment of emergent chemicals if centralised treatment facility is equipped. +**tive**: Population constraints: Easy to roll-out *en masse* at short notice. **-tive**: Management constraints. Fuels tenderpreneurship contracts. **-tive**: Management constraints. Susceptible to operational failure if service provision fails. **-tive**: Financial constraints. Relatively expensive since it requires regular servicing with effluent removal and chemical additions. **-tive**: Waste accumulation constraints. Susceptible to failure through flushing of non-biodegradable objects. **-tive**: Health constraints. Requires regular cleaning in close proximity with faeces. **-tive**: User constraints. Sharing of facilities results in security and cleanliness issues. **RED FLAG**	No. Primarily due to substantial negative management and user constraints	Yes. Widespread implementation in unplanned and informal settlements	Yes, although despised by end-users. **RED FLAG.** Barely qualifies as Basic Sanitation.
Urine Diverting Dry Toilets (UDDTs)	+**tive**: Biophysical constraints. Does not require water in a water-scarce country. +**tive**: Energy constraints. Does not require energy source to operate. +tive: Financial constraints. Relatively inexpensive to purchase and install. +**tive**: Waste accumulation constraints. Possible reuse of faeces as fertiliser if land is available. Possible reclamation or nutrients from urine. +**tive**: Waste accumulation constraints. Possible treatment of emergent chemicals if faeces and urine can be transported to central facility. **-tive**: Financial constraints. Relatively expensive to maintain for removal of dry faecal matter and urine separately by contractors. **-tive**: Financial & Governance constraints. Community responsibility for maintenance unlikely to succeed due to expectations of government responsibility. **-tive**: Health constraints: Transmission risks of infectious organisms when handling faeces for fertiliser and during maintenance. **-tive**. User constraints. Limited social acceptability due to cultural taboos in handling faecal matter. **RED FLAG**	Potentially, especially in the context of Biophysical and Energy constraints. Potential to recycle nutrients.	Yes. Large scale implementation in eThekwini.	Unsuccessful implementation. Strong local cultural taboos against handling faeces and governance constraints. **RED FLAG.**
Decentralised Wastewater Treatment Systems (DEWATS)	+**tive**: User constraints. Satisfies flush toilet requirements. +**tive**: Financial constraints. Costs for piping reticulation systems and effluent transport are much lower than WWTPs. +**tive**: Energy constraints. Less of a risk because fewer (or no) pumping required. +**tive**: Waste accumulation constraints. Possibility to deal with emergent chemicals if treatment technology can be applied locally. **-tive**: Governance constraints. Requires significant community - municipality cooperation. Expected resistance from municipalities because revenue collection is difficult. **-tive**: Governance constraints. Requires significant skills at local level to manage systems. **-tive**: Management constraints. Uncertainty	Yes. Positive outcomes largely exceed negative outcomes. User constraints less critical and can be managed.	Yes. But pilot units only.	Unsuccessful in scaling up due to local government resistance to costs from operations and management. **RED FLAG**.

(*continued on next page*)

Table 2 (*continued*)

Type	Constraints (and goals) *	Would this be chosen based on SSoS outputs	Has it been implemented?	Was the implementation successful
	exists around sufficient skills as well as operation and maintenance schedules. **-tive**: Financial constraints. Capital costs for rolling out DEWATS can be higher than centralised WWTPs. **RED FLAG**. **-tive**: Financial constraints: Costs of de-sludging needs to be properly accounted for. **RED FLAG.** **-tive**: User constraints. Lack of trust in local government to appropriately operate and manage distributed units. **RED FLAG.**			

Note that the +tive and -tive attributes of constraints/goals are not intended to denote equal weights. They simply indicate the traits of each possible sanitation solution. It is not intended that one counts the positives and negatives because their weights will vary depending on the timing, the specific context, the people being impacted, and the interactions between the various positives and negatives. Instead, one should identify **RED FLAGS** which indicate high, almost certain, probability of technology solution failure.

Users have found UDDTs difficult to use (especially children), they resist handling faeces themselves (Mkhize et al., 2017), and have complained of odours and flies (Silveti and Andersson, 2019).

4.3.3. *Decentralised wastewater treatment systems (DEWATS)*

DEWATS are essentially small WWTPs connected to multiple households. The intention with DEWATS is that they do not require long, piped sewers with pumping stations. They do require a local water supply and some DEWATS might require a limited energy supply for pumps. Each unit is cheaper to install, operate, and maintain than centralised WWTPs (Arumugam et al., 2023), but if many DEWATS are required, capital and running costs may be significantly higher. Local governments have therefore resisted their widespread implementation (Arumugam et al., 2023). Similarly, some communities distrust local governments to effectively manage the facilities (Ashipala and Armitage, 2011). In other parts of the world, DEWATS have been successfully implemented, but there are significant uncertainties in the South African context around the feasibility of community-government cooperation, especially around responsibilities for operation, maintenance schedules, and the costs of de-sludging (Reynaud and Buckley, 2015).

The SSoS outputs highlight how different scenarios can be compared without the imposition of a preconceived bias or judgement. Once the positive and negative constraints have been identified and listed using the SSoS analysis, a choice could potentially be made for consideration within a specific context, whilst being cognisant of the "red flags". These contextual factors are aspects which would not necessarily emerge during a typical design process. The SSoS outputs allow multiple stakeholders to make a decision based on a range of perspectives; not necessarily through a siloed engineering/technical lens. In effect, this approach, to some extent, embraces the "wickedness" of the problem (Coyne, 2005). Whilst not taming the problem, this approach is able to make it less "wicked". It provides scope for judgement by the professional, to be incorporated with other factors, such as political imperatives, without compromising the integrity of the professionals' judgement (Coyne, 2005).

5. Discussion

5.1. *Reasoning with the systems-thinking tool*

The value of the SSoS outputs is that it takes cognisance of the contextual factors which may be missed, and which may preclude successful implementation, despite appearing to be a "better" technical solution. The SSoS outputs systematise and extend Scott and Cotton's (2020) characterisation of the external factors demonstrating how unique contextual factors can influence the success of sanitation "solutions." In complex contexts, certainty is seldom available. However, linear thinking can lead one into a false sense of security that one can definitively know that there is a single "best" technological solution. It is clear when taking this broader systems approach that there are multiple interlinked constraints which are impinging on the ability of South Africa's urban sanitation systems to provide sustainable sanitation solutions. It is also apparent from Fig. 3 that there is a misalignment of goals between the primary stakeholders, which complicates the implementation of solutions. From the systems analysis the current emphasis on water-borne sanitation systems in a water-scarce context with high energy requirements for transporting and treating the effluent is outdated and under threat, even while the alternative is the preferred government solution for underserved users. Solutions that use less water (or less water-based transportation of sewage) and are decentralised require consideration but must be carefully implemented and managed bearing in mind the context of South Africa's complex socio-historical pathway and currently unequal society. Table 2 provides examples of how the systems-thinking constraints can be applied to evaluate existing options. Systems-thinking can also show where complex problems are interconnected as solutions to one problem can have positive (and negative) knock-on impacts to other problems. Nevertheless, leveraging this interconnectedness is the inherent power in systems thinking.

5.2. *Novel practical implications*

The aim of the SSoS outputs is to characterise the systemic components of this specific context to see what this can uncover about possible solutions and their likelihood to succeed and, more importantly, to identify new directions that have yet to be implemented. The SSoS outputs bring together transdisciplinary knowledge in order to overcome simplistic, linear thinking. The goal alignment exercise revealed where the goals of the major stakeholders are both aligned or misaligned. This broadens the view available to engineers and related professionals to show where the possible hindrances might occur and, by implication, identify the alternatives for that specific context. In particular, if the goals of the stakeholders are misaligned, this will lead to less successful implementations and poor adoptions of "solutions." This analysis shows that South Africa's current sanitation trajectory reveals a failing urban wastewater infrastructure which represents "dirtier production" where the significant sewage that flows into rivers results in serious health and environmental impacts. Various possible alternative technologies exist but have consistently failed within the South African context. The narrative reviews, summarised in the constraints, provide a transdisciplinary reflection and a possible pathway beyond this impasse to a cleaner sanitation future.

First, the paradox of South Africa's sanitation systems is that they exist where skills and experience are badly needed within a context of high unemployment. Solving the skills deficit while simultaneously addressing the unemployment crisis is key to a successful urban sanitation system. In particular, solutions should focus on opportunities for dignified and meaningful work. Second, while the Municipal Finance Management Act is designed for transparency and to limit fraudulent and corrupt practices, it delays processes critical to the delivery of sanitation services at local government level. Downward delegation of authority to speed up supply chain processes could be considered a solution to this problem. However, this will also require effective consequence-management for failures. Third, there are implications for engineering curricula that support multidisciplinary and complex systems-thinking rather than constrained and bounded solutions.

5.3. Novel theoretical implications

The results reveal important policy considerations for sanitation in South Africa including the need to overhaul the management and governance structures, the creation/adoption of legislation to deal with emerging chemical compounds, investment in low-cost technologies to enable the circular economy, and the development of decent work initiatives for the urban sanitation sector. First, the knowledge synthesis emphasises that there are numerous recovery and extraction opportunities from faeces and urine. Opportunities include biobricks (Zat et al., 2021), biocarbons as activated carbon (Huang et al., 2022), and biopolymers (Ali et al., 2022). To simultaneously address South Africa's energy shortages, biogas production (from biodigesters and composting toilets) and extracting ammonia for fuel cells from urine show promise. However, more research is needed to develop better, more cost-effective extraction methods for low-income countries. Second, the removal of chemicals of concern will remain a challenge until either manufacturers stop producing "forever" chemicals (Aryal et al., 2020) or the methods of treating wastewater are able to remove these at scale and at a reasonable cost (Badmus et al., 2018). The preferred option is for the exclusion of these substances from the chain of human economic activity, which will allow meaningful reuse of sludges and solids for fertiliser or agricultural use. This is currently an unrealistic expectation although international legislative efforts are underway, to which South Africa is a signatory. Until that time, feasible monitoring and removal systems are needed. Second, developing new models of governance and management will be important. What is needed is common pacts where governance structures provide non-predatory (not for profit) services for the common good with transparency in how funds are collected, allocated, and spent. From a top-down perspective, steady-state economic models need to be developed rather than the myth of perpetual growth.

5.4. Addressing just transitions

Many transitional steps to a utopian future are envisaged that will require constant updating in the context of new challenges and new technologies. The SSoS outputs raise important questions for any stepwise transition. In transitioning away from water-borne systems how does government and society address the aspiration for sewered, water-borne systems when non-sewered systems are perceived to be unsustainable? The first transition step must involve fixing critical infrastructure, processes, skills, and systems that are not working. This inevitably means acknowledging that WSAs cannot fix these systems on their own. They are simply not provided with sufficient (or able to raise) finances, procurement processes, and governance structures that will allow the efficient transformation of current systems. The national DWS may need to take a proactive approach to addressing pervasive local government failures with an emphasis on assistance (which is constitutionally permissible) rather than interference (which is not acceptable). A second transition step means acknowledging that all sanitation systems (not just for the underserviced) must consider alternatives to water-centricity. Potable water is simply too scarce and valuable to flush down toilets. Greywater circulation technologies already exist and could be considered for those people with "flush" systems and the installation of new systems with "flush" capabilities. A third transition step must include decentralised systems and centralised blackwater reclamation.

Further transition steps will require interdisciplinary and transdisciplinary approaches with more in-depth population analysis and modelling, financial investment, technological development, regulatory oversight, and behaviour change interventions that integrate human needs, culture taboos, and expectations. It is likely that part of the solution will involve systems that create decent jobs through the extraction and sale of valuable materials (e.g., nitrogen, phosphates, ammonia, etc.) from urine and faecal waste. Cost-effective circular economy approaches might out-compete linear economy end-of-pipe technological solutions, especially as linear economy approaches are often not suited to the local conditions (i.e., water-borne systems in water-scarce contexts).

6. Conclusion

In this study a multidisciplinary team's knowledge synthesis identified the constraints to the sanitation system at different hierarchical levels of influence. The resulting constraints and stakeholder goal matrix was then used to evaluate three existing sanitation solutions which demonstrated the value of the complex systems-thinking approach. Not only can the constraint and stakeholder goal matrix be used to evaluate existing options but can be used to identify future possibilities including the need for solutions that can operate in water-constrained contexts, consider opportunities for extracting value from circularity, promote skills development and job-creation, and integrate the implications for financial and educational systems. This paper follows the transdisciplinary analysis in the South African urban context. While the results are not transferable to other contexts (or even to rural contexts in South Africa) this paper provides a template process and analysis framework to assist researchers and policy-makers in other, global contexts. The knowledge synthesis was limited by not having end-users from disadvantaged communities or stakeholders from across the entire governance and operational hierarchy. The importance of including these indigenous knowledge systems in the framing exercise is important for future work. It will also be important to compare this framework with other sustainability evaluation tools and particularly to cost-benefit analysis tools to establish the specific value that this approach might add. Through the application of this approach, it was demonstrated how standard engineering approaches would likely fail within certain contexts, but also why a hated solution (the chemical toilet) is repeatedly implemented as a short-term solution. The complex array of factors impacting on South Africa's urban sanitation systems are unsuitable to existing linear problem-solving strategies and require complex systems-thinking approaches. If this approach were expanded to other sanitation solutions, there is the potential that failures could be identified early and that programmes could be implemented to try to align stakeholders' priorities and goals prior to the expensive rollout of that solution. This would have substantial benefits for society and the natural environment.

CRediT authorship contribution statement

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James Topkin: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

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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