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Applying the sustainable system-of-systems framework: wastewater(s) in a rapidly urbanising South African settlement

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ABSTRACT
Addressing wastewater infrastructure needs in urban informal settlements must simultaneously address legacies of past failures, current aspirations and constraints, as well as increasingly changing needs related to global environmental change. This study applied the Sustainable System-of-Systems framework for ergonomics and human factors to gain a better understanding of how small in-situ constructed wetlands could be a form of greywater treatment infrastructure in an informal settlement. Using 24 months of interviews, surveys, workshops and photo-ethnographic observations, we identified that the rapidly changing nature of parent (e.g. residency transience and land ownership) and sibling (e.g. housing and drinking water) systems put pressure on the target wetland system to adapt, often decreasing its capacity to deliver the service of water cleaning. Greywater treatment was not a common goal among stakeholders involved in the nested hierarchy system which likely contributed to the constructed wetlands needing to adapt to remain relevant.

Practitioner summary: The value of the Sustainable Systems-of-Systems framework for ergonomics/human factors professionals in determining the sustainability of an ergonomics/human factors intervention is demonstrated using a greywater treatment system case study for an urban informal settlement. Understanding the variety of stakeholder goals and the pace of change in related systems was key to a sustainable intervention.

Abbreviations: CFU: colony forming unity; CWA: cognitive work analysis; EAST: event analysis of systemic teamwork; E/HF: ergonomics/human factors; FRAM: functional resonance analysis method; HFACS: human factors analysis and classification system; SDG: sustainable development goal; SSoS: sustainable system-of-systems; STAMP: systems-theoretic accident model and processes; URBWAT: URBan WATer systems project; WDA: work domain analysis; WHO: World Health Organisation

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1. Introduction

1.1. Wastewater(s) in a rapidly urbanising world

Globally the majority of people live in cities, and as such the sustainability of urban service delivery is of prime importance (Childers et al. 2019). Historically, the Global North has opted to centralise wastewater infrastructure, often combining different types of wastes and looking to treat and dilute the wastewater to minimise immediate human and environmental health concerns. The collection and treatment of blackwater (human excreta and toilet water) has enormous health benefits; this is why equitable access to sanitation is a United Nations Sustainable Development Goal (i.e. SDG6, target 6.3). Sewer systems which move waste underground and away from people and, under the best of circumstances, towards a functional wastewater treatment plant are considered the 'Gold Standard' by many, including city residents. Stormwater (i.e. water flowing in cities as a result of precipitation events), greywater (i.e. water from cooking and cleaning), as well as other types of

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industrial wastewaters often use the same sewer system even though their composition requires different levels of treatment. Continued rapid rates of urbanisation and a slow capacity for building large greywater infrastructure, in conjunction with the effects of climate change on water availability, flooding, and drought, further highlight why such centralised wastewater systems are not a realistic, or perhaps even desirable, way forward for cities (Öberg et al. 2020).

Urban informal settlements are a common (and dynamic) feature of many cities in the Global South (Lawhon et al. 2018; Mahabir et al. 2016) and are increasingly common in the Global North in the form of refugee camps, homeless settlements, and temporary disaster camps. They arise when rapid urbanisation is not supported by adequate social and physical infrastructure such as electricity, water, sewerage, schools, healthcare facilities, and recreational facilities. Under these circumstances infrastructure that is perceived as most urgent (i.e. shelter) is constructed prior to the provision of other important services such as sanitation, water, electricity, and healthcare. Some services such as water and electricity are relatively easy to retrofit in urban informal settlements because they require very little space and can be installed in a flexible manner. Other services, such as sewerage or greywater removal, are notoriously difficult to implement once an informal settlement has been established because they are less flexible and require a lot more space to implement which often involves the removal of existing infrastructure. Consequently, essential services are dealt with through temporary solutions (e.g. portable toilets for sanitation) or are simply absent (e.g. educational and healthcare facilities).

Given that centralised wastewater systems may not be a desirable or possible solution in the long run, even though the need for such service delivery in informal settlements is acute, alternatives must be examined. Urban ecological infrastructure, an encompassing term for nature-based solutions that highlights the important role of 'blue' and 'turquoise' ecosystem features such as wetlands and hybrid green and grey infrastructure types, is likely part of the solution (Childers et al. 2019). Urban ecological infrastructure often differs from grey infrastructure projects in that they are more adaptable to changing conditions (such as climate change) and provide more than one service at a time (Childers et al. 2019). For example, a public park along a river prone to flooding can provide both recreation and stormwater protection for residents. Separating wastewater types opens-up more sustainable solutions for urban ecological infrastructure, but there is no clear panacea for what sustainable sanitation (Brands 2014; Öberg et al. 2020), stormwater (Barbosa, Fernandes, and David 2012), or greywater (Li, Wichmann, and Otterpohl 2009) treatment should look like. A nimble understanding of the context surrounding these systems is paramount. Cities are complex systems that require researchers and practitioners to examine the social, ecological, and technological perspectives of infrastructure development and the transformational changes needed for cities to sustainably deliver services (Depietri and McPhearson 2017; McPhearson et al. 2021).

1.2. Sustainable system-of-systems (SSoS) framework

The sustainable system-of-systems (SSoS) framework was developed by Thatcher and Yeow (2016) as a means of identifying the principles necessary to design sustainable ergonomics/human factors (E/HF) interventions. The SSoS framework is not a theory or a model, but rather a set of guiding principles, drawn from the functioning of ecological systems, and applied to eco-socio-technical systems (Thatcher and Yeow 2020). Because the SSoS framework uses natural ecosystem functioning as its basis it is therefore an example of green ergonomics (Thatcher 2013). The SSoS framework is also not an analysis tool. Thatcher and Yeow (2020) and Thatcher, Nayak, and Waterson (2020) considered how complex sociotechnical systems tools like Accimap (Svedung and Rasmussen 2002), STAMP (Leveson 2004), EAST (Walker et al. 2006), and CWA (Vicente 1999) might be used to unpack complex eco-socio-technical systems. Descriptions of the SSoS framework have been covered in-depth previously and a summary is given here. For more detailed information, interested readers are directed to Thatcher (2016) and Thatcher and Yeow (2016; 2018; 2020). The SSoS framework has four components: a nested hierarchy of systems; competing goals; nested 'natural lifespans'; and complex adaptive cycles.

Cash et al. (2006) noted that multiple systems need to be considered at cross-scale and multiple levels to address global challenges. The first component therefore views systems as a nested hierarchy with smaller, less complex systems being nested within larger, more complex systems. While the nested hierarchy concept is drawn from ecological models (Costanza and Patten 1995; Gunderson and Holling 2002) this thinking has already permeated into the E/HF literature (Moray 2000; Rasmussen 1997). The nested hierarchy extends the systemic thinking approach, which is already a hallmark of E/HF (Dul et al. 2012), to identify not just a single system, but also all the relevant, related systems. The SSoS framework uses Wilson's (2014) terms to describe the relative placement of systems in the hierarchy. The system of interest is called the 'target' system. Systems with equivalent complexity and spatial influence are 'sibling' systems. Systems of greater complexity and spatial reach than the target system are 'parent' systems. Systems that are less complex and have a smaller spatial reach are 'child' systems. There may be many hierarchical levels of child and parent systems representing the interrelationships with a target system.

The second component considers how the goals of the target system match with the goals of the other relevant systems in the nested hierarchy. A Work Domain Analysis (WDA) also includes an analysis of the purpose (i.e. goals), values, and functions of a system (Vicente 1999). However the SSoS framework recommends that we not only look at the goals of the target system, but also undertake an analysis of the goals of the related parent, sibling, and child systems. For a target system to be sustainable it must integrate within its ecosystem of related systems. Mauerhofer (2008) considers the target system to be sustainable when these goals are balanced between the systems. Thatcher and Yeow (2016) originally conceptualised the goals as being representative of Elkington's (1998) Triple Bottom Line goals of economic, social, and environmental factors, although they emphasised that this was only an example.

The third component draws from the ecological understanding that no system lasts forever. Instead, each system has a 'natural lifespan' (Costanza and Patten 1995) and sustainability refers to each system reaching (but not exceeding) their natural lifespan. The length of the natural lifespan is determined by the relative placement of a system in the nested hierarchy. Larger, more complex systems have longer natural lifespans than smaller, less complex systems. Systems that fail to reach their natural lifespan cause instability in the nested hierarchy, whereas systems that last too long past their natural lifespan become brittle and fail to adjust to the external changes imposed by the related systems (Thatcher and Yeow 2016). For example, a work system that changes too rapidly (e.g. a rapid turnover of new work interventions) will fail to fully integrate with the other external systems (e.g. the management systems, the workplace layout, etc.), meaning that those systems must constantly adapt. Similarly, a work system that is resistant to the changes in its external systems (e.g. changing technology, emergent work tasks, changing economic circumstances, etc.) will soon become outdated and will struggle to survive.

Thatcher (2017) added a fourth component; complex adaptive cycles, taken from Gunderson and Holling (2002). A complex adaptive cycle characterises the evolutionary phases that every system follows: the exploitation of networked connections, the conservation or consolidation of those connections, the release or creative destruction of connections, and the re-organisation or destructuring of the system. Each system in the nested hierarchy would be at their own different phase of the complex adaptive cycle depending on the collective relationships and connections with other systems. Building on the third component, the rate of change of the complex adaptive cycle will be determined by its natural lifespan and therefore its relative position in the nested hierarchy. The relatively larger, slower, more complex systems act as stabilising influencers in the nested hierarchy in a process that is called 'remember' (i.e. forcing systems to maintain existing connections). The relatively faster, smaller, less complex systems disrupt the slower, larger, more complex systems in the nested hierarchy in a process called 'revolt'. Parent and sibling systems are more likely to respond to revolt processes when they are nearing the end of the conservation phase. These co-evolutionary interactions are what enable systems to be resilient and sustainable in unstable environments.

1.3. Case study: greywater treatment in an urban informal settlement

The physical context for this case study is an informal settlement, Setswetla, located along the Western bank of the Jukskei River in Johannesburg's oldest and poorest township, Alexandra (Bonner and Nieftagodien 2008). The initial settlement of Setswetla started in the mid-1980s during Apartheid when the Alexandra township, which also suffered major service delivery issues, could no longer support the continued influx of people coming from rural areas to seek employment in Johannesburg. Since then, Setswetla has seen continued growth and now has an estimated population of 30,000 people living in an area less than 1 km^2 in low-rise buildings. Many of the buildings are makeshift constructions consisting of 'found' materials such as corrugated iron, recycled bricks, plastic sheeting, and cardboard. Local government has provided limited electricity, potable water (communal taps), temporary sewerage (with several households sharing a single portable toilet emptied weekly), and solid waste removal (a single, open-topped skip emptied weekly).

This study looks at the problem of greywater treatment and removal which is often neglected as an essential service because it is perceived to have much lower health risks than sewage (i.e. 'blackwater'). Greywater refers to wastewater from washing and other household chores (Oteng-Peprah, Acheampong, and DeVries 2018). Due to the lack of formal sewerage services in Setswetla greywater is simply thrown onto the ground, where it ends up in the streets and the pathways where people live, running through the informal settlement into the river with no treatment of the water (either chemically or microbiologically). Water quality testing of the greywater in Setswetla indicates that it is a significant health hazard. *Escherichia coli* counts of 5000 to 10,000 CFU/100 ml have been recorded when the World Health Organisation (WHO 2003) guidelines suggest that safe counts for recreational water should be below 200 CFU/100 ml. The investigations reported in this paper form part of a transdisciplinary research project, called URBWAT, whose aim is to design greywater treatment and removal solutions for urban informal settlements.

Following interviews with relevant stakeholders across Johannesburg, a survey campaign on water and wastewater habits among residents in September 2019, and a series of six participatory workshops in November 2019, two small, pilot, sub-surface, constructed wetlands (Sheridan, Hildebrand, and Glasser 2014) were installed in February 2020 (see Figure 1 for the timeline and Figure 2 for an example of the constructed wetland). The URBWAT team worked with construction workers sourced from the Setswetla community and all building materials were purchased locally. Following construction, the research team has had continued regular contact with the community. Learning from these pilot systems, the residents and the research team have worked to re-design the wetlands and build at new sites. These adaptations will be the focus of a future paper.

1.4. Problem statement

While the SSoS framework is well-developed theoretically (Thatcher 2016; Thatcher and Yeow 2016, 2018, 2020), the empirical application of the framework is limited (Thatcher, Nayak, and Waterson 2020). In addition, Thatcher and Yeow (2018) have noted that very few E/HF projects have considered the global problems associated with water issues. The URBWAT project provides an ideal testing ground to empirically assess whether the SSoS framework has any practical value in understanding the real-world E/HF problem for designing an urban water treatment solution. The aim of this paper is to reflect on whether the four components of the SSoS framework add value for the design of a greywater treatment system so that E/HF practitioners can understand, practically, how to apply the SsoS framework. The approach in this paper addresses McPhearson et al. (2021) five key actions for sustainability research: (1) the need for eco-socio-technical systems thinking; (2) moving towards transdisciplinary research; (3) co-designing and co-producing research together with communities to leverage diverse knowledge; (4) questioning the status quo within and across disciplines; and (5) creating positive tipping points for change. As such, the systems level understanding put forward is compatible with fields other than E/HF which are keen to tackle real-world complex sustainability issues.

2. Methods

Thatcher and Yeow (2020) identified four steps in applying the SSoS: (1) stakeholder identification; (2) collecting data from the relevant interrelated and interacting systems in the hierarchy; (3) identifying relevant intervention points in the SSoS hierarchy; and

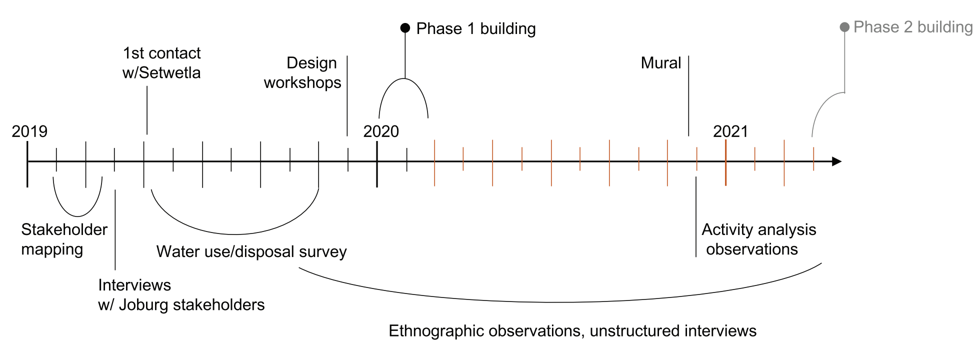

Figure 1. Timeline of research events including quantitative information regarding different data collection and generation activities. Orange-colored marks indicate months where the Covid-19 pandemic affected data collection and interactions.

Figure 2. One of the two pilot constructed wetland systems that were installed in February 2020.

(4) estimating the rate of iteration for an effective intervention. This paper focuses on the first two stages.

Data collection and interpretation for the first two stages took place over more than two years and benefitted from the iterative input of experts in a transdisciplinary context. Transdisciplinary research, for the purpose of creating real-world change, aims to engage diverse stakeholders, which includes multiple academic disciplines but also real-world practitioners and actors that have a stake in the subject, in a process of knowledge co-production (Lang et al. 2012; Norström et al., 2020). The URBWAT research team included psychology, natural resource science and sustainability, ecology, engineering, and microbiology as academic disciplines but was also keenly focussed in co-creating stakeholders, in particular informal settlement residents. To gain a more nimble understanding of how the target system may fit into existing water, waste, and other resource management we started with interviews with key stakeholders, resident water use surveys and design workshops.

2.1. Stakeholder identification and mapping

We first undertook a stakeholder mapping exercise to identify how actors could play a role in designing, implementing, and using the target system (i.e. a greywater treatment system within an urban informal settlement). Following Thatcher and Yeow (2018), Soft Systems Methodology (Checkland 2000) was used as the basis to identify the relevant Customers (i.e. recipients of the intervention), Actors (i.e. stakeholders involved in the implementation of the intervention), and Owners (i.e. decision-making authority over the implementation of the intervention) involved. Stakeholder identification and mapping was an iterative process. The research team wanted to ensure that as many sectors as were relevant to understand greywater management in Setswetla were included, and that within each sector the mapping covered different types of stakeholders (Iwaniec, Metson, and Cordell 2016). We used the research team's knowledge of the system in conjunction with published reports and peer-reviewed literature to draft a preliminary list of stakeholders. When interviewing key actors in the existing local networks, each interviewee added to the representative map (and major connections) of actors involved in the system.

A total of fifteen stakeholder groupings were identified at six levels of influence (see Figure 3). At the level of direct interaction with the intended intervention, stakeholders included community residents and the URBWAT research team (including the first author as the E/HF specialist). These stakeholders were also influenced by a range of other stakeholders at the local (i.e. Community Leadership Forum, Ward Council Committee), municipal (i.e. City of Johannesburg

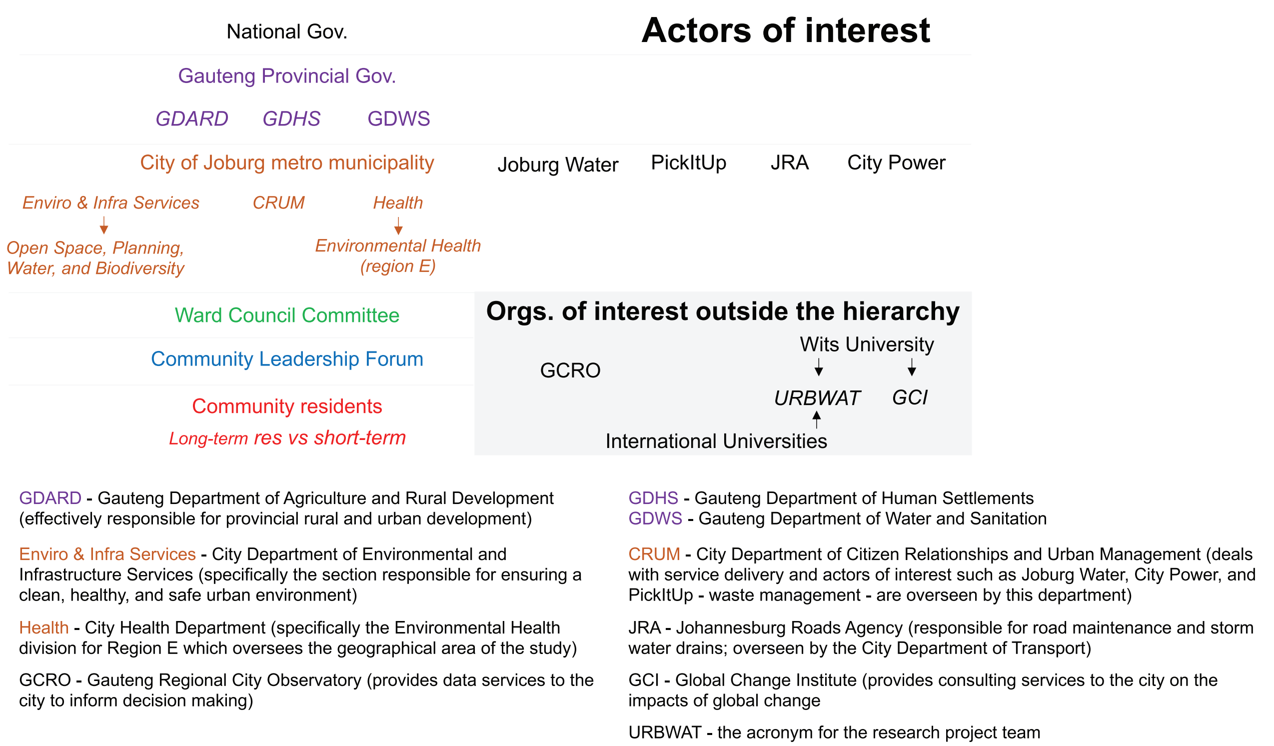

Figure 3. Stakeholder map for actors of interest surrounding the target system. Horizontal lines delineate levels (geographical and organisational) in the hierarchy, where the highest level is at the top, moving towards more local stakeholders towards the bottom of the figure. Colours indicate key organisations which are emphasised in later analyses (see Figures 4 and 6), and italics and smaller font size indicate sub-components of interest within an organisation.

departments, Johannesburg water, City Power, Pick It Up), regional (i.e. respective provincial departments responsible for water, sanitation, housing, and infrastructure), and national (i.e. respective national departments) levels. This step was used to identify relevant systems as a first step towards determining their relative placement within the hierarchy of systems. During the initial stakeholder identification process it became evident that there was a need to distinguish between short-term (i.e. days to months) and long-term residents. Long-term residents would benefit from: (a) being involved in the participatory design process; (b) investment in the sustained success of the intervention; and (c) from any training in how to use the intervention. Short-term residents, although they would benefit from greywater treatment, would not receive any of the benefits above and could potentially derail (even if unintentionally) the success of the intervention.

2.2. Collecting data from the relevant interrelated and interacting systems

Permission was obtained for each component of the study from the University's Human Research Ethics Committee (non-medical) prior to data collection (ethics protocol number H19/11/66).

2.2.1. Interviews

Formal individual and group interviews were conducted with eight stakeholder types in April 2019. One group interview was conducted with provincial stakeholders (i.e. Gauteng Department of Agriculture and Rural Development); three group interviews with the metropolitan municipality (i.e. City Department of Citizen Relationships and Urban Management; Environmental Health Department; Environmental and Infrastructure Services Departments); two group interviews with stakeholder actors of interest (i.e. Gauteng City Regional Observatory; Joburg Water); and one group interview with the Community Leadership Forum. An individual interview was also conducted with the Ward Councillor.

2.2.2. Surveys

A survey on water use was developed to obtain a baseline understanding how water was collected, used, and disposed in the informal settlement. The survey was an adapted questionnaire (Howard et al. 2002) which was originally used to assess water usage in low-income urban communities in Uganda. The survey consisted of seven sections: water acquisition sources; water collection methods; water storage; water usage; water disposal; waste management; and demographics of the respondent. Survey data were collected from 228 residents using ten trained enumerators and a purposive sampling strategy. The enumerators were themselves residents of the informal settlement and were therefore known to other residents. Enumerators were used to establish trust in the community, due to poor literacy levels, and because of the large number of spoken languages. Each enumerator collected 20 to 30 surveys from community residents living in their 'neighbourhood'.

2.2.3. Design workshops (focus groups)

Six participatory design workshops were held in November 2019 with each workshop consisting of 12–20 participants. The aims of the design workshops were to involve community residents in the design process and to explore issues related to the sustainability of any greywater treatment system to be implemented. The design philosophy of the greywater treatment systems was participatory and iterative (Vink, Imada, and Zink 2008). The core principles of the workshops established by the URBWAT research team in collaboration with the Community Leadership Forum were: keeping costs as low as possible; using locally available materials; using locally available skills; causing minimal damage to the environment; and removing any implemented system that was unsuccessful. Participants worked in groups of 3–4 to draw their current living conditions with respect to water collection and water disposal. Next the groups drew their imagined, ideal water collection and water disposal situation. Finally, each group presented their drawings and the advantages, disadvantages, and feasibility of each option which were then discussed by all the groups in each workshop. Without exception, the workshop participants requested the installation of a formal sewer system. Unfortunately, this was beyond the scope of the project and not physically possible given the densely packed dwellings. During each design workshop we therefore presented the concept of a constructed wetland to the participants and discussed the feasibility of this option.

2.2.4. Activity analysis

Two pilot systems were constructed by residents selected by the community, based on their skills and availability. The construction costs, including labour, were paid by the URBWAT project. The pilot systems took approximately eight days to build using materials purchased within the informal settlement. Further design refinements (e.g. the exact placement in the community, the inlet design, etc.) were made by the community during the construction. Once two pilot constructed wetlands had been built and community residents had acclimatised to their presence, a structured activity analysis (Daniellou and Rabardel 2005) was conducted over three days in December 2020. The activity analysis included observations of the two pilot constructed wetlands and two planned sites for constructed wetlands. Two observers for each site spent eight hours per day (96 hours of observations) recording the frequency of use, time of day and duration of tap usage (and constructed wetland usage where applicable), the demographics of users, and a breakdown of the specific activities undertaken at each site. Observers worked for half a day and rotated between observation sites to reduce fatigue. In total, 193 behavioural interactions were recorded during the observation period. The observers were all postgraduate students who had been trained in activity analysis and how to use the data observation sheet. Prior to data collection, a half day was spent by all observers practicing the observation techniques and refining the data observation sheet.

2.2.5. Ethnographic observations

Non-participant ethnographic observations were documented through photoethnography (Harper 2003). Observations were captured through field notes and photographs that allowed the researchers to document changes at the study site and behavioural interactions as the project unfolded. Foster, Plant, and Stanton (2020) identified ethnographic observations as one of the most useful techniques for E/HF to analyse macrosystems, especially for determining aspects such as system adaptation and emergence. The ethnographic observations started with a walkthrough of the entire community before a smaller target area was selected. Data collection involved direct observations of spatial configurations of infrastructure, related geographical features, and services (e.g. waste disposal), and community residents' behaviour and interactions with water collection and water disposal. Except during the stricter Covid-19 lockdown levels, visits to the research site were made on a weekly basis for more than eighteen months (June 2019 to March 2021), on different days of the week (including weekends) and at different times of day by two of the researchers, alternating their visits. In total 74 hours of ethnographic observations were made over this period. The ethnographic observations were augmented with 40 informal interviews with

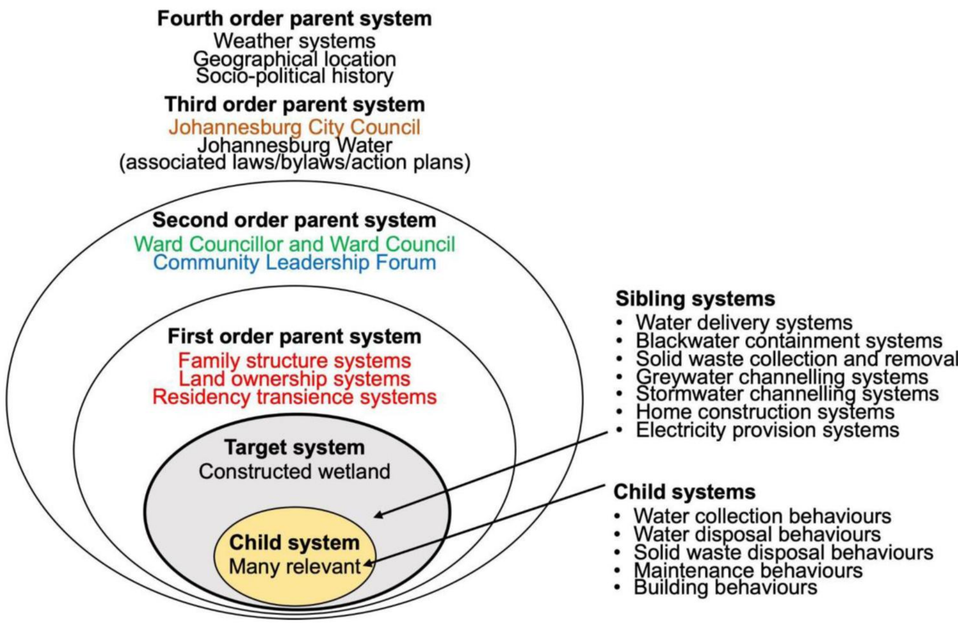

Figure 4. Nested hierarchy with the constructed wetland as the target system, with relevant connected systems highlighted at the appropriate nested levels.

community stakeholders. Community stakeholders included community leaders, community residents who volunteered to take ownership of the system, community residents who used the system, community residents who didn't use the system, and the builders of the greywater treatment system. Some community stakeholders were interviewed several times.

3. Results and discussion

3.1. Nested hierarchy

The emergent nested hierarchy is presented in Figure 4. This is a simplified version which includes most of the relevant systems impacting on the use of the target system. Figure 4 was derived primarily from the formal interviews and was refined through the ethnographic observations. The emphasis in the nested hierarchy is the identification of systems and not the stakeholders. Where stakeholders are mentioned (e.g. Ward Council) this is because of the system/s that they represent (e.g. communication channels with the City Council, enforcement of City bylaws). The nested hierarchy therefore provides a different perspective to stakeholder maps, communication user diagrams (Walker et al. 2006), abstraction hierarchy (Naikar 2013), social network analysis, or Actormaps (Svedung and Rasmussen 2002). Each system might consist of multiple stakeholders and a stakeholder might be a member of multiple systems.

A related point is that the systems consist not only of human actors and technology (i.e. sociotechnical systems), but also ecological objects (e.g. biological agents, geographical agents) and human-manufactured artefacts (e.g. infrastructure and services). The inclusion of non-human actors and agents are important elements required to facilitate sustainable systems (Thatcher and Yeow 2020). Embedded in the systems of the nested hierarchy are other human-manufactured artefacts such as infrastructure (e.g. dwellings, electrical wiring, water pipes, ditches, culverts, and stormwater drains).

However, the determination of spatial reach, complexity, and the natural lifespan of a system is often ambiguous. Two systems might have similar spatial reach, but different levels of complexity (particularly interconnectedness with other systems) and natural lifespans. For example, electricity provision systems might have the same spatial reach as water delivery systems in this community, but water delivery systems are more complex to install because they often require being buried beneath other infrastructure rather than overhead wiring with little consideration of existing infrastructure. Placement within the nested hierarchy is therefore always relative to other relevant systems with fuzzy boundaries between hierarchical levels.

Figure 5 provides a more detailed (zoomed in) diagrammatic representation of the greywater treatment target system and the relationships with the most relevant child, sibling, and parent systems. Two child systems have a significant impact on the target system; the building system during the construction phase and the water disposal and maintenance systems during the use phase. Because physical space is at such a premium, several sibling systems have

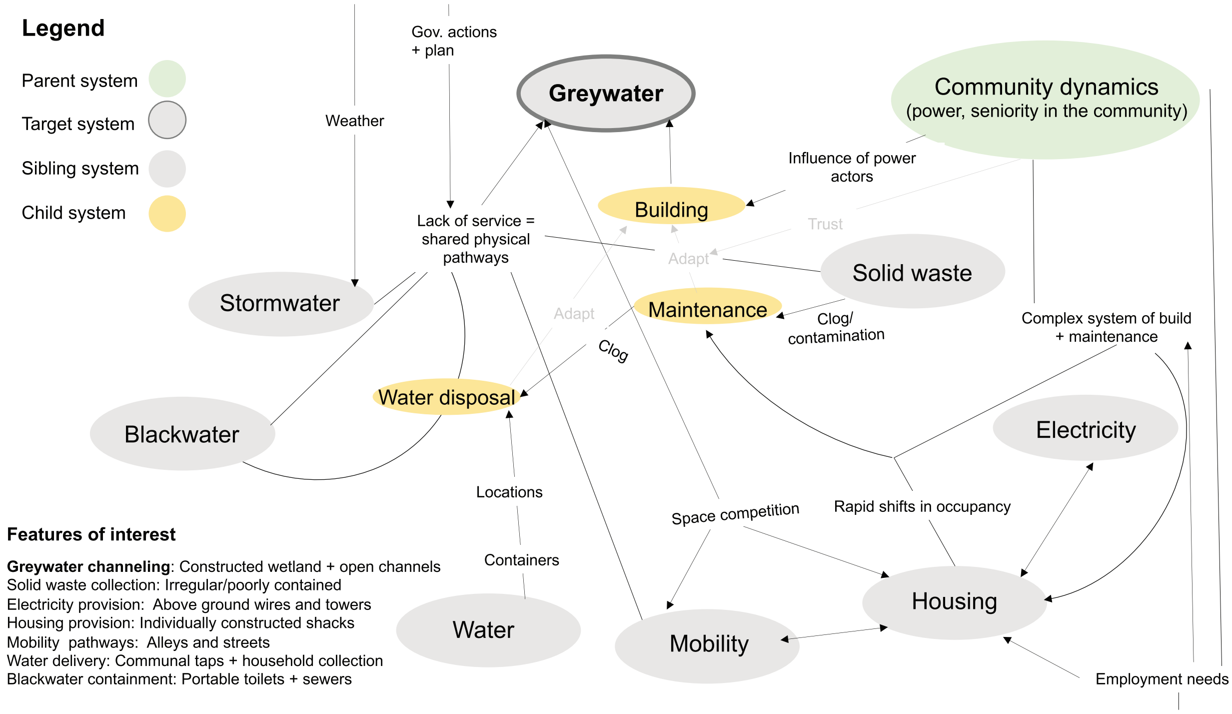

Figure 5. Relationships among various related systems connected directly to the constructed wetland target system.

significant interactions with the target system (directly and through child systems). During the building phase, finding space for the target system, given how fast free space is taken up for home construction, was challenging. Community residents who had power through seniority (which might manifest as land ownership) were inclined to sell rights to build houses close to, or exactly where, the target system had been planned. New residents building houses were then not aware of the target system, creating tensions. The building behaviour system for the wetlands (i.e. a child system) was also intertwined with the community dynamics (i.e. a parent system) with regards to where the target system was built and who was given employment for building. The critical need for employment (i.e. which stems from fourth order parent system characteristics) also meant that individual builders might be more interested in extending the length of employment rather than doing an efficient job, resulting in a system that needs to be repaired more often than is desirable.

The overlap of goals and functions related to space constraints also heavily influenced the maintenance and use of the target system. Many of these sibling systems were considered in the building phase, but their intertwined nature meant that their influence on usage behaviours was continually changing. An adjacent and upgradient formal municipal sewerage system frequently experienced blockages resulting in sewerage flowing into the community and potentially into the greywater treatment system. The stormwater control system consisted of make-shift mounds of rubble that unsuccessfully attempted to channel stormwater away from dwellings but threatened to flood the target system. Thunderstorms are a frequent occurrence during the rainy season and are predicted to become more extreme with climate change (Fatti and Vogel 2011), further threatening the target system with flooding and making access for use more difficult (e.g. stepping over water). The solid waste disposal system was a single, open container for all the community residents. Therefore, litter was widespread and had the potential to clog the greywater treatment system (and sanitation and stormwater systems which then flood) or to disrupt the purification processes. The housing system was closely linked to the availability of land for building and land availability is scarce. The greywater treatment system therefore needed to compete for limited space and multiple other services. In particular the mobility system (i.e. transit pathways for pedestrians, private cars, and service trucks) also competed for the same available space.

The water delivery system consisted of several communal taps serving several hundred community residents. The availability of communal taps constrained where the greywater system could be placed as the availability of water determines where community residents washed and disposed of the majority of their

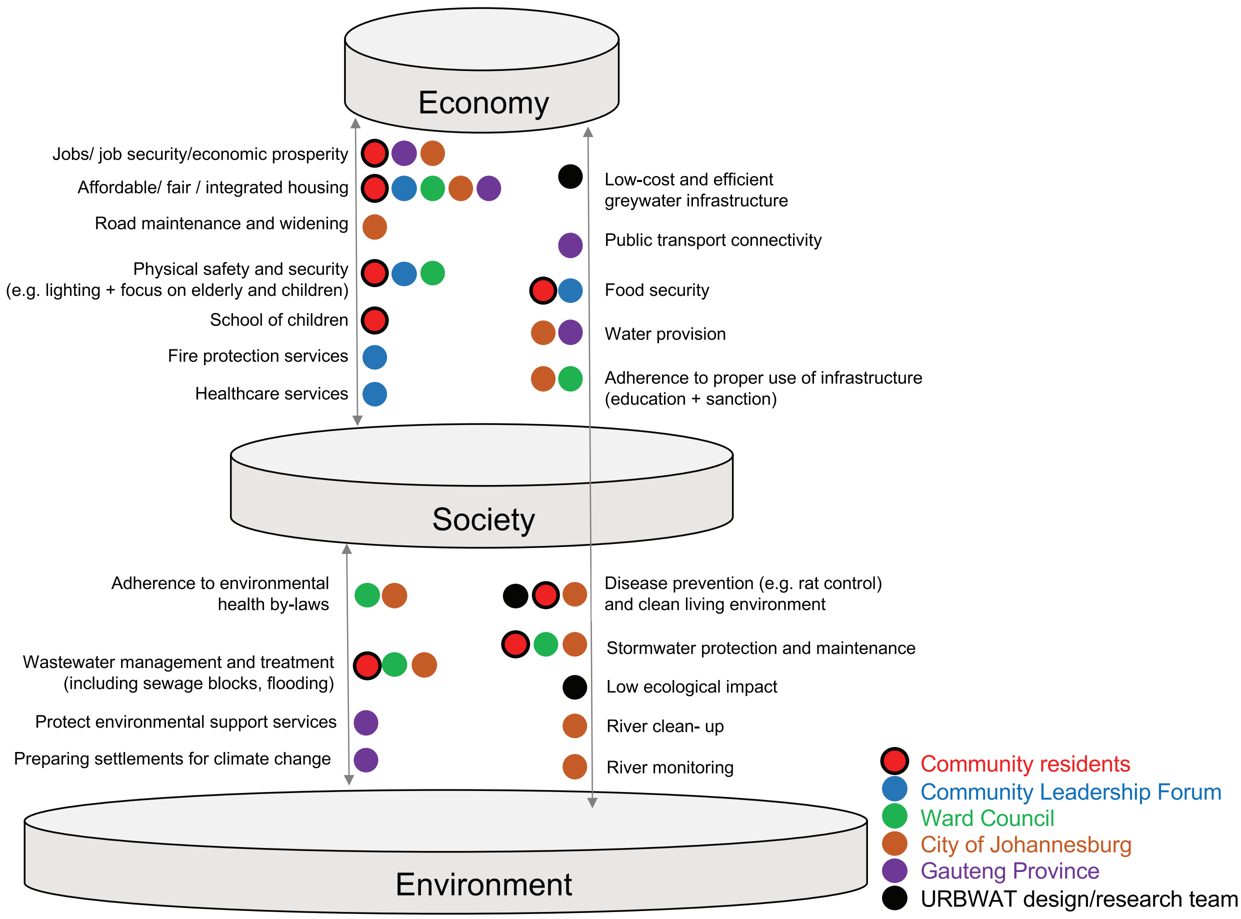

Figure 6. Goals of the six mapped stakeholder types (indicated by colour-coded circles, matching Figures 3 and 4) organised by sustainability sphere.

greywater. As mentioned earlier, the community dynamics parent system had a significant influence not only on where the target system was built, but also on who had access to the target system, who maintained the target system, as well as how the target system was used. Other parent systems such as the Ward Council system and the City Council system constrained the greywater system through the provision (or in this instance the non-provision) of infrastructure services. Issues of trust among actors (e.g. past failures to provide infrastructure, or land competition) also constrained future adaptations of the target system.

Combining a nested hierarchy view with a more detailed system diagram of component interactions through the SSoS framework allowed the team to freely combine multiple data sources into manageable insights for on-going engagement work. Because the framework does not force the user to focus on one type of flow (e.g. water flows, information flows) or one scale or domain, we were able to package information and insights organically (into systems). Interestingly, the systems were transdisciplinary, meaning that the questions and potential solutions that arose from their examination required transdisciplinary approaches. For example, the target system cannot be viewed simply as an engineering challenge, yet there is an obvious engineering component, and the target system also has obvious links to issues such as employment needs, mobility, and solid waste management. This implies that adapting the target system requires other disciplinary approaches (e.g. explicit insight into dynamic behaviours, power structures, and legal frameworks that control different resources other than greywater).

The SSoS approach however does not show us the outcome of the system interactions. Richer narratives explaining the nested hierarchy and a more detailed system diagram are also necessary. The strength of the SSoS framework in mixing diverse types of objects, scales, and flows can also become its limitation. In the case study we found that overlaying the system diagrams with an account of key stakeholder values and goals helped explain why the target system, in its first iteration, fell short of treating a large volume of greywater in a way that all residents appreciated.

3.2. Competing goals

Figure 6 shows that the goals of the design and research team did not significantly overlap with the goals of the other stakeholders. The other stakeholders had similar (but not fully overlapping) goals aligned with issues such as affordable housing, job creation/security, physical safety and security, wastewater and sanitation management, food security, and stormwater protection and maintenance. It was only on the issue of a healthy living environment and disease protection that there was overlap with the other stakeholders. This suggested that the target intervention may meet some resistance from the community (and other stakeholders). Other research in South Africa has also found that greywater management is often a low priority, especially among community residents (Armitage et al. 2009). Indeed, within the first few weeks of the installation, cement had been poured onto one of the constructed wetlands and the most frequently used tap closest to the one constructed wetland had been broken by another community member. Here issues of rapid shifts in occupancy linked to a desire for affordable housing close to available jobs likely came into play.

Previous theoretical work on the SSoS framework has not provided much guidance on determining goals other than to stress the need to find balance among the goals (Thatcher 2016; Thatcher and Yeow 2016, 2018, 2020). This lack of clarity often implies that the goals of the designers take precedence. Different stakeholder goals (especially end-user's goals) provided the design and research team with important input into the intervention process. Even if end-user goals were not directly relevant to greywater treatment they still play a role. For example, while affordable housing was beyond the capabilities of the URBWAT team, this goal played a role in land allocation for housing purposes and therefore land available for the constructed wetlands. Employment and job security was also a priority goal for most stakeholders. This was borne in mind by sourcing labour from the local community during the construction phase (and paying them fairly) and choosing to purchase all construction material locally (even if it was not the lowest cost). When considering design solutions, options that simultaneously dealt with other goals such as stormwater protection and wastewater management were considered. What is evident is that the URBWAT team subconsciously prioritised the incorporation of some of the goals of community residents over other stakeholders. These are stakeholders who have to live with any intervention and therefore it makes sense to prioritise their goals. Moving from a systems mapping (Figures 4 and 5) process, where systems coincided with stakeholder concern areas, to explicit goal elicitation proved to be a valuable tool to reflect on why the target system may or may not be working as planned and to realign the co-development processes. We put an explicit focus on understanding how alternative stakeholder goals might be incorporated into the design.

3.3. Natural lifespan of systems

To understand the context for the target system it is necessary to understand the parent systems (see Figure 4). An important component of the parent systems consists of the land ownership system and the residency transience system. Both these systems had shorter natural lifespans than one would typically expect with a planned community. In particular, the residency transience system had a short lifespan which resulted in significant (almost exponential) space constraint changes. Many community residents were highly transitory, moving into and out of the community after short periods of time due to work availability, changing relationship status, or health concerns. Unfulfilled goals such as job security, affordable housing, physical safety and security, and wastewater management meant that community residents were more likely to either move or were forced to make their own changes to their living conditions. The lack of goal attainment is perpetuated by the third-order parent systems (especially the City Council and associated actors of interest) who were more interested in party-political goals than service provision for this marginalised community. The highly transitory nature of the community meant that training initiatives to embed changes in behaviour in the community on how to use the constructed wetlands were also difficult to implement. In the second-order parent system the Ward Councillor resigned and a new Councillor (from a different political party) was elected during the course of the data collection. The normal expected lifespan of a Ward Councillor (and Ward Committee) is for a period of at least five years and the change in Ward Councillor mid-cycle had the potential to change the priorities of the Ward Council. However, the Ward Committee members remained consistent during this transition, creating a level of stability for this second-order parent system.

Theoretically, all the behavioural systems identified as child systems in Figure 4 should be shorter lasting than the target system and the systems identified as sibling systems should last for an equivalent time period. However, the fast lifespans of two of the

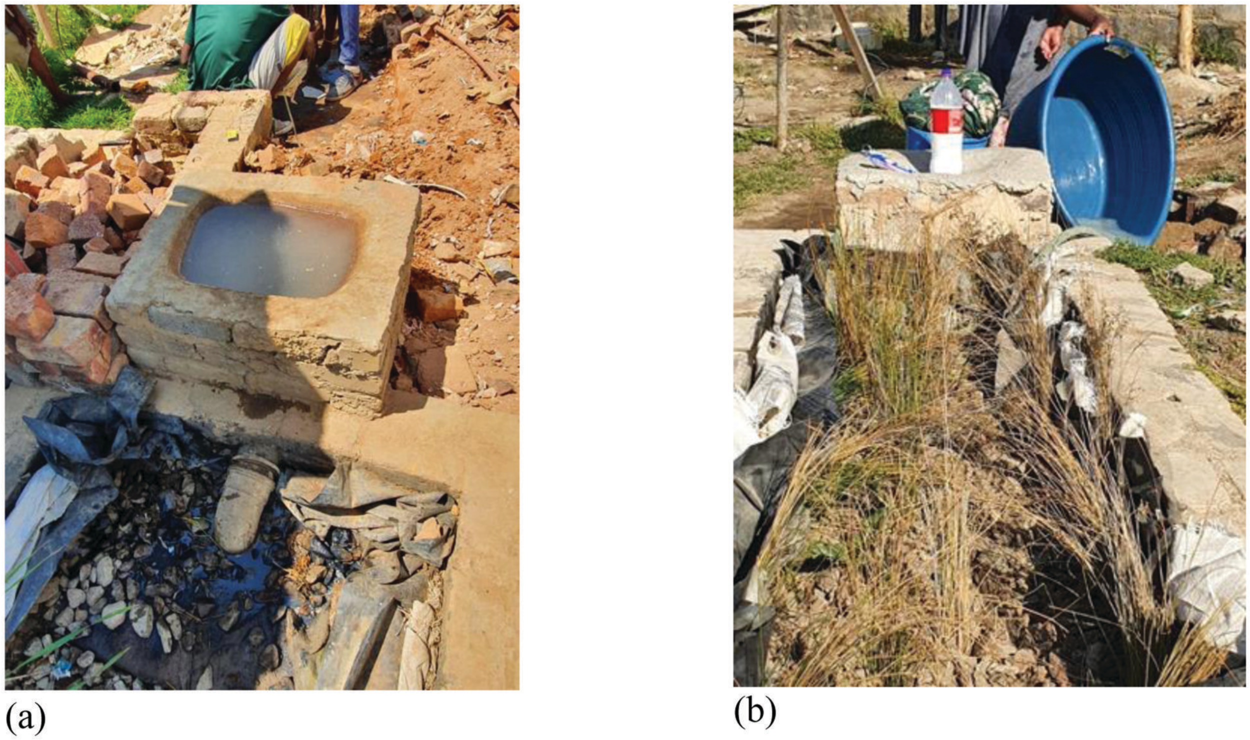

Figure 7. Emergent problems with the installed wetland systems such as (a) blocked entry point to the constructed wetland requiring maintenance; (b) water disposal behaviours showing a community resident disposing wastewater next to the constructed wetland rather than into the inlet of the wetland.

parent systems created a context where the sibling systems were also shorter-lasting in order to maintain their interconnections in this environment. Building and maintenance behaviours were constantly changing. For example, within a month of completing the constructed wetlands one resident had extended their dwelling to incorporate one of the walls of the constructed wetland. The constructed wetlands also required frequent maintenance, especially when entry points became blocked (see Figure 7). The home construction system demonstrated a shorter lifespan. A demand for housing meant that new dwellings were constantly being constructed and existing dwellings were modified or extended. This fast pace of change impacted on the natural lifespans of several other related sibling systems including the water provision systems, the electricity provision systems, the stormwater channelling systems, and mobility and access systems. In contrast to the other sibling systems, the target system was designed to have a longer natural lifespan. This may have explained why the pilot target system struggled to maintain connections with existing sibling and child systems.

Due to the short lifespans of the sibling systems, the child behaviour systems also exhibited shorter lifespans. The points where water was collected and disposed changed depending on the availability of (functioning) communal taps and available disposal points. Behaviour with regards to the target system was variable, with some community residents resorting to past behaviours (see Figure 7) and others adopting new behaviours to incorporate the constructed wetlands. In many cases these behavioural shifts put more strain on the target system (i.e. more water and waste flowing through the community, and community residents coming into closer contact with the target system due to competing land uses).

Identifying the natural periodicity of a system's lifespan proved difficult to document because the systems were always in a state of flux. Modelling the entire nested hierarchy assumes that the hierarchical positioning of the systems is stable at the exact point of constructing the model. This is an unrealistic expectation as the hierarchy would seldom be static. In this case study, the fact that some of the sibling systems had shorter lifespans than expected (as a consequence of shorter expected lifespans of the parent systems) serves as a warning that the relatively long-lasting intervention (i.e. the target system) in an unstable context may be unsustainable. Rather than simply identifying the potential failure of the target system, using the SSoS framework allowed the URBWAT team to identify key areas for further intervention. Recognising the shorter lifespans of the parent, sibling, and child systems means that future designs of the target system need to be faster in making connections with the existing systems. This can be achieved through greater integration with existing systems while also incorporating the goals of the community residents.

3.4. Complex adaptive cycles

The introduction of the target system into the existing hierarchy of systems provided an opportunity to see how the other systems in the nested hierarchy would adapt. According to Gunderson and Holling (2002), the parent systems normally provide stability through 'remember' processes. In this case study, the parent systems had shorter than expected lifespans although there were still components that remained stable (i.e. the community residents remained poorly resourced and the physical context remained highly spatially-constrained). Due to the high rate of change in the parent, sibling, and child systems, one or more of these systems were always in a release/creative destruction of connections or re-organisation/destructuring the stage, meaning that the target system struggled to establish sustainable connections within this highly dynamic environment. Some examples of adaptations in the target, child, and sibling systems are shown in Figure 8.

The primary driving forces in this nested hierarchy with respect to the target system were therefore revolt processes and how the target system might adapt. One might argue that the target system failed to make sufficient connections with other systems. Figure 9 shows the biological collapse of one of the constructed wetlands four months after installation. Initially the tap was broken, meaning that insufficient water entered the constructed wetland to support the plants. When the tap was fixed by the community residents, the plants were unable to cope with the strength (organic, saline, or otherwise) of the water entering the wetland. Nursery-grown plants, while indigenous, were initially planted and it was apparent that they were not well-adapted to the local greywater conditions. After replanting with the same indigenous wetland plants sourced within the community (along the banks of the Jukskei River, a highly polluted river running through the settlement), a vibrant constructed wetland was re-established, although usage levels were still low.

In a nested hierarchy where the system lifespans are shorter than expected, the adaptive cycles will also be operating faster than expected. While this makes it difficult for a target system of relatively longer duration to integrate with the existing systems, it does mean that there were frequent opportunities to exploit the creative destruction of connections or re-organisation of connections in the nested hierarchy. Thatcher and Yeow (2020) argue that this can be done either in a bottom-up manner (i.e. exploiting the rapidly changing child systems), in a top-down manner (i.e. exploiting parent systems near the end of the conservation stage), or in a horizontal manner (i.e. exploiting the links with sibling systems). A range of bottom-up interventions exist that change disposal behaviours. These include formal or informal training or information posters on how to use the constructed

(a) (b) (c)

Figure 8. System adaptations where (a) a constructed wetland inlet being used as a table; (b) a broken communal tap because a community resident has made a direct connection to their own dwelling; and (c) a new plant species is growing in the constructed wetland that wasn't planted during construction.

Figure 9. Interventions and their adaptation to environmental conditions shown as (a) the constructed wetland on final installation with nursery plants; (b) the constructed wetland after four months with all original plants dead; and (c) the constructed wetland after eight months.

Table 1. Possible design interventions emerging from the SSoS framework linked to which data collection sources.

Design intervention	Link to SSoS framework	Data sources
Stormwater protection	Competing values Nested hierarchy	Formal interviews, ethnographic observations, informal interviews
Sewerage spillage protection	Competing values Nested hierarchy	Activity analysis, ethnographic observations, informal interviews. Design workshops
Raised washing areas	Competing values Nested hierarchy	Activity analysis, ethnographic observations, informal interviews
Elevated pathways	Competing values Nested hierarchy	Ethnographic observation, informal interviews, activity analysis
Indigenous plant sources	Competing values Adaptive cycles	Ethnographic observation, informal interviews
Training mural	Natural lifespans	Ethnographic observation, informal interviews
Maintenance cycle for constructed wetlands	Natural lifespans	Ethnographic observation, informal interviews

wetland system. Top-down interventions would be more difficult to implement in this context because they would involve changing some aspect of the community dynamics. One possible top-down intervention could be community planning for inclusion of space for greywater disposal systems. However, given the premium on land and space and the high residency turnover, this intervention is unlikely to be sustainable. Horizontal intervention would include intervening through a sibling system. One such horizontal intervention, intervening through stormwater protection, was suggested by examining the mapping of competing goals (Figure 6). Such a horizontal intervention would consider how the constructed wetland could also be used for stormwater protection. In this case study, an analysis of the complex adaptive systems showed that an obvious point for intervention was better integration of the target system with its sibling systems based on an analysis of shared and competing goals. Examples of specific design interventions that emerge from the SSoS framework analysis are shown in Table 1. This is not an exhaustive list, but rather is a starting point for further co-production with stakeholders.

4. Conclusion

The SSoS analysis was conducted without resorting to any of the common systems analysis tools used in the E/HF field (e.g. Accimap, CWA, EAST, FRAM, HFACS, STAMP). Undoubtedly these tools will add significant value to understanding the nested hierarchy of systems (Thatcher, Nayak, and Waterson 2020) in this study. For example, a complex systems analysis tool such as EAST might prove useful in mapping the community social dynamics and power hierarchies to identify potential pathways for community acceptance or resistance to the intervention. However, this investigation allowed us to see the value of the SSoS framework for sustainable design solutions, independent from these systems analysis tools. Two important design contributions emerged from this analysis which are relevant for E/HF practitioners. First, the SSoS framework provided a deeper understanding of why the initial intervention may have struggled to remain viable. Using the SSoS framework we discovered that while a nature-based system is already supposed to be more multifunctional than grey infrastructure, the space limitations combined with existing heterogeneous infrastructures meant that the constructed wetland's lifespan might have been too long and its lifecycle too slow (relative to the related systems) to establish meaningful connections with related systems and faster iterations of the design process are proposed. A faster iterative intervention design had already been planned by the URBWAT research team according to the implementation suggestions of Thatcher and Yeow (2020), but this could not be realised due to Covid-19 lockdown restrictions.

Second, understanding the goals of the various related systems provided a rich source of alternative design opportunities that could not have been envisaged by only considering the goals of the target system. In particular, an analysis of the various system goals suggests that greater connections with the stormwater protection systems and the wastewater management systems might facilitate broader uptake and integration with existing infrastructure. We also noted that in a real-life context a balance between the different system goals was extremely difficult. The analysis demonstrated that it was sufficient for the analysts to map out which goals were unfulfilled, which goals were competing, and which goals were matched in order to see where these parent, sibling, and child goals might be incorporated into the goals of the target system, or where competing goals might cause resistance. Despite the focus of this paper being on the value for E/HF practitioners, the SSoS also allows our results to be taken up by others interested in solving sustainability issues. This includes those interested in urban ecology and green infrastructure, sanitation, ecological justice, and ecological engineering. We also highlight this point, even if these are not the target audience of the paper. As a final point it should be noted that despite two years of data collection this is still an ongoing research project. We expect to extract further lessons on the application of the SSoS framework in future design iterations.

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