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RESEARCH ARTICLE

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Designing a greywater treatment system in a highly adaptive urban environment: an ergonomics and human factors observational analysis

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ABSTRACT

Unplanned, high-density settlements in low-middle income countries often lack functional wastewater management systems. Nature-based solutions, such as constructed wetlands, are an option for the treatment of greywater, provided they are used by and useful to the community. We explored the effectiveness of iterative design for two pilot constructed wetlands in an informal settlement in Johannesburg, South Africa. Using ergonomics and human factors (E/HF) design approaches, this study evaluated the usability and postural risks associated with interactions with the constructed wetlands to motivate (and evaluate) design changes to increase use and reduce the risk of musculoskeletal pain. An elevated work area reduced musculoskeletal risks and a larger work area allowed more users at one time. The raised work areas provided other benefits such as stormwater and sewerage protection. The value of E/HF as part of a broader transdisciplinary team was demonstrated by embedding the design in the activities of the community.

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Informal settlement; constructed wetland; transdisciplinary; greywater; user behavior

Introduction

Universal access to clean water and adequate sanitation is a cornerstone of the United Nations Sustainable Development Goals (specifically SDG 6), but classical engineering and development approaches have not allowed all countries to meet such access needs (Sadoff, Borgomeo, and Uhlenbrook 2020). Traditionally, in high-income countries wastewater treatment in urban environments has been through engineered systems that use physical, chemical, or biological measures (Willcock et al. 2021). However, sewering a rapidly urbanising world is not possible given historical trends in connection rates and the modern reality facing cities such as climate change and financial and physical constraints (Sadoff, Borgomeo, and Uhlenbrook 2020; Öberg et al. 2020). Residents of informal settlements often find ways of managing their own wastewaters to bypass inadequate levels of formal service provision and mistrust with top-down interventions (Monica 2021; Shoniwa and Thebe 2020). Willcock et al. (2021) note that SDG 6 cannot be achieved through engineered systems alone and that nature-based solutions are also required because they use or mimic natural processes and enable adaptability.

Constructed Wetlands (CW) are particularly relevant for greywater treatment as they can be low-cost and are effective at reducing both pathogens and other contaminants (Arden and Ma 2018; Boano et al. 2020) but are only effective if they are used by the intended people. Disciplines that take a user-centered approach to understanding human behavior are therefore an important component of CW implementation strategies.

Engineers and designers often design, construct, and implement systems that fail to be used or are used inappropriately by the end-user (de Winter and Hancock 2021; Wilson 2014). This is often because there is a mismatch between the design intentions and the physical and mental preferences and capabilities of the users. Dekker (2006) characterised this as the gap between work-as-imagined (WAI) by designers and work-as-done (WAD) by end-users. Effective design requires a closer match between these two perspectives. The applied, multidisciplinary field that attempts to reduce the gap between the designer and the user is known as ergonomics and human factors (E/HF).

Given its definition and emphasis on participatory approaches, it is surprising that E/HF has not been more involved with issues of sustainability. Recently (Stevens et al. 2018; Thatcher et al. 2018) and historically (Helander 1997; Moray 1995) there have been calls for E/HF to contribute to addressing global problems such as climate change, water scarcity and sanitation, food security, urbanisation, pollution and waste, terrorism, and energy supplies. Work linking E/HF to SDG 6 is scarce. Kalantzis, Thatcher, and Sheridan (2016) was the only study we identified that looked at the design of a wastewater treatment system. Their study compared experts' design models to users' mental models of a CW in a small office building. Differences between the design models and mental models enabled the researchers to identify design recommendations to improve the functioning and interaction with the CWs.

While the scientific functionality of CW systems is well-established, comparatively few studies have tested human interactions with these systems in situ (Alfiya et al. 2013; De Paoli and von Sperling 2013). Pradhan, Al-Ghamdi, and Mackey

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(2019) noted possible user-interaction issues such as religious or cultural impediments and maintenance issues but none of these interaction issues were evaluated on an actual system. Given that people are not always aware of their behaviors when it comes to greywater disposal, we aimed to collect detailed observations of the interactions, which could support a more pointed dialogue with residents to anticipate further design needs. We believed that an E/HF lens would be valuable in structuring such observations, given that the field has successfully contributed to better solution design and adoption in a broad range of areas other than sanitation.

In this case study we set out to evaluate CW systems placed in a Johannesburg (South Africa) urban informal settlement by:

(1) Determining whether pilot CW systems were designed appropriately to enable people to effectively dispose of their greywater.
(2) Identifying improvements for the design of a second iteration of the CW systems.
(3) Determining whether the second iteration of the CW systems improved the disposal of greywater from the pilot CW systems and to suggest further design improvements.

Methods

Case study and methodological setup

The research site was a portion of Setswetla urban informal settlement called 'Silvertown', located along the Western bank of the Jukskei River to the North of Alexandria township in Johannesburg, South Africa (Figure 1). Setswetla has an estimated population of 30 000 people living in an area of approximately 1 km^2 in low-rise buildings. Community membership is highly transient with people moving in from rural areas to be close to employment (and shelter) opportunities and leaving when those opportunities change. Local government provides limited services such as communal taps for potable water, shared portable toilets, communal dumpsters for solid waste, and some electricity, but ad hoc and 'illegal' connections abound. Greywater is disposed on-site either onto pathways or into makeshift ditches or channels. In this context, greywater often becomes mixed with blackwater from broken sewers and other waste streams where it flows openly through the community, without treatment, towards the Jukskei river. Greywater refers to wastewater from washing and other household chores like laundry and cleaning floors (Maimon et al. 2010; Oteng-Peprah, Acheampong, and DeVries 2018). Although usually less of a health risk than blackwater, greywater in low-middle income countries may still contain problematic pathogens and pollutants given residents may not always have access to a safe way to dispose of their blackwater (Maimon et al. 2010; Shaik and Ahammed, 2020).

The aim of the larger research project was to design greywater treatment and removal solutions for urban informal settlements using a nature-based solution. Several authors have argued that issues of sustainability require a transdisciplinary approach (Lang et al., 2012; Stokols et al., 2009). By transdisciplinary we mean that academics from different disciplines combine with diverse stakeholders (non-academic actors) the project conception, execution, and evaluation to integrate different knowledges and create shared ownership over (transformative) solutions which fit the problem at hand. It is important to note that within transdisciplinary research there are different levels and constellations of involvement, as well as different methods used (Jahn et al. 2022). Still, there are some central principles for co-production of knowledge which are emerging (Norström et al. 2020; Lam et al. 2021). In addition, the application of transdisciplinary approaches in academic literature in the Global South is more recent than the Global North but is still very active (e.g. Pereira et al. 2020; Thiam et al. 2021).

The full research team consists of scientists from multiple disciplines (ecology, microbiology, natural resource management and sustainability, psychology and E/HF, and engineering) and countries (South Africa, Sweden, and Germany). Diverse types of stakeholders were consulted at the beginning of the project (see Thatcher, Metson, and Sepeng 2022), where residents of Setswetla (in their various roles) were the main engagement group throughout the project. As the project evolved and new emergent problems arose, the research team adjusted accordingly. At the time of writing, we were three years into the four-year research process, with a large part of this time affected by COVID-19 (see Figure 2 for a timeline of the project). The pandemic diminished our capacity to collaborate in-person, slowing down the construction of CWs, and altering our capacity to collect data. In some ways however, this slowing down may have had benefits. After initial consultation processes and construction of two CWs, there was more time to iteratively go back and forth with community members around their evolving user experiences and thus engage in deeper co-design.

In March 2020 two small, horizontal, sub-surface CWs (Sheridan, Hildebrand, and Glasser 2014; Vymazal 2009) were constructed as the first iteration (Phase 1). The CWs were located in close proximity to communal taps because this is where most greywater disposal takes place in urban informal settlements (Carden et al. 2007). These were considered pilot systems that would enable residents to experience the intervention and the researchers to gain a better understanding of community desires and needs. The CWs were constructed from recycled bricks, cement, concrete (for the base), 10 cm diameter plumbing piping for the inlet, and a plastic inner lining for waterproofing the sides, with the work being performed by members of the local community (which formed part of the initial agreements with the community prior to the start of the project). The structural dimensions are given in Figure 3 and the volumes of the treatment portion of the CWs were 1.2 m^3 for Wetland 1 and 0.7 m^3 for Wetland 2.

The intensive and systematic observations focused on E/HF aspects of design which are reported in this study. Thatcher, Metson, and Sepeng (2022) report on how the research team interviewed actors within and outside Setswetla, held community design workshops, conducted water collection and disposal surveys with residents, as well as ethnographic observation work. Ethical clearance was granted from both the University of the Witwatersrand (H19/11/66) and Rhodes University (2021–4983–6145) for the study before any data were collected.

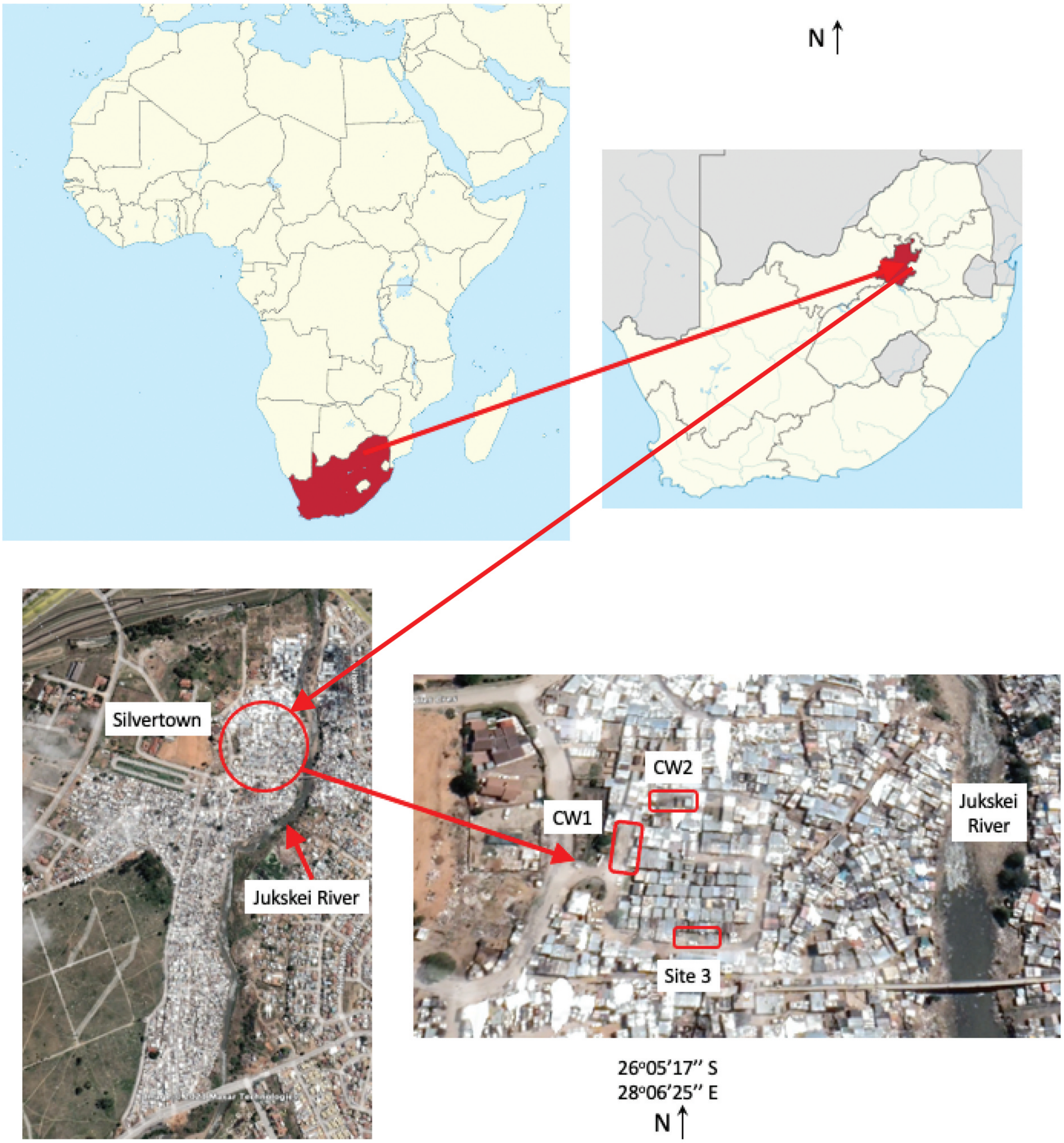


Figure 1. Aerial view of the case study site, with setswetla informal settlement on the left (left bank of the jukskei river) and a close up of 'silvertown' on the right. the three observation sites are marked as red rectangles (images from google earth, October 2021). CW1 = Constructed Wetland site 1; CW2 = Constructed Wetland site 2; Site 3 = site without constructed wetland.

Here we focus on the observational ethnographic activity analysis which aims to build an understanding of behavior, strategies, and interactions within a given situation (Garrigou et al., 1995). The study was undertaken in two phases; Phase 1 examined the two pilot CW systems eight months after building and three months before building the second iteration, and Phase 2, five months after building the second iteration (Figure 2). Observational methods rely on close observation of people as they go about their normal activities (Diego-Mas, Alcaide-Marzal, and Poveda-Bautista 2017). This involved observing the use and disposal of water in and around the CWs and taps. Observations occurred at three sites (see Figure 1). Two were CWs, and their associated taps, and one was a communal tap (Site 3) with no CW but where the community were interested in building one (Figure 3C). Wetland 1 runs along a dirt road next to what the community indicated was a heavily used tap (Figure 3A) and with wastewaters flowing next to the dirt road in an earthen ditch. Wetland 2 (Figure 3B) is located 'downstream' from Wetland 1 and the same earthen ditch runs next to it, flowing down to the Jukskei river. As described in this study, Wetland 1 and 2 were both redesigned in phase 2 whereas Site 3 was used as a comparison site and remained the same.

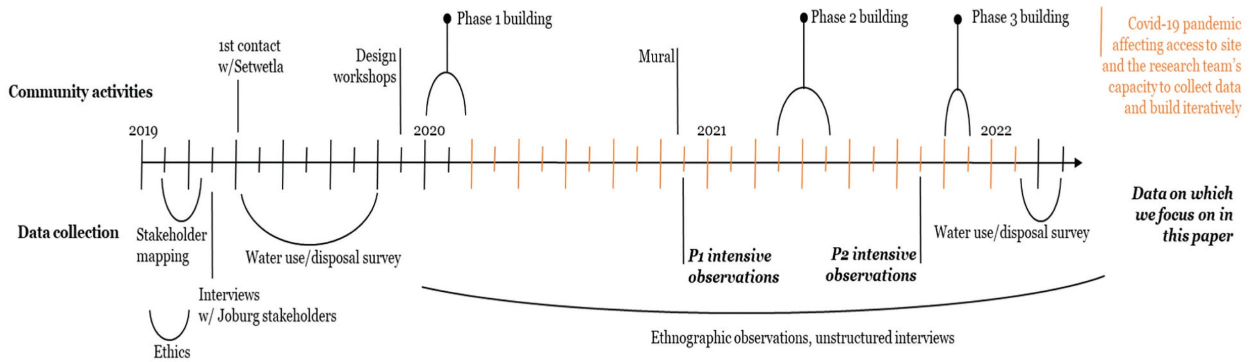


Figure 2. Timeline of activities and data collection of the larger project (extended from Thatcher, Metson, and Sepeng (2022)). Events noted above the timeline (with monthly tick marks) refer to activities with the community. Events noted below the timeline refer to data collection activities. Many of these data collection activities happened in collaboration with the Setswetla community but were more about documentation than co-creation. The bolded activities (P1 and P2) are those datasets on which this paper is focused and the orange color depicts months where covid restrictions negatively impacted our capacity to work unrestricted in the community.

Information collected during observations

Observers captured information on the type of activity/ies undertaken and the postures adopted during each activity (Table 1). Activities were broken down into three categories: water collection, washing, and rinsing/disposal. The characteristics of the tasks undertaken for each of these categories were recorded, including the time of day and the location of the activity at each site, as well as age and gender of the users. From a posture perspective, an additional posture of stooped at approximately 90 degrees was added (i.e. the back was held in a horizontal flexed position) in Phase 2, which was not recorded in Phase 1. Photographic evidence was used to support the postural analysis component.

Furthermore, the activity analysis included notetaking of any other observed behavior that might influence the future design of the CWs. This included short dialogues with residents to better understand their behaviors at the CWs. All such observations and dialogues were recorded on the data collection sheets.

Data collection

In Phase 1, five students were used to collect data, while in Phase 2 there were three students and three community member observers. Before data collection began, all the observers were trained in observation, interviewing, and photographic techniques, and on how to use the data collection sheet. For each phase there was a half day of pilot testing to ensure that all relevant data were obtained accurately and consistently.

Phase 1 data collection took place over 3 days in November 2020 (Friday to Sunday), and Phase 2 was carried out in September 2021 and lasted for seven days (Tuesday to Monday). For each phase, observers conducted their observations from 08h00 to 16h00 each day. Each observer was strategically positioned at sites to easily analyse all approaches and activities. Observers were rotated between locations to reduce fatigue and to enhance the quality of data collected. Observations were supported by photographs when permission was granted by community member. The photographs were taken side-on (Chaffin, Andersson, and Martin 2006) allowing for a clear description of the posture adopted while performing tasks.

Data analysis

Since wastewater disposal is the primary input for the CWs, the analysis focused on disposal at the sites. We also systematically summarised collection, washing, and disposal observations by site. In the analysis, each observation related to one activity, meaning that a person visiting a site could have multiple observations associated with their visit. Observations were not independent from each other; if the same person washed and disposed of water in one visit, the size of the collection bucket influenced both these activities. We also noted that the total number of observations was different between the two phases, and thus reporting both total and relative frequency is important to contextualise the findings.

The results section answers the research aims by drawing from summaries of count data and qualitative descriptions (dialogue notes and pictures). Frequency of disposal by location at each site enables us to see if the CWs were used (aims 1 and 3) and where it was 'natural' for people to dispose of water to improve the design (aim 2). The relative frequency of postures (percentage of observations), along with qualitative descriptions, contributed to suggestions for improvement (aim 2) and if those design changes were effective in increasing use (aim 3).

Results and discussion

Phase 1 - Underutilisation of constructed wetlands

Site 3 (no wetland) had the most observations (86% of the 153 observations). Water collection was the most common activity across all three sites (Figure 4). The communal tap at Wetland 1 was not operational during our visits, and therefore one would expect lower water collection at this site. Females and young adults visited the sites more frequently and performed more tasks during the observation time (Table 2). Washing was most often observed at Site 3. This may be related to the fact that there were two communal taps and a flat area on which to carry out washing activities.

Most activities took place in the mornings (Table 3), with the exception of the two CWs where disposal was more likely to take place in the afternoon. This may be an artefact of who was using the different observation sites.

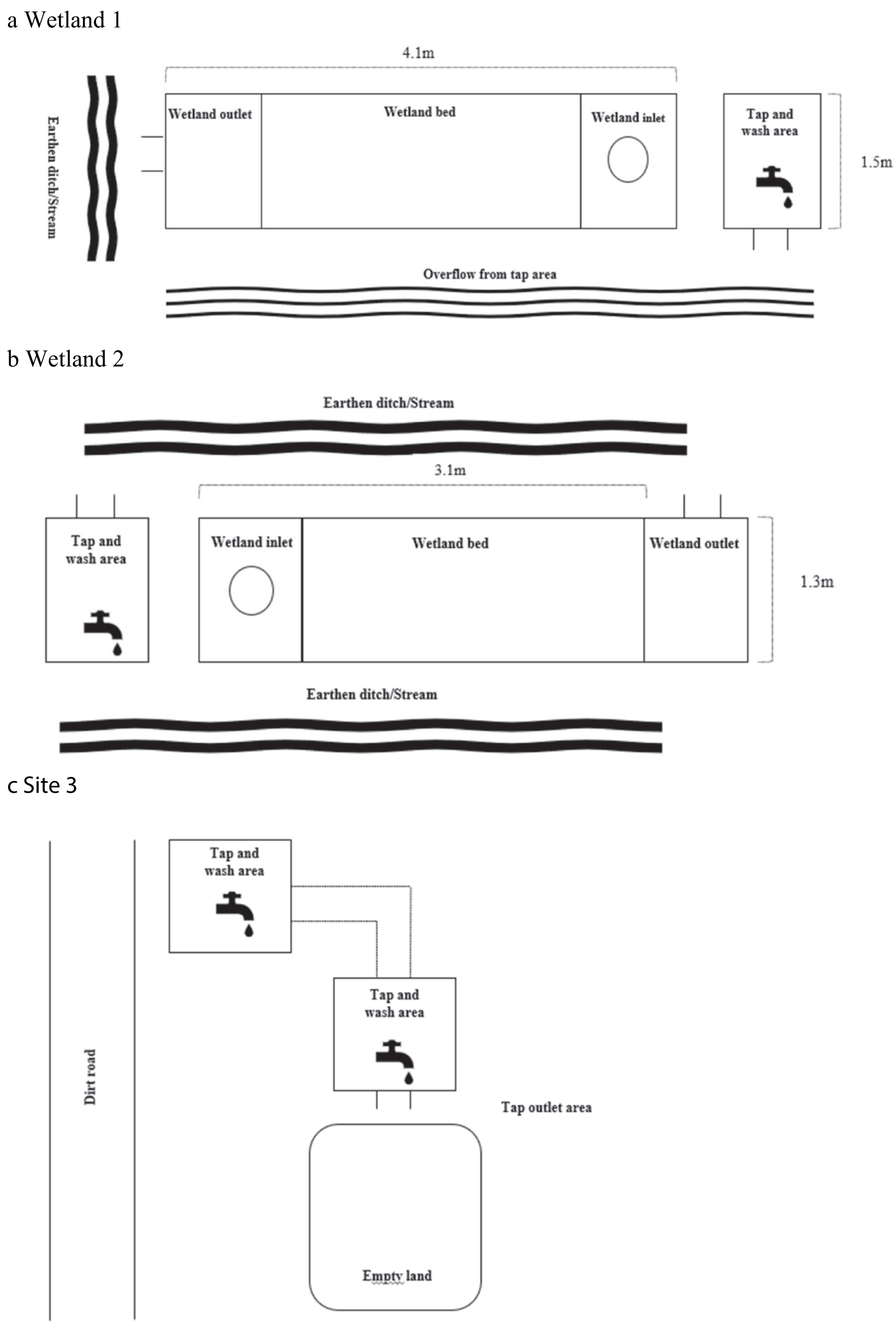
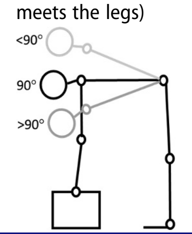


Figure 3. Schematic of the three sites observed, notably wetland 1 (3A), wetland 2 (3B), and site 3 (3C). these are their spatial/schematic arrangement for phase 1. blue arrows = direction in which water flows through each site. X = a tap.

Many of the activities were performed with postures that required significant flexion of the trunk in the sagittal plane (Figures 5A,B), placing high loads on the lower back. The typical static postures adopted are shown with the spine often flexed beyond the horizontal in a stooped position. Some residents found ways to minimise strain, when possible, for both washing and disposal by using a form of natural bracing (resting a forearm on a bended knee or another structure to take some of the load bearing off their lower back) to maintain these postures during the various washing activities. Approximately half the participants were flexing their spines beyond the horizontal (more stooped), with a slightly higher percentage of participants observed in this posture at Wetlands 1 and 2 (Table 4).

Residents used different sizes of containers for washing (e.g. small 10 liter, Figure 5A and larger 40 liter, Figure 5B) and

Table 1. Categories of activities, postures adopted and tasks documented during observations at each site.

Type of observation	Categories	Definition	Tasks documented
Activity	Water collection	Collection of water of any sort into containers	• Number of containers • Type and size of the container • Duration of water collection • Tap usage
	Washing	Use of water in containers to wash items such as clothes, shoes, blankets, kitchen utensils, and floor coverings.	• Type and size of container used for washing • What was being washed • Where was washing being conducted
	Disposal	Rinsing of containers and disposal of water after rinsing, washing, cleaning, or domestic use.	• Rinsing out dirty containers from previous use • Rinsing out containers prior to water collection or washing • Size of disposal container • Location of disposal
Postures during activities	Degree of stooping involved	A description of the trunk posture in the sagittal plane highlighting the degree of trunk flexion.	• Stooped<90 degrees (closer to standing up straight, thus called less stooped) • Stooped>90 degrees (referred to as more stooped) • at 90 degrees (bent exactly where the torso meets the legs) 

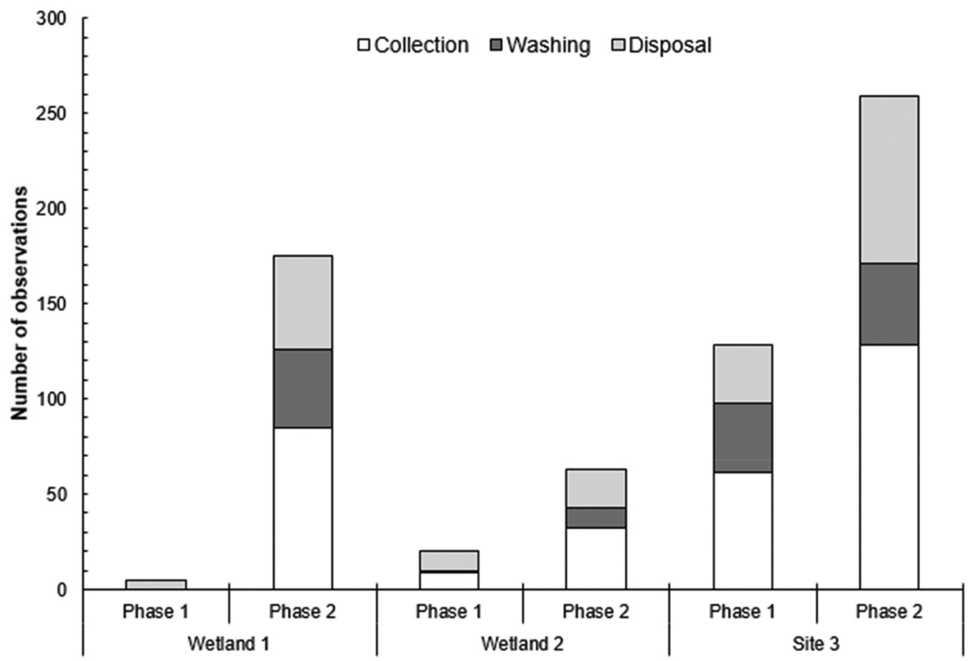


Figure 4. Types of activities across the sites for Phase 1 and Phase 2.

Table 2. Demographic breakdown of community residents visiting the observation sites during phase 1 and phase 2 observations. Total n = total number of observations over three days of data collection for phase 1 and the seven days for phase 2.

	Wetland 1		Wetland 2		Site 3	
	Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2
Total observations (n)	5	175	20	63	128	259
Male (% of n)	40.0	30.8	35.0	50.8	37.5	36.7
Female (% of n)	60.0	69.1	65.0	49.2	62.5	63.3
*Child/Adolescent (% of n)	0	13.7	10.0	11.9	20.3	18.9
*Adult (% of n)	100	68.5	80.0	61.0	70.3	58.1
*Elderly (% of n)	0	17.8	10.0	27.1	9.4	23

**Note: observations of type of person using sites in Phase = 146 for Wetland 1; 59 for Wetland 2 and 217 for Site 3*

Table 3. Activities across the three sites by time of day for phase 1 and phase 2.

		Wetland 1		Wetland 2		Site 3	
		Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2
Total observations (n)		5	175	20	63	128	259
Collection (% of n)	Morning	0	37.1	35.0	36.5	39.8	25.1
	Afternoon	0	12.0	10.0	15.9	7.8	24.7
Washing (% of n)	Morning	0	13.7	5.0	9.5	23.4	9.3
	Afternoon	0	9.7	0	6.3	5.5	7.3
Disposal (% of n)	Morning	40.0	15.4	20.0	23.8	17.2	22.0
	Afternoon	60.0	12.0	30.0	7.9	6.3	11.6

disposal. Some of the tap users did laundry with a sleeping infant strapped on their backs (Figure 5C). This, coupled with the posture adopted, imposed an additional load on the musculoskeletal system. Exaggerated static stooping postures occurred because there was no elevated place on which to place containers while engaging in water use activities. This meant that participants often needed to bend down to the containers resting on the ground to wash clothes, shoes, carpets, and cooking implements.

Greywater disposal most often happened at ground level across sites (Table 4). At Wetland 1 the greywater was disposed (incorrectly) once into the CW outlet of Wetland 1. At Site 3, 68 disposal activity observations were made, with most observations involving the use of 20 litre containers (as at the other sites). Wastewater at Site 3 was disposed of near the tap, with the wastewater naturally running down towards the empty land or along the road. There were some instances where community members disposed of their wastewater directly onto the open land or onto the road next to the taps. No community members were observed disposing of wastewater into Wetland 2; opting instead to use the earthen ditch next to the CW. Similarly, the four disposals observed at the CW outlet at Wetland 1 happened on the ground around the tap, rather than into the CW. After washing clothes, the containers were simply tipped over (Figure 5D). Filled containers were too heavy to carry and lift to the CW inlet for most people. Instead, the CW was used more as a counter to place washing materials on.

The CWs were repurposed by residents in other ways. First, the walls of the CWs acted as raised walkways enabling community members to traverse areas that were potentially hazardous due to greywater accumulations. Second, during a rainstorm people used the walls of the CW to avoid stepping in the stormwater. Additionally, the CW walls acted as a barrier, preventing the stormwater runoff from infiltrating some of the living areas. Third, a burst sewer main directly above Silvertown resulted in raw sewage running into the community. Community members rapidly mobilised to build temporary walls adjacent to the CWs to direct the sewerage away from their homes. These points indicated that the CWs had emergent benefits, not directly related to greywater disposal, which allowed community members to protect themselves from other harmful wastewaters.

Nature-based solutions like CWs, are usually multi-functional, but often it is the biological components that are highlighted for the multi-functionality. CWs can, in addition to treating wastewater, help with flood prevention, aid with urban heat mitigation, and provide a habitat for wildlife (Keeler et al. 2019; Childers 2020). Although it gets proportionally less attention, nature-based solutions can also cause disservices in some areas of concern while producing benefits in others (Ferreira et al. 2020). For CWs this may relate to greenhouse gas emissions contributing to climate change (Childers 2020), or maintenance being problematic (Friedrichsen et al. 2021). Real and perceived services and disservices will also vary by actor group, not just among nature-based solution cases. In our case, it was rather the grey (concrete) component, not the green component, of the CWs that provided multiple benefits. This is more in-line with the conception of nature-based solutions as urban ecological infrastructure (Childers et al. 2019) which accounts for hybrid infrastructural approaches as part of cities as socio-ecological-technological systems (McPhearson et al. 2022).

Outcomes of phase 1 leading to a process of redesign

To answer the first study aim, despite their proximity to the taps and the extensive generation of greywater, the community made very little use of the CWs. Instead, greywater was disposed in the most convenient and least strenuous manner. This is likely due to a combination of previous habits, effort conservation, and poor initial physical integration of the CWs into the daily activities of residents, but particularly those activities linked to the disposal of water. Observations regarding where people dispose of greywater match what others have found in other informal settlements across South Africa (Carden et al. 2007). People tend to dispose of greywater directly on the ground but may also use a combination of disposal locations which varies with available amenities in a community (Carden et al. 2007). This spatial adaptation is what we observed at Site 3 and at Wetland 1.

Further, as argued by Carden et al. (2007), it is important to ensure that the community are aware, understand, and are accepting of the CW intervention to ensure they are used appropriately. Despite the numerous engagements with various members of the community in the establishment of the pilot CWs, the transient nature of the populace in Setswetla (see Thatcher, Metson, and Sepeng 2022) may have resulted in some residents being unaware or unsure what the CWs were for, which may have also contributed to poor utilization.

From a design perspective the CW inlets were physically separated from the taps and the CW inlets were too high (approximately 50 cm) to lift heavy containers filled with greywater. Given that most containers were at least 20 liters in size and most users were women, the containers were too heavy to lift when emptying. Instead, containers were often tipped over where the activity took place; typically, into the earthen ditch or into the road.

Figure 5. Illustration of the typical postures with trunks flexed beyond 90 degrees or washing (5A and 5B); an individual washing with an infant strapped on their back and using elbow and knee to reduce weight bearing (5C); common method of water disposal (5D) into the earthen ditch adjacent to CW2 during Phase 1.

Re-design decisions

To answer the second research aim, while substantial greywater was generated around these three sites, very little of the greywater entered the CWs. As such, a number of design recommendations were implemented for Phase 2. While these decisions were based upon the data collected during our observations, key community leaders and community members that used these areas were also consulted for their input throughout the project, as outlined in Thatcher, Metson, and Sepeng (2022). The consensus from these interactions was that the greywater generation and disposal is less of a priority for the community and they felt that having a decent space around which to wash was more important. Additionally, the community suggested using the CW as storm or flood water protection through expanding the original CW design. In doing this, we used the data collected, observations made, and lived experiences of community members to ensure that the design

Table 4. Observed postures (above 90 degrees and beyond 90 degrees horizontal) for the three sites during phase 1 and phase 2 and the observations around where grey water was disposed of and the size of the container used.

Postural observations		Wetland 1		Wetland 2		Site 3	
		Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2
Total observations (n)		5	175	20	63	128	259
More stooped (below the horizontal) (% of n)		40.0	23.4	40.0	12.7	52.3	34.4
Less stooped (Above the horizontal) (% of n)		60.0	35.4	60.0	52.4	47.7	33.9
* At the horizontal (at 90) (% of n)			41.2		34.9		31.7
Disposal site observations and container size							
Total observations (n)		5.0	48.0	14.0	20.0	68.0	88.0
Site of disposal and container size							
	</ = 10 L	0.0		14.3		10.3	21.6
Tap outlet area (% of n)	20 L	40.0		21.4		67.6	53.4
	40 L	0.0		0.0		13.2	4.6
	</ = 10 L	0.0	10.4	28.6	10.0		
Ditch (% of n)	20 L	40.0	8.3	35.7	0.0		
	40 L	0.0	0.0	0.0	5.0		
	</ = 10 L		29.1		30.0		
Wetland Inlet (% of n)	20 L		39.6		50.0		
	40 L		0.0		0.0		
	</ = 10 L	0.0	2.1	0.0	5.0		
Wetland Outlet (% of n)	20 L	20.0	2.1	0.0	0.0		
	40 L	0.0	0.0	0.0	0.0		
	</ = 10 L	0.0	4.2	0.0	0.0		
Wetland bed (% of n)	20 L	0.0	4.2	0.0	0.0		
	40 L	0.0	0.0	0.0	0.0		
	</ = 10 L					1.5	1.1
Empty land (% of n)	20 L					0.0	17.1
	40 L					2.9	1.1
	</ = 10 L					1.5	1.1
Around taps (% of n)	20 L					1.5	0.0
	40 L					1.5	0.0

solutions were socially and environmentally appropriate. This supports the frameworks proposed by Kanda et al (2021) and Magalhaes Filho et al (2019) around the generation of appropriate sanitation solutions and concepts such as participation and a socio-ecological-technological systems approach from McPhearson et al. (2022). These changes included:

(1) Creating a 'working space' around the communal taps. Since most water-related activities happened in the physical area around a tap, there was a need to incorporate a working space around the taps to facilitate the activities of washing, rinsing, collection, and disposal. Such a space would support the community to conduct their normal activities and perhaps even enhance the performance of these activities without significant behavior change. More specifically, this space needed to:
   a. Physically connect the area where water was being used (and disposed of) to the CW inlet.
   b. Raise the working space to reduce the need for an exaggerated static stooping posture. This change would also create a slope, facilitating the gravitational flow of water into the CWs.

(2) Have the walls of the CW widened and heightened to better serve the dual purpose of acting as a physical barrier to flooding and an elevated pathway so that community members don't need to step in wastewaters.

The design changes for Wetland 1 and Wetland 2 are shown in Figure 6. The structural dimensions of the CWs in the second iteration are shown in Figure 6 (Wetland) and Figure 7 (Wetland 2). The volumes of the treatment portion of the CWs in the second iteration were increased to 3.02 m^3 for Wetland 1 and 2.91 m^3 for Wetland 2.

Phase 2 - Increased use of redesigned constructed wetlands

There were many more observations in Phase 2 than in Phase 1, but the relative contribution of different activities did not change substantially for two of the three sites (Figure 3). There was a substantial increase in water-use activities at Wetland 1 and 2 compared to Phase 1, even after accounting for the extra days of observation. While more females were observed at Wetland 1 and Site 3 during Phase 2 (as at Phase 1), there were approximately equal proportions of males and females using Wetland 2 (Table 2). As with Phase 1, adults were the most observed users. At each site the most common activity was the collection of water, followed by disposal, and washing (Figure 3). This was similar to Site 3 during Phase 1, although at Phase 2 this was represented across all observation sites. During Phase 2 all activities were most common in the morning (Table 3) which was most like the distribution of activities at Site 3 during Phase 1 observations.

Water disposal during the observations at Phase 2 showed that 70.84% of the disposal activities at Wetland 1 were either into the CW inlet or directly onto the CW. Similarly, for Wetland 2, 85% of the water disposal was at the CW inlet (Table 4). This is a substantial improvement from Phase 1 where hardly any

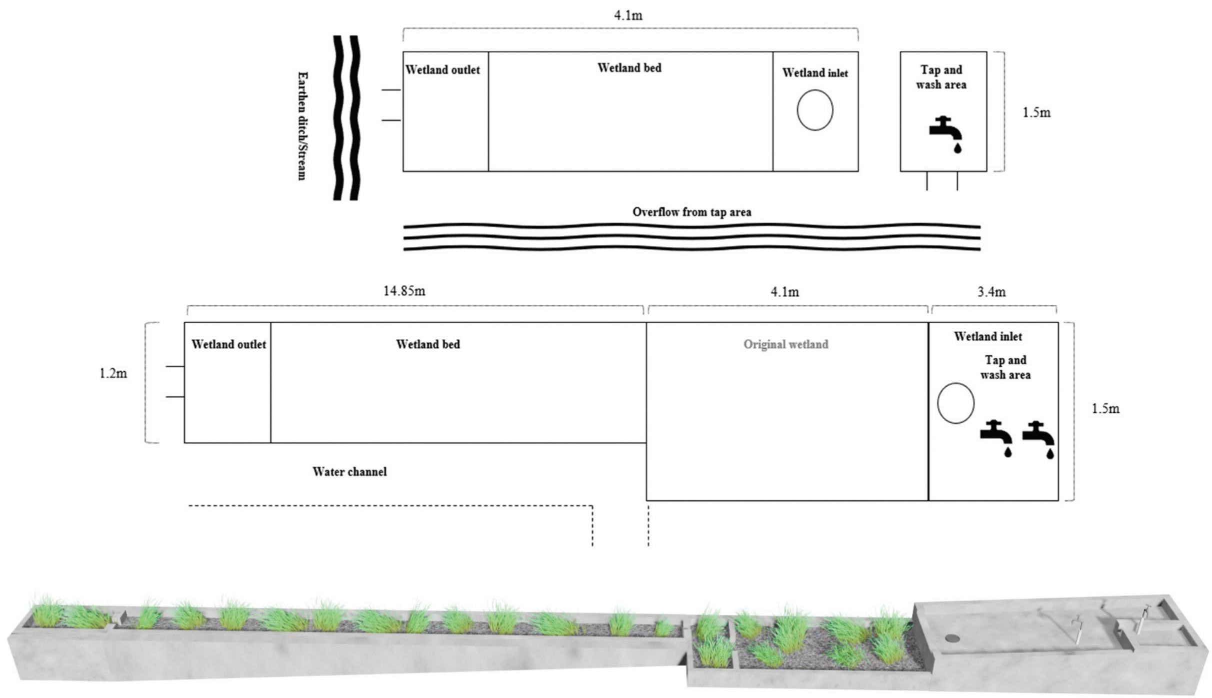


Figure 6. Schematic showing changes to Wetland 1 from Phase 1 to Phase 2 (6A to 6B) and a side-on graphic of Wetland 1 (with tap and working space raised by 40 cm-50 cm).

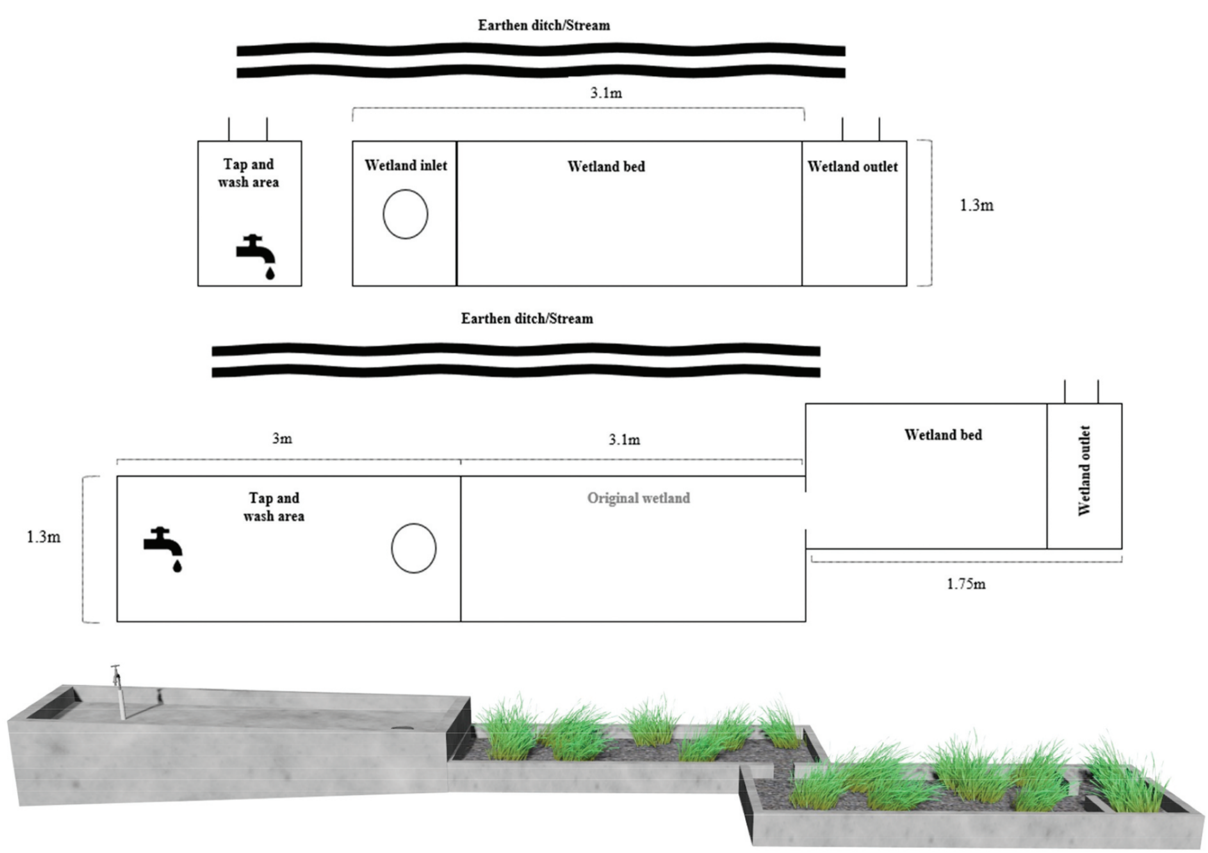


Figure 7. Schematic showing changes to Wetland 2 from Phase 1 to Phase 2, and a side-on graphic Wetland 2 at Phase 2 (with tap and working space raised by 80 cm-90 cm)).

greywater reached the CWs. Once again, during Phase 2 most of the water disposal was from 20 liter containers (Table 4) which were primarily used for washing clothes, shoes, linen, and carpets.

The design of the CWs at Phase 2, with the raised working space, meant that participants were able to adopt a more upright working posture with less trunk flexion compared to Phase 1 (Table 2, Figure 6A-D). The proportion of less stooped postures also increased in Phase 2 (compared to Phase 1) at Site 3, even though there was no raised workspace. Table 2 shows that for Site 3 and Wetland 1 there was a marginal improvement of the posture from below the horizontal to the horizontal. A more substantial improvement was found at Wetland 2 where the working space was raised by 80 to 90 cm.

Several important emergent characteristics of the CWs were also observed during Phase 2 data collection. First, the expanded surface of the cleaning area allowed multiple community members to use the workspace to place the washing containers, the laundry materials, and to carry out washing tasks (see Figure 8). Second, the walls were used as a raised pathway to avoid walking in sewage and stormwater. The walls provided a cleaner, flatter, and less hazardous surface to walk on. Third, the CWs served as an important barrier to guide sewage spills and stormwater away from housing and into a nearby storm ditch. Together, these aspects demonstrate that this nature-based solution was sufficiently adaptable to provide additional benefits to the community and to indirectly address aspects of SDG 6.3.

Given the extent of the design changes at Phase 2 it is probably more accurate to refer to the CW intervention at the two sites as a greywater treatment system which would include the washing area, the walls of the CW, the CW itself, and the channels for wastewaters. Central to each greywater treatment system is the CW.

Redesign increased use but changed the nature of the system

The most striking result in answering the third research aim was the increased activities (especially disposal activities) observed at Phase 2 at the redesigned CWs when normalising for the numbers of days of observation. The number and range of activities at Wetland 1 and 2 more closely resembled the activities of Site 3 at Phase 1. However, the fact that the washing area was directly connected to the CW facilitated the flow of greywater. A contributing factor could be the increased height of the working space of the CWs (especially at Wetland 2) which reduced the physical stress on the participants and therefore increased their use. However, it should be borne in mind that at Phase 2 the observation days included different days of the week and that the tap at Wetland 1 was also functioning.

The implementation of E/HF approaches resulted in significant changes in the postures adopted by the users. Static stooped postures with a flexed spine (with and without trunk rotation) are associated with increased risk for the development

Figure 8. 8A and 8B typical postures adopted while performing washing tasks at the Wetland 1 during Phase 2. 8C and 8D shows the typical postures adopted at Wetland 2 during Phase 2 (including the posture, with significantly less trunk flexion, with a child on the back). 8E and 8F are typical postures at Site 3 during Phase 2 with the trunk flexed more than 90 degrees. Figures 8 G to 8J demonstrate alternative uses for wetlands 1 and 2 in Phase 2. 8 G shows the use of the CW as a walkway, 8 H shows how the CW served as a work surface for washing of clothes, 8I and 8J show how the Wetland 1 and 2 worked as barriers that channel sewage, stormwater, and household greywater.

of lower back disorders (Marras 2000; Davis, Jorgensen, and Gielo-Perczak 2005). When the CWs were raised, it facilitated more upright postures during water collection, use, and disposal activities, which in turn reduced the potential musculoskeletal risks associated with these tasks. Davis, Jorgensen, and Gielo-Perczak (2005) argued that greater trunk flexion results in a greater impact of body mass on the torso structures increasing loading on intervertebral discs. Therefore, the changes made to the CWs reduced the overall loading on the lower back.

The use of participatory approaches to redesign and improved postures is important in recognising the role of both physical and cognitive factors in preserving a state of wellness within individuals (Marras, 2012) and therefore in the promotion and improvement of health within the users of the CWs. However, while the redesign increased the flow of greywater into the CW, much of the greywater was from clothes and linen washing activities and not from other household chores such as house cleaning, personal cleaning, and food preparation. This meant that disposal volumes and detergent concentrations were greater than expected for each disposal event. This may impact the treatment capabilities of the CW. Nevertheless, the treatment of greywater to directly address SDG 6.3 by the CW would be virtually non-existent if it was not actually being used. This supports Sadoff, Borgomeo, and Uhlenbrook (2020) point that behavior is an important component of effective water management.

Transdisciplinary work and the co-design process

Co-design processes used in transdisciplinary research do not always result in all voices being heard (Turnhout et al. 2020). Involving different actors is often done in a way that does not embrace the backdrop of power differences that can bias outcomes towards the status quo. In the larger research project, we were aware that who was involved in the design process was political (e.g. who was told a meeting was happening, who had the time to attend) but the research team did not actively manage or minimise the impact of such effects. In addition, the stated desires of those that did participate in workshops was rooted in historical and current political contexts. Hignett et al. (2005) argued that participatory E/HF places an emphasis on people having sufficient knowledge and power to influence both the processes and outcomes of interventions if desirable outcomes are to be met. Although adding an E/HF lens (and methods) did not explicitly confront power and context issues, it did allow us to circumvent some of the limitations of transdisciplinary engagement by incorporating more (and different users) into the iterative design process and build within the lived context of residents.

E/HF takes a socio-technical systems approach to understanding human behavior (Walker et al. 2008), whilst projects undertaken in building nature-based solutions take a socio-ecological-technological systems approach (McPhearson et al. (2022). Therefore, while E/HF builds an understanding of 'local rationality' focused on the human users' multiple goals (Smith et al. 2002; Woods and Cook 1999), the ecological aspects are sometimes de-emphasised. Instead, E/HF helps identify the multiple human systems aspects (physical, cognitive, or organisational aspects) where value might be found (Dul et al. 2012).

This study aligns with recent arguments by Sinclair, Henshaw, and Henshaw (2021) for E/HF to take a more active role in 'the never-ending renewal processes' (p. 1) of communities facing wicked problems such as a lack of wastewater disposal solutions and the attendant challenges in contexts like Silvertown. To this end, while we still need to continue to work with the community to understand and improve upon the utility of the CWs, the intervention is an improvement on what was there before. This supports the idea that when trying to instil meaningful change in communities, 'gradual, incremental homeostatic adaptation' (Sinclair, Henshaw, and Henshaw 2021, 7) is an appropriate strategy, provided that this process is participatory, promotes learning, and moves the community towards some degree of self-regulation (Smith et al. 2002). By adopting a participatory approach, Laverack (2001) argues that communities can become empowered and it is only through this that effective community development can occur. However, it was not easy to collaborate fully with all members of the Setswetla community, due to the transience of those who lived there.

At this stage, the research team is still evaluating the quality of the greywater treatment. While we have shown that E/HF can facilitate behavior adaptation, we have not assessed the treatment properties of the CWs. Evaluating the treatment properties is critically important to understand the full effectiveness of the system. The iterative process should allow for progressively intensive participation in design solutions by the end-users. François et al. (2017) noted that an iterative, participatory design process should move from 'design for' people, to 'design with' people, and finally to 'design by' people, which supports the importance of adopting frameworks for the development of sanitation solutions by Kanda et al. (2022) and Filho et al. (2019). By the end of Phase 2 the design philosophy fell between 'design for' and 'design with' people. Competing priorities and limited financial capital may be contributing factors to achieving this ideal (Thatcher, Metson, and Sepeng 2022). Finally, we acknowledge that the iterative design process, while mature, is still ongoing and will continue to be informed by the E/HF evaluation process to further optimise human interaction with the CWs. In summary our case study supports the inclusion of E/HF research and methods can make a useful contribution to the design of nature-based solutions as part of a transdisciplinary project.

Conclusion

In Silvertown, we were able to use observations to: 1) determine that the pilot systems did not perform as desired; 2) adapt CWs so that they could meet more than just the goal of greywater disposal such as raised walkways, floodwater protection, and a washing area; and 3) improve usability (healthier postures) even if it was not a stated problem or objective by the users. While E/HF has not played a large role in sustainable wastewater transformation teams, participatory (van Eerd et al. 2010) and green ergonomics (Thatcher 2013) approaches are well suited to contribute to addressing SDG 6 issues.

The postural analysis for the current study was done using only crude observations of posture supported by photographic evidence. Emerging evidence questions whether increasing trunk flexion angle during lifting translates into greater prevalence of back pain (Saraceni et al. 2020). The less stooped postures adopted after the changes to the CWs may not necessarily translate into safer work and reduced prevalence of lower back pain. Future studies should examine the postural evidence in more detail, evaluate the actual physical demands of the activities in more detail, gain a better understanding of participants' perceived effort when engaging in these tasks and examine the biomechanical demands from a dynamic rather than a static perspective. The Silvertown context provides a unique and important opportunity from a low-middle income country (with unique population characteristics) to study these emerging trends in more detail.

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Short synopsis statement

Ergonomics/human factors assisted in the design of constructed wetlands by embedding them in the everyday community activities in an unplanned settlement.

References

Alfiya, Y., A. Gross, M. Sklarz, and E. Friedler. 2013. "Reliability of On-Site Greywater Treatment Systems in Mediterranean and Arid Environments–A Case Study." *Water Science and Technology* 67 (6): 1389–1395. doi:10.2166/wst.2013.687.

Arden, S., and X. Ma. 2018. "Constructed Wetlands for Greywater Recycle and Reuse: A Review." *The Science of the Total Environment* 630 (July): 587–599. doi:10.1016/j.scitotenv.2018.02.218.

Boano, F., A. Caruso, E. Costamagna, L. Ridolfi, S. Fiore, F. Demichelis, A. Galvão, J. Pisoeiro, A. Rizzo, and F. Masi. 2020. "A Review of Nature-Based Solutions for Greywater Treatment: Applications, Hydraulic Design, and Environmental Benefits." *The Science of the Total Environment* 711 (April): 134731. doi:10.1016/j.scitotenv.2019.134731.

Carden, K., N. Armitage, O. Sichone, and K. Winter. 2007. "The Use and Disposal of Greywater in the Non-Sewered Areas of South Africa: Part 2–Greywater Management Options." *Water SA* 33 (4). doi:10.4314/wsa.v33i4.52936.

Chaffin, D., G. Andersson, and B. Martin. 2006. "Occupational Biomechanical Modeling *Occupational Biomechanics*, edited byD. Chaffin, G. Anderson, B. Martin, 4th ed. 605. New York: J. Wiley & Sons, Inc.

Childers, D.L. 2020. "A Decade of Ecosystem-Scale Research at an Aridland Constructed Treatment Wetland." *Frontiers in Environmental Science* 8. doi:10.3389/fenvs.2020.576936.

Childers, D.L., P. Bois, H.E. Hartnett, S. Exploration, T. Mcphearson, and G. S. Metson. 2019. "Urban Ecological Infrastructure: An Inclusive Concept for the Non-Built Urban Environment." *Elementa: Science of the Anthropocene* 7. doi:10.1525/elementa.385.

Davis, K., M. Jorgensen, and K. Gielo-Perczak. 2005. "Biomechanical Modelling for Understanding of Low Back Injuries: A Systematic Review." *Occupational Ergonomics* 5 (1): 57–76. doi:10.3233/OER-2005-5106.

Dekker, S.W. 2006. "Resilience Engineering: Chronicling the Emergence of Confused Consensus." In *Resilience Engineering: Concepts and Precepts*, edited by E. Hollnagel, D. D. Woods, and N. Leveson, 77–92. Hampshire: Ashgate.

De Paoli, A. C., and M. von Sperling. 2013. "Evaluation of Clogging in Planted and Unplanted Horizontal Subsurface Flow Constructed Wetlands: Solids Accumulation and Hydraulic Conductivity Reduction." *Water Science and Technology* 67 (6): 1345–1352. doi:10.2166/wst.2013.008.

de Winter, J. C. F., and P. A. Hancock. 2021. "Why Human Factors Science is Demonstrably Necessary: Historical and Evolutionary Foundations." *Ergonomics* 64 (9): 1115–1131. doi:10.1080/00140139.2021.1905882.

Diego-Mas, J. A., J. Alcaide-Marzal, and R. Poveda-Bautista. 2017. "Errors Using Observational Methods for Ergonomics Assessment in Real Practice." *Human Factors* 59 (8): 1173–1187. doi:10.1177/0018720817723496.

Dul, J., R. Bruder, P. Buckle, P. Carayon, P. Falzon, W. S. Marras, J. R. Wilson, and B. van der Doelen. 2012. "A Strategy for Human Factors/Ergonomics: Developing the Discipline and Profession." *Ergonomics* 55 (4): 377–395. doi:10.1080/00140139.2012.661087.

Ferreira, V., A.P. Barreira, L. Loures, D. Antunes, and T. Panagopoulos. 2020. "Stakeholders' Engagement on Nature-Based Solutions: A Systematic Literature Review." *Sustainability* 12 (2): 640. doi:https://doi.org/10.3390/su12020640.

François, M., F. Osiurak, A. Fort, P. Crave, and J. Navarro. 2017. "Automotive HMI Design and Participatory User Involvement: Review and Perspectives." *Ergonomics* 60 (4): 541–552. doi:10.1080/00140139.2016.1188218.

Friedrichsen, C.N., M.C. Monroe, S.H. Daroub, and S.P. Wani. 2021. "Yuck! Plural Valuation of Constructed Wetland Maintenance for Decentralized Wastewater Treatment in Rural India." *Frontiers in Sustainable Food Systems* 4. doi:10.3389/fsufs.2020.564539.

Garrigou, A., F. Daniellou, G. Carballeda, and S. Ruaud. 1995. "Activity Analysis in Participatory Design and Analysis of Participatory Design Activity." *International Journal of Industrial Ergonomics* 15 (5): 311–327. doi:10.1016/0169-8141(94)00079-I.

Helander, M. G. 1997. "Forty Years of IEA: Some Reflections on the Evolution of Ergonomics." *Ergonomics* 40 (10): 952–961. doi:10.1080/001401397187531.

Hignett, S., J. R. Wilson, and W. Morris. 2005. "Finding ergonomic solutions —participatory approaches." *Occupational medicine* 55 (3): 200–207. doi:10.1093/occmed/kqi084.

Jahn, S., J. Newig, D. J. Lang, J. Kahle, and M. Bergmann. 2022. "Demarcating Transdisciplinary Research in Sustainability Science—Five Clusters of Research Modes Based on Evidence from 59 Research Projects." *Sustainable Development* 30 (2): 343–357. doi:10.1002/sd.2278.

Kalantzis, A., A. Thatcher, and C. Sheridan. 2016. "Mental Models of a Water Management System in a Green Building." *Applied Ergonomics* 57: 36–47. doi:10.1016/j.apergo.2016.04.007.

Kanda, A., E. J. Ncube, and K. Voyi. 2021. "Adapting Sanitation Needs to a Latrine Design (And Its Upgradable Models): A Mixed Method Study

Under Lower Middle-Income Rural Settings." *Sustainability* 13 (23): 13444. doi:10.3390/su132313444.

Keeler, B.L., P. Hamel, T. McPhearson, M.H. Hamann, M.L. Donahue, K.A. Meza Prado, K.K. Arkema, et al. 2019. "Social-Ecological and Technological Factors Moderate the Value of Urban Nature." *Nature Sustainability* 2 (1): 29–38. doi: https://doi.org/10.1038/s41893-018-0202-1.

Lam, D. P., M. E. Freund, J. Kny, O. Marg, M. Mbah, L. Theiler, M. Bermann, B. Brohmann, D. J. Lang, and M. Schäfer. 2021. "Transdisciplinary Research: Towards an Integrative Perspective." *GAIA-Ecological Perspectives for Science and Society* 30 (4): 243–249. doi:10.14512/gaia.30.4.7.

Lang, D. J., A. Wiek, M. Bergmann, M. Stauffacher, P. Martens, P. Moll, and C. J. Thomas. 2012. "Transdisciplinary Research in Sustainability Science: Practice, Principles, and Challenges." *Sustainability Science* 7: 25–43. doi:10.1007/s11625-011-0149-x.

Laverack, G. 2001. "An Identification and Interpretation of the Organizational Aspects of Community Empowerment." *Community development journal* 36 (2): 134–145.

Magalhães Filho, F. J., A. A. de Queiroz, B. S. Machado, and P. L. Paulo. 2019. "Sustainable Sanitation Management Tool for Decision Making in Isolated Areas in Brazil." *International Journal of Environmental Research and Public Health* 16 (7): 1118.

Maimon, A., A. Tal, E. Friedler, and A. Gross. 2010. "Safe On-Site Reuse of Greywater for Irrigation-A Critical Review of Current Guidelines." *Environmental Science & Technology* 44 (9): 3213–3220. doi:10.1021/es902646g.

Marras, W. 2000. "Occupational Low Back Disorder Causation and Control." *Ergonomics* 43 (7): 880–902. doi:10.1080/001401300409080.

Marras, W. S. 2012. "The Complex Spine: The Multidimensional System of Causal Pathways for Low-Back Disorders." *Human Factors* 54 (6): 881–889. doi:10.1177/0018720812452129.

McPhearson, T., E.M. Cook, M. Berbés-Blázquez, C. Cheng, N.B. Grimm, E. Andersson, O. Barbosa, et al. 2022. "A Social-Ecological-Technological Systems Framework for Urban Ecosystem Services." *One Earth* 5 (5): 505–518. doi:https://doi.org/10.1016/j.oneear.2022.04.007.

Monica, F. 2021. "Slums as Opportunities? Spatial Organisation, Microeconomy and Self-Made Infrastructures in Freetown Informal Settlements." In *African Cities Through Local Eyes: Experiments in Place-Based Planning and Design*, edited by G. Faldi, A Fisher, and L. Moretto, 111–127. Cham: Springer International Publishing.

Moray, N. 1995. "Ergonomics and the Global Problems of the Twenty-First Century." *Ergonomics* 38 (8): 1691–1707. doi:10.1080/00140139508925220.

Norström, A. V., C. Cvitanovic, M. F. Löf, S. West, C. Wyborn, P. Balvanera, Bednarek, et al. 2020. "Principles for Knowledge Co-Production in Sustainability Research." *Nature Sustainability* 3 (3): 182–190. doi:10.1038/s41893-019-0448-2.

Öberg, G., G. S. Metson, Y. Kuwayama, and S. A. Conrad. 2020. "Conventional Sewer Systems are Too Time-Consuming, Costly and Inflexible to Meet the Challenges of the 21st Century." *Sustainability* 12 (16): 6518. doi:10.3390/su12166518.

Oteng-Peprah, M., M. A. Acheampong, and N. K. DeVries. 2018. "Greywater Characteristics, Treatment Systems, Reuse Strategies and User Perception—A Review." *Water, Air, & Soil Pollution* 229 (8): 1–16. doi:10.1007/s11270-018-3909-8.

Pereira, L., N. Frantzeskaki, A. Hebinck, L. Charli-Joseph, S. Drimie, M. Dyer, H. Eakin, et al. 2020. "Transformative Spaces in the Making: Key Lessons from Nine Cases in the Global South." *Sustainability Science* 15 (1): 161–178. doi:10.1007/s11625-019-00749-x.

Pradhan, S., S. G. Al-Ghamdi, and H. R. Mackey. 2019. "Greywater Recycling in Buildings Using Living Walls and Green Roofs: A Review of the Applicability and Challenges." *The Science of the Total Environment* 652: 330–344. doi:10.1016/j.scitotenv.2018.10.226.

Sadoff, C. W., E. Borgomeo, and S. Uhlenbrook. 2020. "Rethinking Water for SDG 6." *Nature Sustainability* 3 (5): 346–347. doi:10.1038/s41893-020-0530-9.

Saraceni, N., P. Kent, L. Ng, A. Campbell, L. Straker, and P. O'Sullivan. 2020. "To Flex or Not to Flex? Is There a Relationship Between Lumbar Spine Flexion During Lifting and Low Back Pain? A Systematic Review with Meta-Analysis." *Journal of Orthopaedic & Sports Physical Therapy* 50 (3): 121–130. doi:10.2519/jospt.2020.9218.

Shaikh, I. N., and M. M. Ahammed. 2020. "Quantity and Quality Characteristics of Greywater: A Review." *Journal of Environmental Management* 261: 110266. doi:https://doi.org/10.1016/j.jenvman.2020.110266.

Sheridan, C., D. Hildebrand, and D. Glasser. 2014. "Turning Wine (Waste) into Water: Toward Technological Advances in the Use of Constructed Wetlands for Winery Effluent Treatment." *AIChE Journal* 60 (2): 420e431. doi:10.1002/aic.14297.

Shoniwa, T. T., and T. Thebe. 2020. "Informal and Unserviceable: The State, Informal Settlement Residents, and Sanitation Management in Western Tshwane City, South Africa." *Urban Forum* 31 (4): 533–547. doi:10.1007/s12132-020-09396-3.

Sinclair, M. A., M. D. Henshaw, and S. L. Henshaw. 2021. "On Building Sustainable Communities: A Perspective for HFE Practitioners." *Applied Ergonomics* 96: 103476. doi:10.1016/j.apergo.2021.103476.

Smith, J. H., W. J. Cohen, F. T. Conway, P. Carayon, A. Derjani-Bayeh, and M. J. Smith. 2002. *Community Ergonomics*. *Macroergonomics: Theory, methods, and applications*. Mahwah, NJ: Lawrence Erlbaumpp. 289–309

Stevens, N. J., P. M. Salmon, G. H. Walker, and N. A. Stanton. 2018. *Human Factors in Land Use Planning and Urban Design: Methods, Practical Guidance, and Applications*. Boca Raton, FL: CRC Press.

Stokols, D., S. Misra, M. G. Runnerstrom, and J. A. Hipp. 2009. "Psychology in an Age of Ecological Crisis: From Personal Angst to Collective Action." *The American Psychologist* 64 (3): 181–193. doi:10.1037/a0014717.

Thatcher, A. 2013. "Green Ergonomics: Definition and Scope." *Ergonomics* 56 (3): 389–398. doi:10.1080/00140139.2012.718371.

Thatcher, A., G. Metson, and M. Sepeng. 2022. "Applying the Sustainable System-Of-Systems Framework: Wastewater(s) in a Rapidly Urbanising South African Settlement." *Ergonomics* 1–17. doi:https://doi.org/10.1080/00140139.2022.2068647.

Thatcher, A., P. Waterson, A. Todd, and N. Moray. 2018. "State of Science: Ergonomics and Global Issues." *Ergonomics* 61 (2): 197–213. doi:10.1080/00140139.2017.1398845.

Thiam, S., F. Aziz, S. B. Kushitor, A. B. K. Amaka-Otchere, B. N. Onyima, and O. N. Odume. 2021. "Analyzing the Contributions of Transdisciplinary Research to the Global Sustainability Agenda in African Cities." *Sustainability Science* 16 (6): 1923–1944. doi:10.1007/s11625-021-01042-6.

Turnhout, E., T. Metze, C. Wyborn, N. Klenk, and E. Louder. 2020. "The Politics of Co-Production: Participation, Power, and Transformation." *Current Opinion in Environmental Sustainability* 42 (2018): 15–21. doi:10.1016/j.cosust.2019.11.009.

van Eerd, D., D. Cole, E. Irvin, Q. Mahood, K. Keown, N. Theberge, J. Village, M. Vincent, and K. Cullen. 2010. "Process and Implementation of Participatory Ergonomic Interventions: A Systematic Review." *Ergonomics* 53 (10): 1153–1166. doi:10.1080/00140139.2010.513452.

Vymazal, J. 2009. "The Use Constructed Wetlands with Horizontal Sub-Surface Flow for Various Types of Wastewater." *Ecological Engineering* 35 (1): 1–17. doi:10.1016/j.ecoleng.2008.08.016.

Walker, G. H., N. A. Stanton, P. M. Salmon, and D. P. Jenkins. 2008. "A Review of Sociotechnical Systems Theory: A Classic Concept for New Command and Control Paradigms." *Theoretical Issues in Ergonomics Science* 9 (6): 479–499. doi:10.1080/14639220701635470.

Willcock, S., A. Parker, C. Wilson, T. Brewer, D. Bundhoo, S. Cooper, K. Lynch, et al. 2021. "Nature Provides Valuable Sanitation Services." *One Earth* 4 (2): 192–201. doi:10.1016/j.oneear.2021.01.003.

Wilson, J. R. 2014. "Fundamentals of Systems Ergonomics/Human Factors." *Applied Ergonomics* 45 (1): 5–13. doi:10.1016/j.apergo.2013.03.021.

Woods, D. D., and R. Cook. 1999. "Perspectives on Human Error: Hindsight Biases and Local Rationality." In *Handbook of Applied Cognition*, edited by F. Durso, 141–171. Hoboken, NJ: Wiley & Sons.