ACCESSIBLE GREYWATER SOLUTIONS FOR URBAN INFORMAL TOWNSHIPS IN SOUTH AFRICA

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

The URBWAT project initiated an iterative design process for greywater infrastructure, i.e. small-scale constructed subsurface flow wetlands (CWs)in an informal settlement in Johannesburg, South Africa, where sanitation services are currently limited. In the project, three greywater treatment CWs were built, monitored, rebuilt and maintained in collaboration with residents in the area. Multiple pressures and (competing) goals operating in a dense settlement with little space for infrastructure meant that the physical context and the use of the CWs changed rapidly. Therefore, it became clear that building structures that were more multi-functional (thinking of water collection, washing, and channeling multiple types of water) resulted in a higher use. The results from the project can inform planning processes aiming at addressing wastewater issues in urban slums with limited availability of sanitation services.

BACKGROUND

Greywater in a slum context is not the same as greywater which emanate from an established, sewered urban environment. What constitutes greywater is still not entirely clear, but from literature, it can contain a mixture of washwater, food preparation water, general cleaning water and, depending on the available excreta sanitation system, may also have a blackwater component. As a result of unplanned development, urban informal settlements are typically not sewered and the disposal of greywater is to the street or nearest drainage canal. This greywater is in many cases, a disease vector that flows through the settlements, and would need to be managed in a safer way. In this project, we aimed to design and build small-scale constructed wetlands to test *in-situ* treatment of greywater prior to the discharge to a receiving water body.

AIMS

The following were the aims of the project, and the work packages that addressed the respective aims:

1. To conduct baseline studies at the Langrug site to assess system treatment efficacy and community use, perceptions and assessment of the system. (Initiated (and abandoned) in work package 4)
2. To design, construct and monitor a constructed wetland network within an urban shanty environment (such as Alexandra) treating run-off mixed with variable loads of greywater, sewage and night soil. (Work packages 2 and 3)
3. To measure pathogen and chemical removal and the interplay between hydraulic processes and removal rates. (Work packages 3 and 5, partially achieved)
4. To test various CW matrix media (waste/by-products such as crushed bricks, metallurgical slags) to assess and quantify the potential improvement in performance, with specific focus on hydraulic properties and pathogen removal. (Work package 5 and 6)
5. To install a demonstration site of using CWs and tree wells for greywater disposal and treatment in informal settlements and assess how communities perceive system performance and operational challenges. (Work packages 2, 3, and 4)

METHODOLOGY

Detailed methodologies are described in each chapter. In summary, we followed a combined method of utilising an iterative design process, informed by multiple data collection, co-creation, and analysis methods to provide social insights that could guide the science and engineering parts of the project. The process also served as knowledge co-creation with the practitioners and residential actors we worked with.

Initially, we visited the Genius of Space system in Langrug that inspired our project, assessed the status and conducted interviews with various actors. We then conducted multiple community workshops in Alexandra, Johannesburg, leading to the design and build phase 1 (CW1 and 2), assessed water usage and disposal practices, monitored the water quality effects of the wetlands and conducted an ergonomic study. Next, the iterative design process with the residents led us to expand CW1 and 2 and build an additional wetland, CW3. We monitored both the usage of the CWs, and the water quality effect of the heavily used CW1. For each of these activities appropriate scientific methods were employed, as detailed in the respective chapters.

RESULTS AND DISCUSSION

CW1 and CW2 were found to initially be able to effect remediation, partly because the wastewater load was low as they were not used very much. The ergonomic study found that by raising the wash area, we could get more people to use the CWs since the ease of use was improved. We therefore modified CW1 and CW2 to include raised washing areas at the taps and extended the size of both CWs. Following this, a long-term sewer leak destroyed the function of CW2 as it was clogged by the sewage load. The extended CW1 continued to function. The improved useability of the wash bay, however, led to a wastewater load that exceeded the capacity of the CW. Clogging occurred within 6 months, and this remains a challenge that must be addressed in future work, for example by organising for installation and regular maintenance of a settling tank at the inflow. CW3 was abandoned because of an unforeseen drop in water pressure following the construction, so there was no water in the taps feeding it. This demonstrates the very dynamic nature of urban informal settlements, with uncoordinated interventions potentially affecting the communal availability of a shared resource like water.

The water quality monitoring of CW1 demonstrated the challenges when trying to understand the functioning of a small-scale treatment system receiving an intermittent wastewater load with highly variable quality. We know that some remediation was effected, but the extent thereof remains unknown as it was impossible to implement a continuous water sampling system due to security issues. Grab samples showed that the alkaline inflow wastewater was partly neutralized over the wetland (a one unit drop in pH), and that strongly anaerobic conditions developed over the length of the wetland, suggesting high microbiological activity. However, the quality of the outflow effluent did not meet standards for treated wastewater, as the CW system was overloaded from a treatment process perspective. Studies in lab- and greenhouse scale experiments made it possible to model the impact of varying load conditions on the removal rates. Furthermore, changes in the hydraulic properties of two different waste materials (building rubble and macadamia nut shells) in response to greywater loads could be quantified, which is useful information for enhanced understanding of how the choice of substrate material impacts the interaction between hydraulic load and removal rates. Results from ongoing microbial community studies in greenhouse experiments will improve our understanding of how the plant root and microbial biofilm growth impact the removal rates and the hydraulic performance of subsurface flow constructed wetlands used for greywater treatment. Those results will be reported in mid-2023.

During the project, the Jukskei river was also sampled upstream and downstream of the settlement area. This portion of Alexandra has a substantial and statistically significant negative impact on the Jukskei River water quality, indicating that the lack of services in this portion of Alex are measurable in the river.

The iterative design process remains one of the very strong successes of the project. Developing and redeveloping the CWs was an effective strategy towards successful implementation of a greywater infrastructure that could alleviate some of the greywater challenges the residents are facing, though not entirely alleviating the hazards associated with greywater discharge.

GENERAL

In general, the aims of the project were achieved. The iterative design process helped identify specific challenges related to residents´ water use and disposal as well as to implementation of on-site greywater infrastructures in such dense and dynamically changing urban environments. The close monitoring and collaboration with residents during the intervention also served to identify possible approaches to mitigate some of the problems encountered during the project.

CONCLUSIONS

The community engagement, design, construction, redesign, re-building, and monitoring of the implemented greywater infrastructure were successful. Feedback from the City of Johannesburg and the community was very positive, and modification suggestions from the local residents are well aligned with what is described in this report. On that basis we have applied for additional ESASTAP funding (to inform policy in particular) to extend the project.

RECOMMENDATIONS

For future research projects in the same settlement, we have three additional elements needing to be addressed. The first of these is related to the problem with CW clogging. For this we have proposed to install a settling tank as part of the design and to negotiate with the City of Joburg to use existing 'honeysucker' trucks to empty this tank with regular intervals. The second element is to create a hidden, nested flow measurement system to determine and understand the true flowrates into and out of the system to gather scientifically sound data for assessment of the treatment performance. Finally, there is need for a larger network of disposal points for buckets carried from homes to the constructed wetland (or drainage canals); those points should ideally also be linked to small-scale settling tanks.

ACKNOWLEDGEMENTS

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Affiliation	Name
Community Leadership Forum s'Swetla	Kgabo Raphala
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University of the Witwatersrand	Wits Marketing for assistance with filming and reporting
Isle Utilities	Jo Burgess

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ACRONYMS & ABBREVIATIONS

BMBF	Bundesministerium für Bildung und Forschung (German: Federal Ministry of Education and Research; Bonn, Germany)
CIWaRD	Centre in Water Research and Development
COVID-19	Novel coronavirus SARS-CoV2
CW	Constructed Wetland
FORMAS	Swedish government research council for sustainable development
IC4Water	International Collaboration for Water
LiU	Linköping University
UFZ	Helmholtz-Zentrum für Umweltforschung
URBWAT	Accessible Greywater Solutions for Urban Informal Townships in South Africa
WATER JPI	Water Joint Programme Initiative
WITS	The University of the Witwatersrand, Johannesburg
WRC	Water Research Commission

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BACKGROUND

1.1 INTRODUCTION

The urban shanty town/township is a common feature in many modern cities in the developing world. They typically arise because of very rapid urbanisation, in a socio-political environment which is unable to supply housing and associated infrastructure (Lawhon et al., 2018). Once a township is established it is extremely difficult to change, even for the better, since change requires removal of people. This leads to a dense urban settlement, sometimes consisting of tens of thousands of people, with very little access to sewage and/or greywater treatment.

The first goal within UN SDG6 is ‘universal and equitable access to safe and affordable drinking water for all’ by 2030. In South Africa, great strides have been made; 94% of the population has access to a supply of safe drinking water from a tap within 200 m of their home. However, this pace of development has not been matched by the intrinsically linked goal of ‘adequate and equitable sanitation and hygiene for all’ and improved ‘water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater,’ also by 2030. Only blackwater has been considered, so while open defecation has been largely replaced by pit latrines or communal ablutions, the unintended consequences of the provision of tap water services include rivers of untreated greywater coursing through dense, informal settlements.

The informal water usage and reuse practised by those who have to carry their water into their homes mean that collected tap water is commonly used for more than one purpose (including cleaning of nightsoil containers used in the home overnight). This water is commonly disposed into the ‘street’ or pathway – it is heavy, so carrying it to a disposal point is not easy. This ‘grey’ water emanating from an un-serviced community is not the same as the greywater arising from a serviced/ wealthy suburb. This greywater typically contains traces of black water but may also possess additional human and environmental hazards arising from: home car repairs, home slaughtering of livestock, etc. Waterborne diseases such as cholera resurge under these conditions; the health effects are significant, with absenteeism from school and work a measurable consequence. The discharged ‘grey’ water works its way through the informal settlements and discharges either directly to the nearest river (in the case of this study, the Jukskei River) or through any functioning stormwater drainage systems to the same river. At this point, the discharge poses not only a continuing human health hazard, but also has significant ecological impacts.

The present best practice to address these problems is to replace townships with formal suburbs. Such a practice is extremely challenging technically, owing to the large infrastructure it demands and the Capex required to achieve it. In addition, traditional urban infrastructure drains the suburb as rapidly as possibly, hence opportunities for climate change resilience, such as distributed stormwater storage for drought mitigation, and swales for flood prevention, are missed. Arguably more important are the social challenges associated with displacing thousands of people during the infrastructure upgrade and resettling them in unfamiliar surroundings, outside of their community, after the upgrade. Experience has shown that drastic changes can result in civil disobedience or violent protest, even where the change is intended to be beneficial.

A potentially feasible option to introduce higher hygienic standards without displacing and relocating an entire informal settlement is the installation of an interconnected network of greywater disposal points connected to small-scale treatment wetlands (CWs). The installation and maintenance of CWs is low-cost and simple, critical characteristics within the context considered for this project. Additionally, maintenance of the system could be conducted by trained community members. Such a system was built in the Langrug township in Franschhoek, in the Western Cape Province of South Africa. That system was designed and built by Isidima Consulting as a project entitled, “Genius of SPACE (Systems for Peoples Access to a Clean Environment) sponsored by the Water Research Commission and the Western Cape Provincial Government (Harris, J and Janisch, C. 2017). In this project, we proposed to study and replicate successes of this system in a Johannesburg context. This report describes this replication.

Constructed wetlands are often characterised based on chemical or physico-chemical parameters, and the difference between the in- and outflow concentrations is commonly used to determine the degradation efficiency. Deeper microbial analyses are generally limited to specific microbial groups involved in selected transformations such as the nitrogen cycle, and in some limited cases this is extended to wider substrate spectra. A black box approach is commonly used for legal valuation of the discharge quality, but it does not allow for the evaluation of the microbial waste elimination or transformation potentials of the investigated system. Breaking open this ‘black box’ is very difficult, despite decades of research, and is particularly difficult in the context of greywater handling in an informal settlement with very intermittent wastewater loads.

1.2 PROJECT AIMS

The following were the aims of the project:

1. To conduct baseline studies at the Langrug site to assess system treatment efficacy and community use, perceptions and assessment of the system (whilst Aim 2 was being constructed in Johannesburg)
2. To design, construct and monitor a constructed wetland network within an urban shanty environment (such as Alexandra) treating run-off mixed with variable loads of greywater, sewage and night soil.
3. To measure pathogen and chemical removal and the interplay between hydraulic processes and removal rates.
4. To test various CW matrix media (waste/by-products such as crushed brick, metallurgical slags) to assess and quantify the potential improvement in performance, with specific focus on hydraulic properties and pathogen removal.
5. To install a demonstration site of using CWs and tree wells for greywater disposal and treatment in informal settlements and assess how communities perceive system performance and operational challenges.

Aim 1 was abandoned (discussed later), Aim 2 was conducted in Work Packages 2 and 3, Aim 3 was addressed in Work packages 2, 3 and 5, and was only partially achieved since flow measurement in the field was and remains unknown. Aim 4 was done in WP 5 and Aim 5 was the focus of both Work Package 2 and particularly in work package 4 and 6.

An implicit approach in the project was that as much of the work should be done by the residents of the areas within which we were working. This included catering, building, purchasing of materials, etc.

1.3 SCOPE AND LIMITATIONS

The project was funded through the Joint Programme Initiative (Water JPI) under the IC4Water Call. There are three partners to the project. The South African partner is funded by the Water Research Commission, the Swedish Partner is funded through the Swedish Research Council for Sustainable Development, FORMAS, and the German Partner is funded by the Federal Ministry of Education and Research, BMBF. Due to the COVID-19 pandemic, the research was delayed for more than a year. Each partner entity, however, had slightly different project extensions. As such, this report is complete for the work conducted by the South African partner and for reporting to the Water Research Commission. Work completed and due for reporting to other agencies with different extension timeframes is not necessarily reported upon here. That work will be fully reported upon to that specific agency. Notwithstanding this, summaries are provided as far as possible.

CHAPTER 2: WORK PACKAGE 1. PROJECT MANAGEMENT

2.1 INTRODUCTION

The project has been managed with biweekly electronic meetings between the senior scientists from the partners. This was initially done to facilitate the project due to the distance between the three partners, however with the COVID-19 lockdown(s) this strategy proved highly successful. There were also physical meetings between all the senior parties, listed in Table 2.1. These meetings were complemented with regular work package and or supervision meetings to analyse the collected data, supervise MSc and PhD students and work on joint scientific papers.

Table 2.1. List of in-person meetings within the course of the URBWAT project.

No.	Date	Location	Attending Partners	Purpose
1	5 Feb 2019	Paris	Wits/LiU/UFZ	Kick-off meeting
2	17-19 March 2019	Leipzig	LiU/UFZ	Reviewing greenhouse experiments
3	30 April 2019	Johannesburg / Cape Town	Wits/LiU/UFZ	Field work initiation (work in Langrug and Johannesburg)
4	18 August 2019	Linköping	LiU/UFZ	Setting up Column experiments
5	24 November 2019	Johannesburg	Wits/LiU/UFZ	Fieldwork, design finalisation meeting
6	17 January 2020	Linköping	LiU/UFZ	Field data analysis and Field Trip planning
7	16 November 2021	Johannesburg	UFZ/WITS	Field sampling
8	4-7 January 2022	Linköping	UFZ/LiU	Reviewing data, planning activities for final year, structuring scientific publications and draft content of final report
9	20 March - 1 April 2022	Johannesburg	LiU/UFZ/Wits	Initiating wetland monitoring in Silvertown, setting up lab procedures, reviewing CW2 and 3
10	16-24 October 2022	Johannesburg	LiU/Wits	Analysing monitoring data. Final dissemination workshops with local governmental stakeholders and the

No.	Date	Location	Attending Partners	Purpose
				Silvertown community members
11	1-4 November 2022	Leipzig	Wits/LiU/UFZ	Write final report and drafting papers

During construction, project management of the building phases was conducted by residents of s'Swetla under commission by the project.

CHAPTER 3: WORK PACKAGE 2 – INSTALLATION OF SMALL-SCALE TREATMENT WETLANDS IN AN INFORMAL SETTLEMENT

3.1 MONITORING THE LANGRUG INFRASTRUCTURE PROJECT

The project team visited the system at Langrug with the intention to assess the system treatment efficacy and community use, as well as perceptions of the system, and use this information to inform the design for URBWAT. Upon visiting the site, very early in the project, it was clear that the Langrug system was not operational. No plants were living in the wetland, many of the community disposal points were dysfunctional and the trees in the tree wells were also dead (Figure 3.1). Based on this, we did not use the system for inspiration – rather we started from zero point in Alexandra.

Figure 3.1. Example of a dysfunctional disposal point (A) in Langrug, 2019, and the constructed wetland with no vegetation (b).

3.2 INITIAL DESIGN LOCATION AND BASIS

Through widespread consultation (as discussed in Chapter 4), we chose Silvertown, a portion of setSwetla (s'Swetla) which is an unplanned shanty, north of Alexandra Township and south of Marlboro Road, as the field site for our project builds and studies. The location is shown in Figure 3.2. We initially built 2 CWs (CW1 and CW2) adjacent to locally installed freshwater taps (Build 1; Figure 3.2). Through an iterative design process, we then expanded the design and extended these 2 CWs (CW1A and CW2A – Build 2). Following this we had a third build phase where we installed CW3 (Build 3).

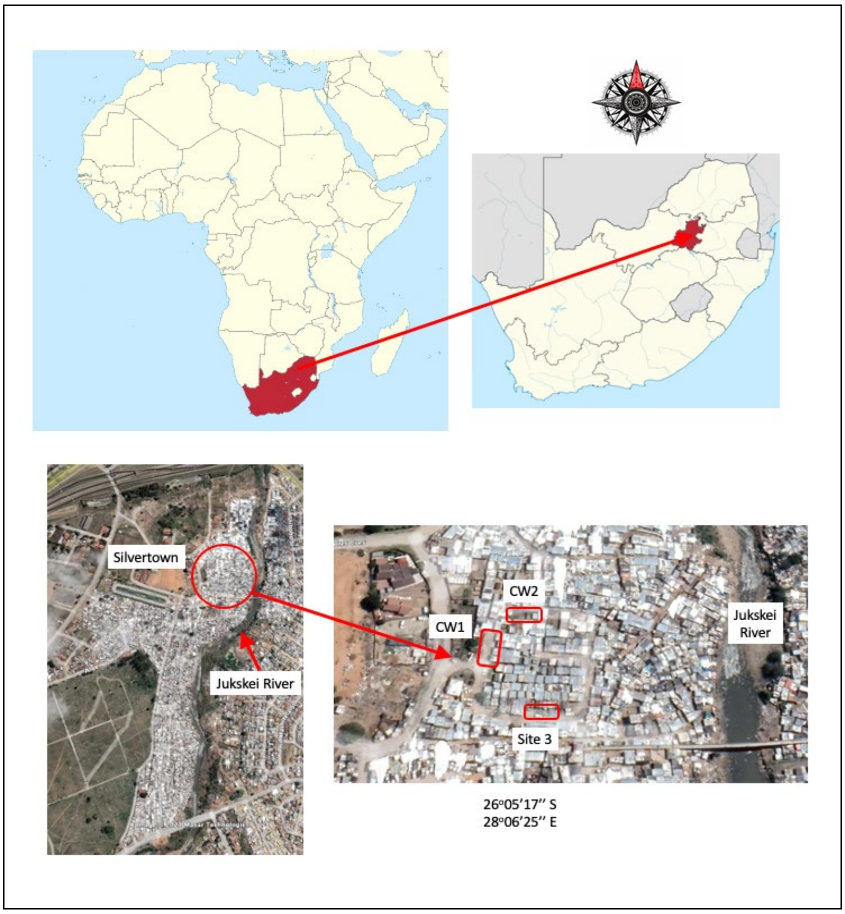

Figure 3.2. Site locality of the URBWAT constructed wetlands 1, 2 and 3 in s'Swetla, Johannesburg.

The basis for the CWs was irregular from an engineering perspective. Engineering practice requests knowledge about expected flow-rate and water composition, requires a time for treatment, and by multiplying the flow by the time, a volume (or size) for the system can be determined. In this location, the flowrate was highly variable and unknown (despite survey attempts to determine flowrate as outlined in Chapter 5) and the composition of the greywater was also entirely unknown. Space was (and remains) also a significant constraint – due to the very high density of shacks, there is not always space available for the creation of large (or even small) infrastructure components (Figure 3.3).

Figure 3.3. Photograph showing very high shack density in s'Swetla precluding the construction of greywater infrastructure.

In this context, we decided that the design basis for the planned CWs would be to build them as large as was possible within these physical constraints. By December 2019, we made the 'GO' decision following acceptance by the residents of s'Swetla and we began construction of the systems.

3.2.1 Construction Materials Selection and Procurement

One of the main aims of the project (of which this Chapter was a component) was to create CWs for water treatment in informal settlements that could easily be replicated in other informal settlements either formally by the public sector, or informally by initiatives from resident communities themselves. Based on this aim, and the design philosophy communicated above, construction materials for the CWs were selected based on several factors including availability in the local vicinity, cost-effectiveness, durability for several years and aesthetics. As outlined above, the materials selected intentionally excluded metals and any equipment that would require electricity.

The following materials were selected for construction:

- Locally-procured 'recycled' bricks obtained from a supplier that recovers bricks from abandoned or demolished houses. These bricks were used for the containing walls of the CWs (Figure 3.5);
- Locally-procured cement and builder's sand;

- Locally-procured coarse gravel as the CWs filtering substrate (shown in Figure 3.4);
- PVC pipes and elbows from a local hardware store. These pipes were used for part of the basic internal reticulation of the CWs;
- 'Pool-pipe' procured from a local hardware store. This flexible pipe was use as a level control mechanism on the outlet of the CWs;
- Drain funnel and grate procured from a local hardware store. This was used as the feeding point for the CW;
- Bitumen Paint and Geotextile fabric procured from a local hardware store. This was used for the internal waterproofing of the CWs; and
- PVC pond liner procured from a local hardware store. This was used for the internal waterproofing of the CWs when the bitumen paint proved to be insufficient.

Figure 3.4. Gravel for constructed wetland bed media that was procured from a local supplier in Silvertown, Alexandra

Figure 3.5. Re-used bricks that were procured from a local supplier in Silvertown, Alexandra for building the containing walls of the constructed wetland

3.2.2 Location Selection

The community workshops discussed in Chapter 5 were followed by site-surveys during which the researchers would walk around the neighbourhood with the residents to better understand the challenges of water provision and sanitation in the area, and to identify potential sites where the CWs could be installed.

Several factors were taken into consideration when assessing the suitability of potential site locations. It was noted that the CWs would be best placed near municipal potable communal stand pipes as residents often washed their clothes and cooking utensils at these taps, and then discarded the wastewater nearby to the ground or in an informal drainage trench. Locating the CWs next to these taps would make it easier for residents to dispose their wastewater in the inlet of the CW. The containing walls of the CW would protrude 30-50cm above ground level, and thus there was also potential to engage with residents regarding the directionality of the CW, to allow for this bund wall to simultaneously act as a stormwater diversion mechanism and a walking path above the informal drainage trenches. Considering these points, four potential sites, Site 1, Site 2, Site 3 and Site 4, were initially identified for the constructions of the CWs, with the aim of selecting two of them (Figures 3.6-3.9).

Figure 3.6. Site 1 that was identified for the constructed of a constructed wetland (perimeter outlined in red). Communal tap with resident filling bucket shown on right. (Coordinates: 26°05'17.0"S 28°06'25.3"E)

Figure 3.7. Site 2 that was identified for the CW2 constructed wetland. Communal tap shown to left with resident assisting to take measurements with yellow measuring tape in centre-right. (Coordinates: 26°05'16.1"S 28°06'25.9"E)

Figure 3.8. Site 3 that was identified for the construction of a constructed wetland (perimeter outlined in red). Communal tap shown at left. (Coordinates:26°05'18.0"S 28°06'26.7"E)

Figure 3.9. Site 4 that was identified for the construction of a constructed wetland. Communal tap shown on left with resident filling bucket. (Coordinates: 26°05'18.0"S 28°06'27.2"E)

Site 3 was initially not selected, although it did provide for sufficient space, because it was found that the municipal tap at the site was not regularly used at the time. Site 4 was not selected, although it did include a municipal water tap that was regularly used, because there was not sufficient space for an adequately-sized CW based on the estimated flowrate of wastewater from the tap and the adjacent road on which large trucks (for the removal of blackwater from portable toilets and to deliver construction materials) would frequently pass. Thus, Site 1 and Site 2 were selected for the construction of CW1 and CW2, respectively.

3.2.3 Final Initial Design

Through several design iterations, and considering the design philosophy mentioned in this section, the design shown in Figure 3.10 was chosen for CW1 and in Figure 3.11 for CW2. The designs for both CWs were similar; CW1 was approximately 1.2 m longer than CW2 since there was more space available.

This design incorporates an inlet feeding with a grate to prevent larger solids from entering the wetland. From the inlet, effluent is directed to a settling chamber, to allow for further separation of solids. Effluent then overflows out of the settling chamber and through the gravel bed, planted with wetland species, where the main biological and chemical treatment processes take place. At the end of the gravel bed is a drain pipe connected to a flexible hose or ‘pool pipe’ (Figure 3.14). This flexible hose allows for the water level within the CW to be regulated at a desired level, without the need for valves or electronic equipment. By simply raising or lowering the flexible hose, the water level in the CW could be raised or lowered respectively. Once the treated effluent flows out from the flexible hose, it exits the CW via the drain located at the end of the CW into the existing drainage channels.

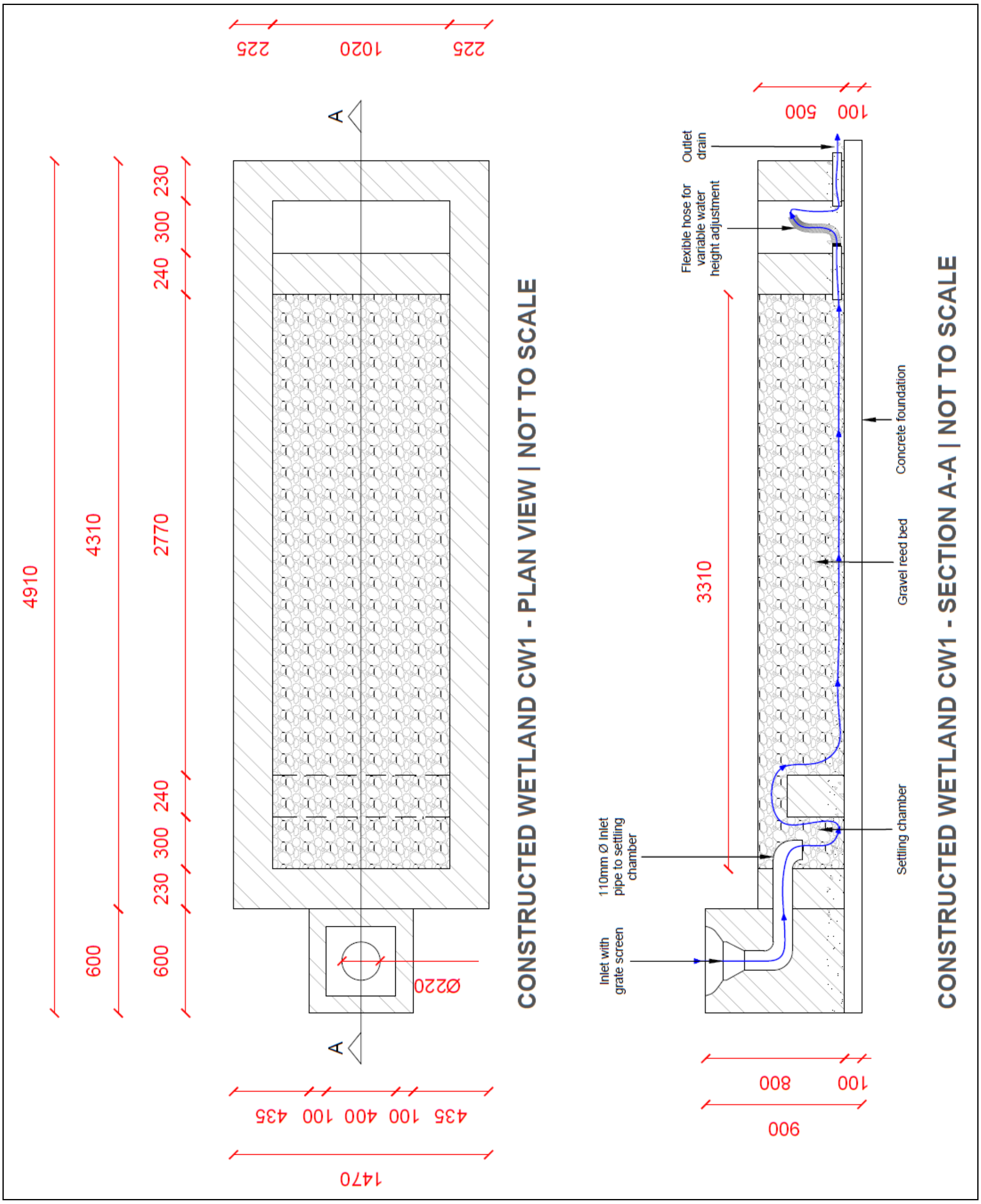

Figure 3.10. Technical Drawing for Constructed Wetland 1

In the initial design of the CWs, we used single brick walls for external and internal walls. However, this was later changed to double brick walls (Figure 3.10 and 3.11), based on the builder's experience and recommendation.

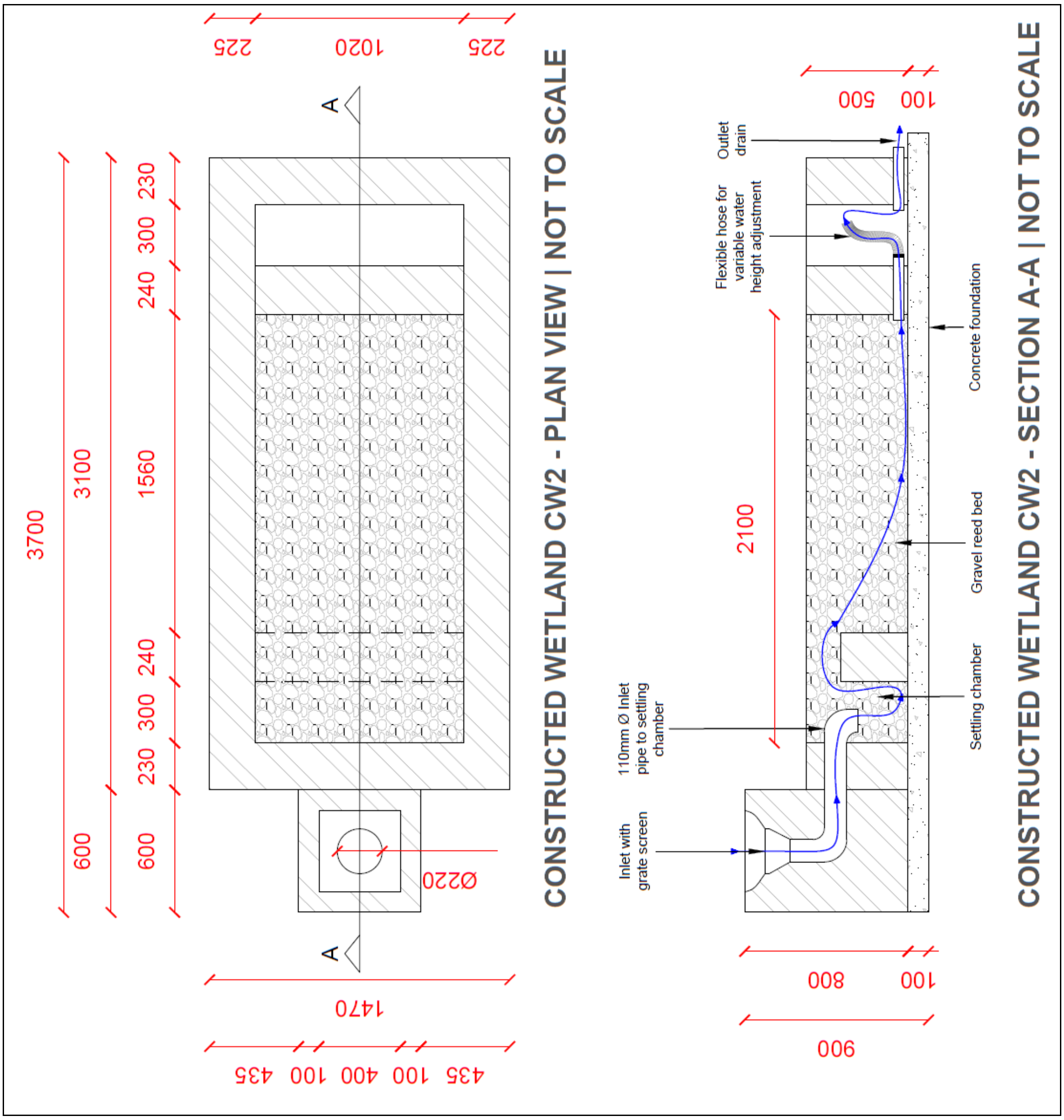

Figure 3.11. Technical Drawing for Constructed Wetland 2

To share a sense of the initial building process in Silvertown, Alexandra, some photos are shared in this section (Figures 3.12-3.15). They show how the concrete foundation and retaining walls were laid, and the CW just before filling with gravel, including the flexible outlet pipe, and workers and community members planting *Juncus effusus* in a completed CW1. Those plants were sourced from a commercial nursery. However, they were found to be poorly suited to this environment and died within a short time.

Figure 3.12. Builders laying foundation and retaining walls for Constructed Wetland 1

Figure 3.13. Constructed wetland 2 showing main retaining walls completed and waterproofed

Figure 3.14. Exiting drain system of constructed wetland showing water flowing through flexible drainage hose

Figure 3.15. Constructed wetland 1 completed with builders and residents planting *Juncus effusus* purchased from a commercial nursery.

3.3 SECOND DESIGN PROCESS FOR ADDITIONAL CWS AND EXTENSIONS

Following observations of CW usage, water quality monitoring and interactions with community members, it was decided to undertake a second and third building process, including extension of the two wetlands. This formed part of our iterative design process which is presented and discussed in Chapter 5.

As mentioned above, the initially planted plants died shortly after planting the CWs in the first phase. For this reason, the CWs were fully replanted with *Juncus sp.* sourced locally – plants which were observed to have colonised the local greywater environment or river bank (it is important to note that this is an extremely impacted environment with almost no aquatic life – plants sourced near the river were taken as daughter plants from existing plants). At the same time, we proceeded to expand and extend CW1 and 2. These extensions were labelled CW1A and CW2A (Figure 3.16 and 3.17). A third CW was also designed and built but was never planted since the freshwater tap which was supposed to supply water stopped working almost immediately following construction (Figure 3.18). This is a consequence of the local water supply being continually plumbed into by the local people for supply into their shanties or for other purposes and thus the pressure in the pipe drops to zero.

During this design phase, and because of consultation with the local community, additional features were included. CW1 and CW1A were built to include thick side wall which served as a flood barrier and raised walkway. This prevented the need for people to cross greywater draining through the area. This wall was extended to CW2 and CW2A and in the other direction for the same purpose. The taps were raised above the ground and incorporated into a platform constructed for the washing of clothes. This platform included a renovated drain to directly drain into the CW (since the original inlet mechanism clogged too rapidly). Detailed design drawings were not made for these extensions, however rendered engineering diagrams were made (Figures 3.16 to 3.18).

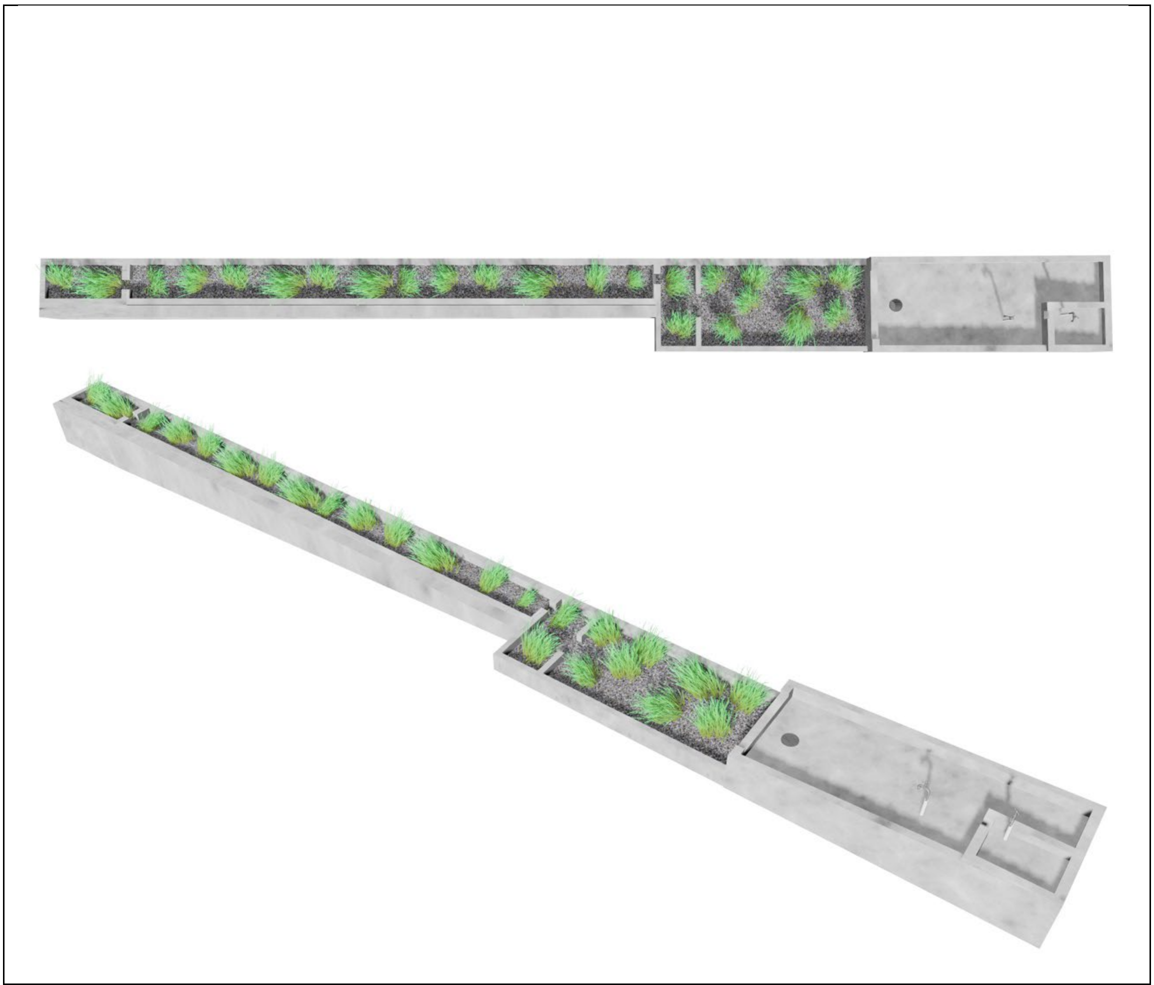

Figure 3.16. Rendered diagram of CW1 with extension CW1A.

Figure 3.17. Rendered diagram of CW2 with extension CW2A

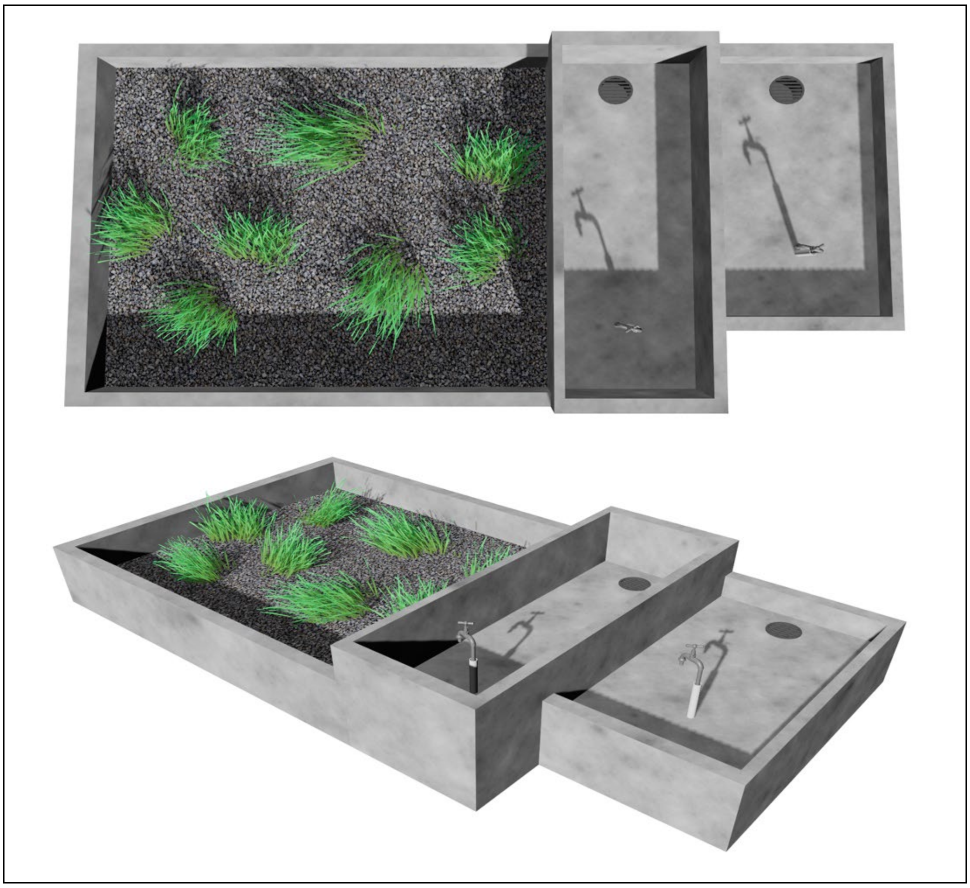

Figure 3.18. Rendered diagram of CW3

As part of the final feedback sessions (with the community and with city and state actors), we discussed the future of the CWs. We have applied for ESASTAP funding for a follow on additional iterative design phase. If we fail to receive this grant, we will abide by community requests and either dismantle and demolish the CWs or upgrade some parts. This will be guided by their preferences in early 2023.

CHAPTER 4: WORK PACKAGE 3 – OPERATION AND MONITORING OF SMALL-SCALE TREATMENT WETLANDS IN AN INFORMAL SETTLEMENT

4.1 INTRODUCTION

As described in Chapter 3, there were two phases of construction for the CWs. In this Chapter, the operation and monitoring of the CWs after both Build Phase 1 and 2 are presented and discussed. Following the installation of CW1 and CW2, samples were taken and analysed over a 12-week period in 2020. This sample period was severely limited by the hard COVID 19 lockdown in force in South Africa in 2020. These samples were taken from the CWs as well as from the Jukskei River, upstream and downstream of the site, to determine the environmental variability (Table 4.1). This sampling campaign formed part of an MSc Thesis (Rawhani, T.; 2022). Based on the results found in this initial sampling phase and following Build Phase 2 (extensions of CW1 and CW2) additional sampling campaigns were conducted in 2022. Six week-long sampling campaigns were conducted to monitor the performance of the extended CW1 and follow up on the impact of the settlements on river water quality.

Table 4.1. Summary of water quality sampling points and coordinates for each.

Sampling Point (sample point code)	Coordinates	Sampling Point (sample point code)
Constructed Wetland 1 Inlet (CW1 In)	26°05'17.0"S 28°06'25.3"E	Constructed Wetland 1 Inlet (CW1 In)
Constructed Wetland 1 Outlet (CW1 Out)	26°05'16.8"S 28°06'25.3"E	Constructed Wetland 1 Outlet (CW1 Out)
Constructed Wetland 2 Inlet (CW2 In)	26°05'16.1"S 28°06'25.9"E	Constructed Wetland 2 Inlet (CW2 In)
Constructed Wetland 2 Outlet (CW2 Out)	26°05'16.1"S 28°06'26.1"E	Constructed Wetland 2 Outlet (CW2 Out)

4.2 CW1 AND CW2 SAMPLING IN 2020

4.2.1 Sampling locations

Water samples were collected from the inlet and outlet of CW1 and CW1 as well as from the Jukskei River at a point upstream and a point downstream of Alexandra. The exact locations of the upstream and downstream Jukskei river sampling points were determined based on accessibility to the river at those locations (JR1 and JR2 in Figure 4.1).

Figure 4.1. Map showing Alexandra and surrounding areas with pins showing water sampling points and location of constructed wetlands

From the inlet region of CW1 (Figure 4.2) samples were taken using a syringe connected to a thin pipe to extract water from below the gravel level. Water from the outlet of CW1 (Figure 4.3) was collected by lowering the flexible ‘pool pipe’ to allow water to flow out of the pipe and into the sampling jar. At the inlet of CW2, samples were collected using a syringe and thin pipe to extract water from the ‘cylindrical trellis’ access point (Figure 4.4). At the outlet of CW2 samples were collected by lowering the flexible ‘pool pipe’ to allow water to flow from the pipe into the sampling jar (Figure 4.5). Samples from the Jukskei river were collected with a sampling jar both at a point upstream and one point downstream of Alexandra (Figure 4.6 and 4.7, respectively).

Figure 4.2. Inlet region of constructed wetland 1 showing large PVC elbow from inlet drain on the right. Photo taken on 23.09.2020 which was the second week of sampling after the national COVID-19 lockdown in South Africa, and therefore the vegetation in the constructed wetland had not yet grown back. (Coordinates: 26°05'17.0"S 28°06'25.3"E)

Figure 4.3. Outlet drain of constructed wetland 1 showing the blue flexible 'pool pipe' that connects the internal drain in the constructed wetland to the external drain. (Coordinates: 26°05'16.8"S 28°06'25.3"E)

Figure 4.4. Inlet region of constructed wetland 2, with the syringe and glass jars used for sampling. To the left is the large white PVC elbow that connects the incoming drain to the wetland, and in the centre is the black 'cylindrical trellis' used to access inlet water in the wetland. (Coordinates: 26°05'16.1"S 28°06'25.9"E)

Figure 4.5. Outlet drain of constructed wetland 2. The blue flexible 'pool pipe' connects the internal drain in the wetland to the external drain which drain into an informal trench that leads to the Jukskei River. (Coordinates: 26°05'16.1"S 28°06'26.1"E)

Figure 4.6. Jukskei River sampling points upstream of Alexandra located under the bridge on London Road. (Coordinates: 26°06'35.1"S 28°06'46.8"E).

Figure 4.7. Jukskei River sampling points downstream of Alexandra located in a site that is property of the University of Witwatersrand (Coordinates: 26°04'43.4"S 28°06'39.7"E)

4.2.2 Sampling Frequency

Sampling was done on a weekly basis for a 12-week period from 16 September to 3 December 2020 (Table 4.2). On occasion, personal security risks were a challenge and as such samples could not be taken. Also, as discussed, COVID 19 posed challenges to the project not only with accessing the site, but also with accessing laboratory services for analysis. Although lab personnel made great effort to assist as much as possible, staff changes and computer system challenges resulted in some of the results from ion chromatography not being recorded for certain samples (again – these are linked to COVID-19).

Table 4.2. Samples that were collected on each sampling date from the various sampling points. Samples marked with '*' were not collected due to security concerns

Sample Collected: Yes/No						
Date	**Jukskei Upstream of Alexandra**	**Jukskei Downstream of Alexandra**	**Inlet of Constructed Wetland 1**	**Outlet of Constructed Wetland 1**	**Inlet of Constructed Wetland 2**	**Outlet of Constructed Wetland 2**
16.09.2020	Y	Y	Y	Y	Y	Y
23.09.2020	N*	Y	Y	Y	Y	Y
30.09.2020	N*	Y	Y	Y	Y	Y
08.10.2020	N*	Y	Y	Y	Y	Y
14.10.2020	Y	Y	Y	Y	Y	Y
22.10.2020	Y	Y	Y	Y	Y	Y
29.10.2020	N*	Y	Y	Y	Y	Y
05.11.2020	N*	Y	Y	Y	Y	Y
12.11.2020	Y	Y	Y	Y	Y	Y
19.11.2020	Y	Y	Y	Y	Y	Y

Sample Collected: Yes/No						
Date	**Jukskei Upstream of Alexandra**	**Jukskei Downstream of Alexandra**	**Inlet of Constructed Wetland 1**	**Outlet of Constructed Wetland 1**	**Inlet of Constructed Wetland 2**	**Outlet of Constructed Wetland 2**
26.11.2020	N*	Y	Y	Y	Y	Y
03.12.2020	N*	Y	Y	Y	Y	Y

4.2.3 Sampling Techniques

For Phase 1, the following sampling procedures were used:

- Sterilised glass vessels with securable lids that had been washed and rinsed thoroughly with deionised water were used as the sample vessels;
- Each sample vessel was rinsed three times with the water that was to be sampled before finally filling the sample vessel and securing the lid tightly;
- The sample vessels were stored in a cooler box to maintain a consistent and low temperature of the vessels between sampling in the field and analysing in the laboratory;
- Nitrile gloves were used in the sampling procedure to maintain hygienic standards and reduce any possible contamination from the sampler's hands (especially for microbiological studies);
- Results for measurements taken in the field and laboratory were recorded in the researcher's field diary and later transcribed into Microsoft Excel.

4.2.4 Chemical and microbiological variables and analytical methods

The following variables were analysed:

- pH, electrical conductivity (EC) and Redox Potential (ORP) were measured in the field using a pre-calibrated Hannah Instruments HI98195 Multiparameter PH/ORP/EC/Pressure/Temperature Waterproof Meter. The machine was used, calibrated and maintained according to the manufacturer's specifications.
- Chemical Oxygen Demand (COD) was measured in the laboratory using a Merck Pharo 300 and Merck test kits 1.14679 and 1.14680 (COD Solution A and B). These were used according to the manufacturer's specifications.
- Sulfate, nitrate, nitrite, phosphate, fluoride, and chloride were analysed at a flowrate of 1.2 mL per minute using a Dionex DX-120 Ion Chromatograph with an AS40 Automated Sampler. The IC was coupled to a suppressor prior to the conductivity detector.
- *E. coli (*Faecal indicator bacteria (FIB)) and Total coliform are widely accepted indicator organisms for routine monitoring of domestic water. Microbial water quality monitoring is currently based on the Colilert 18 system which leads to rapid results. *E. Coli* and Total Coliform bacteria were analysed using an IDEXX Quanti-Tray system following the manufacturer´s protocol, and the results were recorded as most probable number (MPN) (number / 100 mL).

4.2.5 Water quality results for 2020 (after Build 1)

A comprehensive listing of these results is provided by Rawhani (2022). CW1 and CW2 were studied for treatment efficacy following the removal of hard Covid-19 lockdown restrictions. Both CW1 and CW2 were observed to have been used, although not extensively. These are shown in Tables 4.3 and 4.4.

Table 4.3. Water quality results at the inlet and outlet of CW1, CW2 and the Jukskei river upstream and downstream of Alex for the period September to December 2020 (weekly samples).

Parameter	Constructed Wetland 1	Constructed Wetland 2	Jukskei River+
Mean COD inlet (mg/L)	3937	3503	61
Mean COD outlet (mg/L)	3063	3580	70
P (t.test)	0.0691*	0.8104	0.0034**
Mean ORP in (mV)	-204	-316	61
Mean ORP out (mV)	-302	-329	-44
P (t.test)	0.0000**	0.3130	0.0439**
Mean E.C. in (µS/cm)	2761	2480	420
Mean E.C. out (µS/cm)	3279	3269	542
P (t.test)	0.1844	0.0255**	0.0007**
Mean E.C. in (µS/cm)	2761	2480	420
Mean E.C. out (µS/cm)	3279	3269	542
P (t.test)	0.1844	0.0255**	0.0007**
Mean pH in	7.17	8.24	7.89
Mean pH out	7.91	8.36	7.52
P (t.test)	0.0054*	0.3590	0.0036**
Mean *E. coli* in (MPN)	1.14E+10	4.28E+08	1.82E+07
Mean *E. coli* out (MPN)	3.58E+09	1.59E+08	2.11E+09
P (t.test)	0.1498	0.1130	0.0011**
Mean Total coliform bacteria in (MPN)	1.41E+11	8.04E+10	2.88E+08
Mean Total coliform bacteria out (MPN)	2.30E+10	8.08E+09	2.73E+10
P (t.test)	0.0703*	0.0177**	0.0115**

+For the Jukskei River, in samples were taken at London Road bridge, and out samples were taken downstream of Marlboro Road bridge
*Significant at 90% confidence
**Significant at 95% confidence

The data indicate varying degrees of remediation in both wetlands for various variables (Table 4.3), with a factor 10 reduction of indicator bacteria, though outflow concentrations were still very high. CW1 was better at removing COD, whilst CW2 was better at removing coliform bacteria. The lack of flow measurement, however, was, and continues to be a limitation for the interpretation of the results as removal rates are always dependent on flow. Regarding other chemical variables, significant removal of phosphate concentrations was observed in both wetlands (Table 4.4).

Table 4.4. Changes in concentrations of selected inorganic variables from inlet to outlet in CW1 and CW2 between September and December 2020

Variable (all in mg/L)	Constructed Wetland 1	Constructed Wetland 2	Jukskei River+
Mean F^- in	16	81	No value
Mean F^- out	19	35	16
P (t.test)	0.5992	0.2347	#
Mean Cl^- in	156	1077	25
Mean Cl^- out	151	69	44
P (t.test)	0.4547	0.3686	0.6590
Mean NO_3^- in	384	1	23
Mean NO_3^- out	1	28	12
P (t.test)	#	0.4920	0.3150
Mean NO_2^- in	446.43	4005.26	32.92
Mean NO_2^- out	157.90	64.86	13.43
P (t.test)	0.0990*	0.3931	0.3150
Mean PO_4^{3-} in	59.62	38.32	#
Mean PO_4^{3-} out	16.52	7.48	21.86
P (t.test)	0.0253**	0.4527	#
Mean SO_4^{2-} in	113.52	392.41	48.60
Mean SO_4^{2-} out	187.83	123.89	58.32
P (t.test)	0.5242	0.1333	#

+For the Jukskei River, 'in' samples were taken at London Road bridge, and 'out' samples were taken downstream of Marlboro Road bridge
*Significant at 90% confidence
**Significant at 95% confidence
#Insufficient data for statistical analysis

There is considerable uncertainty with both sets of data (Tables 4.3. and 4.4.). This was caused by security concerns (on some days it was felt to be too unsafe to enter and sample), analytical uncertainty (the University of the Witwatersrand was shut despite the lifting of lockdown restrictions and accessing a lab was not always possible) and sample uncertainty (the variability of the data was too large and thus dilution ratios for analysis could not always be correctly determined prior to sample depletion). Notwithstanding this uncertainty, the trends of the data indicate that the CWs were functioning. In particular, the redox potential was found to be either strongly negative or became negative. This correlated with sulfate reduction in CW1 and CW2 and this indicates that both CWs were working hard. The deteriorating quality of the Jukskei River as it passes s'Swetla and other settlements is indicative of the pressure placed on the river – despite natural turbulence, the river progressed from an oxidative to reducing state indicating extreme loading in this portion. As a result of the uncertainty, further sampling was conducted.

4.3 CW1 PHASE 2 WATER QUALITY OBSERVATIONS

At the end of 2021, a sewer (which the community has no access to, but which transmits sewage from Marlboro Gardens uphill of Silvertown) blocked and flooded our CW areas. This large-scale sewage discharge occurred for a period exceeding 12 weeks. The extended CW1 had an integrated flood protection wall and thus withstood this pressure. The extended CW2 was unfortunately flooded and clogged entirely with settled night soil. As a result, they were abandoned. Thus, sampling occurred only on the extended CW1. The location of the sampling points is shown in Figure 4.8.

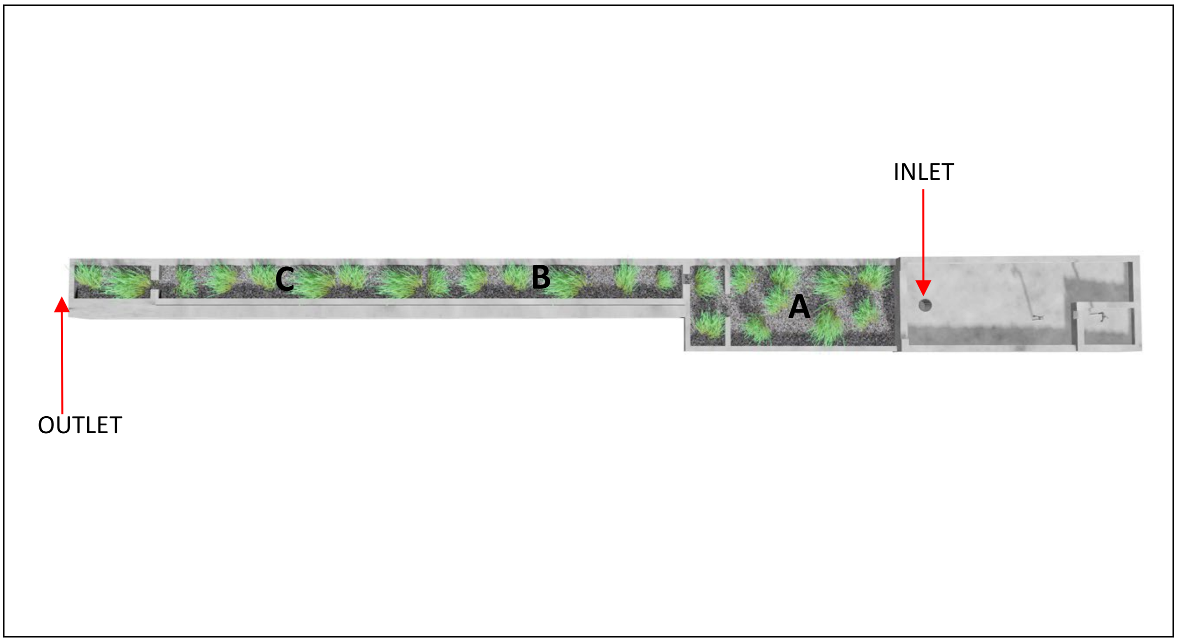

Figure 4.8. Sample locations for the extended CW1 for the second phase of monitoring, after Build 2. Sample points A, B and C indicated on the diagram.

4.3.1 Sampling procedures

Water samples were collected from the inlet and outlet and three intermediary points of the extended CW1 after the reconstruction in Build 2. The constructed wetland was divided into 3 sections namely; A (the middle of previous CW1A, after the inlet sampling point), B and C with C being the area just before the outlet sampling point (Figure 4.8). Six sampling campaigns were conducted in 2022. These were:

- 28 March to 1 April;
- 20 to 22 May;
- 20 to 24 June;
- 1 to 5 August;
- 5 to 9 September; and
- 17 to 21 October.

In each sampling campaign, samples were taken twice (1-hour interval) in the morning between 8:30 and 10:00 am for 5 consecutive days. Nitrile gloves were used in the sampling procedure to maintain hygienic standards and reduce any possible contamination from the sampler's hands (especially for microbiological samples). 50 mL water samples were taken at 0.05-15 m depth at each point A-C of the CW. 150 mL water samples were taken from the inlet and the outlet points. All samples were kept and transported at 4°C to the laboratory before analysis. Samples that were not immediately analysed were filtered and kept in the freezer at -20°C overnight.

For microbial samples, the following sampling procedures were used

- Samples were extracted from each sampling point using a sterile plastic syringe.
- Sterile 50 mL polypropylene bottles were used to collect microbial water samples.
- Samples for physiochemical analyses were collected in 500 mL polyethylene plastic bottles. Each bottle was rinsed three times with the water that was to be sampled before finally filling the sample bottle and securing the lid tightly.
- The sample bottles were stored in a cooler box to maintain a consistent and low temperature of the sample between sampling in the field and analysis in the laboratory. All samples (as collected from the field) were immediately analysed in the laboratory.

4.3.2 Water quality analyses

*E. coli (*Faecal indicator bacteria (FIB)) and Total coliform are widely accepted indicator organisms for routine monitoring of domestic water. *E. Coli* and Total Coliform bacteria were analysed using Idexx Colilert-18/Quanti-Tray method following the manufacturer´s protocol, and the results were recorded as most probable number (MPN) (number / 100 mL). The Colilert-18/Quanti-Tray method for detecting total coliforms and *E. Coli* is done according to ISO 9308-2:2012.

Some physiochemical variables were analysed in the field on the inlet and the outlet water samples. Those were pH, electrical conductivity (EC) and Redox Potential (ORP) and they were measured using a pre-calibrated Hannah Instruments HI98195 Multiparameter PH/ORP/EC/Pressure/Temperature Waterproof Meter. The instrument was used, calibrated and maintained according to the manufacturer's specifications.

All other chemical analyses were carried out on water samples filtered through Whatman Glass microfiber filters CAT No. 1820-047 in the laboratory. The following variables were analysed and recorded in concentrations (mg/L) using Merck Pharo 300/600 Spectroquant. Samples were first prepared according to the respective Merck test kits instructions given below before being analysed.

- Chemical Oxygen Demand (COD) – Merck test kit 1.14540
- Sulfate (SO_4^{2-}) – Merck test kit 1.01812
- Nitrate-N (NO_3^- N) – Merck test kit 1.09713
- Phosphate-P (PO_4^{3-} -P) Merck test kit 1.14842
- Ammonium-N (NH_4^+-N) – Merck test kit 1.00683

All results from field measurements and laboratory analyses were recorded in the researchers' field diary and later transcribed into Microsoft Excel.

4.3.3 Water quality results and discussion

In 2022 after the Build 2 phase, the extended CW1 and the new washing area at the inflow 1 was used a lot (discussed in section 5.4.3.2). Consequently, the CW received a high and irregular hydraulic load of both wastewater buckets from the homes and laundry water from the washing area. It is likely that, from an engineering point of view, the CW1 treatment system was heavily overloaded after the extension, as also indicated by the redox potential drop from the inflow to strongly reducing condition in the outflow water (Table 4.5). Overall, there was no difference in concentrations between inlet and outlet water, suggesting little removal of compounds in the wetland. However, this may be a misinterpretation as evidently there was microbial activities going on leading to the anaerobic conditions. The water quality monitoring setup, with two morning sampling rounds with an hour pause in between, resulted in biased samples from the CW inlet. The intense washing activity in the mornings resulted in inlet water samples that were heavily affected (diluted) by the laundry and rinsing water. As shown in Figure 4.9 and 4.10, samples taken at point A were probably better representations of the actual type of inlet water disposed of in the wetland during a full 24-hour cycle. Interestingly though, the alkaline laundry water resulting from the use of detergents was partly neutralized by the wetland processes, with a one-unit lower pH at the outlet (Table 4.5).

Table 4.5. Mean water quality in the inflow and outflow of CW1 in 2022, sampled on average twice per day for five consecutive days once per month for six months in 2022.

Mon		Tot. Coli	*E. coli*	COD	TSS	NO_3^--N	NH_4^+-N	PO_4^{3-}-P	SO_4^{2-}	pH	Redox (mV)
				----------------------	mg/L		------------------------				
Mar	IN	5.64E+07	1.53E+06	199	345	1.6	n.a.	4.6	n.a.	8.9	-3
	OUT	5.78E+07	2.40E+06	430	359	1.5	n.a.	3.4	n.a.	7.5	-163
May	IN	5.32E+07	8.33E+05	712	265	1.7	12	14	211	8.7	120
	OUT	456E+07	7.14E+05	593	227	1.5	10	9.1	176	7.5	103
Jun	IN	1.21E+07	3.40E+06	592	216	1.5	7	5.8	207	8.6	100
	OUT	3.12E+07	2.51E+06	844	68	0.7	66	8.3	170	8.1	-84
Aug	IN	5.20E+06	1.57E+05	945	167	1.9	13	1.5	259	9.1	114
	OUT	2.07E+08	9.29E+06	874	183	1.3	57	5.4	271	7.8	-210
Sep	IN	2.30E+08	2.01E+06	486	175	2.4	19	4.1	199	8.9	35
	OUT	1.34E+08	1.58E+06	912	237	2.8	78	3.3	285	8.2	-197
Oct	IN	1.26E+08	3.18+E06	609	257	3.5	20	3.1	127	8.3	30
	OUT	2.38E+08	7.34E+06	658	183	3.2	63	2.5	166	7.6	-268
	IN	**8.06E+07**	**1.85E+06**	**587**	**233**	**2.1**	**13**	**5.5**	**219**	**8.8**	**73**
	OUT	**7.15E+07**	**1.59E+06**	**731**	**215**	**1.8**	**53**	**5.3**	**225**	**7.8**	**-110**

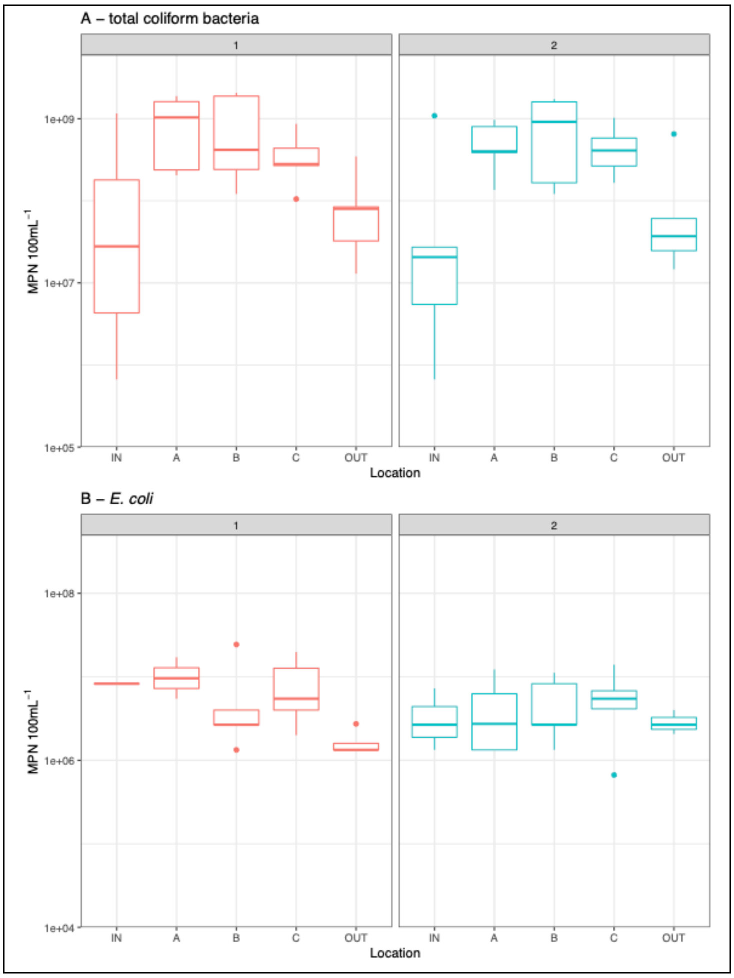

Figure 4.9. Microbial indicator counts from the IN-flow to the OUT-flow of CW1 in September sampling week. MPN for total coliform microorganism (A) and *E. coli* (B) displayed in logarithmic scale. The left-hand panel displays the early samplings and the right-hand panel the later samplings.

The water quality monitoring indicated that the concentrations of Total coliforms at the inlet section of the wetland were lower than the concentrations in the water sampled along the length of the wetland, and about the same as the concentrations in the outflow water (Fig. 4.10). The higher concentrations in point A-C are not surprising as the sampling methodology used resulted in a mixed sample composed of both the water flowing through the wetland and the microbial biofilm growing on the stones in the wetland. The same pattern was also seen for the concentrations of COD, inorganic nitrogen and phosphate-P (Fig 4.11). Higher concentrations in point B and C could also be caused by the fact that the inhabitants discharged greywater buckets from their homes directly into the wetlands at point B, affecting also the concentrations measured in point C.

The lower inlet concentrations were most likely caused by the fact (based on observations) that people were commonly washing their clothes during the sampling hours, thus a lot of rinse water was discharged into the wetland, diluting the inflow greywater. This reasoning is further supported by the results regarding sulfate concentrations in September the 7th. The concentrations for the first sampling were 10-20 times higher than in the tap water, suggesting the source was sodium sulfate, which is commonly used as a filler in laundry detergents. By the time of the second sampling, the concentration peaks had moved to the sampling points further downstream in the wetland (B, C and OUT).

When looking at the changes in water quality from point A to the outflow, the wetland removed some of the COD and phosphate-P, whereas the concentrations of ammonium-N rather increased from point A to the outflow. This would be consistent with decomposition of organic compounds (measured as COD) containing nitrogen, which was released as ammonium-N. The strongly reducing conditions in the wetland (redox levels dropped from 35 mV in the inlet to < -197 mV in the outlet) would explain why we did not detect a corresponding formation of nitrate-N.

In contrast to this general pattern of higher concentrations within the wetland than at the inflow and outflow, the *E. coli* values were relatively stable along the transect. As mentioned above, the samples from A-C included the microbial community growing on the substrate in the wetland. Hence this suggests that the heavy load leading to strongly reducing conditions in the wetland may have favoured survival of *E. coli*.

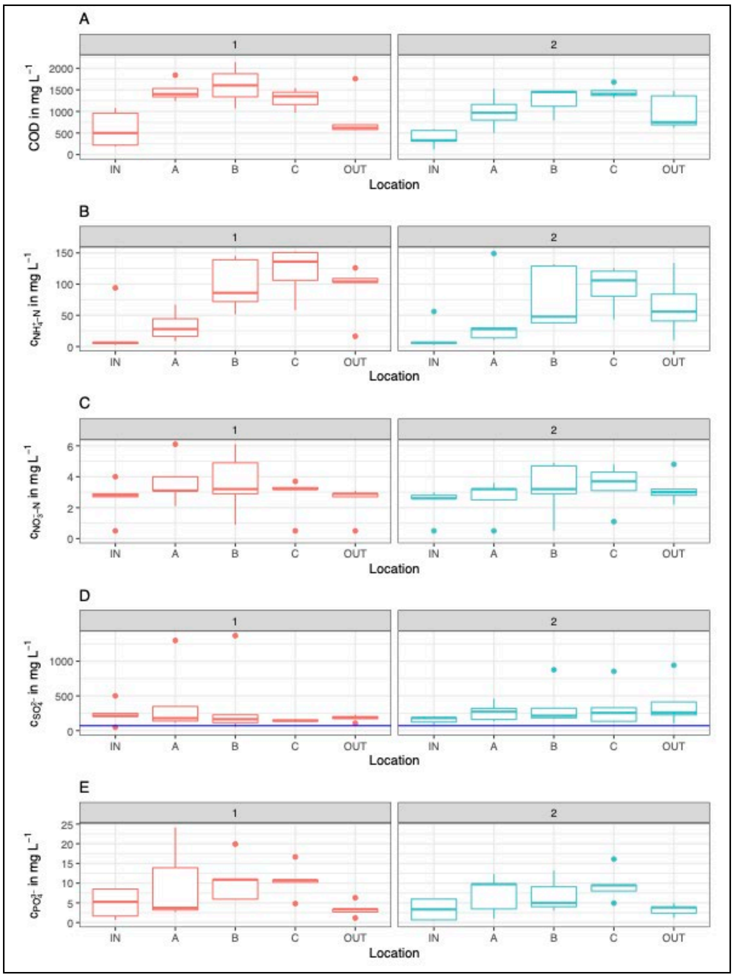

Figure 4.10. Water quality results from the IN-flow to the OUT-flow for CW1 in the September sampling week (5*2 sampling occasions). Concentrations of chemical oxygen demand, COD (A), ammonium-N (B), nitrate-N (C), sulfate (D) and phosphate-P (E). All outlier results values in panel D were detected in water sampled on 7 of September.

CHAPTER 5: WORK PACKAGE 4 – SOCIO-ECONOMIC STUDY OF ACCEPTANCE AND USER EXPERIENCES WITH WETLAND-BASED GREY-WATER MANAGEMENT

5.1 INTRODUCTION

Access to safe wastewater disposal infrastructure in informal settlements is widely lacking, jeopardizing human and environmental health. The density of settlements, in addition to other land use, governance, and financial characteristics, often make it challenging to implement conventional centralised grey and black water infrastructure. There are however alternatives being tested. Work package 4 was responsible for initiating a relationship with a community that was receptive to working with the research team, as well as for assessing past projects and current socio-technical context at multiple organisational scales to facilitate the building and use of greywater treatment systems (Figure 5.1). We utilised multiple data collection, co-creation, and analysis methods to provide insights to other work packages, the practitioner and residential actors we worked with, and the wider academic community. More details on methodology and results can be found in Thatcher et al. (2022), Todd et al. (in review), Metson et al. (in prep), and the research reports for Boitumelo Malunga (Masters research report, University of the Witwatersrand), Ayomide Eyitayo-Ajayi (Masters' research report, University of the Witwatersrand), and Andiswa Mathebula (Masters' dissertation, Rhodes University).

Ultimately, we found that a process that did not focus on early co-design, but rather continuous engagement centred on 'editing'/re-building/removing' built greywater management systems was more fruitful. We refer to this as an iterative design process (Chapter 3). Multiple pressures and (competing) goals operating in a small space meant that the physical context and use of wetlands changed rapidly. Trying to build a system that was more multi-functional (thinking of collection, washing, and channelling multiple types of water) resulted in more use (building phase 2 and 3).

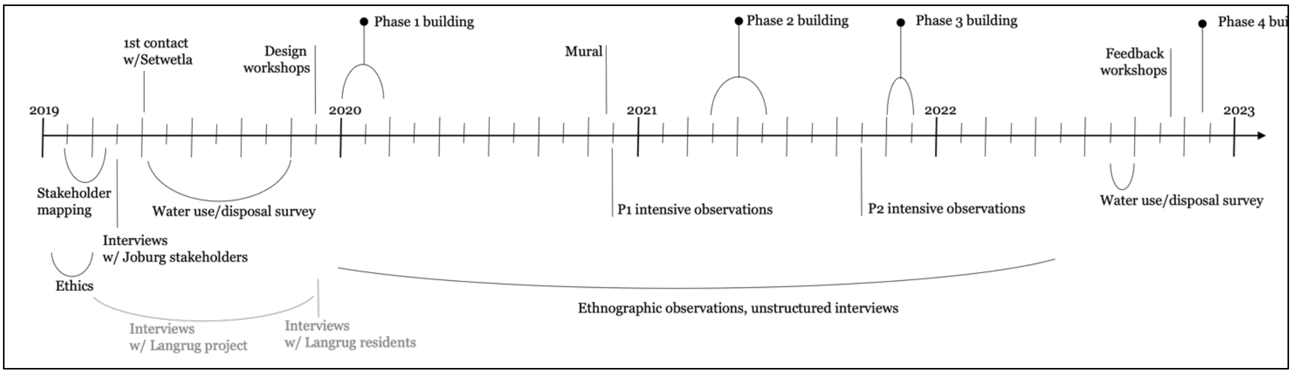

Figure 5.1. Engagement timeline for the greywater treatment project in s'Swetla

5.2 LANGRUG SYSTEM REVIEW

One example of a greywater treatment wetland in an informal settlement was the Genius of Space project which was implemented in the Langrug community near Franschhoek in the Western Cape, South Africa. From 2013 to 2017 diverse stakeholders worked together to install a series of disposal points, tree gardens, and a retention pond/constructed wetland to deal with wastewater in part of the community. It was the intention of visiting the Genius of Space system in Langrug to assess the system treatment efficacy and community use, perceptions and assessment of the system and use this information to inform the design for URBWAT. However, upon visiting the site, it was clear that the Langrug system was not operational. No plants were living in the wetland, many of the community disposal points were dysfunctional and the trees in the tree wells were also dead. Based on these observations it was not possible to use the Genius of Space system for URBWAT inspiration. Instead, we decided to try and learn from the Genius of Space system what might have gone wrong.

To evaluate the outcomes of the Genius of Space project and gather lessons learnt, we conducted two week-long site visits, reviewed project documents, interviewed 12 experts involved in the project, and conducted 33 oral surveys with residents in April and November 2019. We then coded these materials using Ostrom's (2007) common pool resource governance framework for understanding Socio-ecological systems. The project as a whole was viewed as a partial success (engagement with the community) and as a failure (environmental outcomes weren't met, and the project was never fully implemented to provide revenue for maintenance) by the implementation team. For residents, success was mostly tied to the system's capacity to drain wastewater away from dwellings and drains not getting clogged. Although never intended to become a common pool resource that needed to be managed by the neighbourhood, the disposal point system has become a common infrastructural good. It is however not managed as one system. Three types of disposal point management emerged: 1) closed/broken; 2) fenced-in and managed by individual households; or 3) kept on communal land and used by many households (Figure 5.2). All three outcomes were decisions made together with neighbours and were tied to very different neighbour relationships. 'Failures' were often not failures but rather a decision that, given how people were using a disposal point, made sense to close or restrict use. 'Successes', where a disposal point was kept open, still came with conflictual use behaviours. Ostrom's (2007) common pool resource governance has not often been applied to greywater management and we found it to be a helpful framework as it allows us to not only to reconceptualize 'the community' or 'infrastructure', but also understand why different outcomes for one system could emerge within just a few metres of each other. In such a dense and rapidly changing context common pool resource decisions may be happening at very small spatial scales.

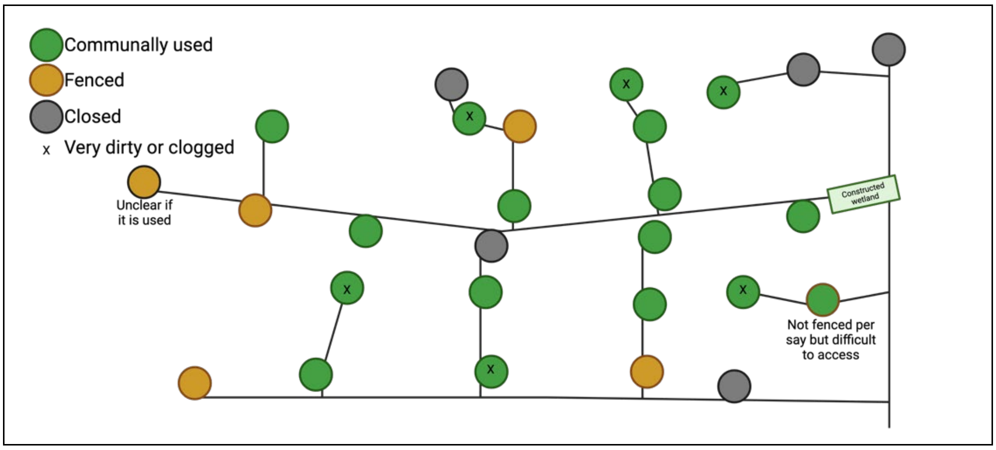

Figure 5.2. Working status of disposal points for alternative greywater disposal system in Langrug in November 2019. Each circle is a disposal point, where the colour indicates if it is communally used, fenced, or closed. 'X' denotes communally used disposal points that were clogged.

5.3 STAKEHOLDER ANALYSIS: S'SWETLA INFORMAL SETTLEMENT

5.3.1 Initial stakeholder mapping process

Following from the investigation of the Genius of Space system, we explored the possibility of identifying a project site in an urban informal settlement. A potential site to the North of Alexandra Township was identified and a stakeholder mapping process was conducted. Initially a total of fifteen stakeholder groupings were identified at six levels of influence (Figure 5.3). At the level of direct interaction with the greywater treatment system, stakeholders included community residents and the URBWAT research team. These direct interaction 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 departments, Johannesburg Water, Pick It Up), regional (i.e. respective provincial departments responsible for water, sanitation, housing, and infrastructure), and national (i.e. respective national departments) level. 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 community residents. Long-term community 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 community 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.

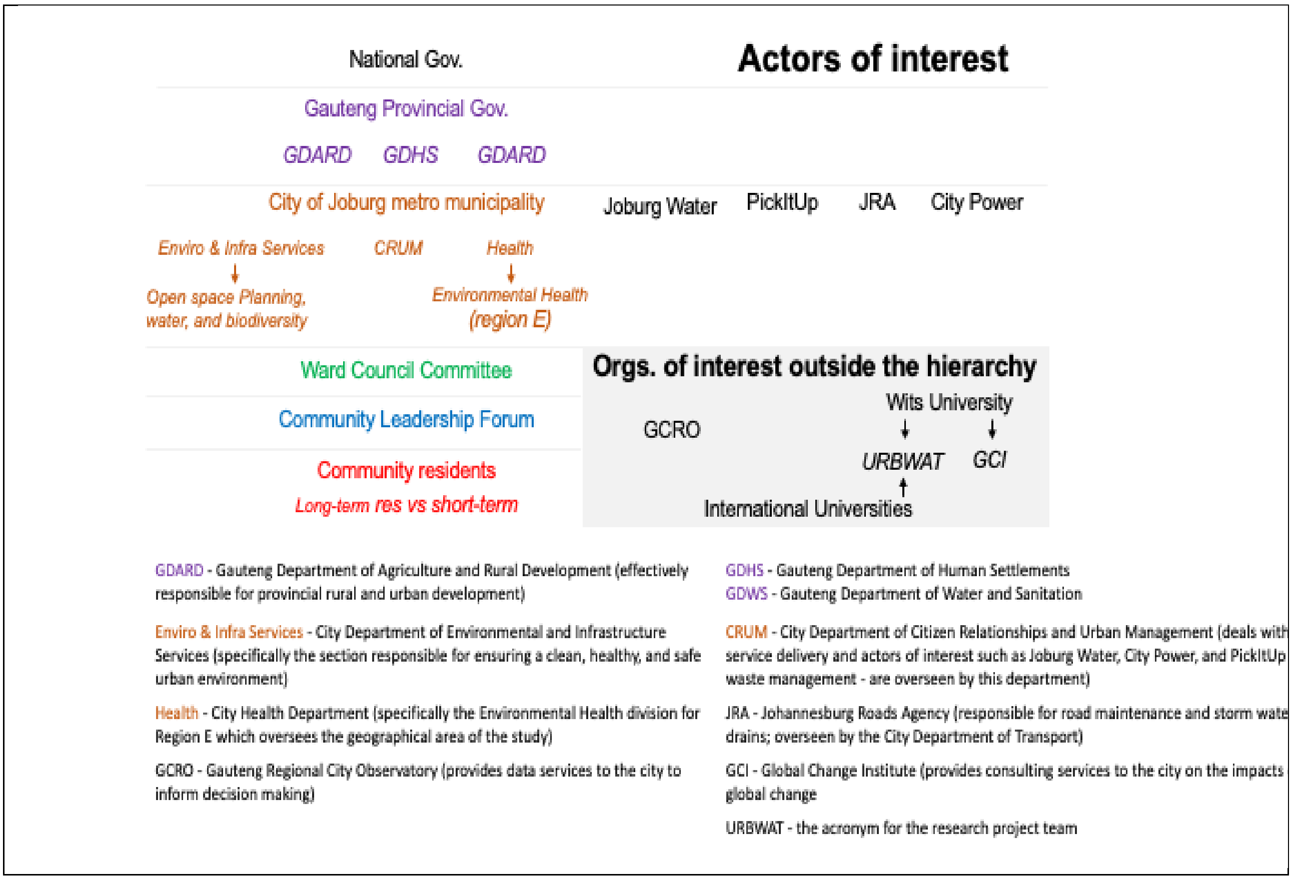

Figure 5.3. Stakeholder map for a potential greywater treatment system in s'Swetla

5.3.2 Stakeholder interviews to determine roles/goals

Formal individual and group interviews were conducted with eight stakeholder types in April 2019. Not all stakeholder groups were deemed directly relevant to the implementation of greywater infrastructure (e.g. Johannesburg Roads Agency City Power, or the Global Change Institute). 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 were held with other stakeholder actors of interest (i.e. Gauteng City Regional Observatory; Joburg Water). One group interview was held with the Community Leadership Forum. An individual interview was conducted with the Ward Councillor. The goals of the six main stakeholders (i.e.

community residents, Community Leadership Forum, Ward Council, City of Johannesburg, Gauteng Province, and the URBWAT team) were mapped to identify overlapping goals and possible competing goals (Figure 5.4). It was obvious, even at this early stage, that the problem of greywater infrastructure was not a primary concern for most stakeholders (i.e. only the URBWAT team identified greywater infrastructure as a goal).

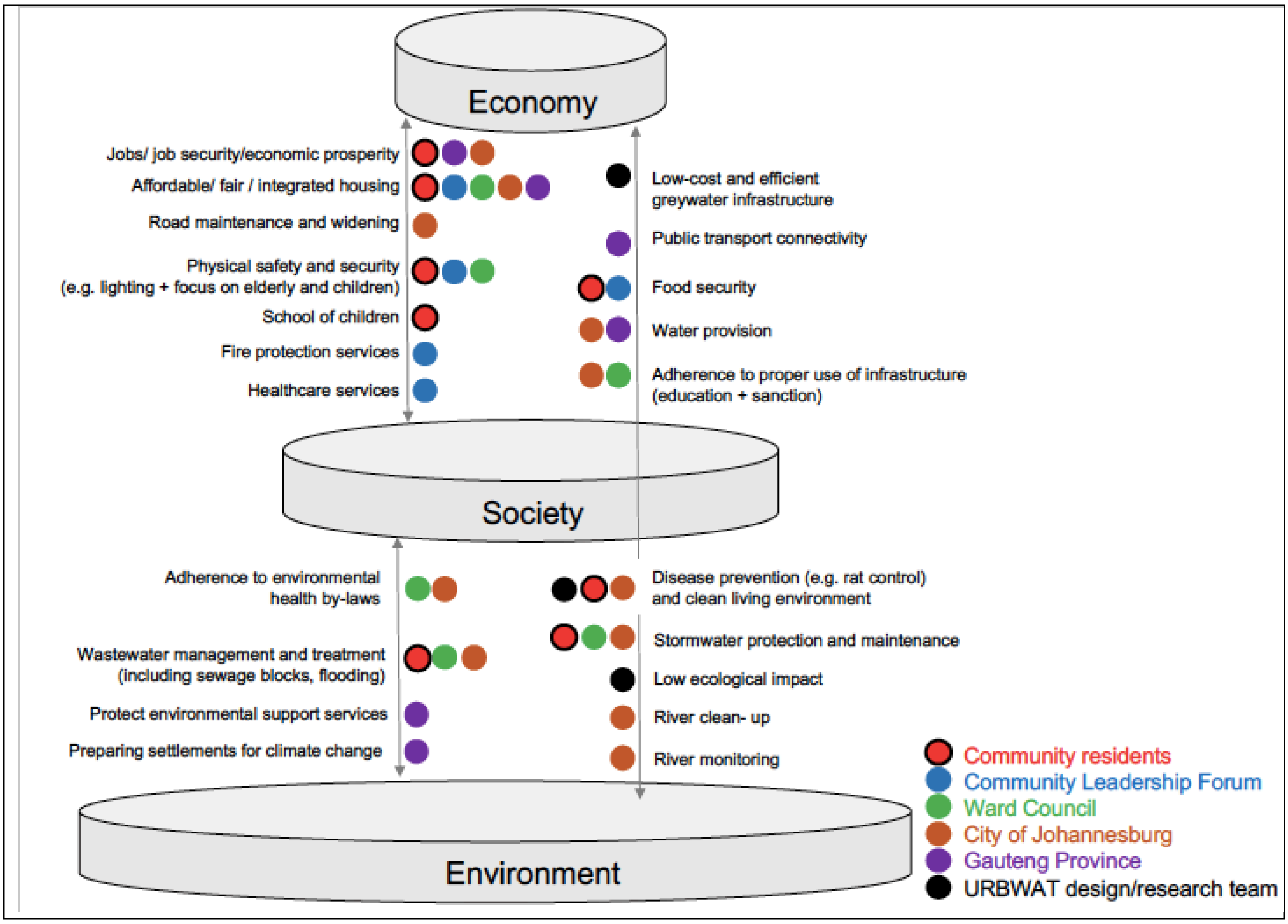

Figure 5.4. Goals of the six mapped stakeholder types interviewed in the early phase of the URBWAT project.

For the community residents in particular, issues such as job prospects, affordable housing, physical safety, blackwater sanitation (especially flush toilets), and stormwater protection were perceived as far more urgent issues than the relative unimportance of greywater infrastructure. This highlighted the fact that for the URBWAT project to gain traction in s'Swetla (and with other stakeholders) would therefore involve significant community awareness of the problem and/or incorporating some of these other goals into the greywater treatment infrastructure systems.

The stakeholder analysis also allowed us to develop good contacts in the community, initially through the s'Swetla Community Leadership Forum and then through other community leaders in various areas of s'Swetla. The Community Leadership Forum was very supportive of an intervention, despite greywater removal and/or treatment not being a primary goal. During the stakeholder analysis, community leaders took the project team on several walkthroughs of the area showing the *ad hoc* greywater removal systems that residents had constructed as well as the impact of greywater on the Jukskei River.

5.4 CONTEXTUAL ANALYSIS OF S'SWETLA

5.4.1 Water Use Survey

To understand the greywater issue in s'Swetla, a water use survey was developed to obtain a baseline understanding how water was collected, used, and disposed. The survey was adapted from a questionnaire by Howard et al. (2002) who originally assessed water usage in low-income urban communities in Uganda. Their survey was more concerned with water collection and use rather than water disposal. The water use 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 (and paid) enumerators from s'Swetla and a purposive sampling strategy aiming to acquire at least 20 surveys per demarcated area in s'Swetla. The demarcated areas were those assigned by the residents (Figure 5.5). The enumerators were themselves residents of s'Swetla and were therefore known to other residents and spoke several of the languages commonly spoken in s'Swetla. 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". The majority of respondents to the survey were female (62%), who spoke Sepedi (35%) or Xitsonga (31%), although there was also a wide variety of languages spoken. Nearly half the sample (48%) had less than a matriculation certificate, while a further 33% only had a matriculation certificate. Surveys were obtained from all demarcated areas in s'Swetla with a large proportion (32%) coming from a densely populated area known as Xitshoba and only 8% coming from the area where we eventually built; Silvertown.

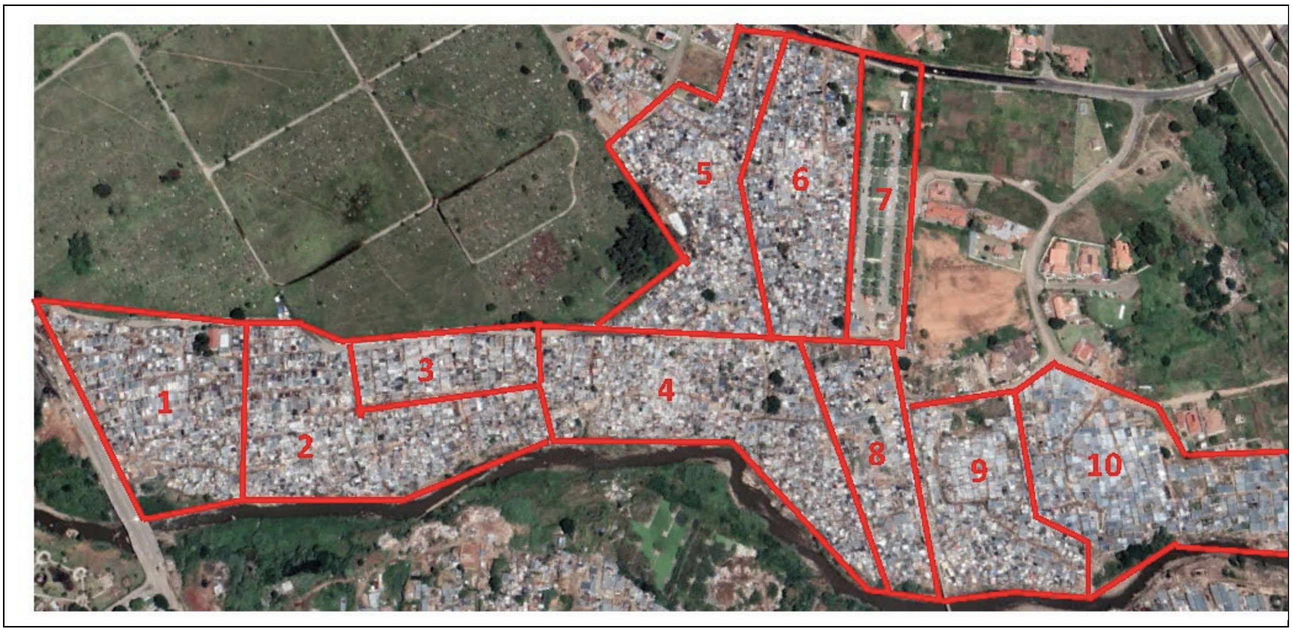

Figure 5.5. Portions of s'Swetla: 1= Bridge; 2 = Giyani; 3 = Mazinyo; 4 = Old s'Swetla; 5 = Xitshoba; 6 = Mashemong; 7 = Greenhouse; 8 = New Stand; 9 = Silvertown; 10 = Maponyane (Maponyane was called "Island" in 2019 at the time of the survey and consisted of only a few shacks)

5.4.1.1 Water collection

From Table 5.1 it can be seen that most respondents collected their water from a communal stand-pipe tap (93%). It was important to note that no respondents collected their water from the river, even though this was offered as one of the options in the survey. Residents were apparently well-aware that the river water was not fit for human use.

Table 5.1. Primary source of water collection in s'Swetla in 2019

Primary water sources	Frequency	Percentage
Not stated	5	2.2
Communal stand-pipe tap	212	93.0
Community centre	3	1.3
From neighbours at a cost	3	1.3
From neighbours without cost	2	0.9
Other public space (e.g. water container)	1	0.4
Tap outside building	2	0.9
Total	228	100.0

Most respondents collected their water close to their dwelling (Table 5.2), with a surprisingly large proportion of respondents (24.6%) having water piped directly into their dwelling. Most of the connections into a dwelling would be considered "illegal" by the municipality who installed the communal taps but were a fairly common occurrence. Only a small proportion of respondents (3.5%) went a considerable distance to collect their water. These would usually be respondents who were building a dwelling in a new area.

Table 5.2. Distance of dwelling from the primary water source in s'Swetla in 2019

Distance from respondent's house	Frequency	Distance from respondent's house
Not stated	18	7.9
Few dwellings away	115	50.4
Inside the dwelling	56	24.6
Short distance	31	13.6
Long distance	8	3.5
Total	228	100.0

Most respondents (82%) (Table 5.4) collected water in 25 L containers (Table 5.3). The 20 L containers were frequently recycled containers (previously paint or pool chemical containers). Smaller containers were used when washing cooking utensils or smaller household objects. It should also be mentioned that the containers listed in Table 5.3 refer only to water that was transported away from the primary water collection source. In addition to containers that were carried away, larger containers (40-80 L) were used to wash clothes, shoes, carpets, and linen very close to the water collection site. These larger containers were usually too heavy to carry once filled with water.

Table 5.3. Containers used for water collection in s'Swetla in 2019

Size of Containers	Frequency	Percentage
Not stated	15	6.6
5 L	4	1.8
10 L	15	6.6
20 L	186	82.0
25 L	7	3.1
Total	228	100

Table 5.4. Frequency of water collection among s'Swetla residents in 2019

Frequency of water acquisition	Frequency	Percentage
Not stated	10	4.3
Once a day	114	50.0
Twice a day	92	40.4
Once every two days	4	1.8
Only when needed	3	1.3
Once a week	1	0.4
Other	3	1.2
6 times a day	1	0.4
Total	228	100.0

5.4.1.2 Water use

The purposes for which the collected water was used is shown in Table 5.5. The water that was collected was used for bathing (96.6%), drinking (95.6%), cooking (95.2%), laundry (94.7%), cleaning the household (89.9%), and cleaning "chimbas" (78.5%). A "chimba" is the local name for a chamber pot or night bucket, where residents collect their nightsoil rather than risk their safety by going to one of the portable toilets at night. The large proportion of respondents indicating that they used collected water to clean chimbas suggests that there is a significant risk that greywater will contain some blackwater. Collected water is very infrequently used for watering vegetables or other plants (6.1%) or for pets (0.9%). A variety of soaps and detergents were used in the laundry, bathing, and household cleaning activities. The laundry products were usually a variety of washing powder brands, although antibacterial liquids are sometimes used. The bathing products were usually a variety of bathing soap brands, although again there were a fair proportion of respondents (10.5%) who indicated that they used antibacterial liquids when bathing. Household cleaning involved the widest range of cleaning products including washing powder brands, soap brands, but also bleach brands (14%), and antibacterial liquids (2.6%).

Table 5.5. S'Swetla residents´ uses of collected water in 2019

Purpose	Frequency	Percentage
Cooking	217	95.2
Household cleaning purposes	205	89.9
Drinking	218	95.6
Laundry	216	94.7
Bathing	221	96.6
Gardening	14	6.1
Water for animals	2	0.9
Cleaning chimba	179	78.5

5.4.1.3 Water disposal

Given that there were no formal means of disposing of wastewater, the most common methods for the disposal (Table 5.6) were into the street (39.5%) or into makeshift drains (30.7%). Makeshift drains could vary quite considerably (see Figure 5.6 for examples of makeshift "drains"). They were usually used as disposal points that directed the wastewater towards the river mostly overground. In some instances, there were also makeshift pipes underground. Those disposing wastewater in front of their house (5.2%) were effectively also disposing of water directly into their living environment. Those respondents who lived close to the river disposed of their wastewater there (12.3%). Throwing wastewater into stormwater drains (7%) had the same effect as disposing wastewater into a makeshift drain as this was also directed towards the river.

Table 5.6. Location of wastewater disposal in s'Swetla in 2019

Location of wastewater disposal	Frequency	Percentage
Not stated	33	14.5%
In front of the house	12	5.2%
In the street	90	39.5%
Into makeshift drainage	70	30.7%
Into stormwater drains	16	7%
Into portable toilets	5	2.2%
Watering plants/vegetables	1	0.4%
Into the river	28	12.3%

Figure 5.6. Three of the different types of makeshift “drains” found in S’Swetla.

5.4.2 Design workshops

Following best-practice (e.g. Turnhout et al., 2020), it was the original intention of the user-centred participatory design process to hold design workshops where the URBWAT could work together with the s’Swetla community to co-design solutions to their greywater disposal problem. The six design workshops, each focusing on a different section of s’Swetla, were held in October and November 2019. Each workshop consisted of between 12 and 20 participants. The core principles of the design workshops established by the URBWAT project 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 or modifying any implemented system that was unsuccessful. During the workshop, participants worked in groups of 3-4 to draw their current living conditions with respect to water collection and wastewater disposal. Next the groups drew their imagined, ideal water collection and wastewater disposal situation. Finally, each group presented their drawings and the advantages, disadvantages, and feasibility of each option to the rest of the group. These suggestions were then discussed by all the groups in each workshop. The final stage of each workshop involved the participants taking us to their respective sections of s’Swetla to show us what they had drawn. This stage of the design workshop also allowed the URBWAT research team to identify possible areas where there was sufficient space to build.

Without exception, the workshop participants requested the installation a formal sewer system or a piped removal system (Figure 5.7). Unfortunately, this was beyond the scope of the URBWAT project (to implement a low-cost, nature-based solution) and not physically possible given the densely packed dwellings. During each design workshops we therefore presented the concept of a constructed wetland (CW) to the participants and discussed the feasibility of this option. Instead of a co-design process where the final solution is agreed upfront, we decided to embark on an iterative participatory process of design-build-evaluate-design-build-evaluate with co-design activities occurring during the build and evaluation phases. At this point the URBWAT project team decided to continue with the CW implementation phase of the project.

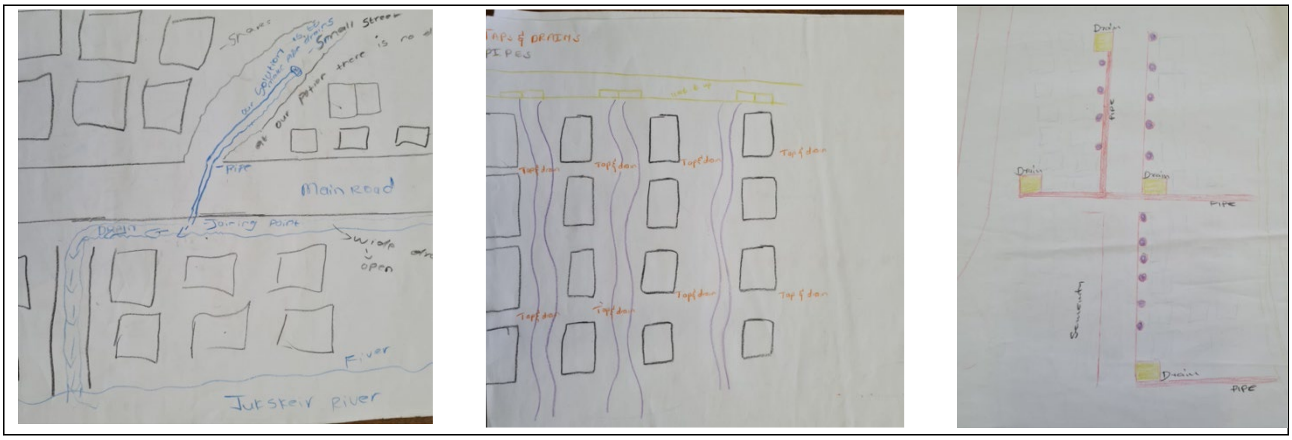

Figure 5.7. Examples of the s'Swetla design workshop drawings depicting different examples of an articulated drainage system.

5.4.3 Structured observations

5.4.3.1 Structured observations for Build 1

Build 1 consisted of two pilot systems that were constructed in March 2020 by residents selected by 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 process. The two CWs (CW1 and CW2) in Build 1 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), 10cm 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).

Once the two pilot constructed wetlands were built, community residents were given a chance to acclimatise to their presence. A structured activity analysis (Daniellou & Rabardel, 2005) was therefore conducted once residents had been given a chance to interact with the CWs. It was the intention to conduct the structured activity analysis three months after completing Build 1, but this became impossible due to COVID-19 lockdown restrictions that meant that the research site was inaccessible. The hand-over of the pilot CWs to the residents in Build 1 happened three days before the country went into a six-week total lockdown (March 2020) and we were only able to regularly access the research site again for human interactions from September 2020.

The structured activity analysis observations for Build 1 occurred at three sites (Figure 5.8). Two were CWs (CW1 and CW2), and their associated taps, and one was a communal tap (Site 3) with no CW but had been identified as a potential future CW site with community interest in building one. The structured activity analysis was conducted over three days (Friday to Sunday) in December 2020. The activity analysis included observations of the two pilot constructed wetlands and a planned site for a constructed wetland. 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, a breakdown of the specific activities undertaken at each site, and the stance of the residents while they were undertaking their activities. Observers worked for half a day and rotated between observation sites to reduce fatigue. In total, 153 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. The activity analysis included note-taking of any other observed behaviour that might influence the future design of the CWs. This included short conversational dialogues with residents to better understand their behaviours at the CWs.

From the structured activity analysis, it was apparent that most of the activities took place at Site 3 (the non-CW site) (Table 5.7). During the observation period the tap at CW1 was broken which explained why no water collection or washing behaviours were observed. It would appear that the activities that would normally take place at the tap next to CW1 had shifted to Site 3 where the taps were functioning. Most activities were conducted by women who were either young adults or middle-aged adults (Table 5.8). The volume wastewater disposed of was clearly much higher at site 3; at CW1 and 2 a considerable proportion was disposed of next to the wetlands rather than into them (Table 5.9).

Table 5.7. Build 1 activity type in relation to the use of sites with (CW1 and CW2) or without (Site 3) constructed wetlands for greywater treatment in s´Swetla in December 2020.

Site	Total Use	Collection	Washing	Disposal
CW1	5	-	-	5
CW2	20	9	1	10
Site 3	128	61	37	30

Table 5.8. Build 1 demographics of the people conducting activities at sites with (CW1 and CW2) or without (Site 3) constructed wetlands for greywater treatment in s´Swetla in December 2020.

		CW1	CW2	Site 3
Total Observations		5	20	128
Gender	Male	2	7	48
	Female	3	13	80
Age Group	Adolescent		2	26
	Young adult	4	12	62
	Middle aged	1	4	28
	Elderly		2	12

Table 5.9. Build 1 volume of containers when disposing wastewater at sites with (CW1 and CW2) or without (Site 3) constructed wetlands for greywater treatment in s´Swetla in December 2020.

Site of disposal	Size of container	Total observations	CW Inlet	Next to CW	CW Outlet	Onto CW
CW1	</=10 L	5				
	20 L		2	2	1	0
	> 40 L	0 0 0	0			
CW2	</=10 L	14	2	3	0	0
	20 L		4	5	0	0
	> 40 L					
		Total observations	**Drain at tap**	**Below tap**	**Around tap**	
Site 3	</=10 L	68	7	1	1	
	20 L		46	0	1	
	> 40 L		9	2	1	

Figure 5.8. Example of the Build 1 CW set up.

Static stooped postures with a flexed spine (with and without trunk rotation) are associated with increased risk for the development of lower back disorders (Marras, 2000; Davis and Jorgensen, 2005). The structured activity analysis therefore paid careful attention to the postures adopted while carrying out the various activities. Where permission was granted from residents, photographs were taken side-on (Chaffin et al., 2006) allowing for a clear record of the posture adopted while performing tasks. It was the intention of the URBWAT research team to make the CWs easier to use and therefore the results were aggregated across all activities, not just the disposal activities. The postures were divided into two categories for Build 1; more stooped (the body was flexed beyond 90 degrees) or less stooped (the body was more upright, at or less than 90 degrees) (Figure 5.9).

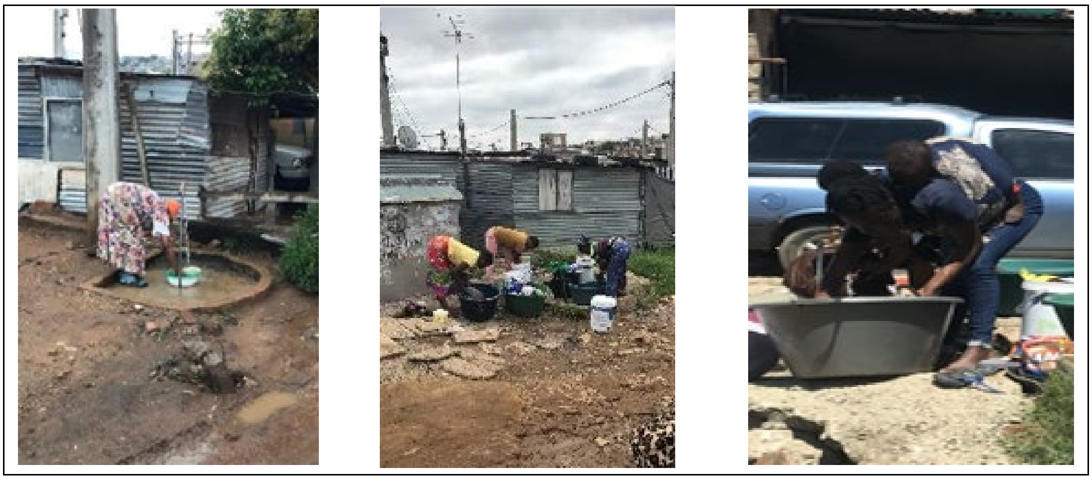

Figure 5.9. Examples of more stooped postures of washing tasks during Build 1.

The postures adopted during the Build 1 structured activity analysis are shown in Table 5.10. It was evident that residents at Site 3 were generally forced to adopt postures that were more stooped. At CW1 and CW2 approximately 40% of the residents adopted a more stooped posture. This was due to a combination of the relatively high instances of washing activities and the lack of raised areas for washing or disposing. Since the entry point to the CWs was raised, this might explain a less stooped posture when disposing wastewater at CW1 and CW2.

Table 5.10. Postures adopted for activities.

Posture	CW1 (N=5)	CW2 (N=14)	Site 3 (N=128)
More stooped	2	6	67
Less stooped	3	8	61

In summary, CW1 and CW2 were used infrequently. 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 L 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 which was typically next to the CW or the tap. The structured activity analysis informed several design changes to the CWs for the second iteration. These design considerations 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 behaviour change.
2. Physically connect the area where water was being used (and disposed of) to the CW inlet.
3. Raise the working space to reduce the need for a more stooped posture. This change would also create a slope, facilitating the gravitational flow of water into the CWs.

4. Widen the walls of the CWs and increase their height to better serve a dual purpose; acting as a physical barrier to stormwater flooding and an elevated pathway so that community members do not need to step in wastewaters.

As an additional measure, the URBWAT team contracted a local resident artist to design and paint a mural on the side of one of the shacks facing CW1 (Figure 5.10). The mural was intended to depict the disposal process into the CW. A mural was chosen because it didn't require any specific language or reading skills and because it served an aesthetic purpose in Silvertown.

Figure 5.10. Mural (and artist) showing the correct way for the CW to be used.

5.4.3.2 Structured observations for Build 2

Build 2 consisted of modifications and extensions of the two pilot systems from Build 1. Build 2 was constructed from March to April 2021 using the same materials and same processes (i.e. locally-sourced materials and labour). A different set of builders and labourers was used to try and diversify the skills development and the spread of jobs. CW1 and CW2 were both extended in length and a washing area was built to connect the taps directly to the CWs. In addition, supporting infrastructure was built to reduce the chances of washing water entering residents' dwellings and to direct stormwater and sewage away from household areas. In September 2021 a second structured observation took place over 7 days from a Tuesday to a Monday to capture behaviour on every day of the week. The same three sites were selected for observation. Six trained observers were used with three observers being postgraduate students and three were paid observers selected from the Silvertown community. All observers were trained in observation techniques and using the data observation sheet. Once again, the observers were rotated between sites and took rest breaks to reduce observer fatigue. A total of 498 behavioural observations were recorded over the observation period across the three sites.

From the structured activity analysis at Build 2 it was apparent that most of the activities still took place at Site 3 (the non-CW) site (see Table 5.11), although there was a considerable increase in the number (and proportion) of activities observed at CW1 and CW2. The most common activity at all sites was the collection of water, followed by the disposal of wastewater.

Most activities were conducted by women (although at CW2 there were more men than women who used this site, perhaps because it is situated away from the main communal areas frequented by women. The activity analysis at Build 2 combined the two adult groups because we had learnt previously that the vulnerable age groups were the younger and older residents. Once again, the adult group performed most activities at all three sites (Table 5.12). There were also a significant number of elderly and adolescents who used the three sites.

Table 5.11. Build 2 activity type in relation to the use of sites with (CW1 and CW2) or without (Site 3) constructed wetlands for greywater treatment in s´Swetla in September 2021.

Site	Total Use	Collection	Washing	Disposal
CW1	175	86	41	48
CW2	63	31	10	22
Site 3	259	128	43	88

Table 5.12. Build 2 demographics of the people conducting activities at sites with (CW1 and CW2) or without (Site 3) constructed wetlands for greywater treatment in s´Swetla in September 2021.

		CW1	CW2	Site 3
Total observations		175	63	259
Gender	Male	54	32	95
	Female	121	31	164
Age group	Adolescent	24	8	49
	Adults	120	38	150
	Elderly	31	17	60

For the extended CW1 and CW2, most disposals now occurred into the CW inlet (which was correct) (Table 5.13), though a fair number of disposals still went into the ditch next to CW1 and CW2. It should be noted that most of this wastewater also contained other materials such as food waste and other solid waste. It therefore made sense for disposals into the ditches next to CW1 and CW2 as these residents didn’t want to clog up the CWs with solid waste materials. The majority of wastewater disposals at CW1 and CW2 involved a mix between 2 0L buckets and smaller buckets. The disposal rates would therefore be higher once the wastewater from washing containers (which typically took place on the washing platforms of CW1 and CW2) was considered. As at Build 1, wastewater disposal at Site 3 mostly involved 20 L (and smaller) buckets which were disposed at the drain next to the tap.

Table 5.13. Build 1 volume of containers when disposing wastewater at sites with (CW1 and CW2) or without (Site 3) constructed wetlands for greywater treatment in s´Swetla in September 2021

			Site of disposal			
CW1	**Size of container**	**Total observations**	**CW Inlet**	**Next to CW**	**CW Outlet**	**Onto CW**
	</=10 L	48	14	8	1	2
	20 L		16	4	1	2
	> 40 L		0	0	0	0
CW2	**Size of container**	**Total observations**	**CW Inlet**	**Next to CW**	**CW Outlet**	**Onto CW**
	</=10 L	22	6	2	1	0
	20 L		11	0	0	0
	> 40 L		0	2	0	0
Site 3	**Size of container**	**Total observations**	**Drain at tap**	**Below tap**	**Around tap**	
	</=10 L	88	19	1	1	
	20 L		47	0	15	
	> 40 L		4	0	1	

The postures were divided into three categories for Build 2; more stooped (the body was flexed beyond 90 degrees), less stooped (the body was more upright, at or less than 90 degrees), or around 90% (Figure 5.11).

Figure 5.11. Examples of less stooped postures of washing tasks during Build 2 when using the washing areas of the CWs.

The postures adopted during the Build 2 structured activity analysis are shown in Table 5.14. It was evident that residents using the CWs were generally able to adopt less stooped postures. At CW1 and CW2, 23% and 17% of the residents adopted a more stooped posture, compared to 34% at Site 3. As was demonstrated in

Figure 5.11, this was mostly due to the raised washing area which reduced the need to bend significantly when collecting water or when washing laundry. The improvement in posture was most prevalent at CW2 which was raised by approximately 80 cm compared to CW1 which was raised by approximately 40 cm.

Table 5.14. Build 2 postures adopted for activities.

Posture	CW1 (N=175)	CW2 (N=63)	Site 3 (N=259)
More stooped	41	8	89
At 90 degrees	72	22	87
Less stooped	62	33	82

Several important emergent characteristics of the CWs were also observed during the Build 2 activity analysis. First, the expanded surface of the cleaning area allowed multiple users to use the workspace to place the washing containers, the laundry materials, and to carry out washing tasks. Second, the walls of the CWs were frequently 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 demonstrated that the nature-based solution was sufficiently adaptable to provide additional benefits to the community and to indirectly address aspects of SDG 6.3. While the redesign increased the flow of greywater into the CWs, the majority 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 have impacted the treatment capabilities of the CW.

5.4.4 Ethnographic observations and informal interviews

Since the start of Build 1 we have been visiting the research site at least twice a week (except where COVID-19 lockdown restrictions prevented access to the sites and over the December holiday periods when most s'Swetla residents left to visit family). 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. 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. For Build 1, 74 hours of ethnographic observations were made. The ethnographic observations were augmented with 40 informal interviews with community stakeholders. For Build 2, a further 82 hours of ethnographic observation were made, and these were augmented with a further 40 informal interviews with community stakeholders. Visits were made on different days of the week (including weekends) and at different times of day by two members of the project team, alternating their visits. 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. The ethnographic observations and informal interviews did not constitute a separate investigation, but was used to ensure continued stakeholder engagement, to inform the more formal research activities, and formed part of a PhD study.

5.4.5 Socio-economic investments

As stated earlier in this chapter, it was the intention of the project team to invest as much as possible of the costs in the community. This included sourcing building materials locally (where possible), sourcing labour and building skills locally, and embarking on an active engagement process with the community to generate design suggestions and to provide feedback on our progress and investigations. All the labour, building expertise, and project management was sourced from s'Swetla, although for Build 1 and Build 2 we had to "import" building expertise from other areas of s'Swetla. For Build 3 (CW3) and Build 4 (the removal of parts of CW3 and minor modifications to CW1 and CW2) we had developed the building expertise within Silvertown. The majority of building materials were sourced from s'Swetla, usually very close to Silvertown. Building materials such as cement, building sand, river sand, and concrete mix were sourced from the edges of Silvertown. Recycled bricks were sourced from two locations in s'Swetla depending on the availability of bricks at the time of building. During Build 3 we had to augment this supply with bricks bought at a hardware store in Alexandra township as there were insufficient bricks available locally. Plumbing (water piping and drainage piping) and waterproofing supplies were also sourced from the same hardware store. In Build 1, the plants for the CWs were purchased from a nursery. These wetland plants soon died and were replaced with locally sourced plants. For the activity analysis at Build 2, we also trained and paid three observers from Silvertown. Catering for discussions with residents, planning sessions, design sessions, and feedback sessions was sourced from s'Swetla or Silvertown, depending on the where the sessions took place. Venues for these meetings were also sourced locally and chairs were hired from a locally source where required. In total, nearly R500 000 was directly invested in the community during the research project.

The proportion of the costs across the four build cycles are shown in Figure 5.12. As was expected., the biggest proportion of costs can be attributed to labour. This includes the labour for the actual building as well as project management and for assistants to help collect observational data. Except for engagement costs, the greatest proportion of money was spent at Build 2. This was when two CWs were extensively re-designed and extended. We experienced labour costs were high and on investigation we discovered that the building expert was drinking on the job. Another building expert had to be sourced and we therefore also hired a trusted local resident to act as a project manager who would always be present on site. As expected, engagement costs were highest during Build 1 (when the initial CW designs were being conceptualised) and Build 4 (when feedback and future challenges were discussed).

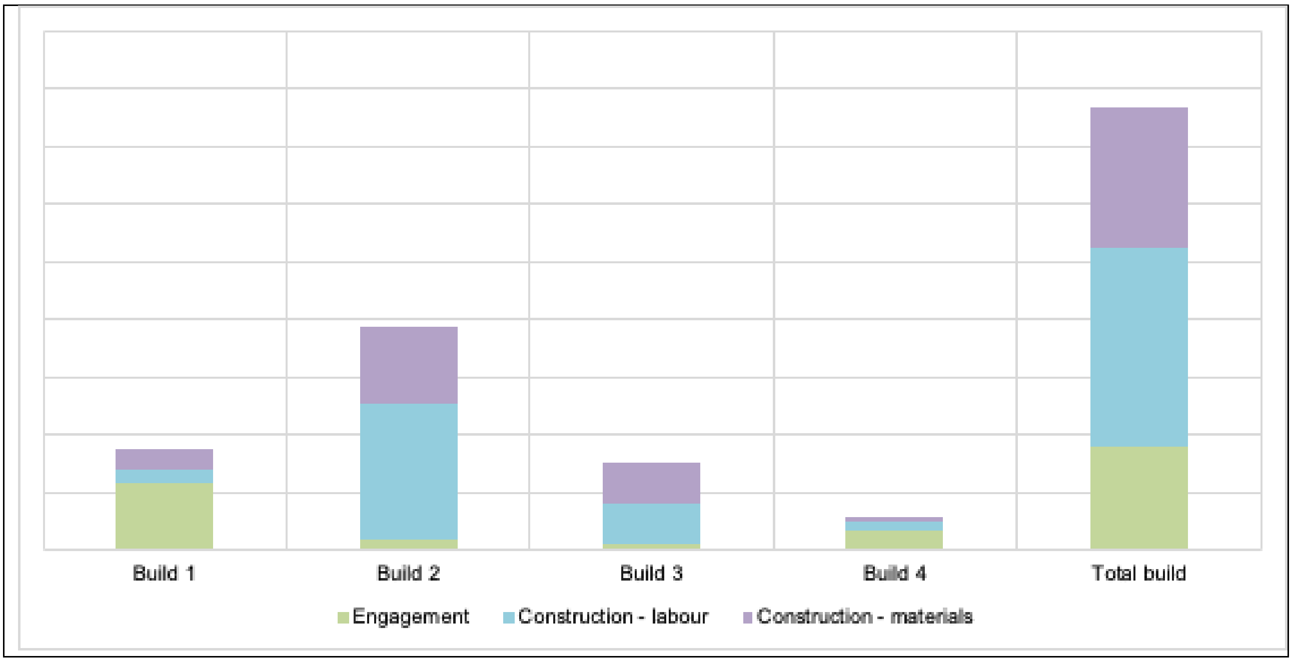

Figure 5.12. The proportion of costs across the four build cycles.

CHAPTER 6: WORK PACKAGE 5 – HYDRAULIC PROPERTIES AND SYSTEM STABILITY TOWARDS LOAD FLUCTUATIONS

6.1 INTRODUCTION

The work presented in this Chapter is based on the PhD research conducted by Stephenson, R. (2022).

The use of CWs for remediating any wastewater requires detailed knowledge and information around how the CW behaves under variable loading. The analysis of a CW is usually done using a tracer study and based on this; various hydraulic properties of the CW can be determined. To understand how the CWs change following loading with wastewater (artificial greywater in this case) we conducted an experiment at Linköping University using nine vertical columns filled with three different types of filter material. This experiment sought to understand the differences between the materials regarding hydraulic behaviour, and how that would change when the columns were loaded with a high load of an artificial greywater. This was studied by injecting a tracer and following the response curve at the outlet of the columns. The purpose of this second experiment was to i) measure the hydraulic properties of constructed wetlands filled with a mixture of the two waste materials used in the columns, ii) follow possible changes in hydraulic properties of the constructed wetlands when exposed to intermittent loads of greywater.

6.2 BACKGROUND: HYDRAULIC MODELLING OF CONSTRUCTED WETLANDS

CWs are essentially reactors and one of the factors which affects the extent of reaction is the time the fluid spends in the CW. Investigation into the hydraulic behaviour of a CW allows for the determination of this time and subsequently the effectiveness of the system in reducing contaminant load. Therefore, for CW models to be accurate the characterisation of hydraulic behaviour must be accurate. The flow behaviour of a wetland influences its ability to break down inlet contaminants (Kadlec and Wallace, 2009). There is a distribution of flow velocities within the system and the combination of these gives the overall hydraulic behaviour of the system. The water moving at the maximum velocity in the profile would normally be in the surface layer of the micro-channels, while the lowest velocity is experienced by water that moves near drag-inducing surfaces, such as the wetland bottom (Werner and Kadlec, 2000). Investigations have found that there are 3 different hydraulic zones in CWs; the main flow path, a temporary storage zone, where components and water are exchanged with the main flow path, and a dead zone (Buchberger and Shaw, 1995; Zahraeifard and Deng, 2011). By investigating the hydraulic behaviour of a CW, it is possible to give an indication of whether there are hinderances to ideal flow such bypassing, dispersion, and dead zones. All these factors contribute to the time that wastewater spends in the wetland, known as the residence time. This in turn relates to how long the water is in the system to break down organics, convert nitrogen species, and degrade other contaminants. If a wetland has poor hydraulic behaviour, then pollutant removal will be poor and conversion for which the system was designed, will not be achieved.

6.2.1 Ideal Reactor Equations

For design purposes CWs can be modelled assuming ideal flow behaviour, either as a plug flow reactor (PFR) or as a continuously stirred tank reactor (CSTR). In an ideal PFR every fluid particle moves through the reactor with the same velocity and have the same residence time. There is assumed to be no dispersion or longitudinal mixing. The design equation for a first-order reaction in a PFR is given in Equation 6.1. In an ideal CSTR it is assumed that the system is perfectly mixed which implies that the effluent concentration is the same as the concentration anywhere in the reactor. Equation 6.2. gives the design equation for a first order reaction in an ideal CSTR. However, it has been shown by multiple researchers that the hydraulic behaviour of CWs is far from these ideal cases, and likely lies somewhere in between (Kadlec, 2000; Werner and Kadlec, 2000).

$$C_{i,out} = C_{i,in}e^{-kt} \quad (6.1)$$

$$C_{i,out} = \frac{C_{i,in}}{(1+kt)} \quad (6.2)$$

The reason an ideal PFR equation is often chosen is that the solution to the kinetics is the same as a batch reactor, with time 't' being the same as 'tau'. While this makes the equation easy to use, it is not necessarily accurate. If the hydraulic behaviour of CWs is to be modelled accurately, non-ideal flow must be considered.

6.2.2 Reasons for Non-ideal Flow

The flow characteristics of CWs are elaborate and non-ideal owing to the changing root structure and the complicated flow pathway of fluid through gravel or soil matrix (Bonner et al., 2017). Factors such as wetland shape (Persson, 2000; Wörman and Kronnäs, 2005), inlet and outlet location (Persson, Somes and Wong, 1999; Suliman, Futsaether et al., 2006), and vegetation distribution (Persson, Somes and Wong, 1999; Serra, Fernando and Rodríguez, 2004; Kjellin et al., 2007; Keefe et al., 2010) can affect the hydraulic behaviour of CWs. These factors result in non-ideal phenomena like dispersion, short-circuiting, and dead zones.

Dispersion
Dispersion is an effect of micro-mixing of the fluid in the direction of the flow. This leads to a 'spreading' of the pocket of fluid. This phenomenon occurs because the flow channels are non-ideal and have different lengths and are oriented in different directions.

Short circuiting
Short circuiting occurs when some of the fluid bypasses the main flow channel and follows the path of least resistance, resulting in this pocket of fluid passing through the system in a much shorter period than the rest of the fluid.

Dead zones
Dead zones are areas of very low or no flow within a system. In these stagnant pockets the dominant process for solute transport is diffusion. The presence of dead zones decreases the effective volume of the overall system and therefore reduces the system's ability to treat wastewater.

Wetland clogging
Wetland clogging is one of the biggest operational problems of subsurface flow CWs. This phenomenon is typically caused by the following processes (Kadlec, 2009).

- Deposition of suspended solids at the system inlet;
- Deposition of organic compounds, which are resistant to microbial degradation, at the system inlet;
- Chemical precipitation;
- Introduction of organic matter to the system which encourages growth of microbial biofilms in the plant rhizosphere;
- Growth of plant roots within the packed media; and
- Gas bubble dynamics.

Heterogenous subsurface media
Gravel and soil are among the most used CW media. These materials are typically heterogeneous in nature and are found to have particle size distributions (Suliman, French et al., 2006). This variation in particle sizes results in a variation in pore sizes throughout the wetland that can lead to the development of preferential flows paths. The presence of vegetation also increases the heterogenous nature of the system. Vegetation distribution is a variable barrier to flow in terms of the plant size, shape, and position. As a result, there is

bypass and short circuiting around plant mass, forming dead zones, which leads to a hold up of water in certain areas.

6.3 TRACER TESTS

The most common way to characterise the flow patterns and assess the hydraulic behaviour of a CW is by conducting residence time distribution (RTD) studies or tracer studies (Headley and Kadlec, 2007). The residence time distribution of a reactor gives the probability of a fluid element spending a specific amount of time in the reactor and is characteristic of the mixing that occurs within the system (Fogler, 2006). The RTD is obtained by running a flow tracer study on the system. A flow tracer study is a stimulus-response experiment in which an inert flow tracer is injected either as an impulse or as a step-change in concentration into the system inlet pipe and the tracer concentration is measured continuously at the effluent. An effective tracer study requires the flow to be laminar (Sheridan, Hildebrandt and Glasser, 2013) if the data is to be successfully extrapolated (scaled) to other operational flow rates (as long as they are also laminar). Data from these experiments are then used in RTD modelling methodologies to analyse the flow characteristics of the reactor and can be used to quantify a set of characteristics that describe the hydraulic behaviour of CWs (Bonner et al., 2017). In order for these tracer tests to be effective the tracer used must be conservative, i.e. should not be consumed or degraded (Cucco and Umgiesser, 2006). The tracer should also not be susceptible to biological, chemical, or photochemical decay, should be highly soluble in water, and should be easily detectable and not exist at high background levels within the system. It is also assumed that for any experiment run, the tracer flow behaviour is similar to a normal effluent liquid (Lappalainen et al., 2011).

6.3.1 Impulse-Response tracer tests

The type of tracer study most commonly used to determine the hydrodynamic behaviour of a CW is the impulse-response test (Headley and Kadlec, 2007; Kadlec, 2007). When conducting an impulse-response test a small volume of highly concentrated tracer solution is injected instantaneously (mathematically equivalent to an impulse function) into the inlet of the system and the concentration of the tracer is measured at the effluent at regular time intervals (Fogler, 2006). In Figure 6.1 a graphical representation of the concentration-time response at the inlet (a) and outlet (b) can be seen. The very short impulse is observed to spread (or disperse) through any system. If the results follow a normal (Gaussian) distribution, the flow is normally ideal. The shape of the distribution can tell the experimenter many things: if it is bi- or multi-modal (two or more peaks) it can indicate bypass, if it has a very long tail, it can indicate dead-zones as the tracer ‘bleeds’ back from the dead-zone into the outlet.

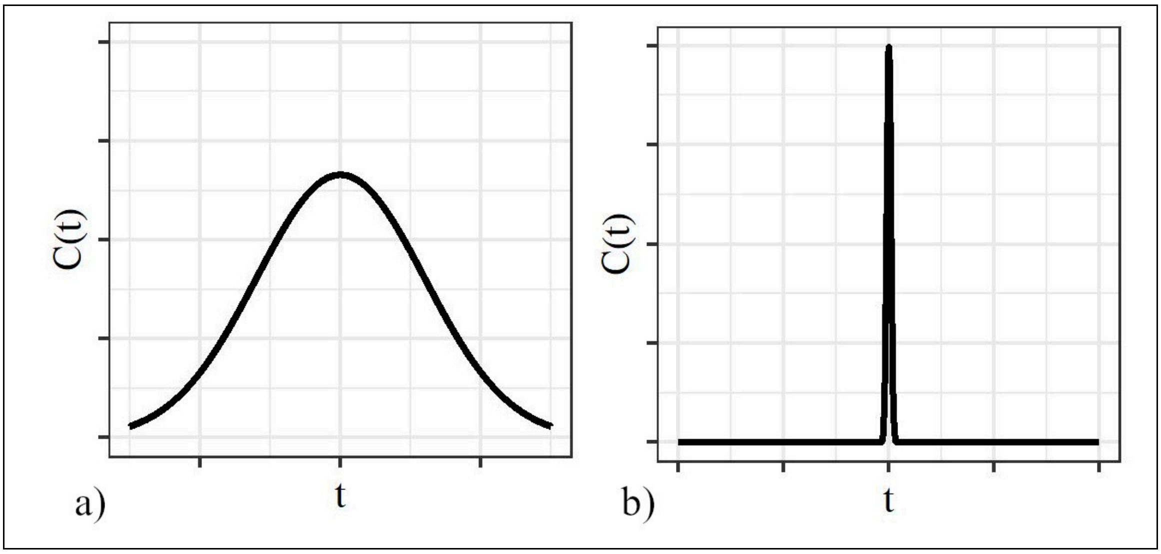

Figure 6.1. A graphical representation of the concentration-time response of an impulse-response tracer test: inlet (a) and outlet (b).

The residence time distribution function, E(t), which is a quantitative description of how much time the fluid particles have spent in the reactor, can be obtained from concentration-time data of the impulse-response curve, and is given by Equation 6.3. The basis assumption for Equation 2.18 is that the inlet volumetric flow rate of the system is constant. E(t) is calculated using the area under the concentration-time curve; by doing so the area underneath the E(t) vs t response curve is 1. The calculation of E(t) is important as the first step towards calculating the moments of the distribution (i.e. the first moment is the mean of the RTD, the second moment is the spread of the distribution – these are discussed further later).

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \tag{6.3}$$

Two of the problems associated with an impulse-response tracer study are ensuring that the injection of tracer takes places over a period which is short compared to the residence time of the system and ensuring negligible dispersion of the tracer between the point of injection and the feed to the system. Another issue than can arise is that if the experiment has been concluded too early, then the analysis of the concentration-time data from the effluent can lead to inaccuracies. It is important is extrapolate the tail of the impulse-response to prevent this. A further major obstacle with the impulse-response tracer test is that there may be the same concentration at various times (i.e. on the way towards the peak(s) and on the way down from the peak(s)). This means that the actual time a molecule has spent in the reactor is not known, and rather there are probabilities of time that reactants spend in the reactor.

6.3.2 Types of tracers

There are many options of tracers available which include, but are not limited to: salt ions, fluorescent dyes, and stable isotopes, or a combination of these of tracers. All these options have been used by researchers conducting tracer tests in CWs.

6.3.2.1 Salt tracers

Salt tracers, also known as ionic tracers, are considered to be effective for studying the hydraulic behaviour of CWs as they are easily soluble and are unlikely to interact with the biota of the system (Lin et al., 2003). Sodium chloride is one of the most common salt tracers and has been used by many researchers. Heiderscheidt et al. (2020) used it to determine the residence time under frozen and frost-free conditions of an unplanted, peat-based, pilot-scale wetland (Heiderscheidt et al., 2020), Sun et al. (2019) used it to determine hydraulic parameters of a horizontal sub-surface flow CW (Sun et al., 2019) and Hua et al. made use of the tracer to investigate the effect of clogging and resting processes on the flow behaviour of a vertical flow CW (Hua et al., 2018). One study used lithium as a tracer to validate the hydraulic model used in a CWM1-RETRASO mechanistic model in the simulation of a horizontal sub-surface flow CW (Mburu et al., 2013), while another used lithium chloride to test the effect of inlet configuration and vegetation type on the hydraulic performance of 18 free water surface wetlands (Bodin et al., 2012). Potassium iodide was used by a group of researchers to determine the hydraulic behaviour of drained peatlands (Postila et al., 2015).

One of the limitations of salt tracers is that the salt solutions typically have higher densities than the wetland water (Bodin et al., 2012) and so a halocline could be formed. This results in the stratification of fluid which prevents mixing and is thermodynamically stable. Density induced stratification may be aided by low flow velocities (Schmid, Hengl and Stephan, 2004). Special care needs to be taken, especially in the case of impulse-response tracer tests, to ensure that salt tracer settling does not take place. Density differences are also affected by temperature, but in FWS wetlands the temperature difference from top to bottom is approximately 1°C which is not considered enough to create stratification (Kadlec and Wallace, 2009). Any temperature differences greater than this may cause a problem (Bodin et al., 2012).

When choosing a salt tracer, choosing one with ions that have minimal interaction with the system is important. For example, Cl^- and Li^+ are good ionic tracers but NO_3^- will be transformed in the system and therefore is not a conservative tracer. It is also important to consider the charge of the ion and the charge of the wetland medium, to ensure minimal interaction between the two.

Chemical analytical methods most used for salt tracers are electrical conductivity and ion chromatography and, in some cases, atomic absorption spectrophotometry. Electrical conductivity is a cheap and effective method of analysis and can be used as a proxy for determining the concentration of ions in the system.

6.3.2.2 Fluorescent tracers

The use of fluorescent tracers in the RTD studies of CWs is common. Fluorescent dyes such as fluorescein and rhodamine are inexpensive, easy to handle and easy to detect (Russell et al., 1992). One study used rhodamine WT to evaluate hydraulic behaviour and performance indicators of various wetlands designs and from this information were able to choose the optimum design from the systems tested on (Guo et al., 2019). Guo et al. (2019) used rhodamine WT to determine the residence time and other hydraulic parameters of a tundra wetland and from this were able to determine first-order rate constants of the contaminants which can be used to further improve the wetland design (Hayward and Jamieson, 2015). Another common fluorescent dye tracer is uranine. Pálfy et al. (2017) used uranine to determine the hydraulic behaviour of a wetland treating combined sewer overflow and from this information the researchers were able to identify short circuiting as a limitation of the system (Pálfy et al., 2017), while Laurent et al. (2015) used uranine and sulfurhodamine B to successfully determine the hydrodynamic behaviour of three surface flow CWs (Laurent et al., 2015). These dyes are for the most part conservative but have the potential to adsorb onto certain materials, are susceptible to photodegradation and biodegradation, and can be pH sensitive (Lin et al., 2003; Gerke, Sidle and Mallants, 2013).

6.3.2.3 Combinations of different types of tracers

A combination of two or more types of tracers is being trialled by wetland researchers for RTD studies. Different tracers have different diffusion coefficients, and this allows researchers to determine the presence and location of stagnant zones and diffusion dominated transport processes (Knorr et al., 2016). Birkigt et al. (2018) conducted a multi-tracer RTD experiment using bromide, uranine and deuterium oxide to determine the flow behaviour in three dimensions of a pilot-scale HSSF CW (Birkigt et al., 2018). From this research it was noted that bromide and deuterium oxide had similar behaviour and the data from the tracer studies yielded similar hydraulic parameters while uranine displayed a different hydraulic behaviour. It was suggested that there was a lag in the response of uranine due to organic matter in the system. Mailard et al. (2016) used bromide, uranine and sulforhodamine-B as tracers to determine the impact of batch versus continuous-flow modes on the dissipation of the chiral herbicide S-metolachlor in a CW (Maillard et al., 2016). These researchers found that plant uptake, sorption, and photodegradation is greater in batch mode operation than continuous flow operation, but the extent for each tracer was slightly different. Bromide was most susceptible to plant uptake, uranine was most susceptible to photodegradation and sulforhodamine-B was most susceptible to sorption (Maillard et al., 2016). Pugliese et al. (2020) used uranine and potassium bromide as conservative tracers to study the hydraulic behaviour of a shallow-deep, compartment-designed subsurface flow CW and were able to identify the presence of multiple flow paths and internal mixing in shallow zones (Pugliese et al., 2020). Montalván et al. (2017) used natural tracers (Cl^-, Br^-, Na^+, Mg^{2+}) and environmental isotopes (^{18}O, ^{2}H, ^{14}C, ^{13}C and ^{3}H) to estimate residence times of brine waters and identify recharge areas of the different flow subsystems in a hypersaline wetland (Montalván et al., 2017). Bruun et al. used bromide and tritium (in the form of $^{3}H_2O$) to investigate intra-granular diffusion in a woodchip based sub-surface flow CW (Bruun et al., 2016). This study indicated that there may be a slight anion exclusion on bromine in the wood chip matrix.

6.3.2.4 Other tracer options

While the tracer types mentioned above are the more common, a few others have been used. Bonner et al. (2017) developed a mapping methodology for the use of heat as a non-conservative tracer in HSSF CWs. The researchers were able to accurately quantify the hydraulic parameters of the system being tested on from the mapped heat tracer response. It was shown that if certain parameters of transport can be determined then this technique can be used. One study used stable isotope ratios of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) in water to study the hydrology of forested wetlands (Bugna, Grace and Hsieh, 2020). Through this, the researchers were able to identify the contribution of surface water and rainwater to three different wetland systems and the extent of surface evaporation. Abu-Bakar et al. (2017) investigated the use of microbial tracers and in this study the researchers calibrated and validated the transport and decay of four microbial tracers and used the data to refine a model for better water quality processes in a macro-tidal coastal basin. Modelling the decay of the microbial tracers proved to be more computationally intensive than the researchers expected so the technique is not considered useful for design (Abu-Bakar, Ahmadian and Falconer, 2017).

6.4 HYDRAULIC MODELLING TECHNIQUES

In an ideal plug-flow system, all fluid particles move through the wetland with the same velocity and reach the system outlet at the same time. This exit time is the simplest way to account for time in a CW and is called the nominal residence time (τ) which is defined in Equation 6.4 (Headley and Kadlec, 2007). The nominal residence time is only a function of velocity ($\dot{v}$) and volume (V) and is an intrinsic parameter of any reactor. This method does not account for any non-ideal flow through the wetland system and a tracer test is not required to determine the nominal residence time. Owing to the non-ideal nature of wetland hydraulic behaviour, the nominal residence time is not considered sufficient to characterise wetland flow behaviour.

$$\tau = \frac{V}{\dot{v}} \tag{6.4}$$

6.4.1 Method of moments

In the method of moments technique for interpreting RTD data, three parameters are determined: the mass recovery, the mean residence time, and the variance. The mass recovery of tracer in an RTD study is important, especially in an impulse-response study, as many parameters used to quantify the hydraulic behaviour of a system are determined based on the assumption of total mass recovery. A mass recovery of tracer of 80% or higher is generally considered acceptable (Headley and Kadlec, 2007). The percentage of mass recovery of conservative tracer in a tracer study is considered the zeroth moment of the RTD. The mass recovery can be calculated using Equation 6.5. (Holland et al., 2004).

$$M_{out} = \int_0^{\infty} Q_{out}(t)C_{out}(t)dt \quad (6.5)$$

The first moment of the RTD study is the centroid of the response curve and is called the mean residence time (t_m), which is the average amount of time that the fluid particles have spent in the reactor. This can be calculated using Equation 6.6. (Fogler, 2006) for impulse-response tracer studies and Equation 6.7 (Bonner et al., 2017) for step-change response tracer studies.

The second moment of the RTD is the variance. The variance is an indication of the spread of the impulse as it passes through the reactor system (Drummond et al., 2012; Jackson et al., 2012). Equation 6.8. (Luo et al., 2008) and Equation 6.9. (Bonner et al., 2017) give the equation used to determine the variance from an impulse-response and step change tracer study, respectively. The variance gives an indication of the global mixing in the system (Giraldi et al., 2009).

$$t_m = \frac{\int_0^{\infty} tE(t)dt}{\int_0^{\infty} E(t)dt} \quad (6.6)$$

$$t_m = \int_0^{\infty} [1 - F(t)]dt \quad (6.7)$$

$$\sigma^2 = \int_0^{\infty} (t - t_m)^2 E(t)dt \quad (6.8)$$

$$\sigma^2 = 2\int_0^{\infty} t[1 - F(t)]dt - t_m{}^2 \quad (6.9)$$

Dimensionless variance is calculated using Equation 6.30. The dimensionless variance gives an indication of local mixing.

$$\sigma^2{}_0 = \frac{\sigma^2}{t_m{}^2} \quad (6.10)$$

$$\boldsymbol{t_m = \frac{\int_0^{\infty} tE(t)dt}{\int_0^{\infty} E(t)dt}}$$

The mean residence time (t_m) can be compared to the nominal residence time (τ) to provide the effective volume utilisation (*e*). This is given in Equation 6.11 (Bodin et al., 2012). The effective volume utilisation is a function of aspect ratio (Molle, Prost-Boucle and Lienard, 2008), positioning of inlet and outlet ports (Sheridan *et al*., 2013), presence and location of plants in the system, and root density (Pedescoll et al., 2013) as well as the extent of clogging in the system due to biofilm growth (Knowles et al., 2011). Evapotranspiration can influence the mean residence time and effective volume utilisation. If a large fraction of water is lost from the system due to evapotranspiration it has a concentrating effect on the tracer. This affects the outlet concentrations of tracer obtained during tracer studies which in turn affects the mean residence time and other hydraulic parameters.

$$e = \frac{t_m}{\tau} \quad (6.11)$$

One of the limitations of the method of moments is that the anomalies in the tail of the impulse-response tracer test can lead to incorrect estimation of parameters and curve fitting (Kadlec and Wallace, 2009). Early truncation of the tail can also lead to an under estimation of the mean residence time (Martin, 2000). It has been indicated that a disadvantage of using the method of moments technique is that a single mean residence time (t_m) can describe an infinite number of distributions, thereby stating that there is a 'loss of information' when determining other parameters, such as dispersion, from the mean residence time (Bachmann and Tsotsas, 2015). The methods of moments is also sensitive to non-continuous data sets (Bodin et al., 2012). The benefit of the method of moments technique is that the hydraulic parameters values can be obtained directly from the measured data (Bodin et al., 2012).

The Peclet number (Pe) represents the ratio between the advective and dispersive contributions to solute transport within the system and is defined according to Equation 6.12.

$$Pe = \frac{uL}{D} \quad (6.12)$$

6.4.2 Tanks in Series Model

The tanks-in-series model is a reactor model and is a gamma distribution of residence times. The model is given in Equation 6.13 (Kadlec and Wallace, 2009). In this model the results from the tracer test, either step-change or impulse-response, are analysed to determine how many continuously stirred equally sized tank reactors in series would provide the same response curve as the experimental wetland curve. The number of tanks in series, N, is determined using Equation 6.14 (Bodin et al., 2013). When N=1 there is a large degree of back mixing, and the wetland is considered to behave as a CSTR and can be modelled as such. As N tends to infinity the degree of back mixing tends to zero and the behaviour of the wetland tends to that of an ideal plug flow reactor (PFR) and can be modelled as such. In Figure 6.2 the residence time distribution's varying values of N can be found. A physical representation of 6 tanks in series is given in Figure 6.3. Based on reported literature values, Kadlec & Wallace (2009) estimated that N = 4.1 ± 0.4 for free water surface (FWS) wetlands, and N = 11.0 ± 1.2 for horizontal subsurface flow wetlands (Kadlec and Wallace, 2009).

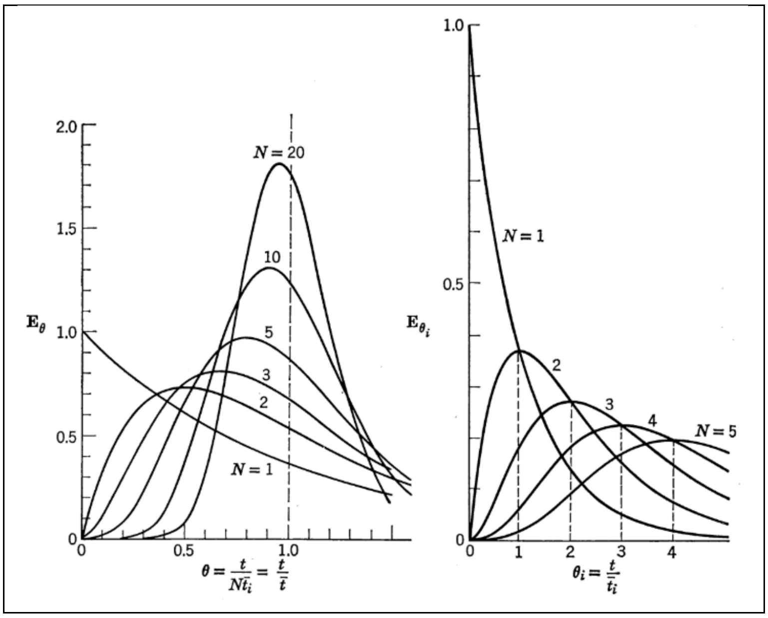

Figure 6.2. Residence time distributions for varying values of N (Levenspiel, 1999).

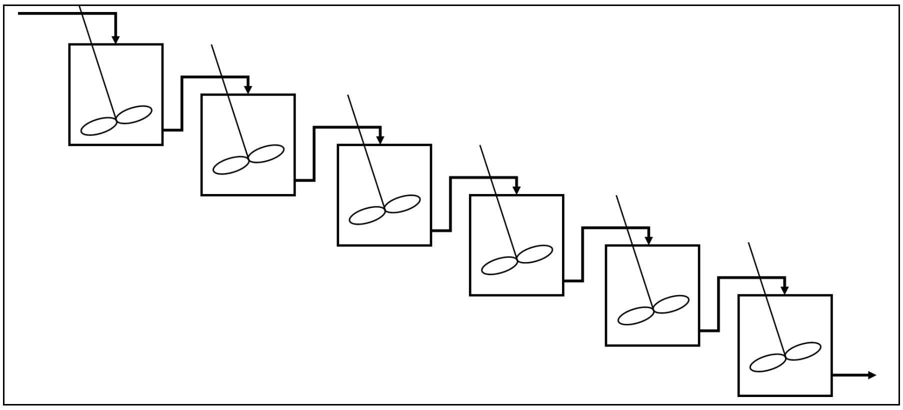

Figure 6.3. Physical representation of multiple tanks in series where N=6

$$E(t) = \frac{t^{N-1}}{(N-1)!\tau_i{}^n} e^{-\frac{t}{\tau_i}} \quad (6.13)$$

$$N = \frac{t_m{}^2}{\sigma^2} \quad (6.14)$$

From the number of tanks in series another factor can be determined, the hydraulic efficiency, which is defined in Equation 6.15. Hydraulic efficiency is a measure that can be used to compare different wetland designs (Persson and Wittgren, 2003). It considers the effective volume utilisation (e) as well as the degree of mixing by making use of N.

$$\lambda = e * \left(1 - \frac{1}{N}\right) \quad (6.15)$$

One study used the tanks-in-series model to investigate the hydraulic behaviour of three large-scale surface flow CWs and it was determined that the vegetation density had a large effect on the dispersion of the system (Laurent et al., 2015). Another study used the tanks-in-series model with exchange between active and dead zones to simulate the RTD of a horizontal subsurface flow CW (Goswami et al., 2019). From this model the researchers were able to determine the optimum inlet flow rate and water level in the CW being studied.

6.5 MATERIALS AND METHODS

6.5.1 Impulse-response Tracer Studies

In this experiment, we sought not to conduct detailed, in-depth hydraulic studies, but rather to use these techniques to understand how the more common variables such as the mean of the residence time distribution (RTD) changed following loading and to compare how different packing media impacted the RTD. The experiment is described here.

6.5.2 Vertical column studies

Impulse-response tracer studies were conducted on nine vertical flow columns at the Linköping University, Sweden (three are shown in Figure 6.4). The columns were made of orange PVC and covered with a lid made of the same material. The columns were identical in size with the dimensions being 0.15 m x 0.4 m (d x h), and the experiment was run in triplicate. Three of the columns were filled with pea gravel which had a diameter of 2 mm-8 mm and a void fraction of 0.36; three were filled with macadamia nut shells and three others with crushed building rubble. Each column was filled with the packing media to a height of 0.37 m. The system consisted of two ports, the inlet port at a height of 0.04 m above the base and the outlet port at a height of 0.37 m above the base. At the inlet and outlet ports, flexible transparent tubing with an internal diameter of 0.02 m was attached. There was ~20 cm of tubing between the inlet port and the feed pump, and ~20 cm from the outlet port to where water was collected. The height of the outlet port determined the height of the water level, which was therefore also at 0.37 m. The water volume of the system was 2.16 L. A peristaltic pump was used to deliver water to the columns at a continuous and consistent flow rate. The impulse-response tracer studies were conducted one at a time on the individual vertical flow columns.

Figure 6.4. Picture of the vertical flow gravel columns on which impulse-response tracer studies were conducted.

A medical syringe was used to inject tracer into the inlet of the system at a time of $t = 0$. Uranine was used as the tracer. 10 ml of 10 ppm tracer was injected into the inlet of the system. A needle was used to pierce the inlet pipe so that tracer could be injected as close to the inlet port as possible, thus minimising mixing before entering the column. The injection site was closed after injection to prevent leaking. Based on the inlet flow rate and volume of the system, the nominal residence time in these impulse-response tracer tests was 70 minutes. The duration of the test was long enough for the concentration of the tracer to reach background concentrations; this took 280 minutes. 4 ml of sample was taken every 4 minutes and stored in a plastic tube until analysis. Samples were analysed within 20 minutes of being taken.

6.6 ANALYTICAL TECHNIQUES

The samples taken for the impulse response tracer studies conducted on vertical flow columns in Linköping, Sweden were analysed using a FluoroSELECT® fluorometer (Sigma-Aldrich). To calibrate the fluorometer, two standards are required, one blank and another of known uranine concentration. The second standard used was 100 ppb. The calibration was done automatically by the FluoroSELECT® fluorometer. Standards of 25 ppb, 50 ppb and 100 ppb were kept at hand and used between every five samples to ensure the calibration still held. Samples were placed in 0.2 μl PCR tubes and then into the fluorometer. Each sample was analysed three times.

6.7 RESULTS

In each of the triplicate experiments, one result was found which was entirely contradictory. Based on the other two results being similar, the contradictory experiment was discarded.

The void fraction as measured for each material is presented in Table 6.1. The measurements showed the macadamia nutshells and rubble had a substantially greater void fraction than rubble. This has an impact on the calculation of tau.

Table 6.1. Void fraction of the CW matrix

Material	Nutshells	Rubble	Gravel
Void Fraction	0.63	0.58	0.37

The calculation of theoretical residence time for the columns in each replicate experiment is shown in Table 6.2. The flow rates were calculated to give each of the reactors a similar tau, i.e. due to the difference in void fraction, the reacting volumes were different for each column. The flowrates were therefore adjusted to give similar theoretical residence times (i.e. tau values).

Table 6.2. Residence time calculations for the nine replicate columns

Nutshell column 1			Rubble column 1		Gravel column 1	
Run 1	Inlet flowrate (ml/min)	53.00	Inlet flowrate (ml/min)	49.00	Inlet flowrate (ml/min)	31.00
	Theoretical residence time (min)	75.47	Theoretical residence time (min)	75.31	Theoretical residence time (min)	75.81
Run 2	Inlet flowrate (ml/min)	48.00	Inlet flowrate (ml/min)	44.00	Inlet flowrate (ml/min)	31.00
	Theoretical residence time (min)	83.33	Theoretical residence time (min)	83.86	Theoretical residence time (min)	75.81
Nutshell column 2			**Rubble column 2**		**Gravel column 2**	
Run 1	Inlet flowrate (ml/min)	53.00	Inlet flowrate (ml/min)	49.00	Inlet flowrate (ml/min)	31.00
	Theoretical residence time (min)	75.47	Theoretical residence time (min)	75.31	Theoretical residence time (min)	75.81
Run 2	Inlet flowrate (ml/min)	44.00	Inlet flowrate (ml/min)	44.00	Inlet flowrate (ml/min)	31.00
	Theoretical residence time (min)	90.91	Theoretical residence time (min)	83.86	Theoretical residence time (min)	75.81
Nutshell column 3			**Rubble column 3**		**Gravel column 3**	
Run 1	Inlet flowrate (ml/min)	53.00	Inlet flowrate (ml/min)	49.00	Inlet flowrate (ml/min)	31.00
	Theoretical residence time (min)	75.47	Theoretical residence time (min)	75.31	Theoretical residence time (min)	75.81
Run 2	Inlet flowrate (ml/min)	48.00	Inlet flowrate (ml/min)	50.00	Inlet flowrate (ml/min)	31.00
	Theoretical residence time (min)	83.33	Theoretical residence time (min)	73.80	Theoretical residence time (min)	75.81

6.7.1 Residence time distributions

The RTD graphs for the macadamia nutshells are presented in Figure 6.5, for rubble in Figure 6.6 and for gravel in Figure 6.7. For each of the replicates, for all materials there were significant changes in both the shape of the RTD and the location/peak of the RTD. For the nutshell and gravel columns a spreading out of the RTD was observed, indicating that there was greater dispersion with time and the peak of the tracer arrived a little later. For the gravel, however, which serves as a control, the peak was observed to exit earlier although the peak was still observed to show greater dispersion.

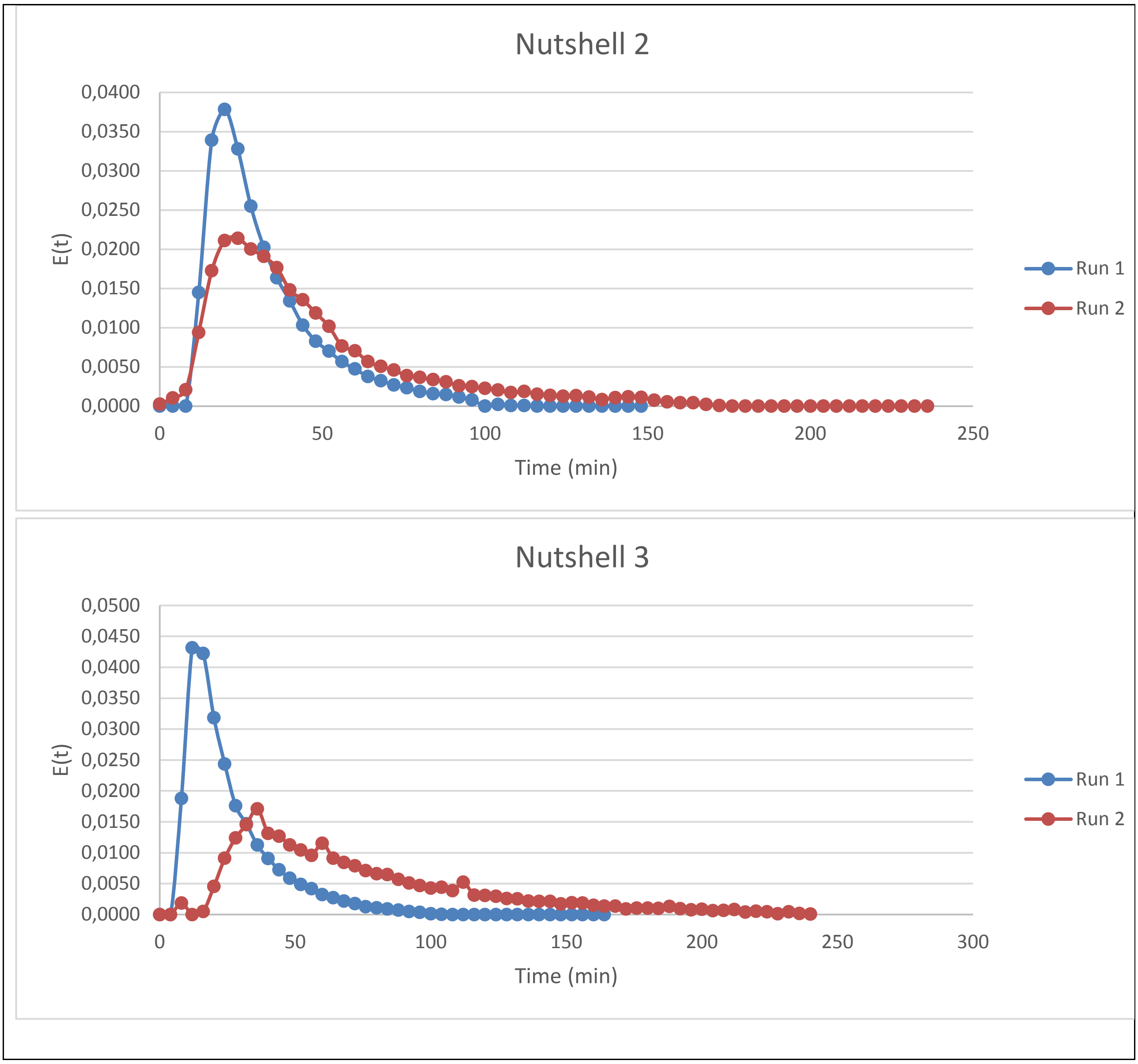

Figure 6.5. RTDs for Macadamia nutshells for column 2 and 3

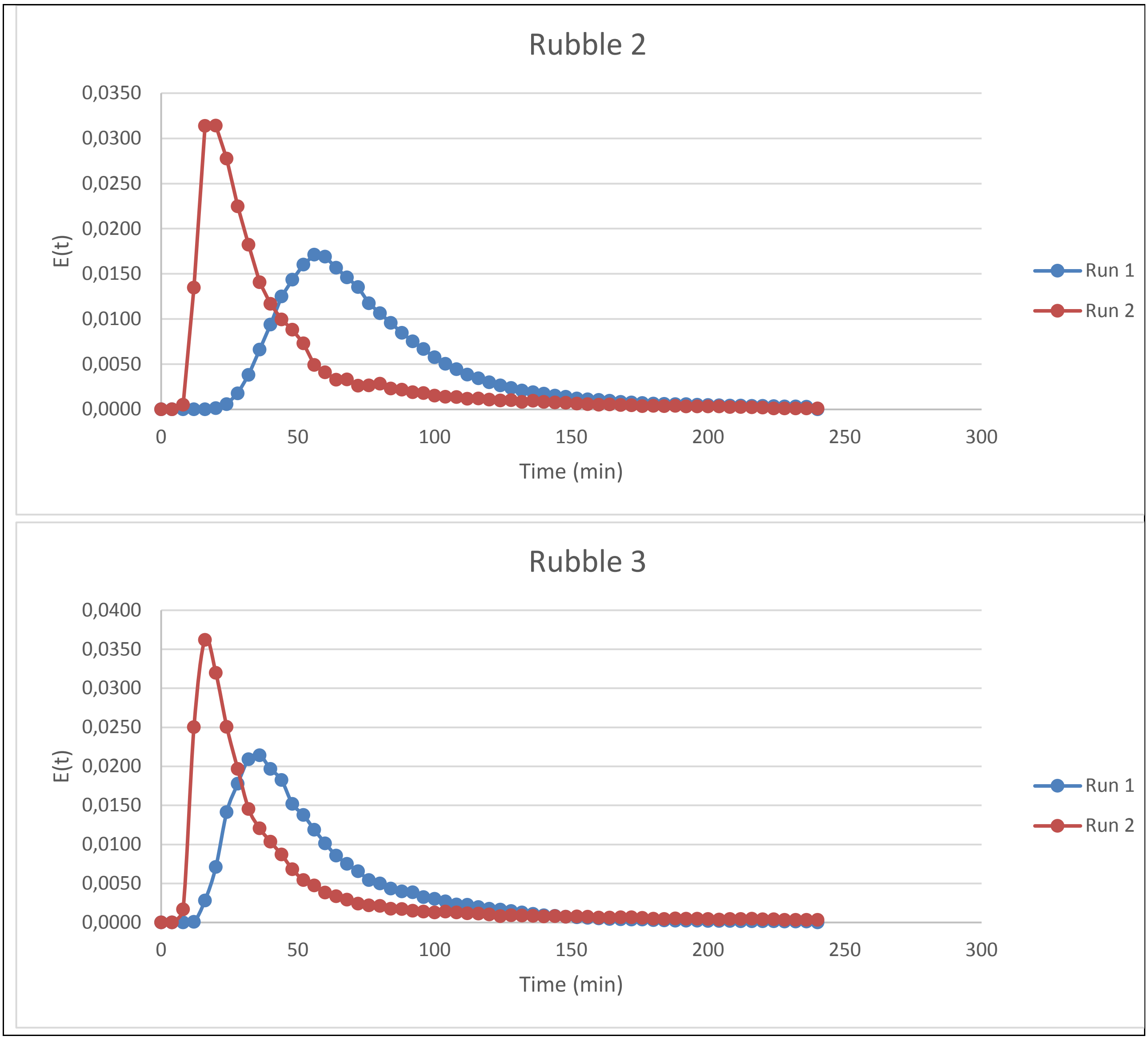

Figure 6.6. RTDs for rubble for column 2 and 3

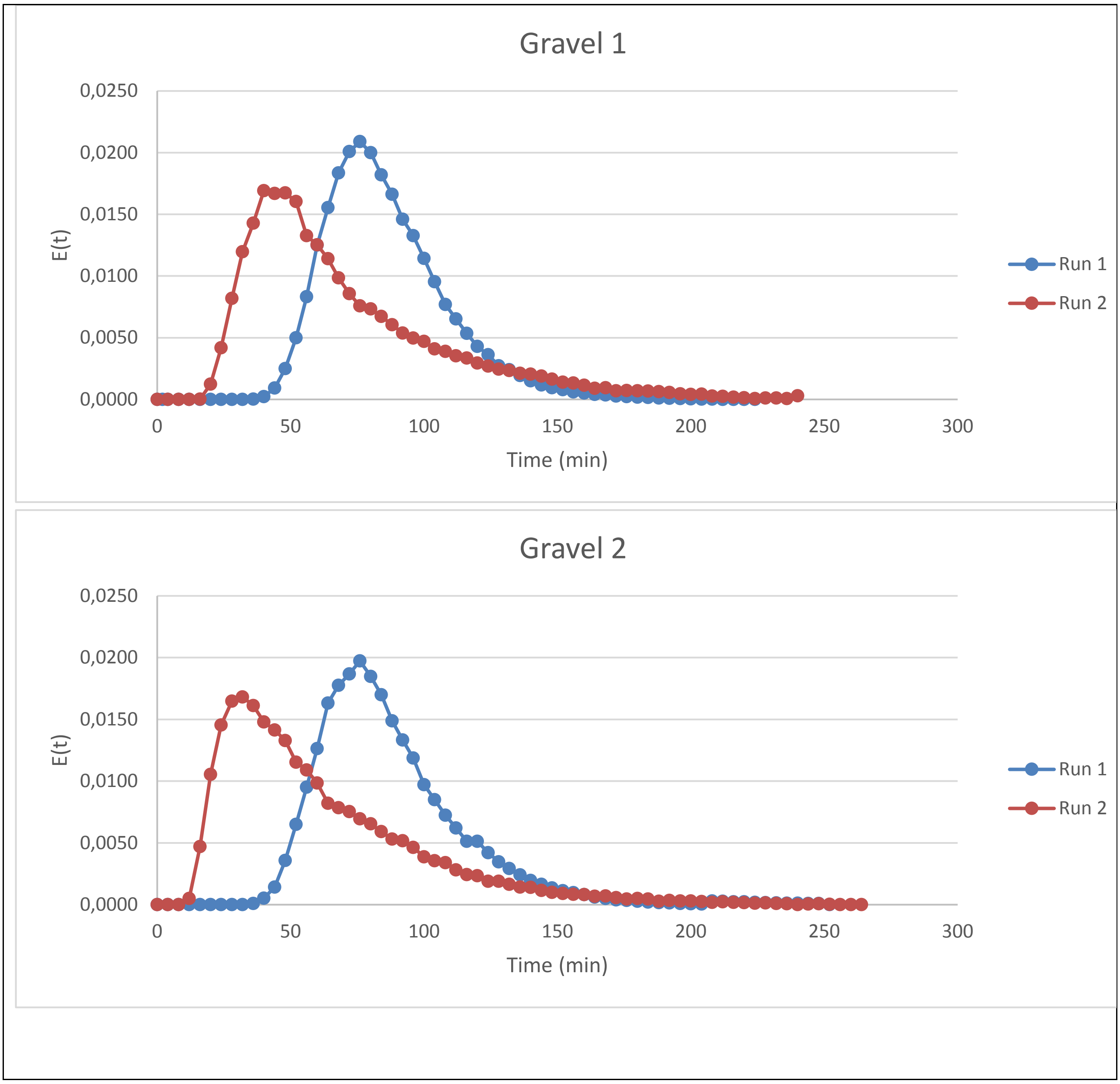

Figure 6.7. RTDs for gravel for column 1 and 2

The hydraulic variables are presented in Table 6.3.

Table 6.3. Hydraulic variables as calculated from the RTDs

Run Number	Variable name	Nutshell Column 2	Nutshell Column 3	Rubble Column 2	Rubble Column 3	Gravel Column 1	Gravel Column 2
1	tau (min)	75.47	75.47	75.31	75.31	75.81	75.81
	tm (min)	32.17	25.78	77.91	56.94	85.99	87.63
	Number of tanks (N)	3.37	2.44	4.65	2.82	14.19	9.91
2	tau (min)	90.91	83.33	83.86	73.80	75.81	75.81
	tm (min)	46.44	73.48	42.80	42.96	71.00	61.42
	Number of tanks (N)	2.18	2.65	1.35	1.03	3.45	2.69

The value for N was calculated to decrease for all columns except nutshell column 2. This indicates that the reactors are behaving less like ideal flow reactors implying that non-ideal behaviour is increasing with loading. The data indicate that the growth of biofilm has a *significant* effect on the flow regime through the CWs.

6.8 CONCLUSION

From these column experiments it is concluded that:

1. The use of alternative materials for the packing of CWs, such as locally procured waste materials such as building rubble or macadamia nutshells (or potentially other agricultural residues) has a significant impact of the residence time of the CWs;
2. The loading of wetlands with organic-rich wastewater has a significant impact on the flow of wastewater through the CWs as time increases; and
3. The loading of organic-rich wastewater has a significantly different impact on the flow, depending on the type of matrix used for the packing of the CW.

These findings have implications for design: it may not be possible to directly transfer design knowledge from gravel-based systems to systems using other media such as shown in this study. The growth of biofilm also has a significant impact, which is as yet, not fully quantified. This biofilm growth and characterisation forms part of the ongoing experiments in this study.

CHAPTER 7: WORK PACKAGE 6 – DESCRIPTION OF MICROBIOME AND RESPONSE TO INFLOW VARIATION INCLUDING STRESS AND SHOCK LOADING.

7.1 INTRODUCTION

This Chapter highlights the experiments conducted to understand the microbiome response to a changing inflow. The greenhouse-based experiments followed an experimental plan with decreasing concentrations and composition of the inflow synthetic greywater. At the end of each experimental phase microbial samples were taken and DNA were extracted. This portion of the project was funded through the BMBF and forms a deliverable to that funding agency. The Helmholtz UFZ secured an extension to this deliverable as a result of COVID and as such, only a summary is presented here. The final deliverables to this Section will be presented to the BMBF later. At the date of presentation of this report, experiments are ongoing as is resultant data exploration. Therefore, only preliminary results are shows here.

7.2 GREENHOUSE MODEL EXPERIMENTS WITH 1M SUBSURFACE HORIZONTAL CONSTRUCTED WETLANDS

7.2.1 Materials and methods

The experiments were conducted in three 1m long horizontal subsurface wetlands placed in the greenhouse at the UFZ in Leipzig as shown in Figure 7.1. Two of these 1m systems were filled with an equal quantity of building rubble and macadamia nut shells mixed together. The third system was filled with gravel with a mean particle size of 6-8 mm, and this acted as a control CW. The results of the sieve analysis for the rubble are presented in Table 7.1. This filling matrix was selected to reduce the building costs by using easily accessible waste material as would typically be found in s'Swetla or in other similar locations. All three systems were similarly planted. The first half of the CW was planted with *Cyperus* species, whilst the second half of the system with *Zantedeschia aethiopica* (see Figure 7.2). Both species are endemic to South Africa and the *Zantedeschia* (Arum Lilies) can be harvested as an ornamental plant, which could provide an economic incentive to adopt and maintain the systems.

Small-scale constructed wetland
The 1m CWs were located inside a greenhouse at the Helmholtz Centre for Environmental Research – UFZ, in Leipzig Germany. The wetland dimensions were 1 m x 0.21 m x 0.15 m (L x H x W). The wetland consisted of one inlet port at the height of the gravel surface, 21cm from the base, and one outlet port 1.5 cm from the base of the bed. A syphon breaker was used at the wetland outlet for level control. PVC 90° 3-way ball valves were placed on the inlet and outlet lines for tracer injection and sampling. A schematic of the experimental setup is shown in Figure 7.3.

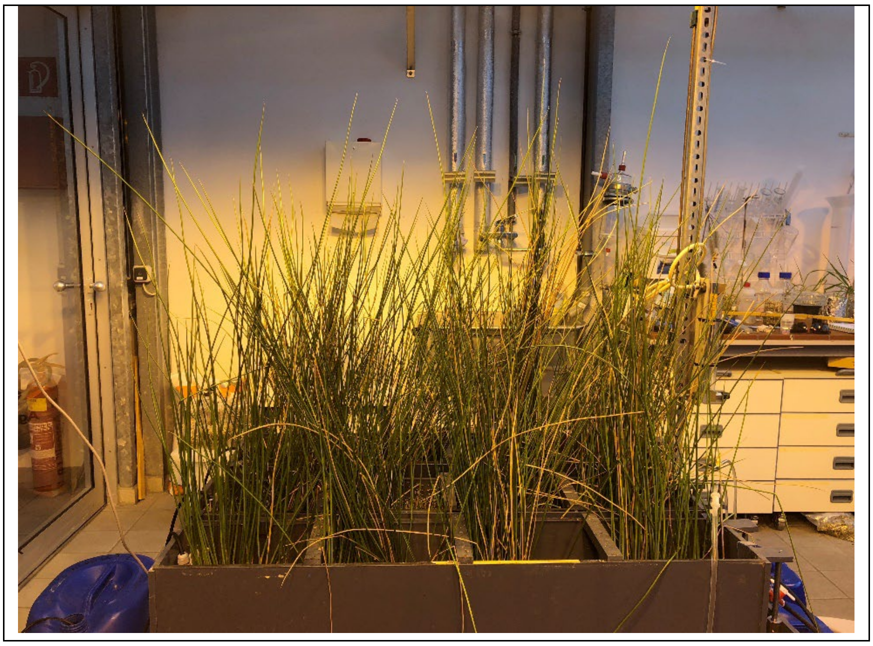

Figure 7.1. Picture of the HSSF CW on which impulse-response and step change tracer studies were conducted

Figure 7.2. Picture of the planted 1m systems showing the Arum Lilies

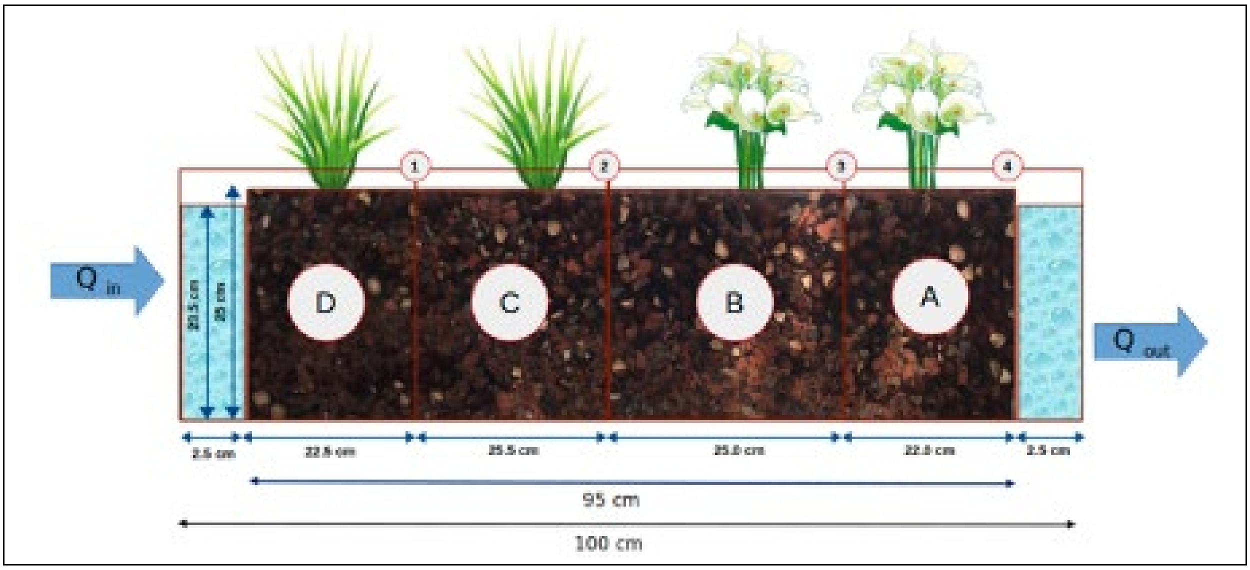

Figure 7.3. Schematic of the constructed wetlands: sampling points from 1 to 4, sections marked from A to D, planted with *Cyperus longus* in section D and C, planted with *Zantedeschia aethiopica* in section B and A

Table 7.1. Sieve analysis results of crushed building rubble

Class	Size	Mass fraction in class
1	s > 19 mm	11.664
2	16 mm < s <= 19 mm	15.41
3	13.2 mm < s <= 16 mm	7.967
4	9.5 mm < s <= 13.2 mm	17.796
5	6.7 mm < s <= 9.5 mm	9.8
6	3.35 mm < s <= 6.7 mm	11.886
7	2.36 mm < s <= 3.35 mm	4.543
8	0 mm < s <= 2.36 mm	20.933

A grab sample of greywater was taken from Langrug and s'Swetla in February 2019 as an initial screening for designing an artificial greywater in the laboratory. The results of screening of this water indicate that it is significantly different to the composition of greywater found in the Global North. For this reason, an artificial greywater was designed with the main constituents being starch and meat extract (or peptone) as the sources of carbon and ammonium. The recipe is given in Table 7.2. These compounds were weighed and added to tap water at the correct concentration. This mixture was autoclaved prior to laboratory usage.

Table 7.2. Recipe for artificial greywater based on initial screening

Compound	Concentration
Starch	2.5 g/L
Peptone	0.5 g/L
Sodium dihydrogen phosphate	113.3 mg/L
Ammonium chloride	78.9 mg/L

Based on the assumption of a highly used CW, the hydraulic retention time was set to three days (based on an assumed inflow of water). The experiments follow a statistical 2^2-factor experimental plan where the greywater strength was the main factor and the flow rate the second. The first factor was actively changed, and the second factor was monitored over time.

In contract to the established procedure for constructed wetlands where a longer adaptation phase of the system is recommended (Kadlec and Wallace, 2009) the 1m system was filled and operated with tap water for several weeks. After this short adaptation phase, the experiment using full-strength synthetic greywater was started.

7.2.2 Results

Phenomenologically, it was not surprisingly found that the plants died after a short time (within a month) and there was a strong odour emanating from the CWs. In the test phase with the 100% greywater load. An average depletion of the phosphate load of 93% occurred with an average effluent concentration of 6 mg/L of phosphate.

7.2.2.1 Carbon Removal

The analysis of TOC concentration along the flow section in the 1m system showed a continuous removal from approximately 650 mg/L at the inlet to 350$\pm$50 mg/L at the outlet. Random samples taken for COD analysis showed comparable behaviour, with a removal from 1800 mg COD/L to 520 mg COD/L at the outlet. This trend was similar for the entire test period.

After each phase of loading with greywater a so-called flush phase followed. For this phase, the inflow was tap water and this was designed to monitor the background behaviour. The physico-chemical data of these flush phases are to be analysed later, together with the sequencing data which will be submitted in a separate report to the BMBF upon completion of the project.

In the second year of the project, data were mainly collected from loading with a 50% strength artificial greywater while maintaining the theoretical residence time of 3 days. However, additional tests were carried out with a very high load (430 mg/L TOC) to simulate operation in s'Swetla, because there too it was observed that the high load was not controlled but rather came in pulses as and when discharge to the CW occurred. Thereafter from November 31, 2020, to January 7, 2021, the second flushing phase took place, where only tap water was used as feed. These flushing phases are intended to determine the system resilience after the greywater loading phase, which would approximate for a high stress loading of the system.

In Figure 7.4, the concentrations of dissolved organic carbon (DOC) are presented. These data are shown as examples for CW I and CW III – the CWs filled with crushed building rubble and macadamia nutshells. CW2 is the control which is not shown because behaviour was similar. In the graph, the solid lines represent the influent values with vertical lines indicating a change in the loading rate. The data triangles represent the measured values at the respective sampling location. The graph shows the chronology of loading – an initial loading with full strength greywater, followed by a flushing phase. This was followed by a 50% strength greywater followed by flushing and finally a high strength greywater was fed to the CW. In each case, the removal of dissolved organic carbon was highest at P1 (which is the first 25% of the CW).

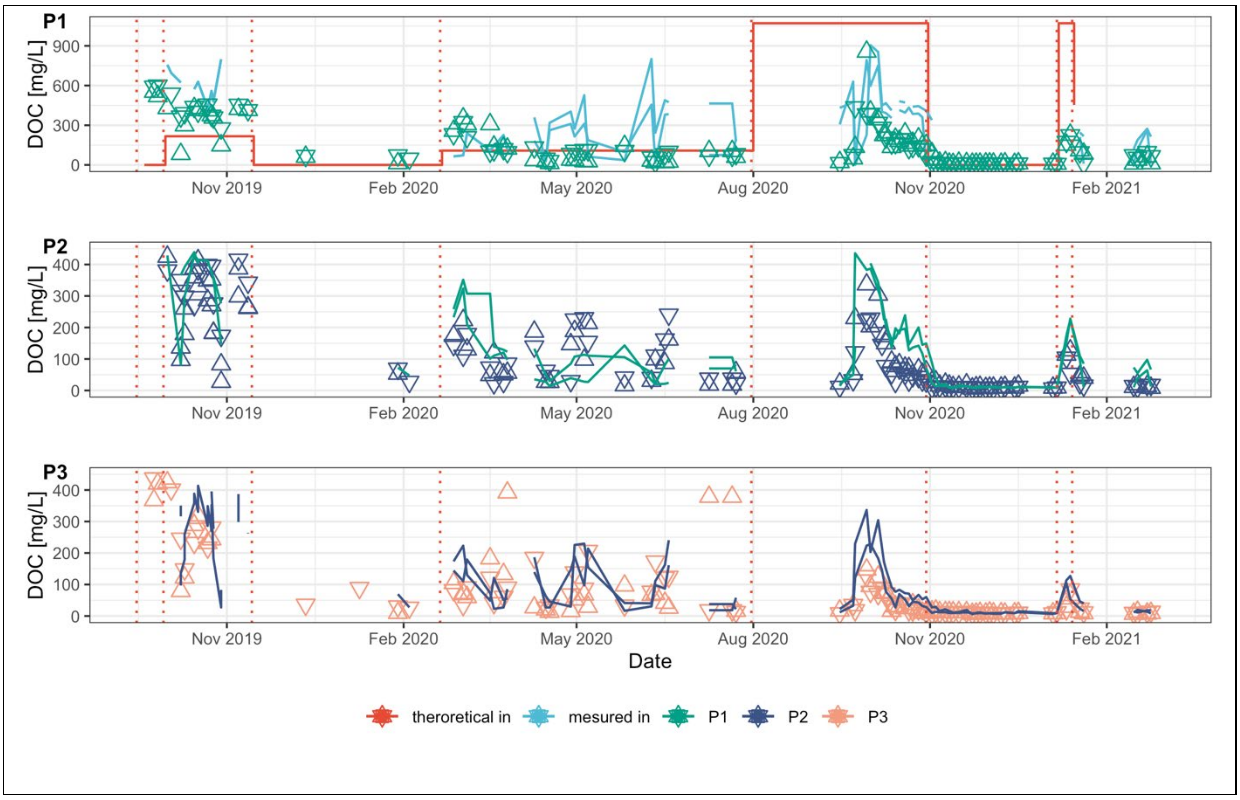

Figure 7.4. DOC values in CW I and CW III for the different measurement points within the bed compared to the respective inflow values. P1, the point is located 25 cm from the inlet, P2 in the middle of the bed between the areas planted with *Cyperus* and *Zantedeschia*. P3 is located 75 cm from the inflow. The solid line shows the inflow, this is always the measuring point before the actual one or for P1 the inflow into the CW.

An evaluation of the DOC efficiency during the entire experiment is compiled in Table 7.3. There was no significant difference between CW1 and CW3 during the loading with 100% greywater. In contrast, for the high strength loading phase there were observable differences in the removal rate between the CWs. One possible explanation could be the absence of an adaptation period. The sequencing results will also possibly explain some of the observed differences. When comparing the test series with each other, a higher removal efficiency during the late February 2021 high loading phase becomes apparent. This indicates the necessary adaptation time of the microbial community in the CWs as well as to the simple carbon sources used in the GW model recipe and/or for the establishment of sufficient plant biomass. It was found that in contrast to the 100% phase, which occurred relatively quickly after planting with a short adaptation period, a longer period of low loading had a positive effect on the resilience and tolerance of the overall CW to periods of very high loading. In addition, by planting during the late February 2021 the high load phase did not experience the adverse results seen in the 100% GW phase.

Table 7.3. Comparison of the DOC removal efficiency of the different laboratory CWs calculated from influent and effluent values of the stable flow periods

Greywater strength (Phase)	DOC Inflow (mg/L)	CW1 – DOC Removal (%)	CW3 – DOC Removal (%)	CW2 (Control) – DOC Removal (%)
100% Strength	293.9	49.4 ± 0.4%	48.8 ± 7.6%	48.8 ± 7.6%
High Strength (Feb 2021)	427.1	87.7 ± 9.6%	69.2 ± 13.3%	69 ± 13.3%
50% Strength	146.9	86.4 ± 5.6%	92.4 ± 1.3%	92.2 ± 1.3%
25% Strength	73.5	95.1 ± 4%	93.8 ± 3.4%	92.2 ± 4.3%

The long-term experiments with high loading (above the 100% strength of the synthetic greywater) were followed by an experiment with greywater at 25% strength. The results of the sampling of all three 1m systems for DOC are shown in Figure 7.5. It can be seen from these graphs that the behaviour in the beds (following the flow path) conformed to a classical horizontal constructed wetland concentration gradient. The highest removal was observed in the first 25% of the flow path through the CW (reactor).

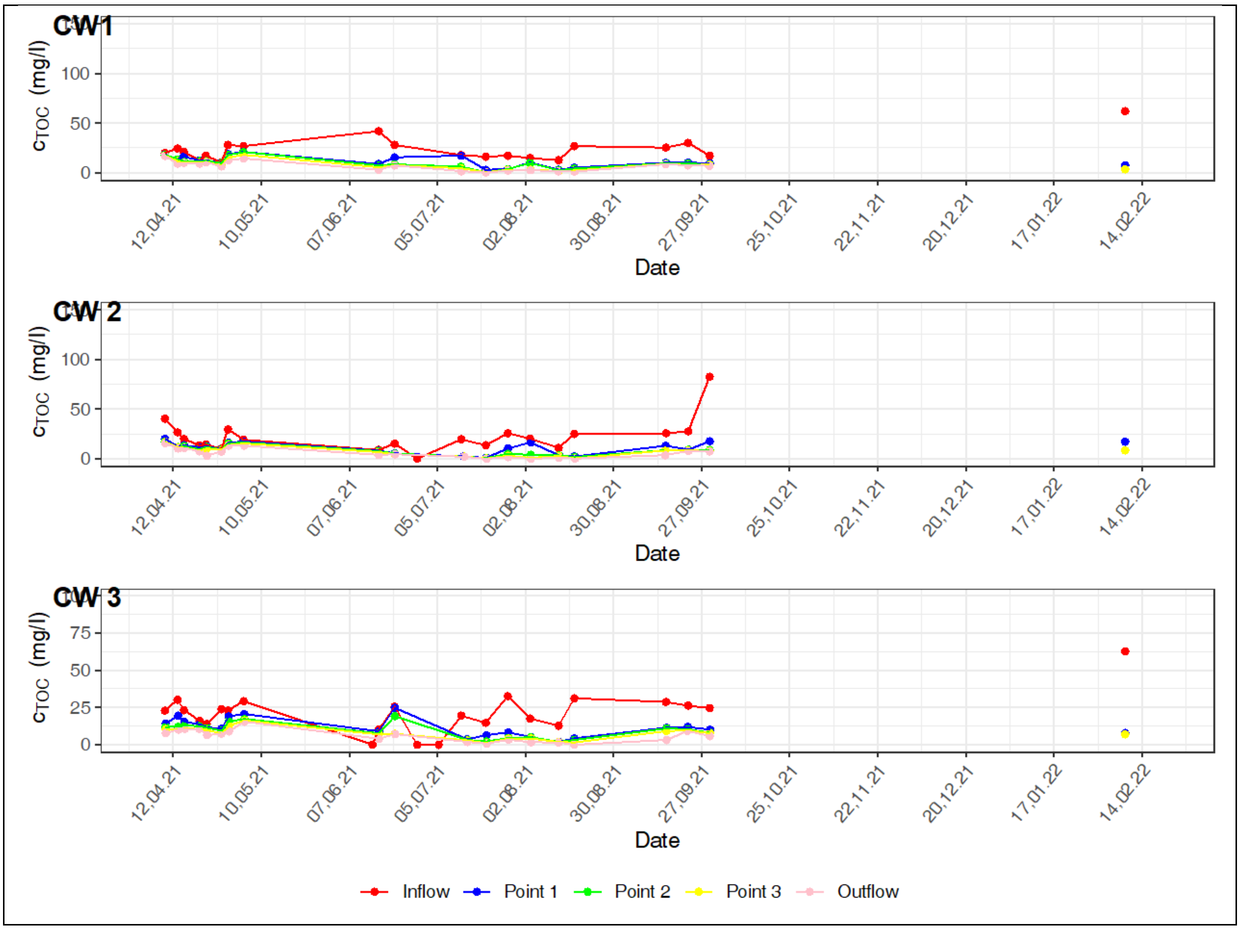

Figure 7.5. DOC values measured in 1m subsurface horizontal constructed wetlands operating under the 25% load.

For all three 1m small-scale lab-based wetlands, the classic behaviour of a horizontal flow constructed wetland was observed. The strongest decrease in concentration occurred initially, decreasing with increasing length.

To illustrate or compare the conversion in the first CW segment (one quarter of the bed length), Figure 7.6 shows the conversion rate versus the inflow concentration to this first segment (25% of the CW) over all test periods. It is the calculated reaction rate for this part of the bed and plotted against the inflow concentration of DOC for each of the wetlands. Two correlation lines are presented on the graph. For the short line, only the correlations up to and including 800 mg/L DOC are presented whilst the full dataset is used for the longer correlation line. Since they overlie each other, it is safe to assume that the behaviour is consistent across the entire data range. Further investigations of this over a wider range is ongoing. During all experimental loadings where samples were taken for chemical analysis, additional sample were taken to characterise the microbial community.

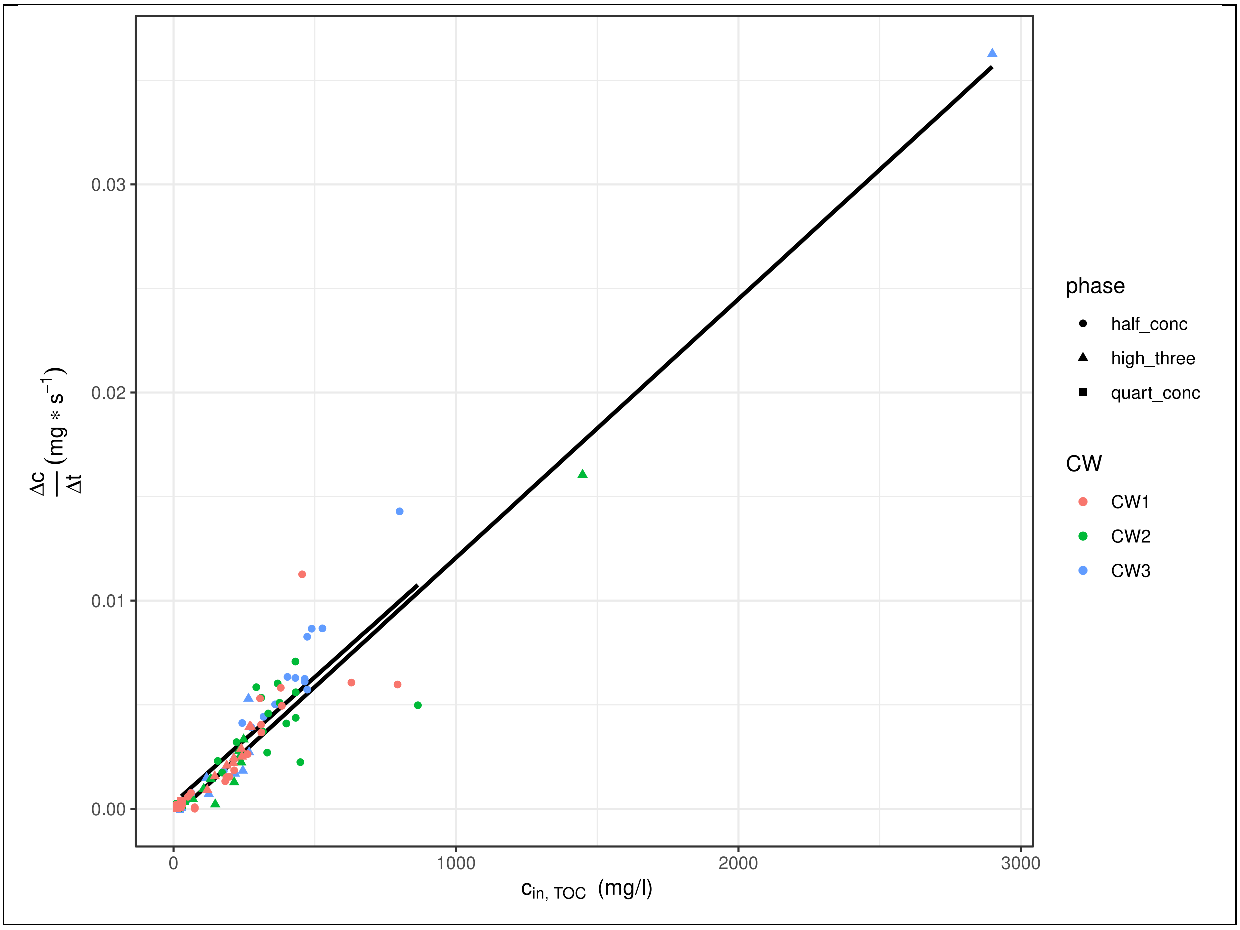

Figure 7.6. DOC turnover rate over all experimental periods for the area of the influent to the first sampling point of the three 1m systems

7.2.2.2 Nitrogen removal

Total dissolved nitrogen (TN) is used as a summative lumped parameter for ammonium, nitrate as well as organic nitrogen. This consideration of inorganic nitrogenous compounds is important because the study area drains towards the Jukskei River and thus adds to its (the Jukskei River) nutrient load.

Nitrogen removal for the 100% strength greywater was poor as shown in Table 7.4. This is a result of low adaptation time during the start-up period. Following the start-up, the CWs were loaded with high strength greywater and the removal for CW1 and CW3 was high (60% and 90%). The nitrogen removal efficiency of the control CW, on the other hand, was in the same order of magnitude as in the 100% greywater dosing phase, i.e. approximately 20%. Since the external conditions are similar with respect to the planting and inlet flowrates and concentrations, the difference can be hypothesised to be a result of action of an established microbial community (this has yet to be reported since the sequencing has not yet been done). For this reason, water samples and material samples were taken from the beds at the end of the different phases of the experiment to investigate the composition of the planktonic microbial community as well as that of the established biofilms from the material surfaces.

Table 7.4. Comparison of the TN removal efficiency of the different laboratory CWs calculated from influent and effluent values of the stable flow periods mg/L (percent removed

Greywater strength (Phase)	TN Inflow (mg/L)	CW1 – TN Removal (%)	CW3 – TN Removal (%)	CW2 (Control) – TN Removal (%)
100% Strength	22.5	0.0±0.02%	0.1 ± 0.1%	19.5±6.5%
High Strength (Feb 2021)	34.4	58.3±17.9%	87.2 ± 16.3%	22.5 ± 10.3%
50% Strength	11.2	86.9 ± 3.5%	90.2 ± 1.2%	90.1 ± 4.4%
25% Strength	5.6	62.3 ± 25%	45.9 ± 12.8%	68.5 ± 12.8%

The ammonium and nitrate concentrations in all CWs during the flush phase shows that where there was a longer washout from the bed, the concentrations returned to a background concentration of approximately 5.2 mg N/L for TN and 92 mg DOC/L.

7.3 MICROBIOME DATA

From the samples collected, DNA was extracted, the quality was checked (using 16S rDNA directed PCR) and they were preserved for further processing. These samples were taken from the existing CW (without any remaining living plants) at Langrug during the 2019 fieldwork campaign, from CW1 in s'Swetla and from all experiment using the 1m systems in the greenhouse. The column experiments operated at Linköping University (for WP5) were also sampled using a similar methodology as applied; DNA was also extracted and preserved for further processing after quality testing.

The 1m systems operated in the project at UFZ were sampled at the end of each experimental phase. The first sampling was done during the adaptation phase of the plants, with only tap water and a light fertilizer solution applied to the CWs. Subsequent sampling occurred at the end of each experimental phase. All samples were immediately extracted or preserved with a mixture of 50%strenght of 1:1 ethanol: Phosphate buffer solution. These were frozen until extraction was completed within one month of sampling. Extracted DNA was preserved after positive quality control (i.e. there was sufficient quantity of sufficient quality to use).

The chosen DNA extraction method (NucleoSpin Soil, Macherey-Nagel) allows sequencing in the so-called short-read protocol on an Illumina platform. However, long reads of at least some sample sets would be desirable for the preparation of a more detailed description of possible conversion pathways and taxonomic assignment.

Biofilm DNA from the nutshell surfaces, from gravel and from the rubble surfaces was separately extracted prior to DNA extraction of these samples. The planktonic bacteria DNA was separately extracted from the liquid samples. A preliminary analysis of the initial sequencing data from the column experiments, the Langrug Wetland and the 1m CWs is shown in Figure 7.7.

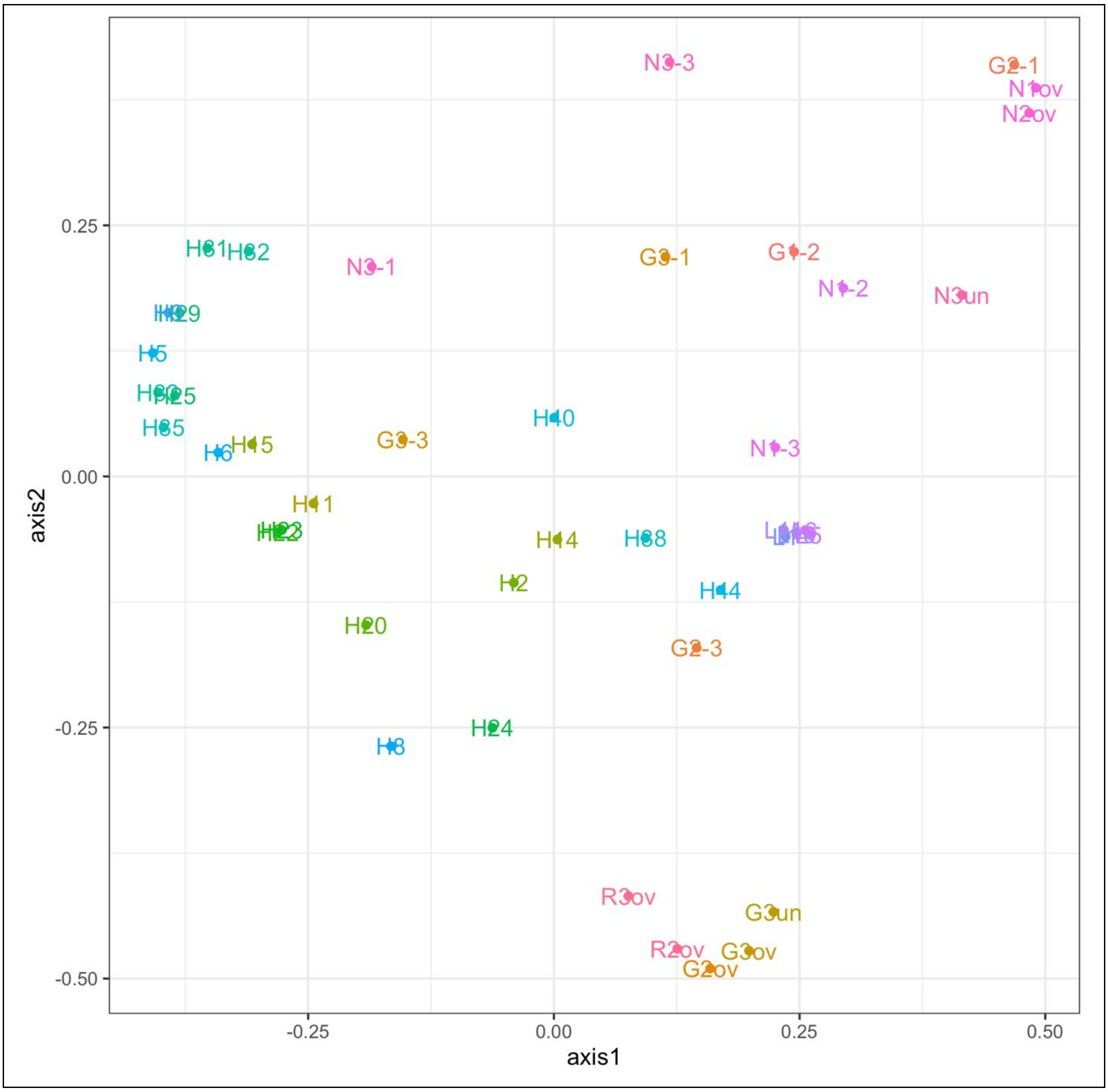

Figure 7.7. Preliminary results of a multifactor analysis (Nonmetric multidimensional scaling analysis – NMDS analysis) of previously sequenced samples from the column experiments, samples from Langrug and the 1m lab-scale test CWs

The first preliminary results of the NMDS based analysis of the 16S rDNA directed sequencing shows that the samples of the nutshell matrix of the CW (N[X]-[X]) cluster together with those of the nutshell filled column experiments (N[X]ov, N[X]un) of the Linköping University column experiments. Similarly, most of the bio-samples extracted from the gravel (G[X]ov, G[X]un) and rubble (R[X]ov, R[X]un) surfaces clustered together. The more widely distributed samples from the 1m systems in the greenhouse indicating again the ongoing adaptation of the biofilm. The samples from the Langrug CW form a close grouping (L[x]). A more detailed analysis for this experiment will follow on from sequencing of all preserved samples.

7.4 CONCLUSION

The lab-based experiments conducted in 1m long constructed wetlands show a removal of DOC and nitrogen over the flow path of the wetlands. There are indications that this type of systems needs an adaptation phase to establish the plant matter and microbial community to handle high-strength grey-water inflow.

The internal sample points along the flow path can be used show the typical gradient behaviour of constructed wetlands, where the highest transformation took place in the first sections of the wetland. The redox potential and first preliminary microbial community analyses show a more anaerobic dominated structure. This agrees with the observed sulfate reduction during high loading phases.

In contrast to the field CW the model systems received synthetic grey-water without any solids such as cloth fibres from washing, sand, etc. and the model system did not show any signs of clogging even after three years of operation in contrast to the CW(s) in s'Swetla.

A more detailed description of the microbial community and response of it to the changed inflow will be conducted after all sequences are generated.

CHAPTER 8: WORK PACKAGE 7 – COMMUNICATION AND DISSEMINATION

This Section has been taken from the Water JPI report. It details knowledge outputs, communication and dissemination activities. Knowledge outputs are given in Table 8.1. and are viewed as major findings from the grant and were disseminated.

Table 8.1. List of knowledge outputs of the project

I. Community water use and disposal habits in an informal settlement in Johannesburg	
Knowledge Output Description	Residents in SetSwetla collect water at communal taps, but disposal differs by water type. Water for home use is stored water in 20l buckets. Laundry is completed next to taps in 50-80l tubs. Postures during laundry were physically demanding. Crime and unemployment influenced the location and time of water disposal. The presence of CWs changed some of these behaviours for Silvertown residents. In the redesign of the CWs, raising the area around the taps increased making it physically easier to do laundry.
Knowledge Type	* Data
Link to Knowledge Output *If you can provide a link to the Knowledge Output then please do so, e.g. digital object identifier (DOI), web address, download, research paper.* *If the Knowledge Output is not publicly available currently but will be in the future, please provide details. Also, if it is available but only upon request, please state this.* *If the Knowledge Output is not planned to be publicly available, please state "Not available for public".*	In the future we plan to publish 2 other papers related to this output, and we have also applied for grant money to continue to delve deeper. Boitumelo Malunga, MA research report 2020: "Water usage and disposal in informal settlements" Hemal Jetha, MA research report 2022: "Adoption of constructed wetlands in informal settlements" The raw data cannot be open access published because this would not be in line with our ethics approval.
Sectors & Subsectors *Choose as many options as required from the list. Pick those sectors that you think would benefit from the application of this Knowledge Output.*	● Water Scarcity and Droughts ● Drinking Water ● Bathing Water ● Emissions and Water Reuse o Consumer Health & Welfare
End User *Choose as many options as required* *Per identified End User, please identify possible applications of the Knowledge Output.*	o Education & Training o Policy Makers / Decision Makers o Scientific Community o Civil Society o Other
IPR	n/a

Policy-Relevance If the Knowledge Output is relevant to the WFD or any other related Directives, please list and explain why	Knowledge of water use in this context could be valuable in determining policy decisions on water and sanitation provision by local and regional governments.
Status *Please identify whether the Knowledge Output is finalised, is still being generated or whose status/future is unknown. Consider:* • *Is your knowledge conclusive enough that it provides sufficient evidence to make an impact on, or be applied by, an End User?* • *Is there a corroborating body of evidence, or are contradictory results, available?* • *Does your knowledge progress beyond the current state-of-the-art / evidence base?* • *Is more research or demonstration needed to validate the results?*	Data collection is complete (but the second survey has not yet been analysed) and represents a relatively large sample size. We plan to write a scientific publication comparing the first and second surveys. As such this description of practices in informal settlements is an important contribution to scientists and managers who aim to improve service provision and environmental health in these areas. Still, given the high density and rapidly changing configuration of buildings, residents, and infrastructure, one must take care in using this output. Working with community members in real-time is important.

II. Impact of informal settlements on river water quality

Knowledge Output Description *Please only include generated Knowledge Outputs, not those that are expected. Note: Knowledge Outputs can be non-deliverables, milestones or 'grey knowledge'. Also, multiple Knowledge Outputs could exist within one deliverable, and should be separated.* *Try to give a comprehensive description, making the Knowledge Output fully understandable to a non-expert.* *If relevant please provide detail of where the Knowledge Output differs from its equivalent, e.g. What are the key characteristics of the Knowledge Output? What research is it adding to and what is innovative about the Knowledge Output? (Max 500 characters).*	Repeated sampling of Jukskei River upstream and downstream of Alexandra settlement in Joburg demonstrated a considerable decrease in water quality. As an example, the *E. coli* levels increase from a mean 1.82×10^7 to 2.11×10^9 over the Build 1 sampling period. The corresponding concentrations of COD increased from 61 mg/L to 70 mg/L. This clearly demonstrates the urgent need to deal with the issue of water disposal and leaking sewer systems in informal settlements to reduce health impacts of river water on humans exposed to it, and to restore the ecological integrity of river ecosystems.
Knowledge Type	Scientific publication (manuscript in preparation) Taraz Rawhani MSc Thesis Data to be submitted to JPI Open access platform.
Link to Knowledge Output	Scientific publication will be submitted to peer-reviewed scientific journal (Journal to be confirmed) MSc thesis available from Wits University WIRED Space

Sectors & Subsectors	• Basin Management
	• Water Scarcity and Droughts
	• Emissions and Water Reuse
	• Others
	  o Governance
	  o Consumer Health & Welfare
	  o Socio-Economics
	  o Stakeholder Involvement

End User *Choose as many options as required* *Per identified End User, please identify possible applications of the Knowledge Output.*	o *Education & Training* of the communities living along the river and in informal settlements o *Environmental Managers & Monitoring* o *Policy and Decision Makers* responsible for wastewater and river basin management o *Civil Society*
IPR	n/a
Policy-Relevance	• WFD as it focuses on river status and sources of pollution; • Urban Wastewater Directive as it highlights the need to manage uncontrolled discharge of wastewater streams;
Status	Knowledge output is conclusive enough to be used as a basis for policy makers to formulate a mitigation plan regarding wastewater infrastructure and management in informal settlements. It is content-wise finalised, but the scientific publication is still to be submitted.

III. Identifying informal community preferences with respect to greywater infrastructure

Knowledge Output Description	We have found that an iterative building process is valuable to provide multifunctional CWs that match the rapidly changing user and spatial context of informal settlements. Still, long-term maintenance of the systems is a challenge. In both Langrug and SetSwetla, residents would prefer for greywater and other liquid and solid wastes to be piped or tucked out by a 3rd party and treated elsewhere. However, the benefits of in-situ management systems were still viewed as a net-positive for many.
Knowledge Type	* Exploitable scientific result
Link to Knowledge Output *If you can provide a link to the Knowledge Output then please do so, e.g. digital object identifier (DOI), web address, download, research paper.* *If the Knowledge Output is not publicly available currently but will be in the future, please provide details. Also, if it is available but only upon request, please state this.* *If the Knowledge Output is not planned to be publicly available, please state "Not available for public".*	In the future we plan to publish 2 other papers about this output, and we have also applied for grant money to continue to delve deeper. Andiswa Mabusela, MSc dissertation 2022 https://doi.org/10.1080/00140139.2022.2068647 Article in review (#2 in the publication list below) The raw data cannot be published open access because this is not approved in our ethics application.
Sectors & Subsectors *Choose as many options as required from the list. Pick those sectors that you think would benefit from the application of this Knowledge Output.*	• Flood Risk Management • Water Scarcity and Droughts • Drinking Water • Bathing Water • Emissions and Water Reuse

	• Others o Governance o Consumer Health & Welfare o Finance o Socio-Economics o Stakeholder Involvement
End User *Choose as many options as required* *Per identified End User, please identify possible applications of the Knowledge Output.*	o Education & Training o Policy Makers / Decision Makers o Scientific Community o Civil Society o Other
IPR	n/a
Policy-Relevance If the Knowledge Output is relevant to the WFD or any other related Directives, please list and explain why	In a low-knowledge, highly volatile environment, we found that an iterative design process was necessary. A policy document on our iterative design process would be valuable for actors intervening in this environment.
Status *Please identify whether the Knowledge Output is finalised, is still being generated or whose status/future is unknown. Consider:* *• Is your knowledge conclusive enough that it provides sufficient evidence to make an impact on, or be applied by, an End User?* *• Is there a corroborating body of evidence, or are contradictory results, available?* *• Does your knowledge progress beyond the current state-of-the-art / evidence base?* *• Is more research or demonstration needed to validate the results?*	Data collection is complete and analysed. A scientific publication is currently under review for publication. We have applied for funding to write a policy document on the iterative design process. Funding would also be used to train end-users how to implement the iterative design process in their own contexts. There are limitations in the data gathering process as investigations have shown that further iterations are required to resolve the maintenance issues. Further, more research is required to determine whether the iterative design process can be replicated in other contexts and with other services in the same or similar contexts.

IV. Impact of intermittent greywater load on the treatment effect of a subsurface flow constructed wetland

Knowledge Output Description *Please only include generated Knowledge Outputs, not those that are expected. Note: Knowledge Outputs can be non-deliverables, milestones or 'grey knowledge'. Also, multiple Knowledge Outputs could exist within one deliverable, and should be separated.* *Try to give a comprehensive description, making the Knowledge Output fully understandable to a non-expert.* *If relevant please provide detail of where the Knowledge Output differs from its equivalent, e.g. What are the key characteristics of the Knowledge Output? What research is it adding to and what is innovative about the Knowledge Output? (Max 500 characters).*	Routine monitoring of model CW in greenhouse showed removal of COD and nitrogen competes from a continuous synthetic greywater inflow. Monitoring of a demonstration CW installed in S'Swetla also indicated removal pattern but due to the non-continuous inflow even at different points into the CW resulting in a nonpredictable flow and difficulties to recognize corresponding values. This clearly shows the need of a monitoring of the flow for better interpretation of removal efficiency of the system. Hence the high usage of a relatively small CW results in a visible overload with very limited removal efficiency. There is probably a negative impact of the non-pre-treated cloth washing water on the sludge accumulation throughout the CW.

Knowledge Type	* Exploitable scientific result – > intensive sampling weeks data * Scientific publication * Report * Data
Link to Knowledge Output *If you can provide a link to the Knowledge Output then please do so, e.g. digital object identifier (DOI), web address, download, research paper.* *If the Knowledge Output is not publicly available currently but will be in the future, please provide details. Also, if it is available but only upon request, please state this.* *If the Knowledge Output is not planned to be publicly available, please state "Not available for public".*	N/A
Sectors & Subsectors *Choose as many options as required from the list. Pick those sectors that you think would benefit from the application of this Knowledge Output.*	● Emissions and Water Reuse ● Adaptation to Global Change ● Scientific Community ● Others o Consumer Health & Welfare o Modelling & Prediction o Socio-Economics o Stakeholder Involvement
End User	o *Environmental Managers & Monitoring* Indicates the efficiency of CWs in this application o *Policy Makers / Decision Makers*. Indicates the efficiency of CWs as a basis for an action programme o *Scientific Community.* Shows the impact of intermittent loading on the functioning of CWs
IPR	n/a
Policy-Relevance	• WFD. The output indicates to what extent, and under what conditions, a subsurface CW can be used to treat diffuse sources of pollution from *e.g.* greywater disposal and occasional sewer overflows; • Urban Wastewater Directive as it highlights the need to manage uncontrolled discharge of wastewater streams;
Status *Please identify whether the Knowledge Output is finalised, is still being generated or whose status/future is unknown. Consider:* *• Is your knowledge conclusive enough that it provides sufficient evidence to make an impact on, or be applied by, an End User?* *• Is there a corroborating body of evidence, or are contradictory results, available?* *• Does your knowledge progress beyond the current state-of-the-art / evidence base?*	Ongoing data interpretation

• *Is more research or demonstration needed to validate the results?*

The list of publication outputs generated through the project are listed in Table 8.2.

Table 8.2. List of publications produced by the project

Audience	Type	Title
International	Peer-reviewed journals	1. Thatcher, A., Metson, G.S., Sepeng, M., 2022. Applying the sustainable system-of-systems framework: wastewater(s) in a rapidly urbanising South African settlement. Ergonomics 0, 1-26. https://doi.org/10.1080/00140139.2022.2068647 2. Davy, J., Todd, A, Metson, G.S., Thatcher, A., 2022. Designing a greywater treatment system in a highly adaptive urban environment: An ergonomics and human factors observational analysis. Urban Water Journal, under review 3. Bui, A, Tonderski, K., Sheridan, C.M. & Kappelmeyer, U., 2022. Removal of greywater organic carbon, nitrogen components, and sulfate along the flow path in Horizontal Subsurface Flow Constructed Wetlands with mixed waste material substrate. Ecological Engineering, submitted. 4. Sheridan, C.M., Kappelmeyer, U., Stephenson, R., Tonderski, K. Retention time response to greywater loaded on constructed wetlands with mixed waste material substrate. Manuscript in prep. 5. Metson, G., Thatcher, A. et al. Managing greywater infrastructure as a common resource – adaptation in Langrug informal settlement. Manuscript in prep. 6. Kappelmeyer, U., Sheridan, C.M. & Tonderski, K. Resilience of a constructed treatment wetland to load variations. Manuscript in prep. 7. Kappelmeyer, U., Sheridan, C.M. & Tonderski, K. Microbial community dynamics in pilot scale subsurface flow wetlands with mixed waste material substrate. Manuscript in prep. 8. Metson, G., Thatcher, A., Malunga, B. (2020). Water usage and disposal in informal settlements. Manuscript in prep. 9. Sheridan, C.M., Kappelmeyer, U., Metson, G., Thatcher, A. & Tonderski, K. Implementing greywater infrastructure and low-cost treatment systems in an informal settlement – experiences from an iterative implementation process. Manuscript in prep. 10. Kappelmeyer et al. Microbial community response to varying wastewater load in a pilot scale treatment wetland, Manuscript to be submitted in 2024.
	Books or chapters in books	11. Thatcher, A., Todd., A., Davy, J. & Metson, G. (2022). Ergonomics in the design of a greywater treatment system for an urban informal settlement. Proceedings

		of the Human Factors and Ergonomics Society Annual Meeting, 66(1), 1643-1647. Sage Publications, https://doi.org/10.1177/107118132266.
	Communications (presentations, posters)	12. Sheridan, C.M., Tonderski, K. & Kappelmeyer, U. 2019. URBWAT: Kick-off meeting at Water JPI; ANR, Paris, 5 February 2019. 13. Sheridan, C.M., Kappelmeyer, U, Metson, G. & Tonderski, K (2019) Water and Wastewater in South Africa. Satellite event, South Africa-Sweden University Forum, Johannesburg 6 May. 14. Kappelmeyer, U, Sheridan, C. M. & Tonderski, K. (2019) The use of constructed wetlands for remediating wastewater in South Africa, Satellite event, South Africa-Sweden University Forum, Johannesburg 7 May. 15. Metson, G. and Tonderski, K. (2019) Presentations in workshops at the South Africa-Sweden University Forum, 2^{nd} Research & Innovation Week, May 9. 16. Sheridan, C.M., Tonderski, K. & Kappelmeyer, U. 2019. URBWAT: Mid-term review meeting, online. 2019. 17. Thatcher, A. (2020). Uncovering sustainable system-of-systems elements in the design of a greywater treatment system for urban informal settlements. Presentation to Human Factors and Ergonomics Society Annual Meeting, Chicago, 6 October 2020. 18. Sheridan, C.M. (2022). Accessible greywater solutions for urban informal townships in SA: Lessons Learnt. Danish Strategic Sector Co-operation WSGO onsite follow up programme. 18 March 2022, Pretoria. 19. Kappelmeyer, U. Sheridan, C. M., Tonderski K. (2022) Greywater an Issue in Urban Slums – Collection and Treatment by Tailor made Constructed Wetlands. 17^{th} International Conference on Wetland Systems for Water Pollution Control, Lyon, France
National, South Africa	Books or chapters in books	20. Malunga, B. (2020) Water usage and disposal in informal Settlements. MA research report, University of Witwatersrand, South Africa. 21. Stephenson, R. (2021) Developing an advanced reactor model for complex, non-ideal reactors. PhD thesis, Univ. of Witwatersrand, Johannesburg 22. Rawhani, T. (2022) Efficacy and sustainability of constructed wetlands in treating wastewater arising in an urban informal settlement. MSc thesis, Geography department, University of Witwatersrand, South Africa (under examination) 23. Eyitayo-Ajayi, A. (2022). Exploring the use and disposal of water around Constructed Wetlands in SetSwetla. MA research report, University of Witwatersrand, South Africa. 24. Mabusela, A. (2022), TBC. MSc dissertation, Rhodes University, South Africa.

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<tr><td></td><td></td><td>25. Sebidi, K. (to be submitted 2023). Finding home in SetSwetla: a psychosocial narrative study of ‘belonging’ in a contested informal settlement in Johannesburg. MA research report, University of Witwatersrand, South Africa.
26. Jetha, H. (to be submitted in 2023). Adoption of constructed wetlands in informal settlements. MA research report, University of Witwatersrand, South Africa.</td></tr>
<tr><td></td><td>Communications (presentations, posters)</td><td>27. Thatcher, A. (2019). Sustainable greywater treatment in urban informal settlements. Keynote address at the South African Geography Teachers Association annual conference. Pretoria, South Africa, 21 June 2019.
28. Thatcher, A. (2021). Sustainable greywater treatment in urban informal settlements. Presentation at Rotary Rosebank, South Africa. 1 October 2021.</td></tr>
<tr><td rowspan="2">National, Germany</td><td>Books or chapters in books</td><td>29. Stein, K. Geoinformatics, Hochschule für Technik und Wirtschaft Dresden
30. Spasevski, H., Carnbrand, L. (2019). Investigation of new bed matrices and involved microbial community during greywater treatment in model constructed wetlands. LITH-IFM-A-EX-20/3751-SE, MSc Thesis, Engineering Biology, Linköping University.
31. Guez, C. (2020). Microbiota and water quality characteristics of constructed wetlands with different matrix materials. LITH-IFM-x-EX-20/3765-SE, MSc Thesis, Engineering Biology, Linköping University.
32. Kocababuç I. (2022) Investigation of microbial transformation in situ in a lab based constructed wetland by using a single-well, “push-pull” test. MSc Thesis, Faculty of Environmental Sciences Department of Hydro Sciences. TU Dresden
33. Schön, H. (2022) Examination of Hydrological Properties in Model Horizontal Subsurface Flow (HSSF) Constructed Wetlands Using Tracer Tests. BSc Thesis TH Bingen
34. Anaia Parada, J.L. (2023) Effect of pulse loading of constructed wetlands on treatment efficiency. M.Sc. Thesis, HTWK Leipzig.</td></tr>
<tr><td>Communications (presentations, posters)</td><td>35. Kappelmeyer, U.
36. Bui, A.</td></tr>
<tr><td></td><td>Books or chapters in books</td><td>37. Spasevski, H., Carnbrand, L. (2019). Investigation of new bed matrices and involved microbial community during greywater treatment in model constructed wetlands. LITH-IFM-A-EX-20/3751-SE, MSc Thesis, Engineering Biology, Linköping University.
38. Guez-Guez, C. (2020). Microbiota and water quality characteristics of constructed wetlands with different matrix materials. LITH-IFM-x-EX-20/3765-SE, MSc Thesis, Engineering Biology, Linköping University.</td></tr>
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National, Sweden		39. Stenlund, E. (2021). Greywater treatment in wetlands. Comparison of scaled-down constructed wetland experiments with kinetic models. LITH-IFM-A-EX--21/3928-SE, MSc thesis, Engineering Biology, Linköping University
	Communications (presentations, posters)	40. Wetlands to purify water in South African informal townships. News post, Linköping University March 4, 2019.
		41. Metson, G.S. & Tonderski, K. (2022). Green infrastructure in informal settlements – working in Johannesburg South Africa to tackle greywater management. Africa Seminar as part of the Linköping University Prioritized Geographical Resources Seminar Series, Oct 24, 2022, Linköping, Sweden
Dissemination initiatives	Popularization articles	42. Artificial Swamp to deal with greywater. 12 Fe 2021. https://www.iol.co.za/undefined/artificial-swamps-to-deal-with-grey-water-19256248
		43. Wits calls for Climate Justice, October 2021. https://www.iol.co.za/news/partnered/wits-calls-for-climate-justice-62d8b7e2-37d0-43e2-b792-5f31d496b5a4
		44. Clean water solutions made possible for Alex informal settlement through water-based research, November 2022. https://www.wits.ac.za/news/latest-news/general-news/2022/2022-11/clean-water-solutions-made-possible-for-alex-informal-settlement-through-water-based-research.html
	Popularization conferences	45. Sheridan, C., Metson, G., Thatcher, A., Tonderski, K. (2022) Joburg URB-Water project, Stakeholder presentation & feedback. Main Metro Building, Braamfontein, Joburg, October 21.
		46. Sheridan, C., Metson, G., Thatcher, A., Tonderski, K. (2022) Joburg URB-Water project, Community presentation & feedback workshop. Setswetla, Joburg, October 24.
	Others	47. When the Water Flows in Alex. Wits News. 9 February 2019. https://www.wits.ac.za/news/latest-news/research-news/2019/2019-02/when-the-water-flows-in-alex.html
		48. Sheridan, C.M., Radio interview with David o' Sullivan, 21 February 2019. Kaya FM.
		49. Sheridan, C.M. Radio Interview with Iman Rappetti (Power Talk with Iman Rappetti) on Power FM, 25 March 2019.
		50. Thatcher, A. (2019, September). Sustainable greywater treatment in urban informal settlements, Presented to the BRICS+ meeting, Xi'an, China, 1 September 2019.
		51. Thatcher, A. (2020, June). Sustainable greywater treatment in urban informal settlements. Presented to geography students at St John's College, Johannesburg, 22 June 2020.

52. Thatcher, A. (2020, December). Designing sustainable greywater treatment systems in urban informal settlements, Presented to industrial design students at the National University of Colombia, 2 December 2020.
53. Sustainability in higher education: clean water with the University of the Witwatersrand. Article written by QS. https://www.qs.com/sustainability-in-higher-education-clean-water-with-the-university-of-the-witwatersrand/
54. Clean water solutions made possible for Alex informal settlement through water-based research. Wits News. 11 November 2022. https://www.wits.ac.za/news/latest-news/general-news/2022/2022-11/clean-water-solutions-made-possible-for-alex-informal-settlement-through-water-based-research.html

In addition to this publication output, the following students/researchers have been or are currently working on the projects as shown in Table 8.3. They have/will generate these which will be deposited in institutional online repositories.

Table 8.3. List of students working on the project

Name	Degree field	Deg.	Dissertation/Thesis title	Country.
Stephenson, R	Chemical Engineering	Ph.D.	Developing an advanced reactor model for complex, non-ideal reactors	ZAF
Sepeng, M	Geography	Ph.D.	To be confirmed	ZAF
Bui, A	Environmental engineering	Ph.D.	To be confirmed	DEU
Eyitayo-Ajayi, A	Organisation. psychology	MA	Exploring the use and disposal of water around Constructed Wetlands in Setswetla.	ZAF
Mabusela, A	Ergonomics	M.Sc.	Using human factors and ergonomics to explore the use and disposal of greywater around constructed wetlands in Setswetla.	ZAF
Sebidi, K	Clinical psychology	M.A. in 2023	Finding home in Setswetla: a psychosocial narrative study of ‘belonging’ in a contested informal settlement in Johannesburg.	ZAF
Jetha, H.	Organisation. psychology	M.A. in 2023	Adoption of constructed wetlands in informal settlements	ZAF
Spasevski, H. & Carnbrand, L.	Engineering Biology	M.Sc.	Investigation of new bed matrices and involved microbial community during greywater treatment in model constructed wetlands.	SWE/DEU
Guez, C	Engineering Biology	M.Sc.	Microbiota and water quality characteristics of constructed wetlands with different matrix materials	SWE/ DEU

Stenlund, E	Engineering Biology	M.Sc.	Greywater treatment in wetlands – Comparison of scaled-down constructed wetland experiments with kinetic models	SWE/ DEU
Csizmadia, E	Environmental Engineering	M.Sc.	Method development and detection of various chemicals in constructed wetlands	DEU
Kocababuç, I	Hydro Sciences	M.Sc.	Investigation of microbial transformation in situ in a lab based constructed wetland by using a single-well, “push-pull” test.	DEU
Anaia Parada, J L	Environmental Engineering	M.Sc. in 2023	Effect of pulse loading of constructed wetlands on treatment efficiency.	DEU
Rawhani, T	Geography	M.Sc.	The efficacy and sustainability of constructed wetlands in treating wastewater arising in an urban informal settlement	ZAF
Malunga, B	Organisational psychology	M.A.	Water usage and disposal in informal Settlements.	ZAF
Meissner, M	Environmental Engineering	Internship.		DEU
Schön, H	Environmental Protection	B.Sc. / Internship.	Examination of Hydrological Properties in Model Horizontal Subsurface Flow (HSSF) Constructed Wetlands Using Tracer Tests.	DEU
Rawhani, T	Chemical Engineering	B.Sc.	N/A 4th year project.	ZAF
Van der Merwe, S	Interdisciplinary studies: global change institute	Q. Res. assist		ZAF

CHAPTER 9: CONCLUSIONS & RECOMMENDATIONS

9.1 CONCLUSIONS

This project had both positive and negative results and impacts. These are described further here.

9.1.1 Positive impacts/findings.

1. It is possible to design, build and implement greywater treatment wetlands for in-situ remediation in an urban shanty context. As many other reports detailing work in this kind of context, it is critical to work with local people for there to be any chance of project success. Furthermore, these CWs can remove COD, *E. Coli* and other constituents of greywater. Whilst this is a positive outcome, the exact extent of remediation is still not fully known.
2. The measurement of greywater sampled in this study very clearly shows that greywater in this context is very different to greywater as would be discussed in the literature, emanating from the Global North.
3. By conducting an ergonomic study, the stresses and difficulties involved in carrying and moving washing water were minimised for the users of this CW. This data was very useful for enhancing the design of the system. This would have helped to reduced back injury risks from excessive stooping postures during washing
4. It might be necessary to follow an iterative design process to optimise usage in these systems, especially through considering point 3. There is, however, a risk in this optimisation that the system may be overwhelmed through excessive usage. This was a key finding of ours. This could probably be remedied by building many additional CWs.
5. Through our revised design, we incorporated a raised wash area, and flood control wall (which acted as raised walkways) to the CWs. This meant that the CW prevented sewage and stormwater from impacting the residents downhill from our location. The CWs were also redesigned to incorporate a community washing area. This had the additional benefit of further developing goodwill and engagement between the project team and the residents.
6. The project had a strong educational impact on the residents of s'Swetla informing on the risks of greywater to people.

9.1.2 Negative impacts/findings.

1. By enhancing the design, we increased greywater loading on the CWs to the point that they were unable to effect remediation. This is a result of reducing the residence time. Essentially, the project became a victim of its own success.
2. Flow measurement is a critical (yet missing) element of this project. The type of settlement within which we built the CWs is highly dynamic and there was a lot of interaction by the local people with the CW. Visible flow measurement devices are therefore not an option and thus the total volume of greywater flowing through the CW is still unknown.
3. As a result of the excessive usage, the CWs were accumulating sludge rapidly, which means that as they currently operate, they need gravel washing and replacement every few months. This implies that they are currently not a low-maintenance solution. The clogging could also be a result of non-biodegradable solids (such as nylon cloth fibres, sand, etc.) entering the system. This component of the design needs further study.
4. The unplanned and chaotic way in water is redistributed from municipal taps poses a risk that any system will not have water following its installation.

5. The maintenance of the CWs needs a clear line of responsibility and needs the energy (of people) to enact it. This is a broader societal challenge in South Africa; however, it was very clearly observed in this project.
6. Finally, service delivery failures are an ongoing challenge. The sewage overflow into s'Swetla for four months without intervention caused total failure of the one CW.

The URBWAT project has succeeded in its goals of conducting this research, even though some of the research is ongoing. Some thoughts for future work are presented in Section 9.2.

9.2 RECOMMENDATIONS

The overall results indicated that a community intervention process leading to provision of an improved greywater infrastructure including constructed wetlands within an urban informal settlement (slum) is a viable approach to manage greywater runoff emanating from these environments. Future work to develop the research further could consider:

- To further develop iterative building and design methodologies and systems for greywater management in informal settlement to address the knowledge gaps.
- To develop a small, concealed flowmeter for these types of systems. The technology available to do this (at low cost) has finally become available. This will help researchers to better understand processes within CWs in these contexts.
- To continue to test and characterise the feed water (grey, black, other chemicals of concern and emerging contaminants) to further our understanding of what greywater in this context is comprised of.
- To further our understanding of these systems by accounting for black-, storm-, and sewer water in the design.
- To conduct research to find ways for regular maintenance or to reduce the maintenance needs.
- To provide a tool or guidelines for developing bespoke iterative building with community members.
- To develop guidelines (i.e. a policy brief) for policymakers on how to design, build, measure and manage these types of systems for deployment in contexts where housing is implemented in an unplanned way.

The project team has started the processes of applying for further funding to address these recommendations.

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