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Pathways to water resilient South African cities – from mono-functional to multi-functional stormwater infrastructure

Julia Mclachlan[a], Craig T. Tanyanyiwa[a], Rachelle Schneuwly[a], Kirsty Carden[a,*], Neil P. Armitage[a], Amber Abrams[a], Patience Mguni[b], Lise Byskov Herslund[b]

[a] Future Water Research Institute, University of Cape Town, P. Bag X3, Rondebosch 7701, South Africa
[b] Department of Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsveg 23, Frederiksberg, Copenhagen, Denmark

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A B S T R A C T

In light of rapid population growth and climate-change pressures on water resources, there is an urgent need in many African cities to shift to more resilient, decentralised, nature-based approaches. In response, the City of Cape Town's Water Strategy document proposes various alternative water supply sources. One is Managed Aquifer Recharge (MAR) using the Cape Flats Aquifer (CFA). Overlying the CFA are a significant number of stormwater ponds that were originally designed solely to prevent flooding. These ponds could be retrofitted to infiltrate stormwater run-off, recharging the aquifer and serving a water treatment function using nature-based approaches. Many of these mono-functional ponds are in neighbourhoods that are socio-economically disadvantaged through former apartheid spatial planning. These ponds are frequently litter-filled, used for dumping rubble and, on occasion, occupied with informal housing. It is in this context that the conversion of engineered single-purpose stormwater ponds into multi-functional space is proposed using a demonstration site in Mitchells Plain, Cape Town. The 'Pathways to water resilient South African cities (PaWS)' project is a collaboration between the Future Water Institute at the University of Cape Town (UCT) and University of Copenhagen (UCPH), funded through DANIDA. This research is revealing how maximum benefit could be derived from these water management systems by adopting low-cost, easy to install blue-green interventions that rely on nature-based approaches. The findings from the research have relevance across Southern Africa where several large cities have existing stormwater ponds designed for flood control or as passive open green spaces. It offers valuable strategies for how these single-purpose ponds can be transformed into multifunctional blue-green spaces in ways that build resilience while addressing the environmental injustice that is a legacy of South Africa's 'green apartheid'.

* Corresponding author.
E-mail address: Kirsty.carden@uct.ac.za (K. Carden).

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Introduction

Water scarcity is a major concern for African cities, where rapid population growth and water-related climate pressures such as the 2015–2018 drought in Cape Town, South Africa are growing. There is an urgent need to shift to more resilient approaches that combine centralised water networks such as dams and reservoirs, with more decentralised, localised nature-based or blue-green options. As part of a pursuit towards greater resilience in the face of increasing impacts of climate change, the City of Cape Town has developed a Water Strategy document that sets out its approach to unlocking alternative water supplies and becoming a Water Sensitive City (City of Cape Town, 2020). Strategies include Managed Aquifer Recharge (MAR) of the Cape Flats Aquifer (CFA) – a ~630 km^2 expanse of relatively coarse sand up to 55 m thick [1] capable of storing considerable volumes of water prior to its ultimate discharge into False Bay. The CFA is replenished through rainwater, sewer, and water reticulation pipe leaks. Extensive urban development over the CFA has increasingly resulted in runoff being directed into a growing stormwater management system comprised largely of concrete pipes and conduits that convey the water to nearby rivers and ultimately the sea.

In many South African cities, stormwater ponds – including both dry detention ponds and wet retention ponds, form part of the urban stormwater management system. Within the City of Cape Town boundaries, there are over 800 of these ponds. They are largely mono-functional, specifically engineered to delay and detain stormwater thereby preventing flooding in built-up areas during storm events. Approximately 280 of these ponds occur in the Cape Flats, a low-lying sandy area overlying the CFA, and have the unexplored potential to offer other water management roles through the use of nature-based approaches, such as enabling stormwater to seep into the ground and recharge the aquifer below for later abstraction via boreholes. This approach potentially supplements the city's water supply, with the additional benefits of reducing pollution levels downstream. Such ponds also offer opportunities for developing multifunctional landscapes that can support human wellbeing and amenity needs in local neighbourhoods.

South African cities face numerous socio-economic, cultural and political challenges such as issues of spatial and economic inequality that reinforce poverty, often haunted by unresolved apartheid spatial planning decisions [2,17]. As with many cities of the global south, Cape Town faces immense challenges in the delivery of basic necessities such as water, food and jobs, creating extreme inequality. Coupled with this is the constrained capacity of municipalities in delivering essential services and infrastructure to city residents. Furthermore, as is true worldwide, stormwater itself is polluted with various contaminants such as solid waste, heavy metals, nutrients, and organic matter. If issues of stormwater quality are not addressed, such contaminants move widely through the lived environment and local ecosystems. The stormwater detention ponds that are key to overall stormwater management systems are often perceived as vacant land. In most cases they are open spaces, with little visible infrastructure and thus often become vulnerable to illegal dumping and have been known to be settled. When these spaces become occupied by informal housing, they can no longer serve the purpose of stormwater attenuation. Relatedly, as they remain vacant, or become inhabited informally, these spaces often in turn become regarded as unsafe spaces by local residents.

It is in this context that the conversion of engineered single-purpose stormwater ponds into multi-functional space is proposed. This involves moving away from conventional stormwater infrastructure – which has only one main function (i.e., flood control) – towards multi-functional stormwater ponds as blue-green infrastructure. These multi-purpose spaces can provide a range of water-related, biodiversity and amenity functions that can play an important role in many previously disadvantaged areas, still characterised by a form of 'green apartheid'; i.e., where urban green infrastructure is unequally distributed across income and race geographies [3].

Whilst the need is clear, what remains uncertain is how these nature-based hybrid transformation strategies could practically be realised, implemented, integrated, and managed within existing urban governance structures and the socio-economic context of global south cities such as Cape Town. There is a dearth of research that demonstrates best practice in this regard – in particular around the challenges of urban MAR using stormwater in such a difficult environment. One significant challenge is the building of supportive institutional structures that promote a new approach such as this. It is thus vital to develop the evidence base for place-specific resilience-building initiatives through engaging in physical and governance experimentation in cities [4].

The 'Pathways to water resilient South African cities (PaWS)' project is a collaboration between the Future Water Institute at the University of Cape Town (UCT) and the University of Copenhagen (UCPH) - to explore what could be done to make South African cities more resilient to water scarcity whilst simultaneously being more 'liveable', particularly for the urban poor. The PaWS project, funded through Danida by the Danish Ministry of Foreign Affairs, is focused on identifying opportunities for, and generating knowledge on, the physical and institutional integration of decentralised nature-based approaches into the urban water cycle to support and accelerate a transition towards water resilience in South African cities. *Inter alia*, the research considers the conversion of engineered single-purpose stormwater ponds into multi-functional spaces in the context of Cape Town's commitment to transition towards a water sensitive future [5]. The project seeks to address the overarching question:

*What are the challenges and the potential for repurposing existing flood control infrastructure (*viz. *stormwater ponds) in Cape Town as multifunctional blue-green infrastructure to allow for the harvesting and treatment of contaminated surface runoff through managed aquifer recharge?*

To do this, the PaWS project has adopted a transdisciplinary approach with UCT and UCPH-based researchers on the project bringing a range of disciplinary perspectives to the research, including Civil Engineering, Environmental Science,

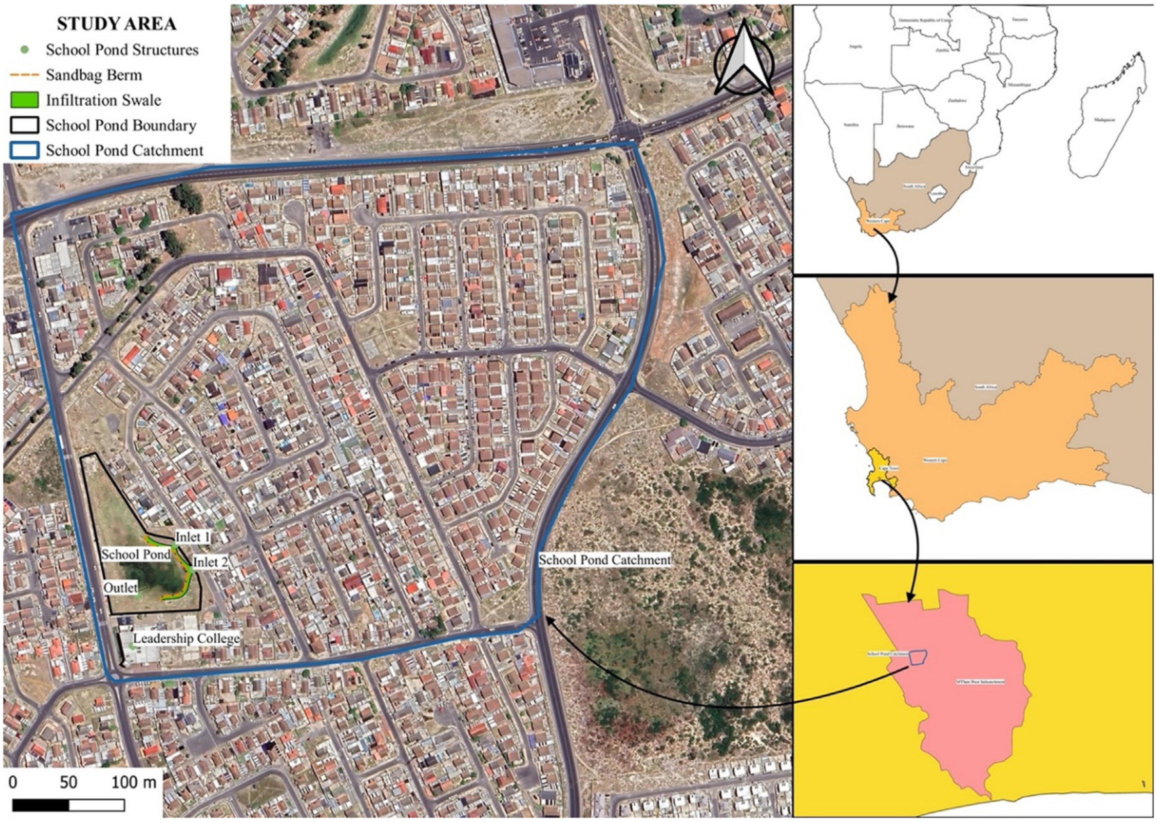

Fig. 1. Location of site, Fulham Rd, Mitchells Plain Cape Town, South Africa.

Chemistry, Landscape Architecture, Environmental Anthropology, and Public Health. Together with the involvement of local residents in a collaborative and co-created approach, the research combines physical experimentation and social engagement at a local pond scale – a stormwater pond on Fulham Rd in Mitchells Plain, Cape Town.

The project research is expanded on in the sections below. Section 2 sets out the methods adopted to investigate the selected study site. The physical experimentation includes design and construction of the pond retrofit, evaluation of aquifer recharge under different scenarios and evaluation of the water quality and treatment potential. Section 2 also discusses methods used for determining how local residents and other stakeholders view such an intervention – and expands on active engagement activities conducted to cocreate a locally acceptable space, in the hope that similar interventions could be rolled out across the city. Section 3 discusses the results and findings, and then considers the broader implications of such an approach going forward. We argue, drawing on provisional findings, that stormwater ponds offer considerable potential as multi-functional blue-green infrastructure; as spaces that can simultaneously prevent flooding, harvest stormwater to supplement the city's water supply, and offer local residents safe, secure green spaces.

Methods

A stormwater pond was selected as an experimental site in consultation with the City of Cape Town's Catchment, Stormwater and River Management Branch, their groundwater management consultants, Umvoto, and the local community. The pond (the 'School Pond') lies along Fulham Rd in Mitchells Plain (Fig. 1), a low-to-middle income neighbourhood in Cape Town that was conceived in the 1970′s according to apartheid spatial planning ideologies. The legacy of this planning approach of racial segregation persists today, with areas like Mitchell's Plain continuing to experience limited access to resources and opportunities, included limited recreational green spaces. The area in which the pond is situated is a residential neighbourhood of mostly single-storey houses on small ($\sim$300 m^2) plots in close proximity to two primary schools, one of which borders the site.

The School Pond is similar to many other ponds situated over the CFA that are engineered to reduce flooding in this predominantly winter-rainfall area. In appearance, these ponds are excavated basins, connected to a trunk/main stormwater system by inlets and outlets. Stormwater runoff is directed to these ponds via a piped stormwater network. It is detained in these ponds for a few hours, depending on the severity of the storm, and slowly released to the downstream stormwater

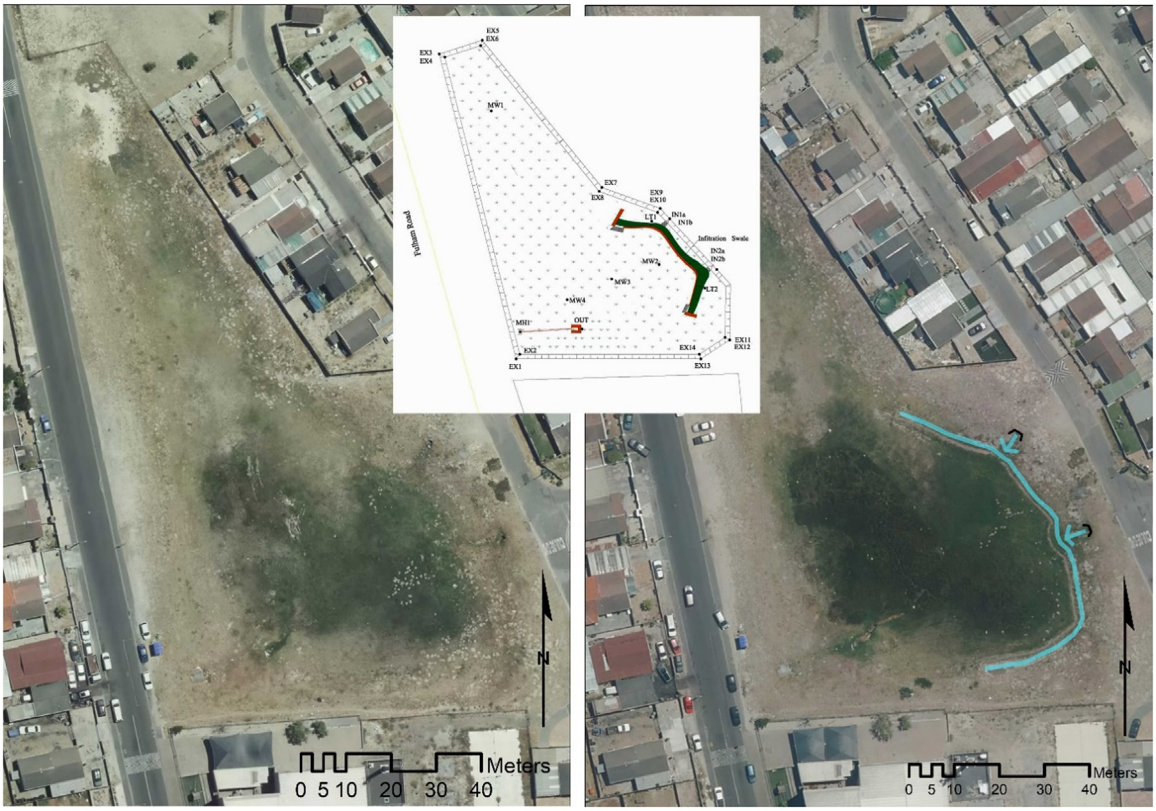

Fig. 2. Aerial image of stormwater pond site before (left) and after (right) construction works, showing outline of completed trench and sandbag wall, positioned to intercept the stormwater inlets based on the technical design (central image) (Sources: CoCT GIS dataset; C. Tanyanyiwa).

conduits, leaving the pond to dry out between storm events. This mitigates flooding by extending the flow periods – thus reducing the downstream peak flows – following large storms.

The research adopted a nature-based approach, retrofitting the pond such that it could become part of a blue-green infrastructure network that uses natural processes to recharge the aquifer and provide additional benefits like water quality improvement and amenity. The project's design is inspired by social learning processes and transition management methodology [6] building on the growing adoption of sustainable urban water management approaches in SA cities [7,8], wherein the momentum for transformation towards sustainability through decentralized water management systems is facilitated by both technological (i.e., physical) and governance innovation. Such efforts together work towards hybridizing conventional water management infrastructure with nature-based approaches.

Physical experimentation

The physical experimentation component of the research involved design and construction of an infiltration trench and sandbag wall at the stormwater pond and subsequent evaluation of the aquifer recharge and water quality improvement potential of the retrofitted infrastructure.

Infiltration trench and sandbag wall design and construction

A technical design was developed that incorporated an infiltration trench and weir walls to determine if stormwater ponds can be adapted to increase infiltration for aquifer recharge (Fig. 2). Though the construction activities were impeded by the COVID-19 pandemic, site work commenced in August 2021 with the consent of local residents and community leaders. Local residents formed themselves into teams of workers to construct the retrofit elements with the assistance of a contractor who specialised in non-concrete, labour-based forms of building – in this case, through the use of sandbag construction.

The School Pond was retrofitted to incorporate an infiltration trench behind a low impermeable wall, 90 m long by 450 mm high, constructed along a contour in front of the two stormwater inlets. The wall incorporated a vertical sheet of reinforced uPVC held in place by the sandbags and capped with reinstated grass sods. This technical design approach maximised the groundwater recharging volume while ensuring that the pond maintained its primary function of managing stormwater discharges from the local drainage network during storms.

Fig. 3. The stormwater pond retrofit illustrating the different components.

Material for the sandbag wall was secured from the upgradient side which, given the relatively steep slope, resulted in the effective creation of an infiltration 'trench'. Ideally, a larger infiltration area should be created but could not be achieved in this instance owing to the high-water table beneath the site. This low-tech intervention using sandbags, amongst others, was intended to be simple, enabling local resident groups to participate in its construction after a short training program and using locally resourced materials as far as was possible.

The construction also included the stabilisation of the areas in front of the inlets through the placing of rip-rap (small angular rocks) on a geofabric, the creation of enlarged level areas (forebays) after this to further dissipate the energy of the inflow, and the use of small, loose rock check dams as litter traps on either side of the forebays. The construction was completed over a period of 4–5 weeks with most of the work being completed by September 2021 (Fig. 3).

Evaluation of aquifer recharge

Field and laboratory experiments measured the flow and quality of the stormwater through the system. Automated data logging equipment could not be installed at the site owing to the high risk of theft. Therefore, the flow into the pond could only be physically recorded for selected storm events in the presence of the researchers. A calibrated and validated surface and groundwater (geo-hydraulic) model was developed using PCSWMM software. The model was used to simulate the hydraulic processes in the catchment area and within the pond. The groundwater levels (measured in monitoring wells, see below) were also used in the PCSWMM model for calibration and as input data for simulating the MAR in the pond. The model was then used to establish the inflow and infiltrated volumes (MAR) using rainfall and temperature data obtained from the South African Weather Services and an internet-linked weather station that was installed at the adjacent school.

Evaluation of water quality and treatment potential

Field monitoring of groundwater quality was conducted every 2 to 4 weeks for 1 year and were used to evaluate the water quality changes in response to seasons and rainfall. Laboratory column experiments were used to determine possible treatment during recharge through the unsaturated soil and treatment in saturated zones.

The column study comprised 6 $\times$ 2 m tall PVC columns, four of which were packed with 1.5 m of soil and aquifer material from the site, and 2 were packed with silica sand. The columns were loaded every 2 weeks (9 cycles) with synthetic stormwater (SSW) and sampled from ports at 0.5 m, 1.0 m and 1.5 m below the media surface. A saturated zone was created after 3 cycles (0.5 m) and raised after 6 cycles (to 1.0 m) which allowed for sampling of infiltrated water from above the saturated zone as well as sampling of the saturated zone.

The field monitoring comprised installation and sampling of groundwater monitoring wells. Nine monitoring wells were installed at five locations across the site at various depths, between 1.5 and 3.8 m below ground level (bgl) (Fig. 4).

Well Location 1 is a background well outside of the main pond area, while Locations 2 to 5 are located across the infiltration and wetland area. The wells were designed to target specific depths through the siting of the screened section (which allows water into the well from the surrounding aquifer) in the lowest 0.5 m. Every 2 to 4 weeks over one year, groundwater

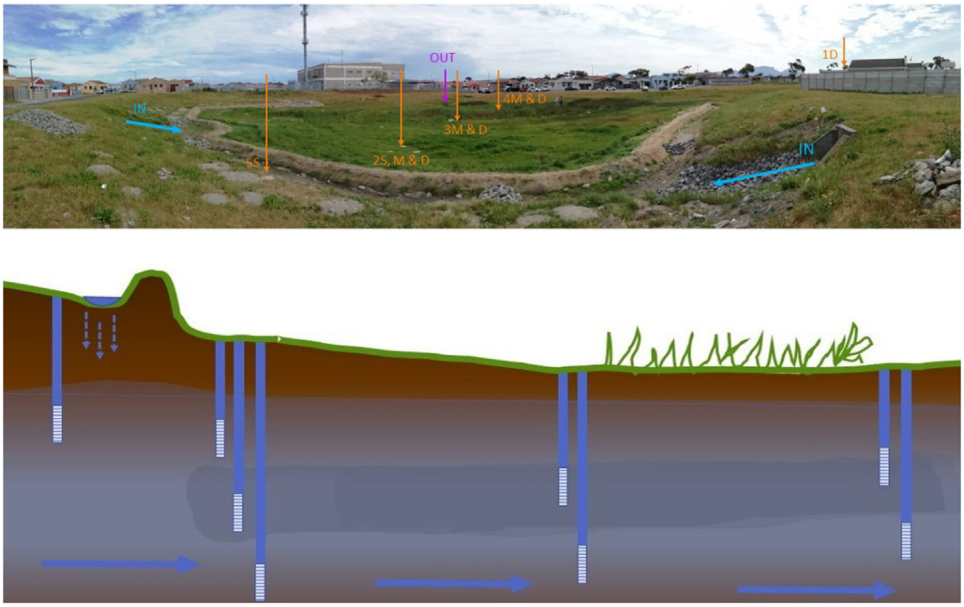

Fig. 4. Monitoring well locations indicated with yellow arrows, inlets with blue arrows, and outlet with pink arrow (top) and cross section showing monitoring wells at positions 2–5 (below).

levels and field parameters were measured, and samples collected for laboratory analysis. Low-flow sampling – after purging to stabilise the wells – was conducted to ensure samples were representative of the surrounding groundwater. Grab samples of the inlet stormwater and outflow water were taken on four occasions, and on two occasions groundwater samples were collected on the day following a rainfall event. Water samples (from columns, stormwater, outflow, and groundwater) were tested for a range of field parameters, nutrients, organic carbon and metals.

Activating' the pond and social engagement

Key to this research has been the transformation and activation of the mono-functional pond as a multi-functional blue-green landscape to provide a range of water-related biodiversity and amenity functions. Nature-based approaches, such as those employed in the promotion of pond infiltration and aquifer recharge, have the potential to enhance access to recreational amenities, community gardens, traditional cultural resources, nature-education opportunities as well as human well-being benefits. This approach necessitates engagement with, and involvement of, local residents and neighbouring schools to secure their 'buy in and ownership', providing a platform for them to share local insights as part of knowledge co-production and in valuing the infrastructure. This aims to develop the potential that local residents would contribute to ongoing stewardship and maintenance of the space as part of the co-creation of the multi-functional landscape.

A variety of activities have taken place to enable local residents and teachers and students from local schools to actively participate and engage either in the physical blue-green retrofitting of the pond or in associated workshops engaging around perceptions of the pond and opportunities for stewardship.

- Sandbag wall and infiltration trench construction works: These works formed part of the project co-creation strategy with construction commencing in August 2021 after consultation with local residents and community leaders, and initial contact facilitated by the local school headmistress. Meetings were held with key local residents to explain the project and secure their assistance and support. Interested residents were employed through the appointed contractor and given a short training programme – working on new technologies such as using sandbags, hessian and the reinstatement of existing turf over the sandbag wall to construct a green wall.
- Spring Planting Day: A Spring Planting Day with the theme, 'Restoration in Progress' was facilitated by a community conservation specialist and involved children from the local schools in September 2021. Seedlings indigenous to the area's vegetation type, Cape Flats Dune Strandveld, were planted on the pond site by the children with a demonstration around the value of the plants, their propagation and particular watering regimes.
- Educational Visit to local nature reserve: A plant exploration outing to a local nature reserve was then conducted to explore the potential for developing a relationship between the reserve and local residents. This also included knowledge sharing on plants indigenous to the area and their various benefits, as well as a short workshop on how residents would shape their pond.
- Interviews with local residents: Interviews of local residents were conducted to gauge use and perceptions of the pond as well as to explore how people might use the added functions of a retrofitted pond. These interviews, largely aimed

at understanding local residents' perspectives of amenity, and have helped to formulate plans for further development in the space, including the mural (see below) and plans to install benches and more opportunities for planting, e.g. to access shade.

- Mural painting: A mural painting on the boundary walls of selected houses adjacent to the pond was initiated by the project team to communicate the role of the pond and showcase the project's intent, while also working as a place-making device to give the pond more agency. A series of workshops were conducted to co-create the mural, involving the research team, local residents and an artist collective with experience in mural-making facilitation (CareCreative and HC360 crew). A 'visual harvesting' workshop was held where residents contributed ideas and drawings focused on how they see the pond and its role in their neighbourhood. This was followed by a preparatory painting day where residents and particularly children, were invited to paint the wall using an eco-friendly, South African produced paint (ProNature), after which the artist collective completed the mural. A launch event, to which all local residents and other interested stakeholders were invited, was held in November 2022 to formally activate the space. Benches, and a plaque explaining the PaWS project interventions and the mural were also installed.

Results and discussion

Physical experimentation

Infiltration trench and sandbag wall design and construction

Retrofitting detention ponds that facilitate enhanced infiltration was made possible in this context with the involvement of local residents. The construction process cost 300,000 ZAR in 2021, and post-construction observations at the pond indicate that low-cost building materials can successfully be used in pond retrofits and provide adequate strength and aesthetics. The sandbag berm wall, in particular, has shown itself to be durable, even acting as a pathway for children and other pond visitors. The rock check dams act as effective litter traps facilitating the ease of pond clean-ups. Further, the areas in front of the inlets and between the litter traps are effective forebays which trap litter, oil, and silt. As a result, it has been observed that since the retrofit, the volume of litter within the pond has decreased and is mainly concentrated at the inlets. However, there are still isolated instances of dumping within the pond. One notable incident involved the disposal of used motor oil at one of the inlets and in upstream stormwater catch pits. Residents were alerted of this via WhatsApp messages, and many responded to say that this was unacceptable and implored the perpetrators to desist from further oil dumping. This further reinforces the need for engaged communities so as to ensure successful pond retrofits and maintenance; community outreach and co-creation approaches serve to facilitate and strengthen the engagement. This is particularly important as the residents in the area of the pond will need to take over its maintenance in the medium to long term and collaborate with the CoCT to ensure its continued function as an infiltration swale and a well-maintained public space.

Aquifer recharge results and discussion

The calibrated and validated surface and groundwater model was used to evaluate potential recharge volumes in the pond considering 15 scenarios. In these scenarios, the long-term performance of the pond pre and post retrofit was investigated using climatic data from 2005 to 2022 as well as climate change projections (2023–2100).

For purposes of brevity, only three scenarios are presented in this paper – using rainfall, temperature, and groundwater level data from 2021 which was a particularly wet year (880 mm) with a 1 in 17 return period. Using the 2021 data represents a 'worst case' scenario as the high-water table would limit infiltration and frequent rainfall would impact the aquifer recovery and present a below average unsaturated zone depth.

Scenario A represents the pond before the retrofit acknowledging that the pond had some infiltration potential before the retrofit. Scenario B represents the pond after the retrofit at the observed 2021 high water table, while Scenario C simulated the impact of a lowered water table due to the CoCT's planned MAR and abstraction scheme. The CoCT plans to abstract 50 ML/d from the CFA as part of its new Water Strategy [5] and will recharge the CFA with 40 ML/d of treated wastewater effluent. This process on its own would result in a predicted lowered water table at the School Pond of about 2.5 m, thus presenting an opportunity for increased MAR in the pond.

The total annual stormwater volume in the pond due to inflows via the pond inlets and runoff within the pond was found to be 31.1 ML for all scenarios. The scenario analysis shows that in the pre-retrofit scenario (Scenario A), 6.18 ML of the infiltrated stormwater contributed to MAR (Fig. 5). The installation of the retrofit (Scenario B) increased the MAR in the pond by 83% resulting in an additional 5.13 ML stored in the CFA. The pond retrofit was thus determined to provide 11.3 ML of MAR over a year, which equates to approximately 1% of CoCT's daily demand of 912 ML/day during the summer of 2022 [9]. The increase in MAR is facilitated by the berm detaining stormwater that would otherwise flow out of the pond. Finally, the results from Scenario C revealed that if the CoCT implements its planned abstraction and MAR in the CFA the pond would provide 20.8 ML of MAR in 2021 which is an 237% increase from the pre-retrofit scenario (A).

There results show that pond retrofits have the potential to increase MAR via stormwater harvesting even in areas with high water tables. Admittedly, the MAR volumes might appear insignificant in the context of the CoCT's total supply, but it is important to note that this is just one pond with a 312 m^2 infiltration basin. If more of these systems are used across the city there is potential for stormwater harvesting at catchment scale (as per [10]).

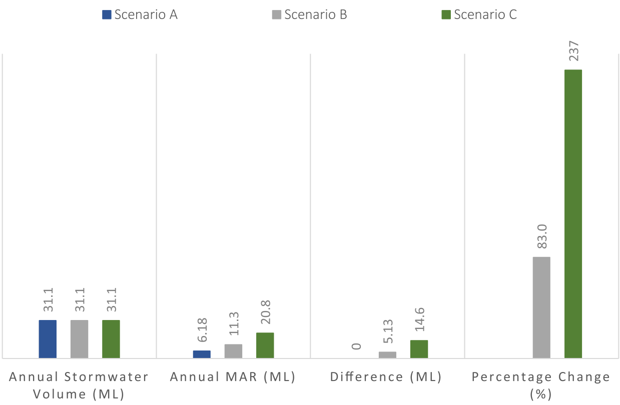

Fig. 5. 2021 School pond 2021 MAR scenarios.

Water quality results and discussion

Water quality results are discussed in the context of the challenges and potential for water treatment in repurposed stormwater infrastructure. In this research the impact on groundwater quality was the primary focus, however, grab samples from the outflow of the pond indicated potential improvement of water quality returning to the stormwater network as compared to inlet water quality. Future studies of outflow water quality should distinguish between large rainfall events which overflow the weirs on the ends of the infiltration trench (thereby by-passing infiltration through the soil) and reach the outlet rapidly, and smaller rainfall events which infiltrate through the soil. Seepage of water from the soils into the outlet channel was visible in spring and early summer (in the year of monitoring) when the groundwater level was elevated.

During well installation it became clear that there is a lower permeability soil layer at around 1.5 to 2.5 mbgl which consists of clay/sandy clay/clayey sand, while most of the remainder of the soil profile is dominated by sand. The low permeability (but not confining) layer influences the movement of water through the site, but a tracer study will be required to better understand this process. Analysis of chloride (a natural tracer) in stormwater and groundwater samples indicated that the plume of infiltrated stormwater post rainfall events was largely concentrated in the shallow zone close to the infiltration area, i.e., positions 2S [shallow] and 5 (see Fig. 4). An important finding of the field study was that the nitrate concentration in the background groundwater is both high (16 $\pm$ 3 mg/L as N) and much higher than the inlet stormwater (0.2 to 0.8 mg/L as N). The measured concentrations are consistently above the South African drinking water standard limit of 11 mg/L (as well as the General limit of 15 mg/l for wastewater discharge to a water resource) and would be considered hypertrophic in a freshwater ecosystem (Department of Water Affairs and Forestry (DWAF) [11]a). Compared to the background concentrations, nitrate concentrations in other wells (5 $\pm$ 5 mg/L as N) are significantly lower, due to a combination of dilution and denitrification. This process requires a source of labile organic carbon which may be mobilised from aquifer sediments, moved through the soil by infiltration or supplied directly by infiltrated stormwater. Stormwater samples collected at the site showed a wide range of organic carbon concentrations (2.5 to 93.5 mg/L), and consistent detection of organic carbon in groundwater on the day following a rainfall event suggests that direct input of organic carbon from the stormwater is a likely source of carbon in shallow wells while in deeper wells, where no appreciable amount of infiltrated stormwater is present, mobilisation of carbon from the aquifer material is more likely. Table 1 shows mean values of the contaminants determined in the field monitoring screened against the South African drinking water standard (South African Bureau of Standards (SABS), [12]. Guideline values for aquatic ecosystems are included for reference. Number of measurements are shown in brackets; bold values indicate that the samples exceed the drinking water standard.

High groundwater levels meant that the depth of unsaturated soil (vadose zone) below the infiltration trench varied between 0.5 and 1.2 m in the year of monitoring; however, this may vary year-to-year and may increase under groundwater abstraction scenarios. Vadose zone thickness is thought to be an important factor with greater thicknesses being more protective of groundwater quality [13,14]. Laboratory column experiments allowed for the assessment of contaminant removal during infiltration for different depths of soil (Fig. 6). These studies, using soil media from the pond showed, inter alia, that metals (Cr, Cu, Pb, Ni, Zn) and phosphorus were removed in the top 0.5 m (76% removal) and there was a 85% removal of organic carbon in the top 0.5 m. Total nitrogen was not well removed during infiltration (−20% to 23% for 0.5 m soil depth); however better removal rates were achieved in the saturated zone (85 to 96% for 0.5 m infiltration followed by 0.5 m saturated). The only metal which was found to exceed the South African drinking water standard chronic health limits, even though it was not added to the SSW, was Arsenic – assumed to have mobilised from the pond's soil/aquifer material under iron-reducing conditions [15,16].

In summary, increased stormwater infiltration can potentially improve groundwater quality through dilution and denitrification. As shown in column experiments, the soil at this site shows good removal rates for metals, phosphorous and labile organic carbon even with limited vadose zone thickness. There is potential to mobilise arsenic from aquifer material under iron-reducing conditions, and there may be other long-term groundwater geochemical considerations which need to be

Table 1
Contaminant concentrations in stormwater and groundwater at the school pond site.

Contaminant	Stormwater	Background groundwater (1D)	Deep wells (2D, 3D and 4D)	[1]SANS:241 drinking water standard	[2]Guideline for aquatic ecosystems
NH4-N (mg/L)	0.4 ± 0.03 (2)	0.01 ± 0.01 (12)	0.02 ± 0.06 (36)	1.5	0.007
NO2-N (mg/L)	0.04 ± 0.03 (2)	0.13 ± 0.06 (12)	0.04 ± 0.03 (36)	0.9	0.5*
NO3-N (mg/L)	0.5 ± 0.5 (2)	**16.2** ± 3.2 (12)	6.2 ± 4.5 (36)	11	0.5*
PO4-P (mg/L)	<0.15 (2)	<0.15 (12)	<0.15 (36)		0.005
Dissolved P (mg/L)	0.155 ± 0.120 (2)	0.017 ± 0.011 (4)	0.014 ± 0.017 (36)		0.005
TOC (mg/L)	**33.5** ± 42.0 (4)	1.3 ± 2.2 (11)	2.4 ± 3.6 (35)	10	
Dissolved Al (μg/L)	38 ± 10 (2)	8 ± 5 (4)	8 ± 9 (12)	300	10
Dissolved As (μg/L)	2.4 ± 0.4 (2)	1.5 ± 2.1 (4)	1.1 ± 0.8 (12)	10	10
Dissolved Cr (μg/L)	1.3 ± 0.4 (2)	0.3 ± 0.3 (4)	0.3 ± 0.3 (12)	50	7
Dissolved Cu (μg/L)	4 ± 1 (2)	1 ± 2 (4)	1 ± 1 (12)	2000	0.8
Dissolved Pb (μg/L)	<0.4 (2)	0.8 ± 1.2 (4)	0.8 ± 1.0 (12)	10	0.5
Dissolved Mn(μg/L)	<1.5 (2)	1.9 ± 0.9 (4)	4.7 ± 10.4 (12)	100	180
Dissolved Ni (μg/L)	0.5 ± 0.07 (2)	0.7 ± 0.2 (4)	0.8 ± 0.4 (12)	70	
Dissolved Zn (μg/L)	50.6 ± 37.7 (2)	7.9 ± 3.6 (4)	5.5 ± 5.5 (12)	5000	2
Dissolved Fe (μg/L)	16 ± 0.5 (2)	9.9 ± 13.5 (4)	130.6 ± 428.7 (12)	300	

1 [12].
2 [11].
* Value for inorganic nitrogen.

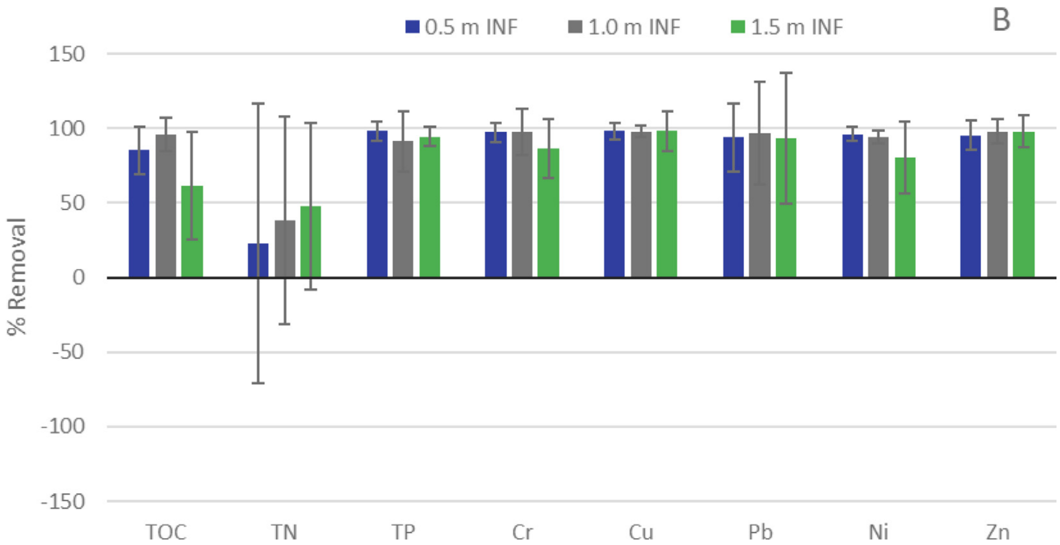

Fig. 6. Percentage removal of selected contaminants during infiltration in column experiments for soil media with high SSW concentrations (μg/L: Cr, 8.3; Cu, 63.3; Pb, 3.7; Ni, 9.1; Zn, 480; TP, 1151; and mg/L: TN, 24; TOC, 64). TN=total nitrogen; TP=total phosphorous; TOC=total organic carbon.

studied. Current results indicate that there are potential benefits of retrofitted stormwater infrastructure for both stormwater and groundwater quality.

'Activating' the pond and social engagement

The various engagement activities involving local residents have revealed that multiple-engagement approaches are highly beneficial, with each engagement type providing a platform for knowledge co-production, in several cases through the co-creation of physical changes to the landscape for the project. The findings from these engagement approaches include the following:

- Sandbag wall and infiltration trench construction works: There was initially a level of resistance to the project as some local residents had assumed from the initial specialist monitoring well drilling works at the pond, that they were not being included, especially at a time when the COVID-19 pandemic had adversely affected many in terms of employment. Once their involvement was explained and confirmed, local residents formed themselves into teams of workers for the infiltration trench / wall construction process. The construction was completed over a period of 4–5 weeks, with the project offering a temporary income source for some as well as an opportunity to gain new skills such as sandbag construction (a sandbag-building workshop was subsequently conducted following interest expressed by some of the local residents in learning how sandbag houses could be built using low-tech systems). Whilst there were challenges, both

in the construction, and between various role-players, later interviews with some of those involved in the construction reflected on how their perception of the pond space had changed, with some explaining that they now saw the pond as part of nature they wanted to protect for future generations, and no longer just an empty, vacant space. Other respondents acknowledged a new recognition of nature at the pond, seeing dragonflies, frogs/toads and lizards, amongst others. Some residents described it as a wetland and acknowledged the value of these natural systems for water.
- Spring Planting Day: The 'Restoration in Progress' planting activity on 1 September 2021 helped to reinforce the emerging ecological literacy among younger community members, but with some ongoing challenges. New planting in this winter-rainfall area should preferably be done in autumn months enabling plants to adapt in the wet winter months. Whilst local school children initially helped to water some of the young plants this was not a sustainable solution and many of the plants did not appear to survive the dry, hot summer. Though this was a setback, the process itself was beneficial as it showed the possible community dynamics that would characterise community stewardship of the pond. For example, some of the local residents took to protecting some of the smaller trees from local council maintenance grass cutter crews by demarcating the areas that needed to be protected with bits of rubble or rocks. With the planting activities, one resident remarked that she was looking forward to seeing all the flowers. Scholars from the local school's Eco-Club are also 'inhabiting' the pond, occasionally clearing windblown litter from the space.
- Interviews with local residents: The space is understood in a variety of ways; however, many residents agree that to provide amenity, shade and places to sit are needed. The interviews were used to guide further plans for the project, including those for interventions as part of the next phase of the project (PaWS2). In this way, the surveys have also been instrumental in co-design.
- Mural painting: Despite working with local residents since 2020, the mural painting event in August 2022 highlighted that the concerted efforts of the team to communicate as widely as possible, accessing multiple overlapping WhatsApp groups and other channels for communication, were still not reaching all local stakeholders. The public work on the mural, as well as the social media efforts to disseminate the various activities led the project team to find more local people with an interest in the space even two years on. This highlights the value in using a variety of, and layered approaches to engagement while also suggesting that the notion of engagement as a continuous process (much like consent) should be seriously considered.

The layering of approaches and punctuated engagement activities offers a variety of opportunities to activate the pond; this creates opportunity for local residents with different interests to engage with the pond space more actively, and in their varied, preferred ways. Post-COVID experiences have made it increasingly apparent that direct-engagement opportunities with the space are valuable in changing perceptions and highlighting how people interact with the stormwater ponds as urban green infrastructure. The social learning by both residents and researchers about pond functions and perceptions of it, is an added benefit – particularly as this relates to: increased awareness of the role of water and blue-green spaces in a resilient city; the need to adopt a water sensitive approach [5]; and local residents valuing the infrastructure and thereby contributing to its maintenance and upkeep.

Since the physical work began on the pond – the sandbag wall and infiltration trench construction; new planting; and a wall mural – mowing of the central wetland area has not occurred to date, purportedly stopped by residents and further supported by a 'grow do not mow' approach from the CoCT. This has provided the opportunity for a variety of species to appear – mostly plants and amphibia observed to date, with the expectation that ecological diversity will continue to increase. More diverse, indigenous vegetation will also likely result in decreased maintenance requirements in the future. Recognising that the pond itself possesses agency, further planting is planned to include indigenous plant cultivation, curating the pond landscape as part of educational fynbos rehabilitation. Opportunities for co-design workshops with local residents focusing on how they would like to design the pond space for added functions and use are also envisaged.

Conclusions

In summary, the research has shown that stormwater ponds offer significant potential as multi-functional blue-green infrastructure; preventing flooding and creating opportunities for the harvesting of stormwater to supplement the city's water supply (thus contributing to resilience), all whilst providing local residents with safe and useful green space for purposes of amenity and well-being.

The research is also revealing how additional benefit can be derived from these water management systems by adopting low-cost, easy to install blue-green interventions utilising local labour (thus providing employment opportunities), that rely on nature-based approaches, as well as insights into the potential for activating these spaces together with local residents in a variety of ways. Importantly, the study has given a view into the dynamics of operationalising a city's climate action policies, e.g. the CoCT's Water Strategy, via nature-based experimentation whilst further building the evidence base for supporting decision-making and policy in the city's governance structures.

These findings have relevance both across South Africa, as well as among cities facing similar challenges across the African continent, where existing stormwater ponds and passive green open spaces have been designed largely for flood control or ecological purposes only. This research offers valuable strategies for how single-purpose ponds can be transformed into multifunctional blue-green spaces in ways that build resilience into a city's water supply system whilst also addressing the environmental injustice that is a legacy of South Africa's 'green apartheid' past.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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