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Toward a water-sensitive precinct with stormwater harvesting: a case study in South Africa

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ABSTRACT

The study assessed static management, i.e., without planned periodic maintenance of the storage (no sediment dredging) denoted as SC1, or with maintenance denoted as SC2. The second approach was dynamic management based on applying Real-Time Control (RTC) techniques to scenario SC1 and scenario SC2 denoted as RTC-1 and RTC-2, respectively. The dynamic management of the UCT dam with RTC-1 and RTC-2 approaches increase yield by 2.1 and 1.1 ml, respectively. Additionally, RTC-1 and RTC-2 approaches increase volumetric reliability by 5.3 and 2.5%, respectively, while maintaining the required level of service of a stormwater harvesting system. SC1 and SC2 results in water savings of up to 21.15 and 21.45 ZAR/kl, respectively, while RTC-1 and RTC-2 could save up to 19.35 and 19.45 ZAR/kl. Thus, static configurations results in water savings approximately 9% in comparison to RTC. In addition, static configurations harvested stormwater at a relatively lowest unit cost in comparison to RTC configurations. Notwithstanding this finding, the RTC system exhibits a great potential in reshaping the stormwater harvesting system to simultaneously deliver water conservation and stormwater management.

Key words: irrigation, real-time control, South Africa, stormwater harvesting, water supply

HIGHLIGHTS

- Assessed the extent to which stormwater harvesting could contribute to 'net zero', i.e., transitioning the University of Cape Town toward a 'water-sensitive precinct'.
- Impact of planned periodic maintenance in enhancing harvested stormwater volume.
- Benefit of Real-Time Control (RTC) in enhancing harvested stormwater volume

INTRODUCTION

South Africa is a water-scarce country with inadequate freshwater resources due to unevenly distributed rainfall. With the rapid increase in water demand due to population growth, it has been reported that there would be a gap between water demand and water supply of some 17% by 2030 (Okedi 2019). Furthermore, there is evidence that climate change will continue to increase temperatures especially in urban areas such as Cape Town, South Africa and reduce mean annual rainfall (Okedi 2019). Unless there is a meaningful change in water supply and use patterns, the impact on water demand, for example, for irrigation, industry and the services sector, will directly and adversely affect the economy. An example of the impact of variable water supply in an urban area was when the City of Cape Town faced the possibility of taps running dry in 2018 due to a prolonged drought that commenced in 2015. To address these challenges, a more holistic, resilient, and sustainable water management approach is required to integrate the utilization of various water sources such as groundwater, rainwater, stormwater, and wastewater. Various studies have shown that with rapid urbanization, the role of stormwater becomes crucial for the sustainability of urban environments (Okedi 2019; Schmit *et al.* 2020). Urbanization is known to restrict infiltration, thus altering flow regimes of groundwater and surface waters resulting in 'flash' floods and larger runoff volumes characterized by higher velocities and increased peak discharges (Dietz & Clausen 2008; McGrane 2016). The changes result in a loss of biodiversity and aquatic habitats as well as increased erosion and sediment loads (Jackson & Booth 1997; Vietz *et al.* 2015).

While stormwater infrastructure is largely static, the ability of dynamic weirs, gates and valves to more closely achieve desired hydraulic conditions have long been recognized. The use of manually adjustable valves can be applied for dredging purposes, emergency facility drawdown, or other maintenance activities and is common practice in the design and maintenance of extended detention ponds (Nashville & Davidson County 2009; ODOT, 2014; USEPA 2009). It is feasible to add automatic controls to previously manually or passive controlled stormwater facilities due to recent advancements and reduced cost of internet connected sensors and actuators (Kerkez *et al.* 2016; Bartos *et al.* 2017). A heuristic or rule-based control (RBC) algorithm is commonly applied as an automation of RTC (Jacopin *et al.* 2001; Middleton & Barrett 2008; Gaborit *et al.* 2013; Goodman & Quigley 2015). Here, control rules are manually programed typically in the style of an 'if-then-else' logic structure before the RTC system is on-line (Schmit *et al.* 2020). Design and implementation of RBC typically require expert knowledge of the urban drainage system (Vitasovic 2006).

In this study, an investigation was undertaken to determine the extent to which stormwater harvesting could mitigate water scarcity in a highly urbanized area. Increasing the physical capacity of storage components may be required for the multi-functional use of stormwater infrastructure for water harvesting and to mitigate flood risk. Physical increases of storage capacity in an urban area may require the demolition of infrastructure such as buildings and roads (García *et al.* 2015). To minimize the need to demolish existing physical infrastructure in an urban area, some studies such as Borsanyi *et al.* (2008); Okedi (2019) and Mogano & Okedi (2023) have shown that Real-Time Control (RTC) can provide the required additional storage capacity within existing stormwater detention facilities. This can be achieved through dynamic management of the existing storage within the stormwater system by applying RTC operational rules to minimize redundancy in the detention facility (Colas *et al.* 2004; USEPA 2006). In the studies in the literature, operational rules have been based on water levels with limited integration of inflow data. Some case studies are discussed as follows.

In Québec city, Canada, RTC was implemented of a grassy, dry, on-line stormwater detention basin located at an outlet of a residential catchment. The catchment area was 15.3 ha with an imperviousness area of 33% (Gaborit *et al.* 2013). The catchment had a dual drainage and sewer system for stormwater that utilized the streets for major flow conveyance and an underground sewer for the conveyance of frequent flows (the minor system). The benefits of RTC implementation included reducing overflows while maximizing the detention time. Runoff retention enabled a smooth drawdown during discharge to minimize TSS re-suspension and minimize hydraulic shocks on receiving water bodies. Overall TSS removal increased from 46 to 90%.

Another study in Tehran, Iran applied on-line RTC with controllable and uncontrolled gates and openings to temporarily store excess storm runoff due to a lack of hydraulic capacity in the drainage network (Jafari *et al.* 2019). The operation focused on reducing flood inundation at downstream end of the system, hence rules on how to regulate gate openings were used to optimize the system performance. It was determined that the efficient use of the regulation capacity was influenced by the ability to regulate all controllable elements in the system. Application of RTC led to the optimal utilization of the reservoir capacity where excess water was temporarily stored. This water can be later used for other purposes such as irrigation of urban green landscape. Additionally, partial control of the system compared with a fully controlled case led to a 17% increase in flood inundation.

Thus far, the use of optimization-based control approaches such as model predictive control and linear-quadratic regulators is a shift that RTC practitioners and researchers have turned toward for prevention of downstream capacity exceedance by urban drainage systems (Marinaki & Papageorgiou 2003; García *et al.* 2015; Wong & Kerkez 2018). However, operations personnel cannot easily understand and adjust these systems which are computationally intensive and make decisions in a 'black box' (Vitasovic, 2006). The implementation of translucent, rule-based or optimization-based control could mitigate the novelty of RTC technology for stormwater management applications that may be a hindrance to its adoption (Schmit *et al.* 2020).

Rohrer & Armitage (2017) used a Life Cycle Cost Analysis (LCCA) as an economic assessment which revealed that stormwater harvested in a decentralized manner – i.e., harvesting from multiple ponds – tends to maximize the volume harvested, which also increases the overall cost of the system due to increased maintenance, operation and capital costs. By contrast, centralized systems – i.e., harvesting from a single pond – minimizes the infrastructure costs but with reduced yields. Additionally, Fisher-Jeffes (2015) also used an LCCA which noted that subcatchments with higher density populations typically had cheaper SWH systems (when costs were reduced to ZAR per kilolitre), this made sense when considering the cost of the dual reticulation network which is a major component of the cost of a SWH scheme. In general, it was also evident that the higher demand associated with larger population would result in lower cost per kilolitre.

The study described herein simulated an operation approach that integrates RTC into existing stormwater infrastructure through low-cost adaption by adjusting or improving functionality to a changing hydrologic environment as suggested in Kerkez *et al.* (2016); Okedi (2019). The study applied RTC rule-based approaches on a representative urban catchment at the University of Cape Town (UCT) with the objective of determining the opportunity to transition the urban area toward a water-sensitive precinct. Unlike in previous studies were RTC rules were only linked to water levels, in this study, the rules were applied to the UCT dam operations to initiate pre-storm releases in real time based on forecast rainfall volumes. In addition, the study assesses the application of RTC in relation to harvested stormwater. Four stormwater harvesting configurations were modeled, i.e., two conventional configurations (SC1 and SC2) and two dynamically managed configurations with RTC (RTC-1 and RTC-2). An LCCA was also applied to the four configurations to assess the economic viability of the four harvesting stormwater approaches.

METHODS

In this study, the selection of a site was based mainly on the availability of hydrological data, the presence of a suitable storage as well as a non-potable demand. Figure 1 presents an overview of the method. The selected study area was located within the University of Cape Town campus in the City of Cape Town located in the south-western part of South Africa, as shown in Figure 2.

The climate in the city of Cape Town is predominantly Mediterranean with about 50% of Mean Annual Precipitation occurring in the three winter months of June, July and August (Okedi 2019). The average precipitation in Cape Town is 600 mm/year, however, the presence of a mountainous topography results in high variable rainfall and evaporation. The weather in the UCT watershed see (Figure 3), which is located within the Liesbeek River Catchment is greatly impacted by the Table Mountain and the Atlantic Ocean to the West and low laying Cape Flats to the East.

Due to its natural features and topography, the rainfall in the watershed is far higher than the average rainfall for Cape Town ranging from 1200 mm to 1500 mm/year while evaporation varies from 600 to 1500 mm/year (Fisher-Jeffes 2015). The UCT dam and its catchment were selected to represent a typical storage reservoir used for irrigation. The catchment area is 0.33 ha, has a slope the varies from 20 to 30% (average slope of 24.5%) and is 98% pervious, with land use composed of an open greenfield area. The catchment drains into the UCT dam with a maximum depth of 12.5 m and a surface area of 0.82 ha. For modeling purposes, the catchment was divided into 31 subcatchments, with the stormwater conveyance network consisting of open natural channels. A Digital Elevation Model (DEM) was used to define subcatchment boundaries as well as to extract stormwater channel cross sections.

The EPA SWMM 5.1 model is an open-source program for hydraulic and hydrologic studies. It was used to model the rainfall–runoff process in the study area. The EPA SWMM model is commonly used for RTC simulations as control algorithms can be also applied externally via a programing wrapper or programed directly into the model as described in various studies such as Joksimovic & Sander (2016); Gaborit *et al.* (2013, 2016); Goodman & Quigley (2015); Muschalla *et al.* (2014); Degrave *et al.* (2013); Heusch & Ostrowski (2011); Wong & Kerkez (2018).

To model stormwater harvesting, a substantial amount of data was required including a DEM of the catchment, infiltration data, rainfall data, evaporation data, and water demands. The DEM had a 10 m resolution which was adequate for modeling purposes. To estimate infiltration, a Green-Ampt equation was used based on soil parameters, which are widely available in literature. Borehole logs of the University of Cape Town were used to identify the soil conditions (upper soil type zones) within the catchment. The borehole logs were useful when estimating infiltration parameters. Additional data were obtained from the 'as built' drawings of the UCT dam including the outlet structure, the spillway properties, and its stage-storage curve. The behavior of the storage during operation was modeled using a depth versus surface area curve as shown in Table 1.

To model stormwater harvesting, various studies including Mitchell *et al.* (2008) recommended that at least 10 years of hydrological data that includes wet and dry years are required to implement a continuous simulation. In other studies, such as Coombes & Barry (2007), it was established that harvested stormwater volumes were significantly underestimated in model simulations that used daily instead of sub-daily time-steps. For this study, 5-min time-interval data were used to account for the dynamics of rainfall and runoff. Historical rainfall data (at 5-min time-intervals) for the period 2015–2022 was obtained from a local weather station. Evaporation was estimated by applying the Hargreaves's method to temperature data. Satisfactory results have been reported using this method in various studies such as Xu & Singh (2001); Allen *et al.* (2006). Daily temperature data for the period 2015–2022 was obtained from a local weather station and used when modeling

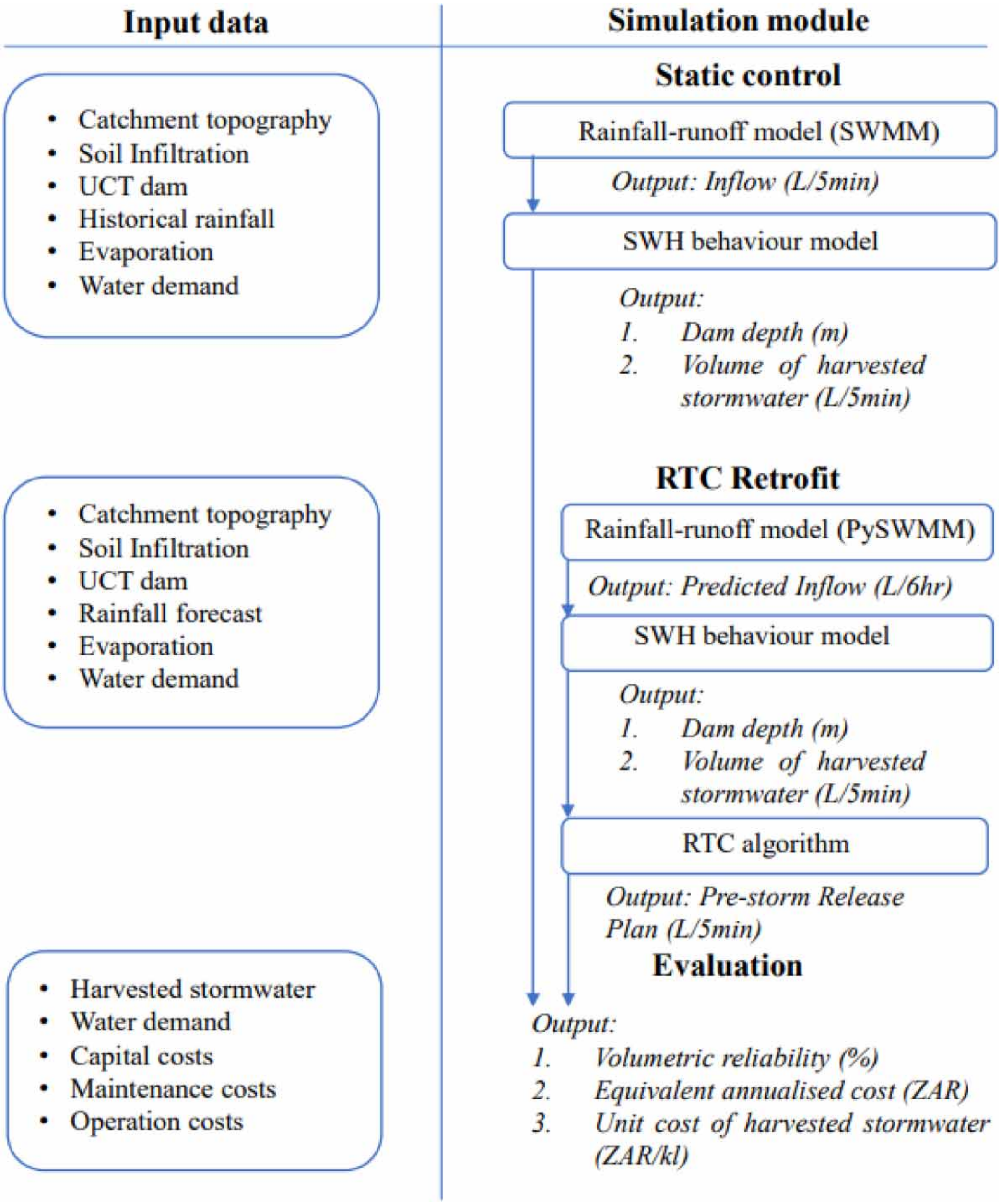

Figure 1 | Conceptual framework for the adopted research approach.

the stormwater harvesting system. For water demand, only outdoor irrigation was considered, i.e., soccer, cricket, and rugby fields (see Figure 4) due to lack of policy on stormwater reuse for indoor and potable water purposes.

While historically, the UCT dam was able to adequately supply water for irrigation of the sports fields, this has not been the case in recent years. The water supply for irrigation is now being supplemented with municipal potable water which is not ideal due to the problems of water scarcity. The estimates of irrigation demands were based on an 'irrigation demand model' and the water demands are presented in Table 2.

The data in Table 2 show that a significant amount of irrigation water (about 50%) was drawn from municipal system. The irrigation demand met by the municipal system accounted for about 26% of the total municipal demand (see Table 2). In this study, the objective was to determine whether management approaches can be applied to the UCT Dam such that the use of municipal water for irrigation can be minimized and allow for irrigation demand to largely met by stormwater harvesting.

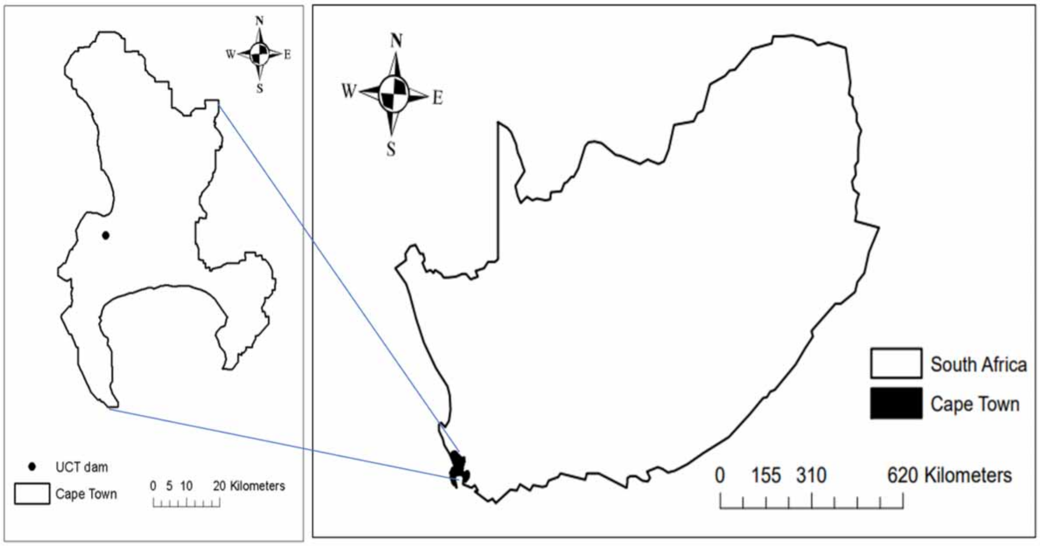

Figure 2 | Location of Cape Town and the University of Cape Town (UCT) dam.

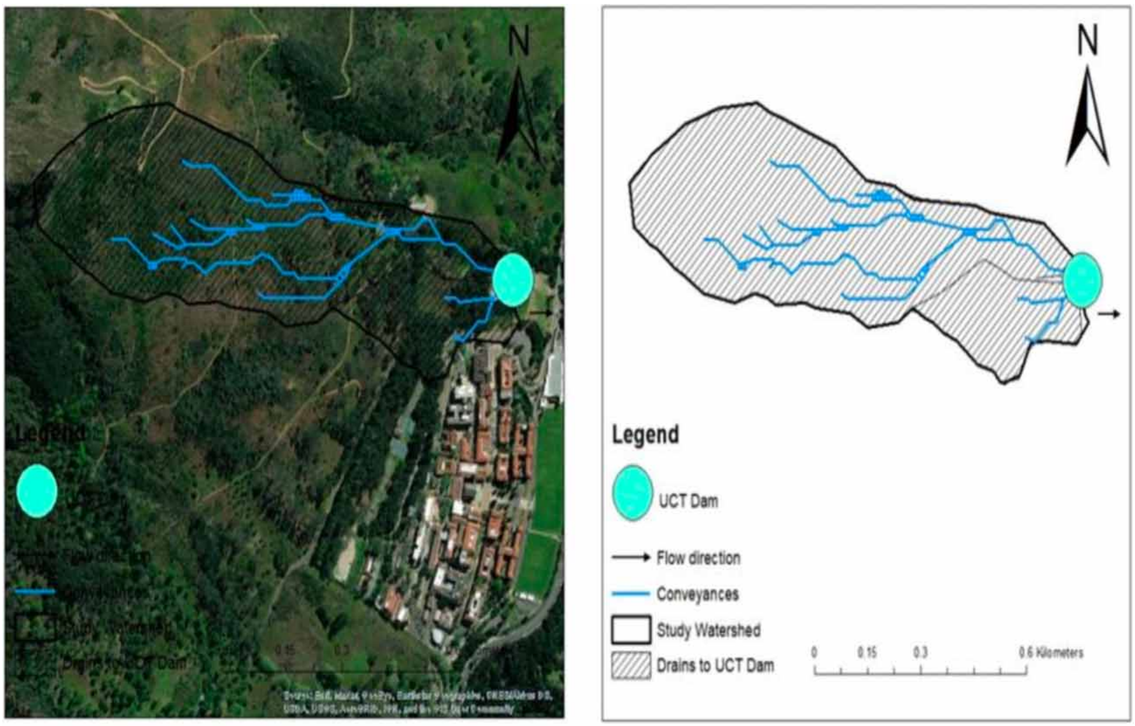

Figure 3 | The UCT watershed.

Table 1 | Depth – area curve for the UCT dam (Zutari 2020)

Depth (m)	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
Area (m^2)	7	113	346	707	1,195	1,810	2,552	3,421	4,418	5,542	6,841	8,200

Figure 4 | Proposed irrigation pipeline routes and pump station location (adapted with permission from Zutari 2020).

Table 2 | Irrigation demand (ml) for sports fields (*Source*: Zutari 2020)

Campus Sport Field	Municipal water: Average Annual Demand excluding irrigation (ml)	Municipal water: Irrigation (ml/yr)	Municipal water: Total Annual Demand (ml/yr)	Water from UCT Dam Sports Field irrigation (ml/yr)
Rugby (Upper)	95.11	12.71	107.82	21.41
Cricket (Middle)	14.05	9.7	23.75	10.12
Soccer (Lower)	3.59	17.63	21.22	10.94
Total	112.75	40.04	152.79	42.47

This study focused on the application of RTC techniques to dynamically manage the available storage in the UCT dam including initiating prestorm releases in real time based on forecast rainfall to increase the capture of stormwater and to reduce overflows from the dam.

In this study, two conventional and static control configurations were applied to the UCT dam namely, Static Control 1 and Static Control 2 denoted as SC1 and SC2 (see Table 3). The clock times are linked to irrigation regimes, i.e., system operations between 08:00–13:00 h.

Various assumptions were made in the application of the RTC rules, i.e., SC1 represents the baseline operational procedure that is currently in practice at the UCT dam without planned periodic maintenance (i.e., no dredging to remove sediments from storage), while SC2 denotes a case with maintenance. SC2 is an improvement to the current practice. It assumes that maintenance is regularly undertaken, i.e., dredging to remove sediments from storage and the catchment is managed adequately and optimally to convey runoff into the UCT dam. The study determined that the sediment deposited in the UCT dam has accumulated to about a 6 m depth, thus depriving the stormwater harvesting system of almost 8% of the dam storage. The

Table 3 | The SC1 and SC2 configurations

Static control 1 (SC1):	Static control 2 (SC2):
If Simulation clocktime > 08:00:00 h	If Simulation clocktime > 08:00:00 h
And Simulation clocktime < 13:00:00 h	And simulation clocktime < 13:00:00 h
And 6 m < =UCT dam depth < =12.5 m	And 3 m < =UCT dam depth < =12.5 m
Then Open orifice to meet demand	Then Open orifice to meet demand
Else close orifice	Else close orifice

SC2 scenario would thus establish the benefit of periodic planned maintenance and account for a situation where dredging would have been undertaken to remove sediments from the UCT dam to maximize its storage. For the modeling of SC1 and SC2 static control simulations, input data consisted of 5-min time-interval historical rainfall time series for the period 2015–2022 obtained from the South African Weather Services (SAWS).

The study then developed two RTC configurations, i.e., RTC-1 and RTC-2 linked to the two static control operations, i.e., SC1 and SC2, respectively. The simulation of the two RTC operations considered actuator settings and control rules to dynamically manage storage available in the two static control operations, i.e., SC1 and SC2 and managed based on rainfall forecast information. Rainfall forecast data used for RTC application in the study was based on Global Forecast System (GFS) that provide predictions over two weeks in a spatial form. A rainfall forecast at 6-h intervals provided by the National Centre for Environmental Prediction (NCEP) was used for this study. The available GFS forecast data were collected for the study area where GFS data were available at latitude 34° 00′ S and longitude 18° 31′ E. The data were extracted for the period 2015–2022 and used for the RTC simulations linked to forecasted rainfall volume to initiate pre-storm releases.

RTC of the UCT dam outlet valves was simulated through the application of RTC-1 and RTC-2 algorithms as shown in Figure 5. The primary objective of applying the RTC-1 and RTC-2 algorithms was to determine level of increase of harvested stormwater volumes due to dynamic management of the storage.

The description of the data used to model the stormwater harvesting system in the study area at the University of Cape Town is summarized in Table 4. The stormwater harvesting model with RTC was developed in EPASWMM 5.1 (Rossman 2015). The software is commonly used for RTC simulations with open-source control algorithms. The dynamic wave routing of conduit lengthening and a routing time step of 15 s was used to represent the hydraulic processes of the system.

To incorporate user-defined controls appropriate for the study area, algorithms were developed and applied externally via PySWMM, which is a Python programming language package that allows for the stepwise observation and modulation of SWMM models. PySWMM tools can observe and manipulate nearly any parameter in SWMM, however, only data that could be feasibly monitored in a real-world application can be used for RTC application to create a realistic scenario (Schmit *et al.* 2020).

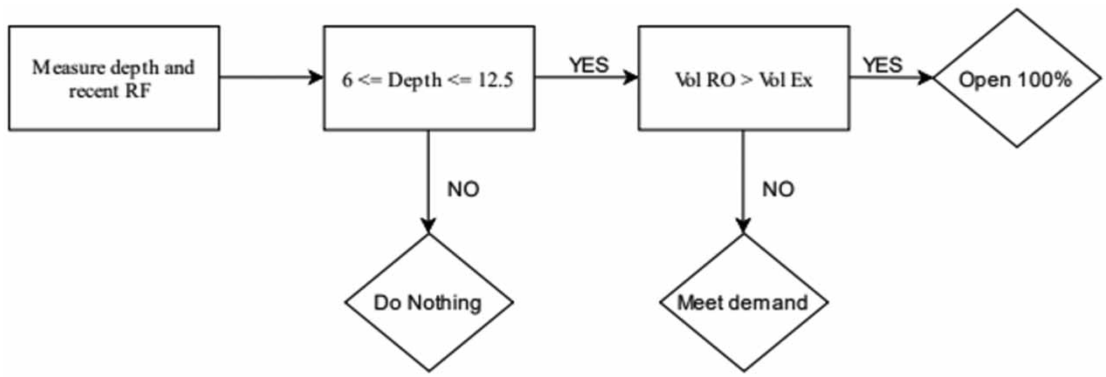

Figure 5 | RTC-1 (6 m < =dam depth < =12.5 m); RTC-1 (3 m < =dam depth < =12.5 m). Where RF = rainfall; Vol RO = Runoff volume; Vol Ex = maximum volume – current volume of water in the UCT dam.

Table 4 | Data used to model stormwater harvesting system

Data	Source
Catchment topography	Digital Elevation Model (DEM) with a spatial resolution of 10 m was obtained from the City of Cape Town to accurately represent the catchment topography.
Soil infiltration	Green-Ampt infiltration model in SWMM 5.1 was used to model infiltration. Borehole logs of the New Lecture Theater and New Engineering Building of the University of Cape Town produced by Kantey & Templer Consulting Engineers were used to identify the soil conditions (Upper soil type zones) within the watershed. The borehole logs were useful in estimating infiltration parameter because the Green-Ampt equation could be applied in the upper soil zone.
UCT Dam	Information that detailed the infiltration losses, outlet structures and storage capacity were obtained from various reports. For example, information required to estimate infiltration was obtained from a report on the UCT dam; and as-built drawings of the UCT dam. The storage capacity of the dam was modeled using a storage curve based on a report prepared by Zutari (2020). The as-built drawings provided information on outlet structure.
Rainfall	The historical data were for the period 2015–2022 while rainfall forecast data were obtained from a local weather station and GFS, respectively.
Evaporation	The Hargreaves's method was used to compute daily evaporation rates based on temperature data obtained from a local weather station.
Water demand	Estimations of irrigation demand were based on an irrigation demand model prepared by Zutari (2020)

The RTC model for the study area was then set up based on various key components and measurements such as depth sensors, actuated valves, and a rain gauge. The extract PySWMM code used to optimize RTC systems is presented in Figure 6.

For model development, a 5-min time step was used for the simulation of rainfall–runoff based on historical data. This has previously been determined to provide a realistic interval to receive and transmit data and control commands while providing

```
from pyswmm import Simulation, Links, Nodes, SystemStats
from datetime import datetime
with Simulation('C:/Users/Malesela/Downloads/CIV5000WProjectV1.inp') as sim:

Or21_Uctdam = Links(sim)["21"]
Pond_Uctdam = Nodes(sim)["12"]
syst_stats = SystemStats(sim)
sim.step_advance(300)

for step in sim:
RRF_Uctdam = syst_stats.runoff_stats["rainfall"]
Vol_ro_Uctdam = PR*RRF_Uctdam*A
Vol_ex_Uctdam = Max volume - Pond_Uctdam.volume
if Vol_ro_Uctdam > Vol_ex_Uctdam:
Or21_Uctdam.target_setting = 1.0
else:
Or21_Uctdam.target_setting = 0
```

Figure 6 | PySWMM code used to optimize RTC systems. Where Or21_Uct dam is the orifice of the dam; Vol_ro = runoff volume; Vol_ex = maximum volume − current volume of water in the UCT dam; PR = Runoff coefficient and A = Catchment area.

adequate temporal resolution (Bartos *et al.* 2017). The GFS of 6-h interval data were used to estimate the forecast rainfall volume, then linked to RTC to initiate pre-storm releases via PySWMM. PySWMM can also be used to interrupt SWMM simulations during processing to retrieve relevant measurements such as precipitation, flow, depth etc., at any interval (Schmit *et al.* 2020). Based on these studies, control algorithms were developed and applied to guide decisions such as appropriate outlet valve opening for prestorm release and normal operation of the UCT dam. The actuator was set to the required position based on a control algorithm input via PySWMM to account for pre-storm release and normal operation requirements, while SWMM simulations continued until the next time step if no interruption was required.

Appropriate parameter estimation and optimization was undertaken in the model development process as described above; however, calibration was undertaken as recommended in various studies such as Sangal *et al.* (1994); Singhofen (2001); James (2005) to provide an acceptable representation of the hydrological process in catchment (Moriasi *et al.* 2007). These studies have recommended various techniques to optimize the calibration of a stormwater model such as: Nash–Sutcliffe efficiency (NSE), Root Mean Square Error (RMSE) and Percent BIAS (PBIAS) Moriasi *et al.* (2007). In this study, the stepwise calibration process was as follows:

(i) The rainfall data were used for the model development and calibration to mimic hydrological processes which can produce short response times in small catchments. The water level data for the UCT dam required for calibration and validation processes was limited to 10 June 2022 to 7 August 2022 recorded at 15-min intervals with no observed values from 2 July to 15 July 2022. Sample water level data extracted from the timeseries and used for comparison is presented in Table 5.
(ii) Calibration was based on water levels taken from 28 to 30 July 2022 while validation was performed from 10 June to 17 June 2022 (see Table 5).
(iii) The water levels were found to be the most sensitive to saturated hydraulic conductivity. Parameters in SWMM such as depth of depression storage for impervious surfaces (DStore – Imperv), depth of depression storage for pervious surfaces (DStore – Perv) and Manning's n for pervious surfaces (N – Perv), which were found to be sensitive according to various studies were not calibrated (Liong *et al.* 1991; Tsihrintzis & Hamid 1998; Barco *et al.* 2008).
(iv) Visual inspection was used when calibrating and validating the model based on comparisons of observed and simulated data (see Figure 7).

The results shown in Table 6 include the calibration and validation errors for runoff quantity continuity and flow routing continuity.

The flow routing continuity error for all configurations ranged between −0.8 and 0.1% while the runoff continuity error was 0%. The calibration results conformed to acceptable range defined in 'rules of responsible modeling' (James 2005). The model was also able to gap fill missing observed data (see Figure 8). Moriasi *et al.* (2007) state that a model calibration provides

Table 5 | Comparison of gauged and sensed water level data

Date and time	Level gauge reading	Sensor readings	Difference
10/06/2022 14:15	9.200	9.150	0.050
15/06/2022 13:15	10.700	10.727	−0.027
19/06/2022 13:10	10.900	10.879	0.021
24/06/2022 14:40	11.100	11.107	−0.007
29/06/2022 11:30	11.100	11.107	−0.007
02/07/2022 17:20	11.200	11.240	−0.04
15/07/2022 13:30	11.800	11.799	0.001
20/07/2022 10:45	11.900	11.894	0.006
27/07/2022 11:30	12.000	11.951	0.049
03/08/2022 17:00	12.100	12.045	0.055
07/08/2022 16:30	12.100	11.932	0.168
08/08/2022 10:00	12.100	11.837	0.263

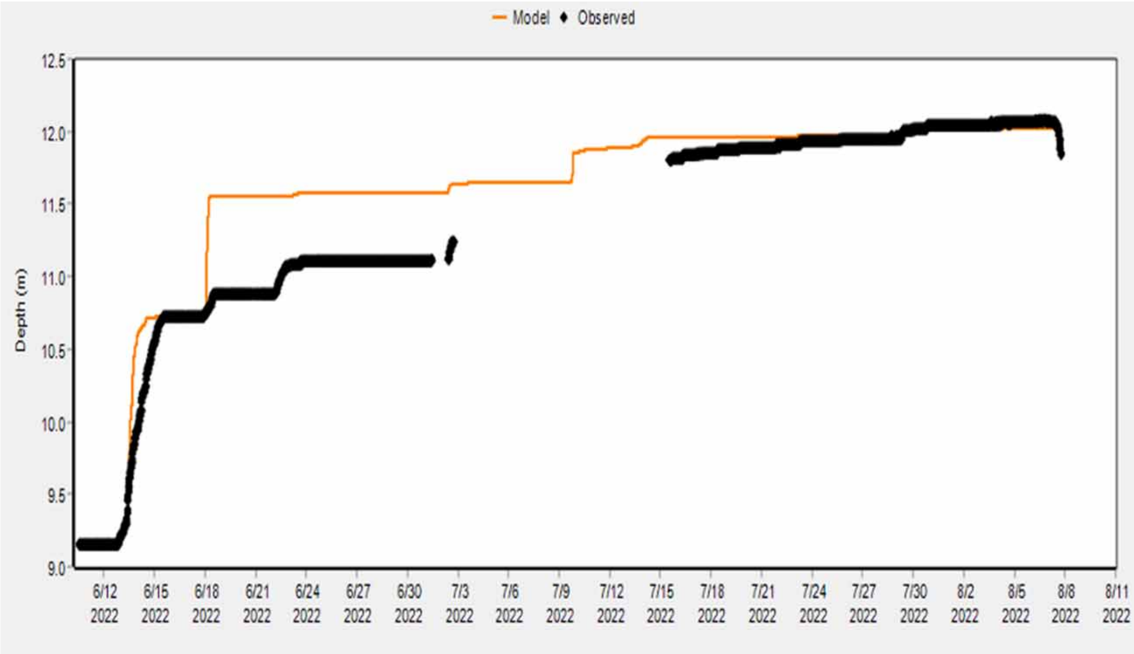

Figure 7 | Observed and simulated water levels.

Table 6 | Calibration and validation results for dam water levels

	Observed vs. Calibrated	Observed vs. Validation
Nash–Sutcliffe Efficiency	0.74	0.91
Runoff quantity continuity error (%)	– 0.003	
Flow routing continuity error (%)	3.75	

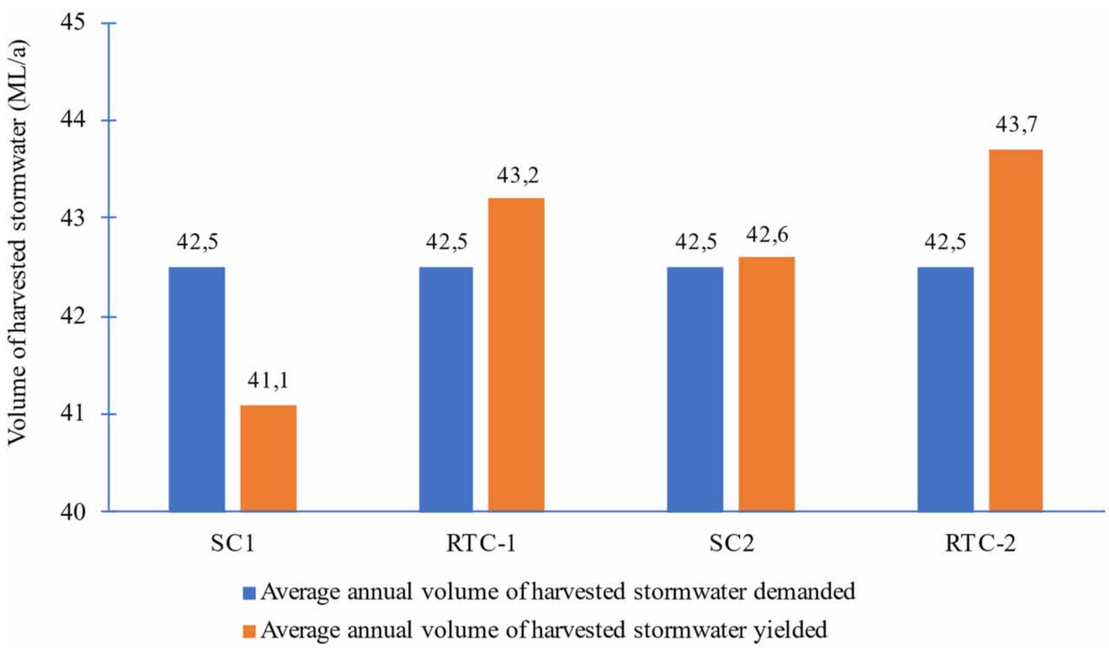

Figure 8 | Average annual harvested stormwater volume per configuration.

reasonable results when NSE > 0.5. James *et al.* (2010) also states that a continuity error below 10% is tolerable, thus the errors are considered acceptable.

A basic economic assessment was also undertaken on the stormwater harvesting approach based on the LCCA, i.e., an evaluation method commonly used for lifetime economic appraisal of an asset (WERF 2011; Armitage *et al.* 2013). The LCCA method is used to compare initial capital, maintenance, and operational costs (Swamee & Sharma 2008; Li *et al.* 2023). In addition, the LCCA can also be applied for monetary appraisals of direct and indirect costs; and economic appraisals of costs and benefits due to anthropogenic changes in the environment. This study used the LCCA on direct costs, i.e., capital, maintenance, and operational costs. The Life Cycle Costs (LCCs) were computed by converting all costs incurred to an equivalent period over its lifespan. All future costs were converted to equivalent present values using Equation (1), while Equation (2) was used to compute the discount factor. Finally, Equation (3) was used to compute the LCC.

$$PV_n = FC_n \times DF_n \tag{1}$$

where PV = present value for year, n (ZAR); FC = total future monetary costs in year, n (in ZAR = South African Rand); DF = discount factor in year, n; and n = number of years from present year

$$DF_n = \frac{1}{(1+i)^n} \tag{2}$$

where DF = discount factor; i = real discount rate; and n = number of years from present year

$$LCC = \sum_{n=0}^{No.\ \text{years}} (PV_n)_{\text{costs}} \tag{3}$$

where LCC = Life Cycle Cost (in ZAR); No. years = total number of years in life cycle analysis; n = number of years from present year; PV = present value for year, n; and Res = residual cost (in ZAR)

The following steps were taken in applying LCCA to the stormwater harvesting system:

(i) The discount rate was taken as the difference between a government 10-year bond rate and the inflation rate (Consumer Price Index) as shown in Table 7.

The values in Table 7 are in line with the National Treasury recommendations, which state that '*For practical purposes, the discount rate is assumed to be the same as the risk adjusted cost of capital to government. The government has been used by some institutions as the discount rate for a particular project over a comparable period. The argument in favor of using the government bond is that it reflects the actual cost to government of raising funds at any given time. This ignores several factors that are difficult to quantify, including: various risk margins relating to increased government borrowing; various tax implications of diverting funds from private to public consumption; and government's time preference of spending*'.

(ii) Life cycle duration – the LCCA was undertaken over a 50-year period that is recommended to represent the lifespan of a stormwater harvesting system. Typical life expectancies of 50 years are recommended for economic analysis of water supply systems (Mackenzie 2010).

(iii) Annual estimates such as the harvested stormwater volume and the cost of energy were selected to coincide with the period used in model simulations.

(iv) Life span of components in the stormwater harvesting system – the future capital costs and residual values of each system component was selected to coincide with the end of the life cycle duration.

Table 7 | Table 3-2: RSA bond yields and inflation (StatsSA, 2022)

Analysis period	Government 10-year bond (%)	Inflation (%)	Discount rate (%)
2012–2022	10.5	7.6	2.9

(v) The Equivalent Annualized Cost (EAC) was computed using Equation (4), and this value was estimated as the cost per year of ownership and asset operation.

$$EAC = \frac{i(1+i)^n}{(1+i)^n - 1} \times LCC \tag{4}$$

where EAC = equivalent annualized cost (in ZAR); n = number of years from present year; i = real discount rate and LCC = life cycle cost (in ZAR).

RESULTS AND DISCUSSION

The assessed average annual stormwater yields are compared in Figure 8. The study determined that RTC improved system performance in terms of average annual harvested stormwater volume by up to 6.3% in comparison to the SC1 scenario (see Figure 8 and Table 8).

For the baseline operational procedure that are currently in practice at the UCT dam (scenario SC1), the results show that application of RTC operation measures increased average annual harvested stormwater volume by approximately 2.1 ml (see Table 6) In the case of scenario SC2 where sediments are removed from the UCT dam to maximize storage and RTC operation measures are applied increased average annual harvested stormwater volume by approximately 1.1 ml (see Table 6). Although the increase seems minimal, the application of RTC-1 and RTC-2 algorithms on the UCT dam provided valuable additional capacity to capture stormwater that is harvested to meet demand. As shown in Figure 10, with application of RTC, harvested stormwater exceeded demand in both RTC 1 and RTC 2, i.e., with or with dredging to increase dam capacity. The study also determined that periodic planned maintenance was essential as it increased stormwater average annual harvested stormwater volume by 1.5 ml. The increase due to maintenance was sufficient to meet irrigation demand.

The estimated EAC is presented in Figure 9. The estimates show an increase in costs for RTC operations by about one hundred thousand rands.

For each configuration, i.e., SC1, SC2, RTC-1 and RTC-2, the unit costs of harvested stormwater were computed by dividing the EAC with the average annual harvested stormwater volume. The unit cost of harvested stormwater for each configuration is presented in Figure 10.

Water usage by sports bodies in Cape Town are billed at a flat rate (excluding VAT) of 29.55 ZAR/kL (CCT 2022). Static (SC1 and SC2) and Real-Time (RTC-1 and RTC-2) configurations harvested stormwater at approximately four times and three times the tariff, respectively. RTC-1 and RTC-2 harvested stormwater was estimated to be about 1.80 and 1.99 ZAR/kl, i.e., 21 and 25% more expensive than SC1 and SC2, respectively.

In summary, the study determined that the average annual harvested stormwater volume from a stormwater harvesting system can be improved by using RTC. This can be accomplished with prestorm release, i.e., collecting rainfall forecasts in real-time and discharging water from the system prior to the occurrence of a rainfall. The use of pre-storm releases would be based on upcoming storm runoff to provide additional system storage capacity. The upcoming storm runoff would be estimated from rainfall forecast data available from platforms such as GFS. However, it was determined that the GFS data had

Table 8 | Summary of SC1, TRC-1, SC2 and RTC-2 results

AASHD (ml/yr) Scenario	42.5 AASHY (ml/yr)	Change in Yield from SC1 (ml/yr)	Change in Yield from SC1 (%)	AAMWID (ml/yr) Stormwater Yield less Stormwater Demand (ml/yr)	AAMWID (ml/yr) Stormwater Yield less Stormwater Demand (%)	40.04 AAMWID Saving (ml/yr)	40.04 AAMWID Saving (%)
SC1	41.1			−1.4	−3.3%	−1.4	
RTC-1	43.2	2.1	5.1%	0.7	1.6%	0.7	1.7%
SC2	42.6	1.5	3.6%	0.1	0.2%	0.1	0.2%
RTC-2	43.7	2.6	6.3%	1.2	2.8%	1.2	3.0%

Notes: AASHD = Average Annual Stormwater Harvest Demand, AASHY = Average Annual Stormwater Harvest Yield, AAMWID = Average Annual Municipal Water Irrigation Demand.

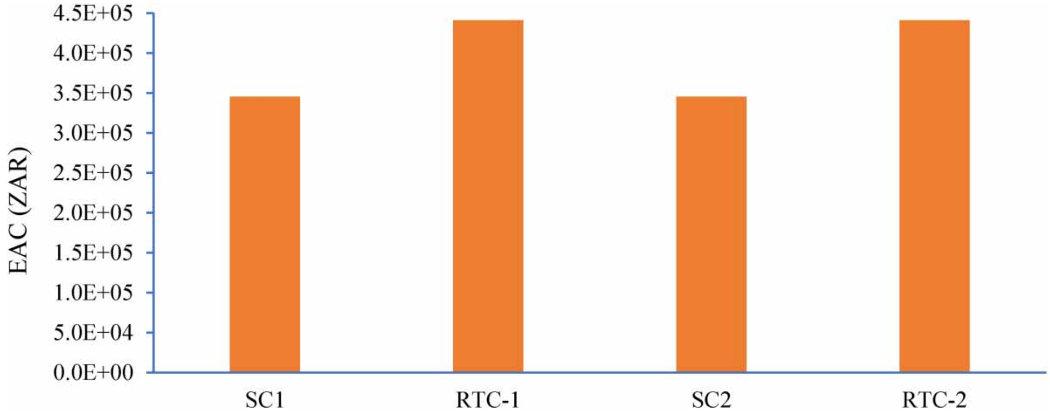

Figure 9 | Equivalent annualized cost for each configuration.

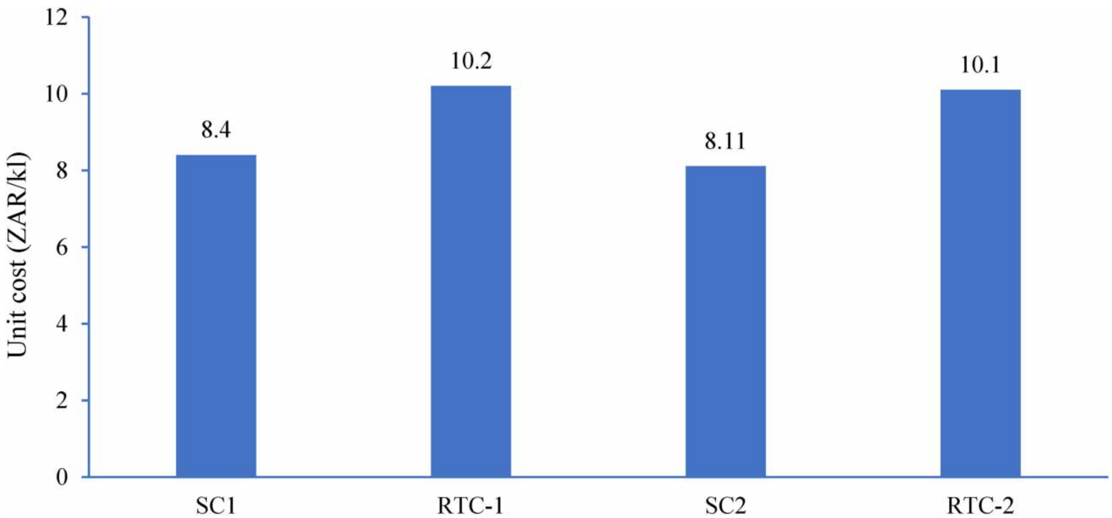

Figure 10 | The estimated unit cost for each configuration.

some differences in magnitude in comparison to observed events especially the time when the peaks occurred. In the study area, some differences were identified such as an event with a peak that was 40% higher than GFS data due to poor quality of the forecast. The disadvantage of an underestimation in the forecast would be no release from the storage (UCT dam) with subsequent occurrence of a flood. The quality of forecast can be improved by implementing a forecast with smaller time-steps (i.e., 5- or 15-h temporal resolution) and forecast revision for better water management. Forecasts can be revised when the difference between the actual conditions and forecast are such that public safety and security are at risk and/or inconveniences the public. In addition, precipitation should be accounted when the chance of precipitation is equal to or greater than 30%. Overall, the GFS data were relatively accurate, but with rainfall depth of forecasts generally lower than real-time which often produced underestimated volume of prestorm release for this study. To mitigate the impact of this observed underestimated, the study implemented prestorm release with additional amount of water on occasion for the RTC system. Hence, this has the possibility of diminishing performance for water supply. This 'underestimation' can be improved by using a more accurate and smaller time-interval rainfall forecast data which optimizes the system.

CONCLUSIONS

In this study, a continuous simulation was conducted to model the ability of two types of SWH system, namely a conventional (static) and RTC system (dynamic) to deliver non-potable water for irrigation. The study determined that the implementation of RTC can significantly improve the annual yield and volumetric reliability performance of a SWH system. The dynamic management of the UCT dam with RTC-1 and RTC-2 approaches increase yield by 2.1 and 1.1 ml, respectively. Additionally, RTC-1 and RTC-2 approaches increase volumetric reliability by 5.3 and 2.5%, respectively, while maintaining the required level of service of a stormwater harvesting system. SC1 and SC2 results in water savings of up to 21.15 and 21.45 ZAR/kl, respectively, while RTC-1 and RTC-2 could save up to 19.35 and 19.45 ZAR/kl. Thus, static configurations result in water savings approximately 9% in comparison to RTC. In addition, Static configurations harvested stormwater at a relatively lowest unit cost in comparison to RTC configurations. Hence, RTC approaches increase yield and volumetric reliability with relatively low-cost implications. Notwithstanding this finding, the RTC system exhibits a great potential in reshaping the stormwater harvesting system to simultaneously deliver water conservation and stormwater management. The ability of an RTC system to provide centralized control and failure detection, which can be readily adapted to variation of climate and local conditions over both the short and long term, opens possibilities of delivering a system that is more stable and reliable.

This research mainly focused on the benefit of RTC in enhancing stormwater harvesting to transition a precinct in Cape Town toward a water-sensitive future. This study represents only a part of a greater effort to reuse water in an urban area including inter alia harvesting and reuse of stormwater and rainwater, and treatment and reuse of greywater. RTC approaches applied in combination with urban drainage system retrofits and periodic maintenance can pave the way for smarter stormwater management.

AUTHOR CONTRIBUTIONS

M.M.M. undertook the research including the literature review, selection of a suitable method, development of the assessment model, generation of the results, wrote the draft paper, and implemented the revisions from feedback/comments received from co-author and reviewer. J.O. (ORCID https://orcid.org/0000-0001-7707-2721) proposed the research topic, managed, and supervised the study, assisted in the paper writing, formatted the paper for submission and is the corresponding author.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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