Water SA 52(1) 35–48 / Jan 2026
https://doi.org/10.17159/wsa/2026.v52.i1.4165.1

The prospects for stormwater harvesting in Cape Town: Part 1 – transforming existing stormwater ponds into reservoirs using real time control

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In 2018, the City of Cape Town (CCT) in South Africa came close to 'Day Zero' – the day taps would run dry due to an extreme drought that began in 2015. With severe droughts likely to be common in future, this study investigated the potential for catchment-scale stormwater harvesting facilitated by the transformation of stormwater ponds into reservoirs. In this new approach, water levels in the ponds would be dynamically managed using real-time control (RTC) to ensure continued use as flood control infrastructure. The study was restricted to the 89 km^2 Zeekoe Catchment situated on the Cape Flats in the southern part of the city. Assuming the water would be used for outdoor non-potable uses such as agriculture and residential gardens, the temporal mismatch between the seasonal demand and winter rainfall meant limited supply. Stormwater could meet a limited percentage of the demand, but with most lost to the sea as overflow. To minimise the effect of the mismatch, it was determined that at least 4 Mm^3 balancing storage i.e., 20–30% of the mean annual stormwater volume estimated at 18 Mm^3, was required. The available 1 Mm^3 storage (5.5% of the mean annual stormwater volume) in the catchment was found to be inadequate as the stormwater supplied from the storage would only meet 44–60% of the demand, with a spill (water lost as overflow) of 35–51%. Dynamic management of the ponds with RTC was investigated to provide the required storage. This involved continuous adjustment of stormwater flow rates with a set of rules to optimise storage capacity. With this management approach, it was possible to achieve the required 4 Mm^3 to meet the identified demand in the study area and minimise the loss through spill.

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DATES
Received: 8 August 2024
Accepted: 8 December 2025

KEYWORDS
catchment scale
stormwater harvesting
surface storage
real-time control
Cape Town

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INTRODUCTION

South Africa is a semi-arid and water-stressed country that heavily relies on surface water from unevenly distributed rainfall, with a mean annual precipitation (MAP) of 450 mm – approximately 50% of the world MAP (Pitman, 2011). With the surface water resources almost fully developed and utilised, it has been projected that there will be a gap between water demand and supply of some 17% by 2030 unless there is a meaningful change in water supply and use patterns (DWA, 2008). The vulnerability of South Africa to water shortages was clearly highlighted by the extreme drought in the Western Cape Province from 2015 to 2018, when the City of Cape Town (CCT) came close to 'Day Zero', the day taps would run dry due to lack of water. Prior to the drought, the water needs of CCT had been almost completely met by 6 large reservoirs situated in the mountainous catchments to the east of the city. The drought exposed the limitations of this reliance on conventional surface water resources alone and forced CCT to seek alternative sources such as stormwater harvesting (SWH).

SWH should not be confused with rainwater harvesting (RWH). RWH is the use of runoff from the rooftops of buildings, typically at a household scale, and has been carried out for centuries (Mwenge, 2010). SWH is a more recent concept associated with urban areas, is normally implemented at a regional scale, and generally requires suitably modified urban stormwater management infrastructure. Wong (2007) and others have made the point that cities are also catchment areas which, if well managed, could provide a substantial proportion of their water needs. Furthermore, Marsden and Pickering (2006) determined that the mean cost per kilolitre of water delivered through SWH can be lower than many other sources including, inter alia, seawater desalination, RWH, and conventional surface water conveyed through long-distance pipelines. Some countries that have adopted SWH as a water resource include China (Hamdan, 2009), Singapore (Lim et al., 2011), UK, USA and Australia (Philp et al., 2008).

In South Africa, stormwater management infrastructure has mainly been designed for flood control, with an emphasis on concrete-lined pipes and channels that rapidly convey runoff to the nearest receiving water, e.g., rivers, lakes and the sea (Armitage et al., 2013). This results in highly polluted runoff with raised flood peaks posing severe limitations for SWH. As a rule, substantial storage is required to bridge the gap between supply and demand, whilst the poor quality of most stormwater presents a health risk for both potable and non-potable water purposes without treatment.

This study investigated the potential for catchment-scale SWH in CCT. Since CCT covers 2 445 km^2, with more than 800 stormwater ponds, the study was restricted to the 89 km^2 Zeekoe Catchment situated on the Cape Flats in the southern part of the city. Two harvesting techniques were investigated: (i) local storage in the existing stormwater ponds with water levels managed using 'real-time control' (RTC) to maintain the flood management capability (Part 1 – this paper); and (ii) underground storage in the local aquifer using managed aquifer recharge (MAR) (Part 2 – Okedi and Armitage, 2026).

LITERATURE REVIEW

Many countries around the world are beginning to consider stormwater as an alternative water resource to augment existing water supplies due to the current and projected future water scarcity. There are two main challenges of SWH: stormwater is generally only available for short periods that, additionally, only occur at limited times of the year, i.e., during the rainy season; and it generally carries physical, chemical and biological pollutants (CCT, 2005) that may require removal before use.

The transient nature of stormwater flows usually necessitates the provision of some form of storage to either: (i) allow sufficient time for extraction, or (ii) bridge the time gap between supply and demand – particularly when the demand is for non-potable uses such as irrigation which is only required during dry periods. Storage options for SWH systems include both closed (e.g., underground tanks), open (e.g., stormwater ponds), and underground (e.g., aquifer) options. The determination and selection of a suitable storage option for a SWH system is case-specific and depends on issues such as: climate, system yield, land availability, topography, geology, demand, and end-uses. It must consider the scale of the SWH system and the intended application of the harvested water. The design of the storage option should consider how the water will be collected, stored, treated, and distributed to end users. Mitchell et al. (2007) determined that the design of the storage option for the SWH system should consider maximising volumetric reliability while minimising storage size and associated costs.

Closed stormwater storage systems such as underground tanks are more common with RWH than SWH. Tanks collect and temporarily store rainwater that runs off roofs and paved areas (Armitage et al., 2013). Permeable pavement is an example of a modified parking space for temporary storage of stormwater runoff, with minimal losses from evaporation and seepage, which may be harvested for later use (Armitage et al., 2013). Due to their limited capacity these options are typically used at small-scale or property level SWH systems (Hatt et al., 2006).

Underground storage is the subject of Part 2 (Okedi and Armitage, 2026) and will not be discussed here.

Open stormwater storage systems include, inter alia, ponds, wetlands, reservoirs, lakes, rivers, streams, and creeks (Goonrey, 2005). Well-designed open storage systems can provide at least 4 types of benefits, viz.: the management of water quantity; the improvement of water quality; the provision of amenity; and the preservation of biodiversity. The management of water quantity can be further broken down into flood control, infiltration and SWH (Armitage et al., 2013).

A major problem with SWH is the general lack of suitable and adequate storage in urban areas. Land is often at a premium with stormwater infrastructure fighting for space against seemingly more pressing – or remunerative – demands. Whilst there may be numerous small ponds for flood control purposes, these seldom provide sufficient space for long-term storage without undermining their primary function – at least as designed. However, it may be possible to increase their effective storm storage without undermining their original purposes using real-time control (RTC). RTC – in the context of stormwater management – involves the dynamic control of the system through the application of specific operational rules to consolidate available storage with the primary objective of minimising redundancy (USEPA, 2006). Typically this involves the dynamic management of water levels in the storage components to increase retention time and optimise hydraulic capacity (Vallabhaneni and Speer, 2011), through the continuous monitoring and adjustment of stormwater flow rates and storage volumes with a set of rules depending on the status and needs in the system (Garcia et al., 2015). The earliest stormwater management systems with RTC were implemented in the USA in the 1960s, with the goal of volumetric expansion of a constrained network (Borsanyi et al., 2008). Subsequently, several stormwater systems with RTC have been designed and implemented, mainly in the developed world, including Europe and North America (Garcia et al., 2015). RTC has been identified as a flexible and cost-effective method to deal with the impact of climate and land-use changes on stormwater infrastructure (Vezzaro and Grum, 2014). The implementation of RTC also provides capacity to incorporate new information such as rainfall forecasts in various data formats, e.g., radar (Thorndahl et al., 2013), and allow for the minimisation of errors and uncertainty in the decision-making processes (Coccia and Todini, 2011). Three approaches for implementation of RTC in stormwater systems have been identified, including: (i) local control – the system is managed using measurements taken at each specific location with adjustments dependent on the prevailing conditions only; (ii) regional control – similar to the local control that adjustments to the system are made based on measurements taken from a location – or several locations – that are remote to the place at which the adjustments are made, and (iii) global control – a server-based system where all the data, controls and adjustments of the actuators for the entire network are centralised so that the operation of the system can be optimised.

In the selection of a suitable RTC approach, consideration is typically given to the level of complexity appropriate for the study area, especially based on the available data and practical requirements for operation and maintenance (Van Daal et al., 2017). Periodic redundant storage in the stormwater network is critical for the successful implementation of RTC, and the extent of the performance would depend on how much capacity can be made available with the optimisation of the control rules (US EPA, 2006). The challenges that need addressing in the implementation of RTC are data accuracy and reliability associated with continuous recording and remote transmission (Schutze et al., 2004).

METHOD

Site selection

The factors considered in the selection of a suitable catchment for the study were:

- Plenty of potential storage options such as stormwater ponds, and open water bodies such as vleis (shallow lakes) that could be adapted for SWH purposes
- The availability of good-quality data to facilitate the modelling of the hydrological processes in the catchment
- Situated over an unconfined aquifer that would allow MAR (described in Part 2)
- Proximity to potential stormwater users, e.g., agriculture, residential areas, and public parks
- Proximity to an existing potable water treatment plant (WTP) to minimise the cost of conveyance for treatment of the stormwater to potable standard and distribution through the existing reticulation system

A preliminary study identified and categorised the stormwater ponds in the various catchments of Cape Town. It established that 70% of the ponds were detention ponds, 23% retention ponds, and 7% wetlands – distributed as shown in Fig. 1.

The high percentage of detention ponds – which are normally kept empty in anticipation of a large storm event – was expected, as the CCT has historically designed their stormwater ponds for flood control alone. Interestingly, 41% of the detention ponds or 51% of all the stormwater ponds had some multi-functionality – mainly for recreational activities. The study further found that stormwater ponds were often concentrated in areas where there

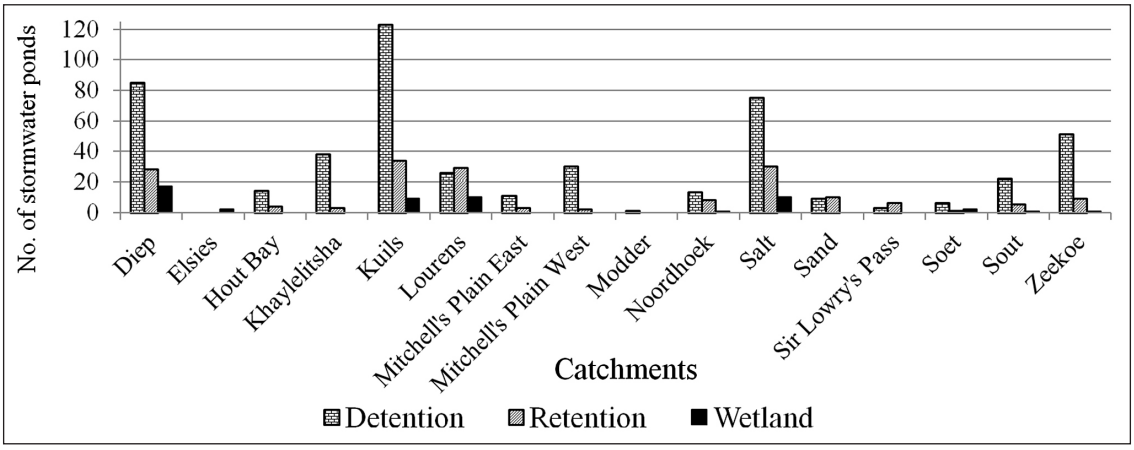

Figure 1. Stormwater ponds per catchment

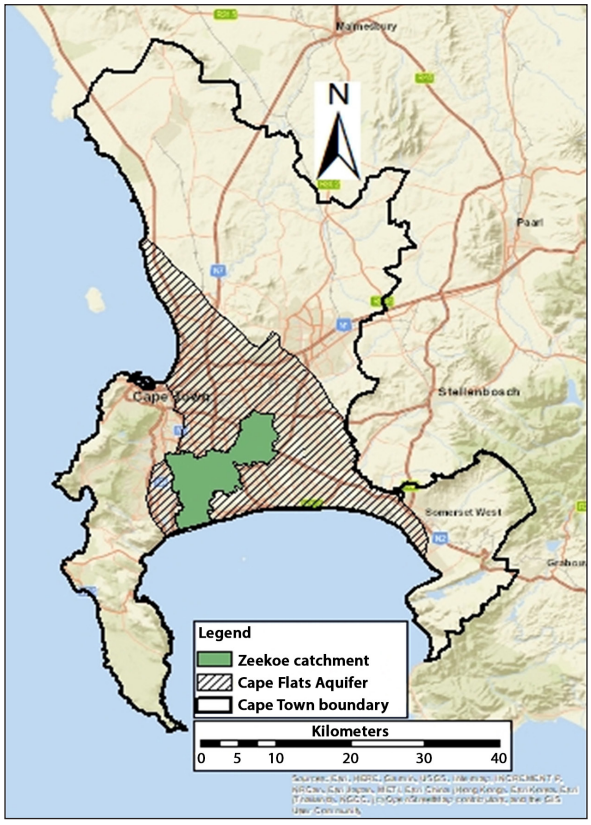

Figure 2. Locality plan (CCT, 2012)

are large numbers of informal settlements (shanty towns). This makes dry ponds vulnerable to invasion by poor people looking for vacant urban land who are unaware of their function. Informal settlements are also associated with poor waste collection services and, consequently, ponds are often seen as convenient refuse disposal points with severe negative impacts on stormwater quality and the general environment.

The Zeekoe Catchment (Fig. 2) was selected for the study as it had 61 stormwater ponds and three large shallow lakes (vleis) with the potential to be adapted for surface water storage.

It is situated over the deepest and most productive part of the Cape Flats Aquifer (CFA). It is also relatively close to the two largest water treatment plants in Cape Town (Faure and Blackheath; both about 30 km from the most southerly (downstream) point in the catchment and proposed location of stormwater abstraction). The main drainage channel of the Catchment is the Great Lotus River (R1 in Fig. 3) that was mainly constructed to drain Cape Town International Airport in the early 1950s and flows through a large proportion of the catchment before discharging into the Atlantic Ocean in False Bay to the south of the area. The other streams in the Zeekoe Catchment are the Little Lotus River (R2 in Fig. 3) and the Southfield Canal (R3 in Fig. 3), which were constructed to drain a military base and racecourse, respectively. Other key features include wastewater treatment works and the Philippi horticultural area (PHA) – a key agricultural land use with rural characteristics.

Prior to urbanisation in the study area and construction of the airport, the drainage channels (Fig. 3) were unconnected and not directly linked to the ocean. After rainfall events, water would flow through the surrounding sand dunes and a series of marshes stretching from the ocean to the south-eastern corner that flooded during high water levels in winter. In the process of urbanisation, naturally occurring marshland was drained and built upon resulting in increased runoff and thus increased flood risk.

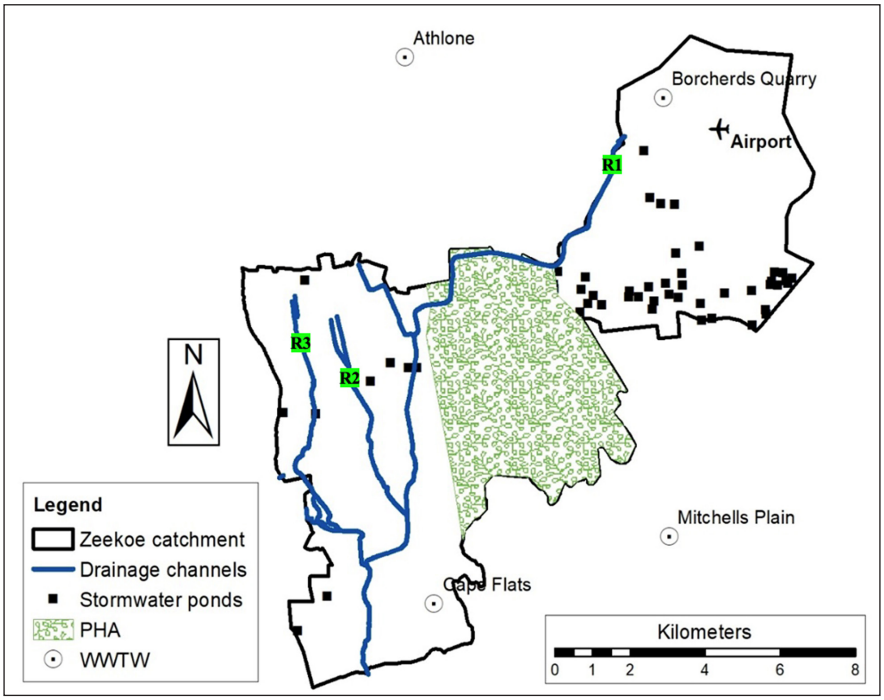

Figure 3. Main features in the Zeekoe catchment (CCT, 2012); R1 – Great Lotus River; R2 – Little Lotus River; R3 – Southfield Canal

To manage the floods, the surface depressions were connected to constructed drains and stormwater canals – including the Great and Little Lotus 'Rivers'. Subsequently, additional flood control infrastructure was created, including various detention ponds (Grobicki, 2001). Most of the ponds are to be found in the flood-prone area in the north-east of the catchment, an area characterised by several informal settlements, poorly drained aeolian sands and a generally high water table (Ziervogel and Smit, 2009).

In the absence of distinct drainage features, the Zeekoe Catchment is largely defined by stormwater drains. The Great Lotus River also drains adjacent industrial areas, some densely populated informal settlements, as well as a substantially low-middle-income residential area. Along the way, it flows around the PHA (Fig. 3), an important urban agricultural area in Cape Town. Since the area is undulating, with only a gradual overall slope to the ocean, availability of land was the basis for determining the flow path of the Great Lotus. The Great Lotus carries the highest pollution load of all the streams in the area as consequence of the areas it drains – most notably the informal settlements that are a source of grey and black water ingress into the stormwater drains. Although most of the Great Lotus is concrete lined, some upstream sections are earth lined, allowing for limited surface–groundwater interaction. The Little Lotus is not as profoundly impacted by pollution as the Great Lotus since it flows through areas of formal residential housing. The Southfield Canal drains the area around the Kenilworth Racecourse before flowing southwards to meet the Big Lotus near the Cape Flats Wastewater Treatment Works. All the drains in the Zeekoe Catchment are periodically maintained to remove excess vegetation growth, litter and sediment deposits, aimed at removing sediment and solid waste deposits and improving flow in the channels for flood management.

Model selection

The prospects for SWH in the Zeekoe Catchment using the existing stormwater infrastructure enhanced by RTC were determined through detailed numerical modelling of the catchment using the available historical hydrological data for the 10-year period 2006–2015. The availability of data for modelling and calibration was essential for the desktop study and was a vital consideration in the selection of the study area. PCSWMM (CHI, 2014) was selected to model the study area for a range of reasons:

- It can model all the main hydrological processes, i.e., rainfall, evaporation, infiltration, and flow, at very high temporal resolution (e.g., in minutes)
- It is possible to define specific functions in the modelling framework, such as extended detention of water in a pond employing RTC, and surface to groundwater transfer via infiltration into the underlying aquifer.
- It allows Google Earth visualisation.
- It is widely used in South Africa, especially in the CCT.
- The developers run annual training workshops in South Africa and provide excellent user support.
- It is free if used for education and research purposes.

PCSWMM data inputs include temporally and spatially varying rainfall, and directly measured and indirectly estimated evaporation and evapotranspiration. Hydrological processes that may be represented in the model include: rainfall abstraction by interception, wetting and depression storage, infiltration (i.e., unsaturated soil layers), percolation (i.e. infiltrated water into groundwater layers), interflow between groundwater and the drainage system, nonlinear reservoir routing of overland flow, retention and infiltration through stormwater ponds (James et al., 2010). Spatial variability is represented by dividing the catchment into smaller homogeneous sub-catchment areas, each containing distinct land use and soil characteristics.

Data availability

There are several rainfall measuring stations in and around the study area (Fig. 4); however, given the desire to produce a reasonably high-definition continuous model with a representative time-series, the preference was for gauges with at least 10 years of data at a 5-minute resolution.

There are 3 stations managed by the South African Weather Service (SAWS) with long time series, i.e., greater than 10 years, collected at a daily timescale. These include Cape Town Airport (since 1992), Rondevlei (since 1952) and Mitchell's Plain (since 2006),

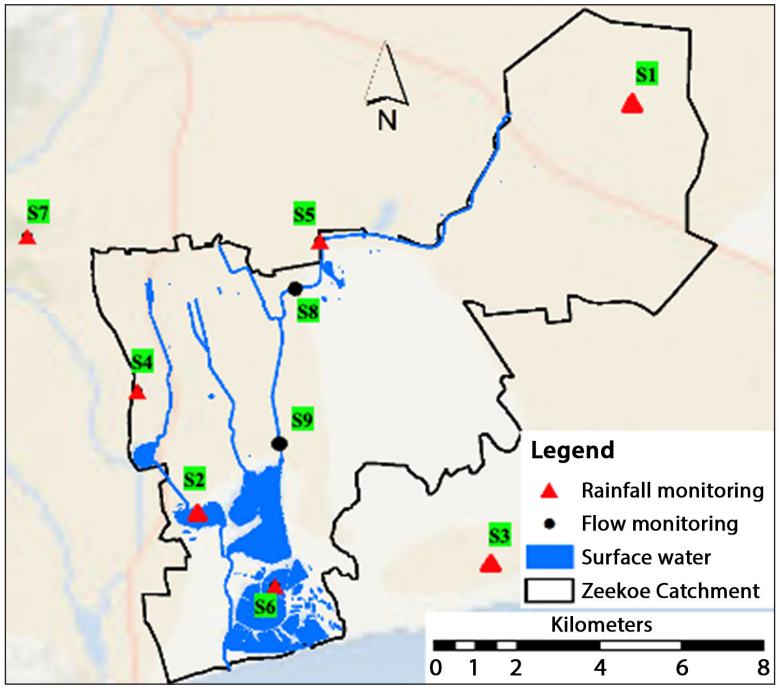

Figure 4. Rainfall and flow-measuring stations (CCT, 2015); S1 – Cape Town Airport, S2 – Rondevlei, S3 – Mitchell's Plain, S4 – Southfield, S5 – Hanover Park, S6 – Cape Flats WWTW, S7 – Wynberg Reservoir

Table 1. Summary of sources of data for the study

Item	Data	Location	Resolution	Period	Sources
Hydrology data	Rainfall	CF WWTW	5 minutes	2012–2015	CCT
		Hanover			
		CT-Airport			
		Wynberg			
		Southfield			
		Mitchell's Plain			
	Rainfall	CT-Airport	5 minutes	1992–2015	SAWS
		Mitchell's plain	5 minutes	2005–2015	
		Rondevlei	Daily	1952–2015	
	Temperature, humidity, wind	CT-Airport	Hourly	1992–2015	
		Mitchell's plain	Hourly	2005–2015	
		Rondevlei	Hourly	1952–2015	
	Rainfall, temperature	CT-Airport	Daily	1960–2100	CSAG climate models
		Mitchell's Plain	Daily	1960–2100	
		Rondevlei	Daily	1960–2100	
	River flow	6th Avenue	5 minutes	2012–2015	CCT
Water use	Billing records	Zeekoe Catchment	Monthly data	2011–2015	CCT
	Land use		Yearly	1998–2012	CCT, Google Earth
Stormwater network	GIS shapefiles	Zeekoe Catchment	Pipes and ponds	2015	CCT

labelled S1, S2 and S3, respectively, in Fig. 4. There are also 4 stations managed by the CCT that provide rainfall data at a 5-minute time interval but over a limited period, i.e., 2012–2015. The stations included Southfield, Hanover Park, Cape Flats WWTW and Wynberg Reservoir, labelled S4, S5, S6 and S7, respectively. The two flow monitoring stations labelled #8 and #9 are managed by the CCT and provided data at 5-min time intervals but over a limited period, i.e., 2012–2015. The study area has a Mediterranean-type climate with over 50% of the MAP in the winter months, from June to August, with about 80% over the extended period May–September. Key sources of data for the study are presented in Table 1.

Evaporation is a critical process in hydrological modelling as it represents a significant water loss. Historically, there were 3 evaporation stations in the Zeekoe Catchment; unfortunately, the stations were not in operation at the time of this research and, furthermore, lacked data for the study modelling period (2006–2015). The existing data were only used to assess the accuracy of computed evapotranspiration (ET_o) values using Hargreaves empirical methods.

The impact of climate change on demand and stormwater yield in the Zeekoe Catchment was also assessed to determine the need and extent required to account for its likely influence. Daily rainfall data for the period 1960–2100 from 26 statistically downscaled Coupled Model Intercomparison Project Phase 5 (CMIP5) were acquired from the UCT Climate Systems Analysis Group (CSAG) for Rondevlei and Airport Stations. The statistically downscaled data were from the General Circulation Model (GCM) of different Representative Concentration Pathways (RCP), i.e., RCP 4.5 (intermediate mitigation scenario) and RCP 8.5 (high emission scenario) (Van Vuuren et al., 2011). The seasonal variation of rainfall was also assessed to determine the likely impact on future rainfall. The climate models predict an increase in temperature by as much as 5°C towards the end of the 21st century. Climate change is particularly significant in the projected dry and hot periods where a limited resource is expected to meet high outdoor water needs such as irrigation of residential gardens, agriculture, and public open spaces.

For the PCSWMM model, the stormwater network layout of the Zeekoe catchment was acquired from the CCT in the form of GIS shapefiles that could be uploaded into ArcGIS and PCSWMM. The catchment was then subdivided into 118 sub-catchments based on the stormwater pipe network and ponds, density of development, road network, and topography. The mean sub-catchment area was 0.83 km^2, with some in the highly dense built-up areas as small as 0.01 km^2 and others in the less dense areas, e.g., agricultural areas and nature reserves, greater than 1 km^2. An attempt was made to include all the available stormwater pipes and channels, catch pits, manholes, and ponds but, owing to missing data, e.g., cover levels, invert levels, and pipe diameters, the stormwater network in the model had to be 'fixed' so that at least all water flowed downstream. The data input was carried out in a stepwise manner, commencing from the most downstream to the most upstream location in the catchment as follows:

- The open channel widths and depths were measured in PCSWMM by drawing transects on the 0.5 m resolution LIDAR DEM. A field visit was undertaken to some of the drainage channels to confirm the estimated values.
- Most of the pipe diameters were available and were presumed to be correct with spot checks being confirmed in field visits. If pipe diameters were missing, these were generally inferred from neighbouring pipes draining similar sub-catchments.
- For the connecting pipes upstream, all the available diameters were presumed to be correct. Missing pipe diameters were assumed to be equal to those just immediately downstream.
- All the pipe lengths were measured with the PCSWMM 'auto-length' functionality using Google Maps.
- All the available invert levels were presumed to be correct. Missing invert levels were estimated from a linear interpolation of the values just immediately downstream and upstream.
- Finally, the modelled network was checked to ensure that the stormwater flowed downstream.

The hydrological model for the Zeekoe Catchment was then developed and calibrated to reasonably estimate the harvestable stormwater volume. The stepwise calibration and verification process was as follows:

- Rainfall data measured at 5-minute time intervals, to represent the fast runoff processes that result in short response times in urban catchments, was used for the model development and calibration.
- A sensitivity analysis was undertaken to determine the uncertain parameters that had the greatest impact on the model results to guide the model calibration process. They were determined to be catchment width, impervious area, infiltration, and depression storage.
- A manual calibration was initially undertaken where the values of the sensitive parameters were changed by trial and error. The selection of suitable values to apply was guided by visual inspection to assess the improvements achieved in how the output from the model mimicked the observed flows.
- An automatic calibration was undertaken to fine-tune and optimise the results using the Sensitivity-based Radio Tuning Calibration (SRTC) tool available in PCSWMM.
- Finally, all the calibrated parameters were inspected to confirm that they were within acceptable ranges.

After completion of the model calibration process, an assessment was undertaken to determine the reliability of the results from the model. The statistical evaluation techniques that are available in PCSWMM are integral square error (ISE), Nash-Sutcliffe efficiency (NSE), coefficient of determination (R^2), standard error of estimation (SEE), simple least squares (LSE), simple least-squares dimensionless (LSE dim), root mean square error (RMSE) and root mean square error dimensionless (RMSE dim). Since the model performance evaluation is based on statistics, the selection of the events to be used in the assessment needed to satisfy the 'independence' criteria requirement. The events are considered independent if the inter-event period exceeds the recession time and the lowest flow value on the recession leg was below base flow. A total of 10 events were identified based on these two considerations for the model performance evaluation. As shown in Fig. 5, the model calibration provided reasonable results, i.e., NSE > 0.50 and R^2 > 0.90.

Verification of the model outputs was undertaken to confirm the reliability of the results with regards to the estimation of the total runoff volume. As shown in Fig. 5, the model verification also provided reasonable results, i.e., NSE > 0.50 and R^2 > 0.90. The standard deviation represented by the solid lines allows visual assessment of the correlation relationship between the computed model results and observed values. The model calibration aimed to minimise the standard deviation by reducing the horizontal and vertical distance of the points from the 45° bisector line. Presence of high scatter (i.e., large deviation from 45° bisector) is an indication of high uncertainty and bias in the model, which would be a source of errors in the estimation and prediction of flow volumes. In the calibration and verification processes, the extent of scattering and deviation from the 45° bisector was minimised to 10%. The summary of the results, including model continuity and routing continuity errors, is shown in Table 2.

The simulation of RTC for SWH in the Zeekoe Catchment considered rainfall data, control rules and actuator settings. Rainfall forecast data were acquired from the Global Forecast System (GFS) model managed by the National Centre for Environmental Prediction (NCEP). The GFS data was selected for the study because it is not copyrighted and is available for free in the public domain. It also serves as the basis for forecasts of many platforms worldwide. The GFS model provides global forecasts with up to 2 weeks prediction in a spatial form. It also provides time-series rainfall forecasts at a 3-hourly temporal resolution, available in the study area at latitude 34° 00' S and longitude 18° 31' E, from 6 May 2011 (system commencement date). The GFS forecast data were extracted for the period 2011–2017 and compared with measured data in the study area. It was determined that there were some differences in the timing of the peak (shift in peak times) and the magnitude of the events, as shown in Fig. 6.

Although the difference in magnitude of peak and associated volume was minimal for most events (i.e. less than 10% difference in 80% of events), some peaks in GFS data were 30% higher than recorded data. The disadvantage of an overestimation in

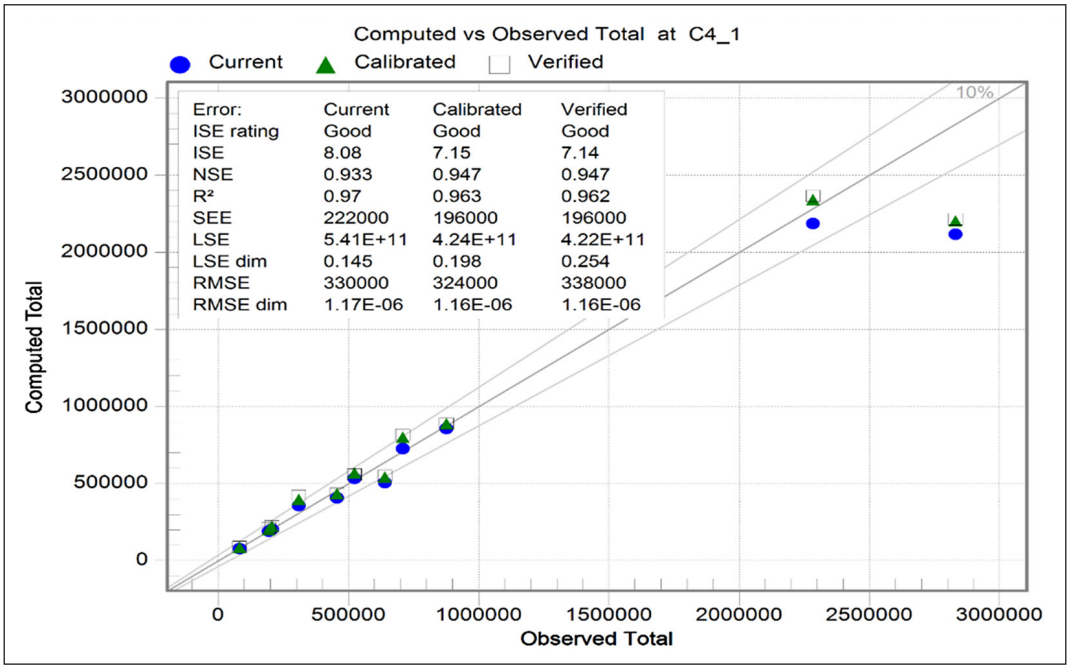

Figure 5. Calibration and verification results of flow volume totals

Table 2. Calibration and verification results of total runoff vs. observed time series

	Observed vs. calibrated	Observed vs. verified
Integral square error rating	Good	Good
Integral square error	7.15	7.14
Nash-Sutcliffe efficiency	0.947	0.947
R^2	0.963	0.963
Flow routing continuity errors	1.207	0.027
Highest continuity errors at nodes	Node J529 (6.98%); Node J643 (3.73%); Node J527 (1.57%)	

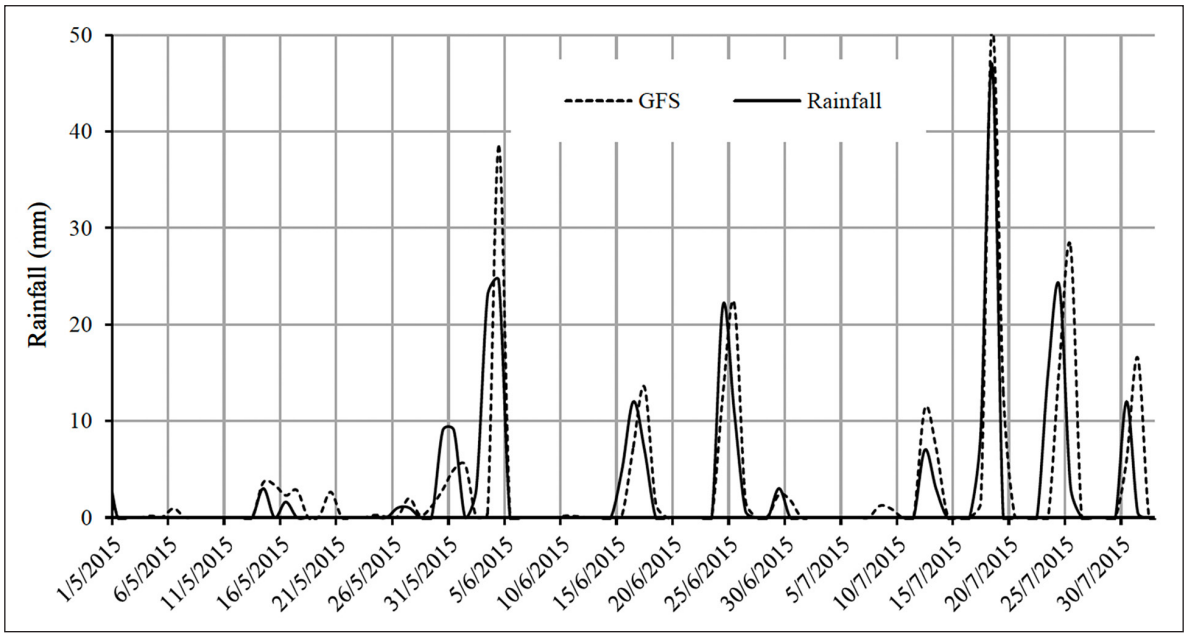

Figure 6. Comparison of GFS and measured rainfall data

the forecast would be in the release of water from storage with no subsequent occurrence of a flood, resulting in the loss of a potential resource but at least conservative with respect to the primary function of the ponds, i.e., flood management. PCSWMM provides various options to model dynamic management of water levels and outflow from storage units with control rules. The options tested on the stormwater infrastructure in the study area included the following:

Control rules linked to specific water levels and inflow rate values

This is a local rule-based control management approach that incorporates 'if-then' rules (i.e., if this happens, then do this) with adjustments made concerning prevailing conditions as discussed. An example of the 'control rule' syntax applied on one of the ponds is given with results in a plot as shown in Fig. 7.

```
Rule SU1A
If Node SU1 Depth = 0
And Node J23 Inflow < 5    (based on capacity and pre-
                            determined rate of filling)
THEN Orifice OR1 Setting = 0 (outlet completely closed)
Priority 1                  (Rule takes priority)

Rule SU1B
If Node SU1 Depth <= 1     (based on depth and capacity
                            of storage unit)
And Node J23 Inflow < 10   (based on capacity and pre-
                            determined rate of filling)
THEN Orifice OR1 Setting = 0.5 (outlet partially open)
Priority 2                  (Rule takes second priority)

Rule SU1C
If Node SU1 Depth > 1.5    (based on depth and capacity
                            of storage unit)
And Node J23 Inflow > 15   (based on capacity and pre-
                            determined rate of filling)
THEN Orifice OR1 Setting = 1 (outlet completely open)
Priority 3                  (Rule takes third priority)
```

This option is commonly used due to the simplicity and straightforwardness of site-specific control, with any errors limited to the site and independent of the whole system (García et al., 2015). The downside of the option is that many commands and syntax are required for each storage unit, limiting the flexibility of the operation. Secondly, the approach does not provide the benefits of a regional control of outflows from various storage units linked to a downstream reservoir, as required in the study.

Control rules linked to specific open/close times

It is possible to regulate outflows from storage with a 'time to open/close' option. An example of the 'control rule' syntax associated with the operation is as follows:

```
Rule SU1A
If Simulation date >= 5/31/2015
And Simulation date <= 6/5/2015
THEN Conduit C1 STATUS = OPEN
ELSE Conduit C1 STATUS = CLOSED
```

This option had similar challenges to the previous one.

Proportional-integral-derivative (PID) controller

PIDs may be used to model controlled outflows from storage with a generic closed-loop which continuously adjusts the system with corrective actions to provide desired conditions (James et al., 2010). In the closed loop, the three PID parameters provide an opportunity to empirically tune the system to converge towards desired pre-defined conditions. The output from the PID controllers is defined as shown in Eq. 1 (James et al., 2010):

$$\text{w.l}(t) = K_p e(t) + \frac{K_p}{T_i}\int e(\tau)d\tau + K_p T_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \quad (1)$$

$$P = K_p e(t); \quad I = \frac{K_p}{T_i}\int e(\tau)d\tau; \quad D = K_p T_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \quad (2)$$

where: w.l (t) is water level; K_p is proportional coefficient; $e(t)$ is error (difference between desired and actual water level); T_i is integral time, $e(\tau)$ is integral time error; T_d is derivative time; t is simulation time step; P is proportional controller; I is integral controller; D is derivative controller.

The PID rule was the one selected. In the process of system adjustment, various PID values were assessed to determine the most suitable options for certain conditions, such as magnitude of storm and capacity of pond. The PID controller parameter values were iteratively modified with a control strategy as follows:

- If there was no forecasted rainfall, water would be held in the pond until there was capacity downstream where the abstraction for water supply was planned.
- If there was forecasted rainfall that exceeded available capacity, the RTC control rules were set to allow for the pre-emptive drawdown of water levels to provide for capacity in the ponds to avoid flooding.

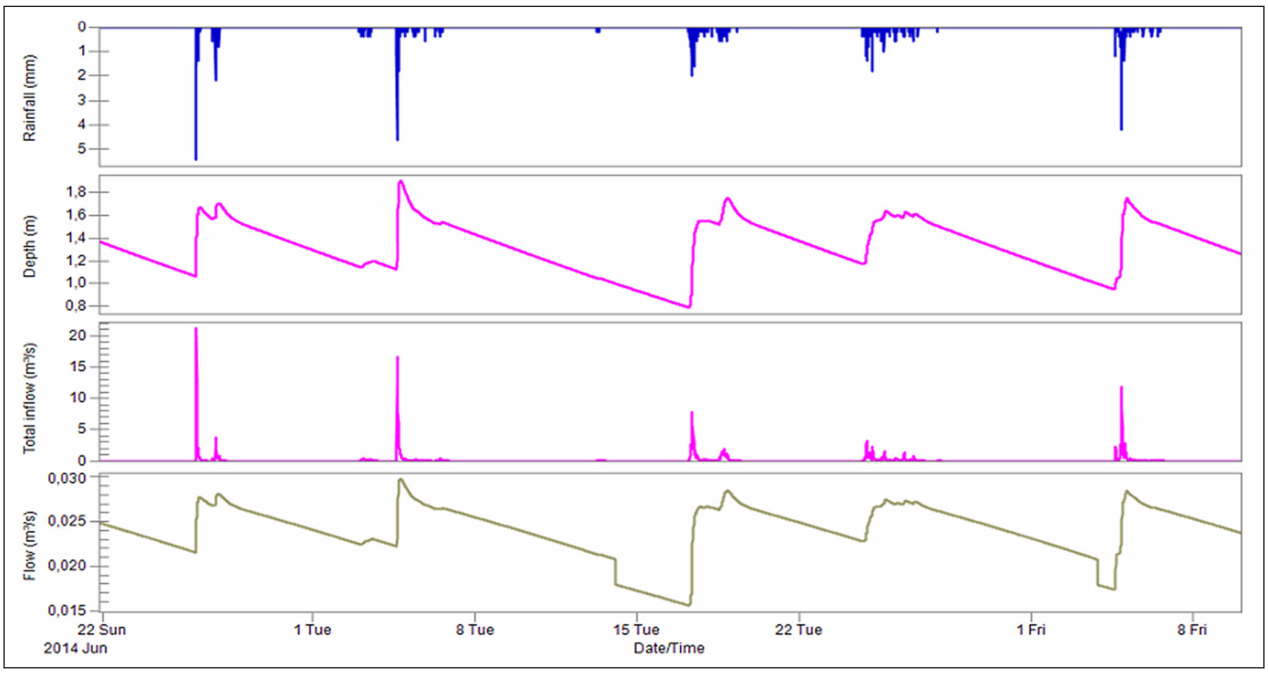

Figure 7. Sample results with control rules linked to specific values

An example of the 'control rule' syntax associated with the operation was as follows:

Rule SU1A
IF Node SU1 Depth = 0; Pond empty
AND Node J23 Inflow < 5; inflow volume less than 5 m^3/s
THEN Orifice OR1 Setting = PID 1 −1 −1; direct action control
ELSE Orifice OR1 Setting = PID −1 1 1; reverse action control

P was initially set at 0.01, and other values (*I*, *D*) given 0 values. The *P* value was then changed stepwise to values such as 0.1, 1, 10, −0.1, −1 until there was no added advantage. With the *P* value locked, *I* and *D* values were also adjusted. Finally, the model was run with optimised PID values. The water-level variation from a selected stormwater pond, comparing scenarios with and without application of PID controllers, is presented in Fig. 8. Comparing the water-level variation for the controlled case (with PID application) and without RTC in Fig. 8, the following key features may be observed.

- The water depth remained constant (horizontal sections) in the 'water levels with PID control' plot) and declined relatively slowly compared with the plot of 'water levels without PID control'. The horizontal sections indicate extended detention required to implement and achieve maximum benefit of storage for SWH.
- With PID control, the water depth dropped rapidly as shown in Fig. 8. The sharp pointed peak section indicates pre-emptive rapid drawdown of water levels to provide for capacity to accommodate anticipated flow from forecasted rainfall and avoid flooding.

It was thus determined that the RTC with PID controller option was sensitive to inflow rate and variation of the water level. These parameters guided the continuous management of the open and close operation of the outlet from the storage unit. The option was independent of the simulation time and was thus suitable for dynamic management of the outlet in the model.

Two fundamental approaches are used to model yield in SWH, i.e., yield after spillage (YAS) and yield before spillage (YBS) (Mitchell et al., 2008) (Eqs 3 and 4):

$$\text{YAS: } Y_t = \min(D_t, \max(V_{t-1} - V_d, 0); V_t = \min(V_{t-1} + I_t + P_t, V_{cap}) - Yt \quad (3)$$

$$\text{YAS: } Y_t = \min(D_t, \max(V_{t-1} - V_d, 0); V_t = \min(V_{t-1} + I_t + P_t, Y_t V_{cap}) \quad (4)$$

where: Y_t is yield, i.e., volume taken from the storage for water use at current time *t*; D_t is demand at current time *t*; V_t is storage volume at the end of the current time-step; V_{t-1} is storage volume at the end of the previous time-step; V_d is dead storage volume; I_t is inflow into the storage at current time t; P_t is current incident precipitation volume; and V_{cap} is maximum storage capacity.

The YAS approach was chosen since it is the most widely used method and provides more conservative results compared to YBS (Mitchell et al., 2008). To assess the impact of time scale in this study area, model results of SWH at 5 minutes and daily time steps were compared. The mean annual volume of harvestable stormwater on a daily time scale was 6% less than the modelled values based on the 5-minute interval. With the minimal difference in results, SWH was thus modelled at a daily data time scale to reduce the computational load. It was undertaken using the historical long-time rainfall datasets, and the impact of climate change on the volume of stormwater assessed using data from climate change prediction models. This data were available on a daily time scale for both long-time historical rainfall and climate change prediction models.

RESULTS

The study assessed the effect of time series length on SWH using a 10-year (2006–2015) and 20-year (1996–2015) time period. The mean monthly modelled flow volumes over the periods are presented in Fig. 9.

The mean annual modelled flow volumes over the 10-year (2006–2015) and 20-year (1996–2015) periods were 18 Mm^3 and 17 Mm^3, respectively. The difference in the mean annual modelled flow volumes in the two periods was likely due to the presence of relatively drier years included in the 20-year period compared with the 10-year period. Flow values from the wettest year (2013) and driest year (2015) were also extracted and plotted against the mean values to indicate limits, i.e., maximum, and minimum, as shown in Fig. 9. The mean annual modelled flow volumes for the wettest and driest years were 25 Mm^3 and 12 Mm^3, respectively. The two limits were applicable for both the 10-year and the 20-year periods.

The impact of land-use change was estimated using the Cape Town Spatial Development Framework (CTSDF), which provided planned developments per suburb up to 2040, as shown in Fig. 10 (CCT, 2012).

With the planned development and future land-use change, some natural 'greenfield' areas will be converted to impervious surfaces – although this can be mitigated through suitable sustainable

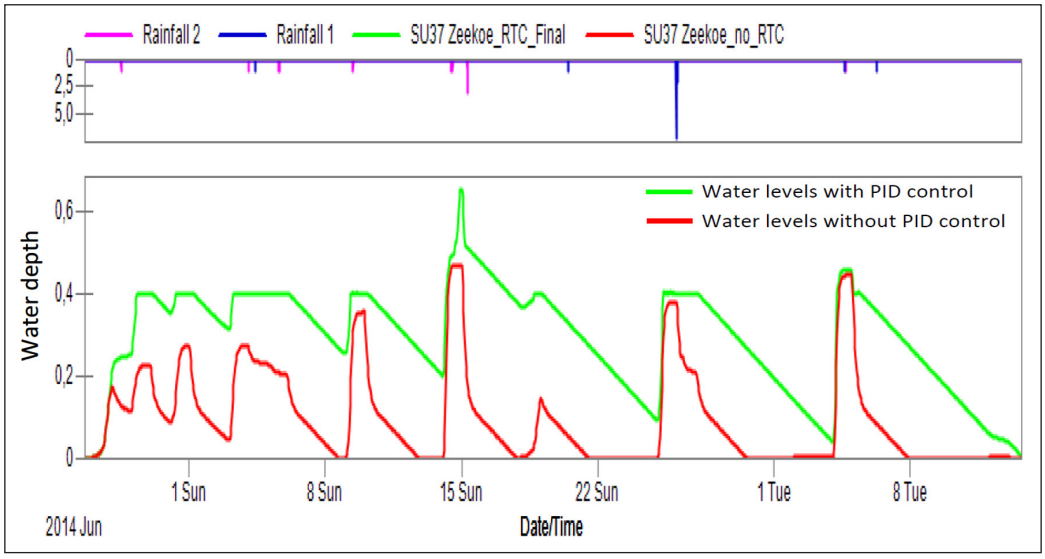

Figure 8. Water-level variation in the selected stormwater pond (1 m maximum depth)

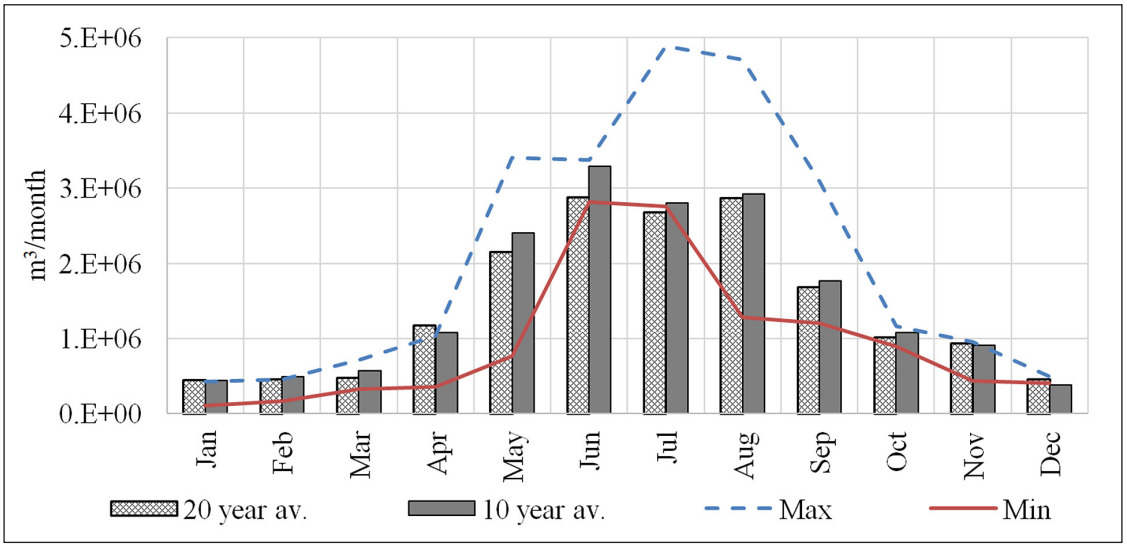

Figure 9. Modelled mean annual flow volume and limits in the study area

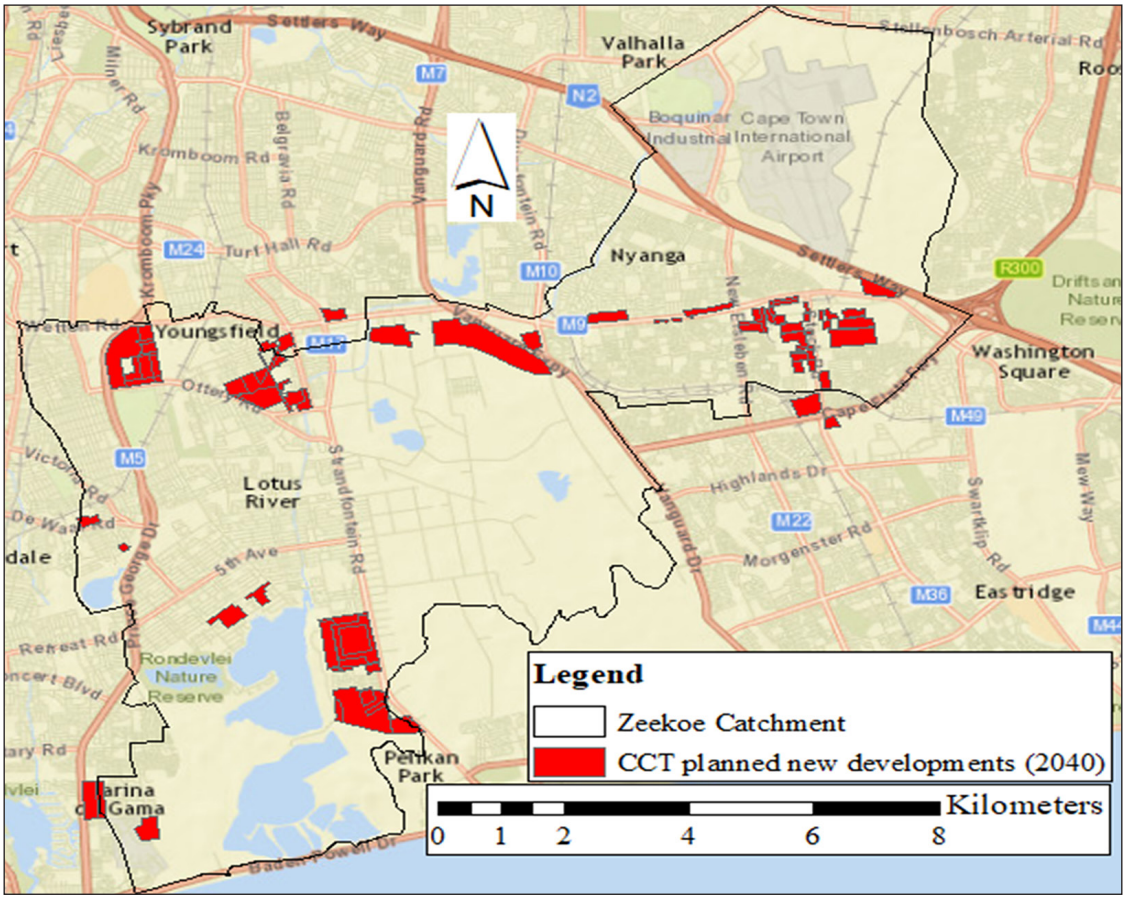

Figure 10. CCT planned developments in the study area (CCT, 2012)

drainage systems (SuDS). The level of imperviousness as a result of the land-use change without application of SuDS was estimated from the CTSDF (CCT, 2015). The land-use changes only provided for an additional 5% imperviousness in the study area up to 2040. An assessment was thus carried out to determine the potential increase in harvestable stormwater from surface runoff with 50% imperviousness corresponding to the planned development up to 2040. Furthermore, an assessment was undertaken to determine the potential increase in mean annual harvestable stormwater beyond 2040, with development scenarios using theoretical imperviousness of 75% as a worst-case situation. The results are shown in Fig. 11. It was noted that with an increase in imperviousness there was a corresponding increase in the potential harvestable water resource as surface runoff – in turn requiring additional storage to enable its capture for re-use.

The ideal storage required in the study area to account for the mismatch in the availability of stormwater and the various demand scenarios was estimated in a stepwise manner with various storage capacity provided for stormwater harvesting. The simulation was based on the YAS model (Eq. 3) with RTC. The results, in Fig, 12, show that SWH with 1 Mm^3 balancing storage (current capacity available in the study area) was only adequate to supply 44%, 60% and 58% of demands in scenarios Sc 1 (agricultural use only),

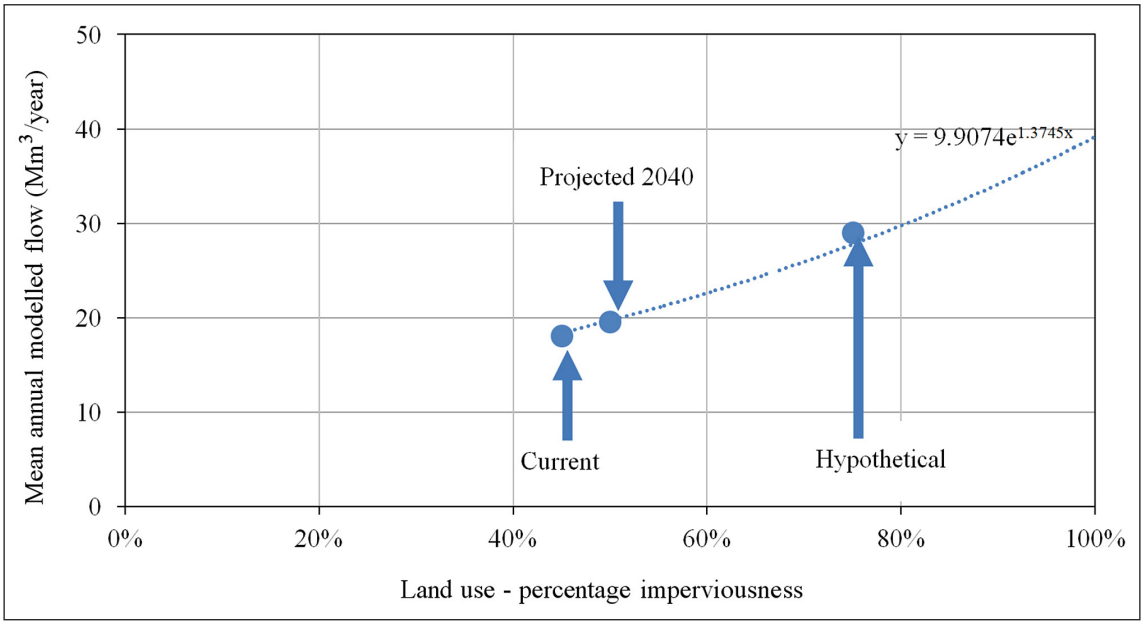

Figure 11. Plot of runoff increase as a function of land use

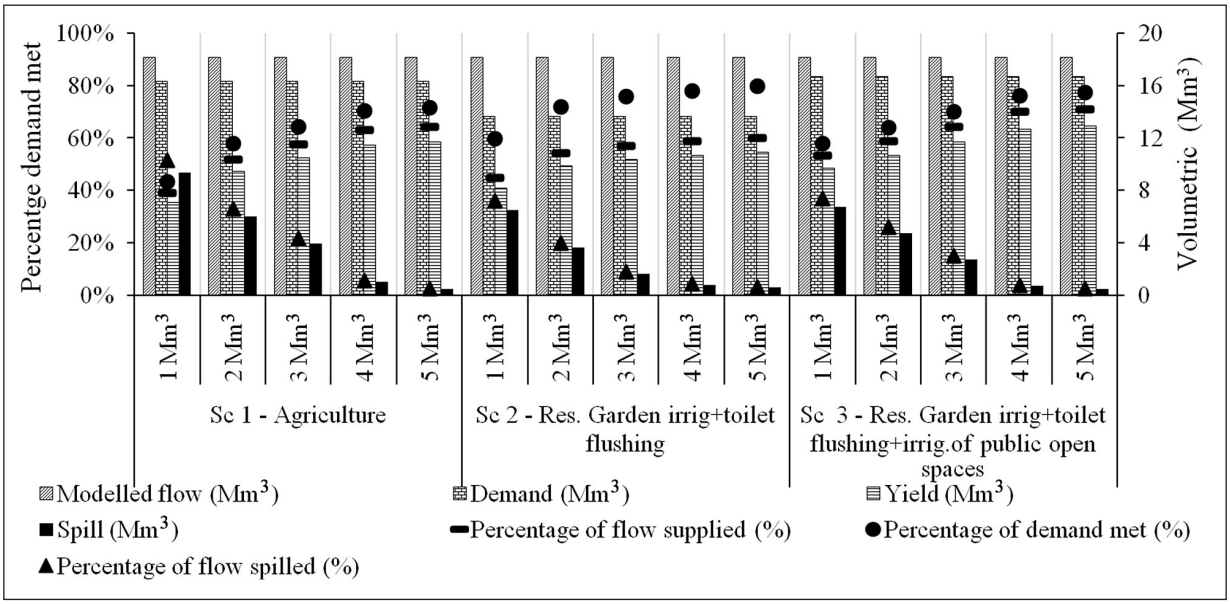

Figure 12. Assessment of storage for the various demand scenarios

Sc 2 (residential garden irrigation and toilet flushing) and Sc 3 (residential garden irrigation, toilet flushing and irrigation of public open spaces) respectively. Increasing the storage had a corresponding increase in yield and decreased spillage in the various demand options (Fig. 12).

It was determined that after 4 Mm^3, there was limited improvement and insignificant additional benefit for the various demand options. Thus, a storage of 4 Mm^3 was deemed adequate for the modelled stormwater volume to meet a significant portion of expected demand with minimal spillage. Since the stormwater ponds could only provide a total of 1 Mm^3 with application of RTC, and their physical expansion is unlikely due to land limitations typical in urban areas, enlarging the vleis (large shallow lakes) to provide the additional storage seems to be the most promising option.

Stormwater could also be abstracted from the two most downstream vleis (Zeekoevlei and Rondevlei), fully treated to potable water standards and injected into the local potable water distribution system. Alternatively, the abstracted water from the vleis could be pre-treated at a new proposed WTP in the study area and then pumped to one of the existing water treatment plants (WTPs). The results with various storage and pump capacities with corresponding yield and spillage are presented in Fig. 13.

It was determined that for potable water that is required all the year round, the yield was not sensitive to changes in storage volume (Fig. 13) but linked to the capacity of the water delivery system. Since the influence of the local storage was limited, optimisation was based on treatment, and pump and pipe capacity, to maximise yield and minimise spillage. As presented in Fig. 13, the most suitable plant was that with capacity of 0.5 m^3/s, since above this there was limited increase in yield and reduction of spillage.

The simulation of SWH was also assessed with climate change prediction data to determine impact in the future. The assessment was based on rainfall and temperature data from 26 models developed and managed by UCT CSAG. The data from the models show that the climate is getting drier, and the impact would be

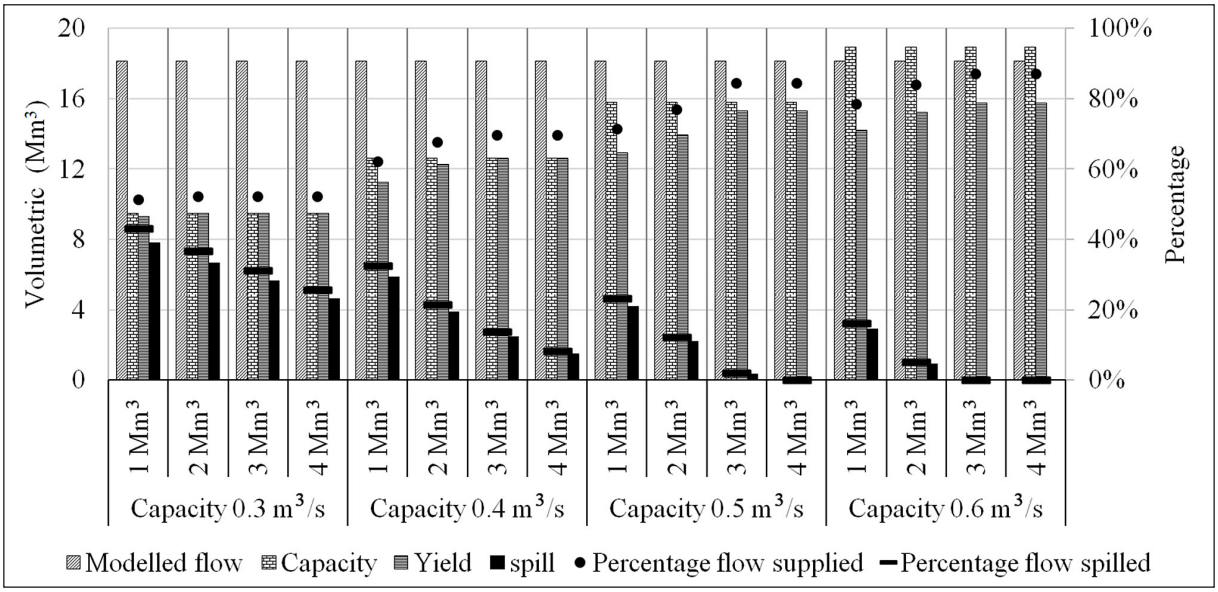

Figure 13. Selection of pump capacity for stormwater transmission

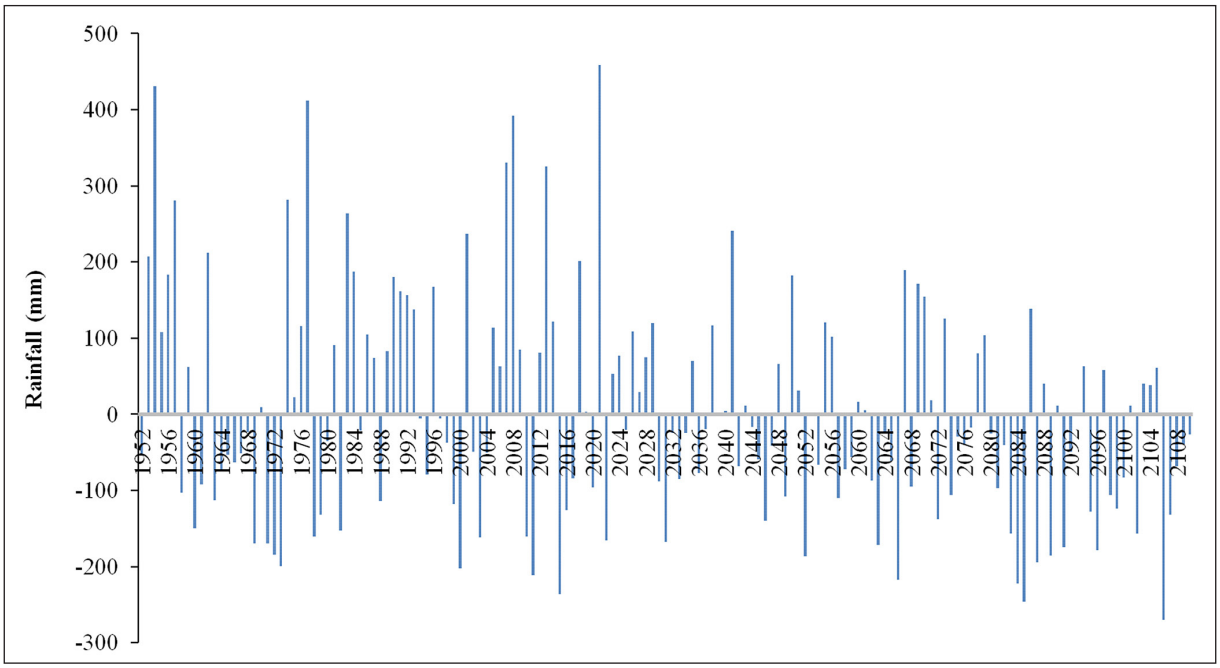

Figure 14. Annual rainfall variation from mean of modelled period (2006–2015) (after Hewitson and Crane, 2006)

a likely reduction in harvestable stormwater. Only one model, HadGEM2-CC-rcp85, showed that the climate would be slightly wetter than the historical conditions. The data from the climate change prediction models also shows significant variability, a characteristic that was identified in the long-time-series historical and future rainfall data. Figure 14 presents an example of data from one of the models showing the variability in the rainfall and the succession of wet and dry years. Although the rainfall variability appears to be on a downward trend, with progressively lower rainfall in the future, there will still be some wet years, even wetter than the mean of the current period. While the predicted data from the climate change models is highly unlikely to be exactly replicated, the ensemble provides an indication of the range of possibilities. It seems that while there will still be some wet periods, the likelihood of dry years will increase, and wet years decrease, towards the end of the century.

SWH was modelled with the data from each of the 26 climate models to determine the likely impact of climate change on future stormwater volumes. The mean annual harvestable surface water resource for the future period 2090–2100 was estimated and compared with the historical period of 2006–2015 as the base case and the volumetric change is as shown in Fig. 15. The climate predictions show a mean decrease of 30% in potential harvestable surface water resource with some models showing over 50% reduction (Fig. 15).

The primary cause of the decrease is due to the reduction in total rainfall and increase in evapotranspiration, as shown in Fig. 16.

CONCLUSIONS

The study determined that the potential harvestable stormwater from the Zeekoe Catchment is about 18 Mm³ (9% of Cape Town water demand in 2018). The mean annual modelled volumes for the wettest and driest years were 25 Mm³ and 12 Mm³, respectively. With the planned development and future land use change, an additional 5% imperviousness in the study area was

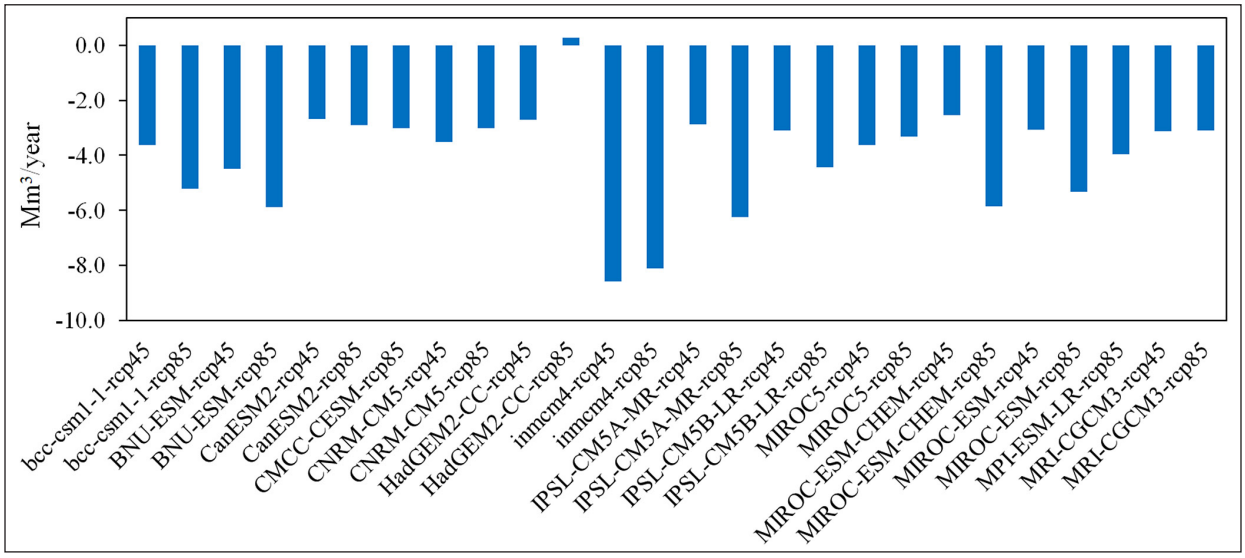

Figure 15. Change in potential future surface water resource from the study catchment

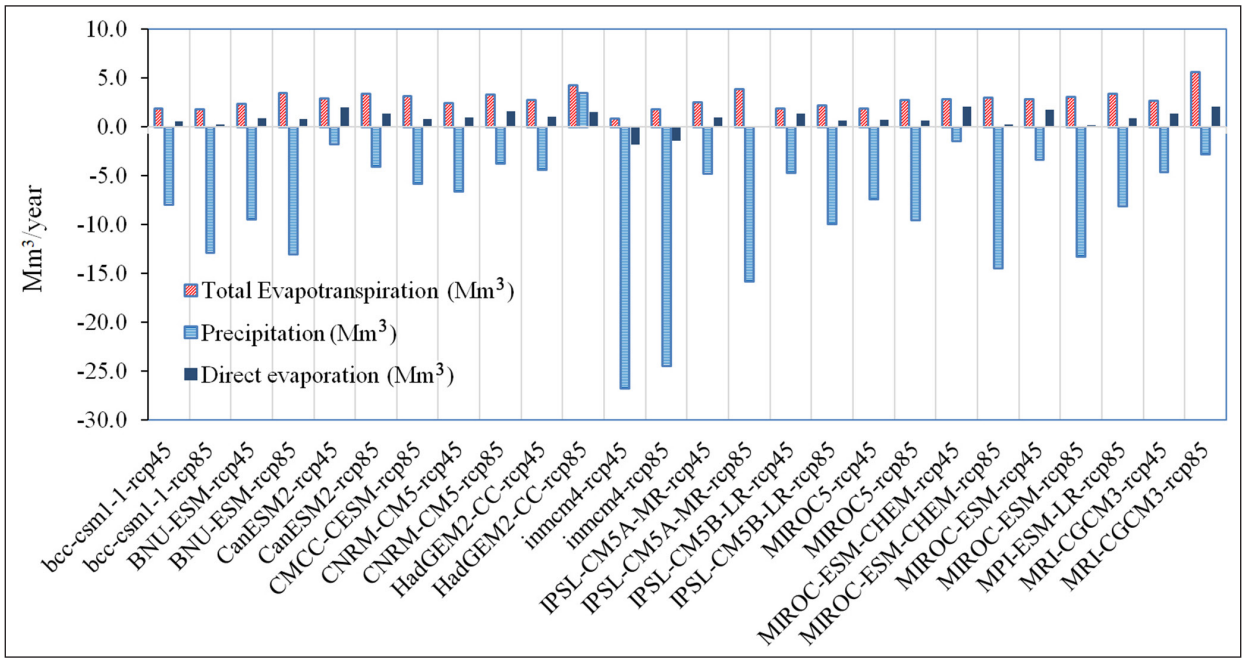

Figure 16. Change in rainfall and evapotranspiration in the study catchment

projected for 2040. An assessment was undertaken to determine the potential increase in mean annual harvestable stormwater, including beyond 2040, with theoretical imperviousness of 75% as a worst-case situation. The results show significant increase in the potential harvestable water resource as surface runoff – in turn requiring additional storage to enable its capture for re-use. The 26 climate change prediction models also show a likely decrease in harvestable stormwater volume of 3–9 Mm³ (15–50% of mean annual modelled volumes).

In the assessment of the prospects for SWH from a catchment with seasonal rainfall largely in the winter period, large storage was required to balance the temporal mismatch in the availability of the resource and demand, particularly for the non-potable water uses, e.g., irrigation of agriculture, residential gardens and public open spaces, as the demands were mainly in the dry summer period. To provide for the required storage, an investigation was carried out into the use of the available stormwater ponds for both flood control and water supply, using real-time-control (RTC) techniques. The use of RTC on the stormwater ponds provided an opportunity to utilise the available 1 Mm³ capacity (about 5.5% of the mean annual modelled volume of stormwater). An assessment was undertaken to determine the reliability and adequacy of the storage to balance the mismatch in availability of stormwater with 3 demand options, i.e., Sc 1 (agriculture), Sc 2 (residential garden irrigation and toilet flushing) and Sc 3 (residential garden irrigation, toilet flushing and irrigation of public open spaces). The storage in the ponds was only able to supply 44%, 60% and 58% of the demands in Sc 1, Sc 2 and Sc 3, respectively. The corresponding spill (water lost as overflow) was 51%, 35% and 37% of the modelled mean annual stormwater volume (i.e., 18 Mm³). To increase yield and reduce spillage, the storage in the vleis was assessed in stepwise incremental volumes of 1 Mm³ to determine the optimal storage required to account for the mismatch in the availability of stormwater and demand. It was determined that at 4 Mm³ storage (22% of the modelled mean annual stormwater volume), 70%, 89% and 76% of the non-potable demands in Sc 1, Sc 2 and Sc 3 were met, respectively. The corresponding spill (water lost as overflow) was 11%, 7% and 4% of the modelled mean annual stormwater flow (i.e., 18 Mm³).

There was minimal increase in demand met and reduction of spillage with 5 Mm^3 storage capacity. In general, it was determined that stormwater supply to non-potable demand was sensitive to balancing storage and required a storage capacity of 20–30% of stormwater volume to maximise demand met and minimise loss through spillage.

AUTHOR CONTRIBUTIONS

John Okedi was responsible for the collection of the data, the construction and running of the various models, the analysis of the model outputs, and the writing of the draft paper. Neil Armitage was responsible for the conceptualisation of the project, critical intellectual input during the research, and the final editing of the paper.

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