Water SA 52(1) 49–61 / Jan 2026
https://doi.org/10.17159/wsa/2026.v52.i1.4165.2

Research paper

The prospects for stormwater harvesting in Cape Town: Part 2 – catchment-scale managed aquifer recharge with stormwater

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The City of Cape Town in South Africa faced the possibility of taps running dry in 2018 due to a prolonged drought that commenced in 2015. With such droughts expected to reoccur frequently in future, this study investigated the prospects for managed aquifer recharge (MAR) with stormwater. This would require temporary storage to collect and hold the stormwater during and immediately after rainfall events while it seeps into the aquifer. The 89 km^2 Zeekoe Catchment located in the southern part of Cape Town was selected as a case study as it had both existing surface storage (61 stormwater ponds) and was lying above a large unconfined aquifer. As the stormwater ponds were largely designed for flood control, they would need to be modified for MAR. In this desktop study, the main objective was to model temporary detention of stormwater in the ponds with the aim of predicting infiltration into, and thus augmentation of, the aquifer. The requirement that the flood control function be maintained, combined with the limited capacity in the ponds, was a key consideration. The study determined that the physical characteristics in the Zeekoe Catchment, i.e., largely flat terrain, pervious sandy soils, and a relatively deep (20–50 m) unconfined aquifer, could support managed aquifer recharge and borehole abstraction rates of 3.5–8.1 L/s per borehole from some 140 boreholes. This could provide a mean annual groundwater yield of 29–33 Mm^3 (about 15% of Cape Town water demand in 2018).

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DATES
Received: 8 August 2024
Accepted: 8 December 2025

KEYWORDS
catchment scale
stormwater harvesting
managed aquifer recharge
Cape Town

INTRODUCTION

In the past 30 years since the 1990s, a water cycle management approach aimed at environmental protection has emerged, variously called, inter alia, water sensitive urban design (WSUD) in Australia, low impact development (LID) in the United States and sustainable drainage systems (SuDS) in the United Kingdom (Fletcher et al., 2014). The approaches are based on a more holistic water cycle management philosophy that aims to minimise net outflow of water from an urban catchment (Fletcher et al., 2014). Wong (2007) notes that cities are potential catchment areas in their own right which, if well managed, would meet a substantial proportion of their water needs. Marsden and Pickering (2006) determined that the mean cost per kilolitre of SWH was lower than many other sources, including, inter alia, seawater desalination, rainwater harvesting and long-distance pipelines. The focus of this study was to investigate the prospects for catchment-scale stormwater harvesting using a groundwater aquifer in Cape Town, South Africa, for medium to long-term storage. The City of Cape Town (CCT) already has plans to implement groundwater extraction from the Table Mountain Group (TMG) and Cape Flats Aquifer (CFA). If not managed well, this could potentially result in severe and irreversible environmental impacts, such as ground subsidence and saltwater intrusion in coastal catchments. In Mexico City, excessive abstraction of groundwater over a long period of time (since the 1950s and greatly increased in the 1980s) has resulted in subsidence of 0.4 m/year since 1984, with the total subsidence reaching 8 m in some areas by 2010 (Ortiz-Zamora and Ortega-Guerrero, 2010). The proposed introduction of stormwater into the CFA could mitigate the negative effects of groundwater extraction – essentially replicating the historic water cycle in the area where little rainwater reached the ocean but rather seeped into the underlying aquifers.

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. The stormwater harvesting technique investigated involved underground storage in the local aquifer using 'managed aquifer recharge' (MAR). The technique is coupled with various demand scenarios: (i) non-potable water for use within the catchment including urban agriculture, public open spaces, domestic gardens, and toilet flushing; (ii) potable water for general use with treatment provided by small 'package' plants situated within the catchment and injected directly into the existing reticulation system; and (iii) potable water for general use with treatment provided at one of the nearby bulk water treatment plants where the stormwater is blended in with the water coming from the surface reservoirs.

LITERATURE REVIEW

Managed aquifer recharge (MAR) has been implemented in many countries, such as Australia (Dillon et al.,2009; Page et al., 2009; Miotliński et al., 2014), the United States of America (USA) (Murray et al., 2007), Namibia (Murray et al., 2007; Tredoux et al., 2009), and South Africa (Bugan et al., 2016). In Australia, MAR has been implemented in Perth, Adelaide, and Melbourne, with aquifer storage capacities of 250 Mm^3, 80 Mm^3 and 100 Mm^3 respectively (Dillon et al., 2009). Some other examples of MAR projects in Australia include Salisbury near Adelaide where stormwater

is treated in a wetland and injected into the aquifer; and the Burdekin Delta in North Queensland where 45 Mm^3 of water is recharged and abstracted for irrigation of sugarcane and other crops; (Dillon et al., 2009; Page et al., 2009; Miotliński et al., 2014). Some examples of MAR in the USA include Peace River in Florida and the Kerrville in Texas (Murray et al., 2007). The Peace River and Kerrville schemes comprise injection of treated water into the groundwater aquifer and recovery of about 68 000 m^3/day and 9 500 m^3/day, respectively. In Namibia, MAR is a water resource for the city of Windhoek, with artificial recharge from the Von Bach Dam and reclaimed treated wastewater injected into the Auas aquifer with a yield of 2–8 Mm^3/year (Murray et al., 2007; Tredoux et al., 2009). In South Africa, the Atlantis Water Resource Management Scheme (AWRMS) is an MAR system with about 7 500 m^3/day of stormwater and wastewater is infiltrated into the aquifer to boost the groundwater resource by more than 2.7 x 10^6 m^3/year (Bugan et al., 2016; DWA, 2010). The system was established to supply water to the town of Atlantis located 50 km north of the Cape Town CBD on the west coast, which was not originally linked to the city reticulation system (DWA, 2010).

METHOD

Site selection

In this study, the Zeekoe Catchment (Fig. 1) was chosen from the various catchments in Cape Town as it has many stormwater ponds (some 61 ponds) and is located over the Cape Flats Aquifer. The area has a flat, sandy terrain while the aquifer is unconfined with thickness ranging from 20–50 m and considerable potential for groundwater abstraction to meet CCT demand.

Selection of the infiltration model

PCSWWM was used to model surface to groundwater transfer in the stormwater ponds, which had been assumed to be transformed into infiltration basins that would be ordinarily dry until temporarily filled with rainwater (Okedi and Armitage, 2026; Okedi, 2019). Infiltration in PCSWMM can be represented by Horton, Green-Ampt or Curve Number methods (James et al., 2010). The selection of the Horton method for this study area was based on the best match, with field-measured infiltration rates with the assistance of a double ring infiltrometer (DRI) in accordance with the ASTM D3385-09 at 3 sites across the study area (Fig. 1 and Table 1) (Mavundla et al, 2025).

Shallow surface core-samples (300 mm) were also retrieved from the sites and tested in the laboratory in accordance with the ASTM D2216–10 to determine the saturated hydraulic conductivity, bulk density, volumetric water content, porosity, saturation, residual water content, particle density, and particle-size distribution analysis (Table 2). Figure 2 shows the particle size distributions.

The results show similarities in the soil particle distribution for all the selected ponds across the study area. Furthermore, other characteristics, such as porosity and coefficient of uniformity and curvature, specific gravity and natural moisture content were also similar. These similarities justify the reliance on a limited number of test sites to provide general infiltration parameters for the study area. The infiltration rates measured with the DRI experiments at the three ponds were then compared with the values estimated with the Green-Ampt and Horton methods to determine the most appropriate approach to be used in the model.

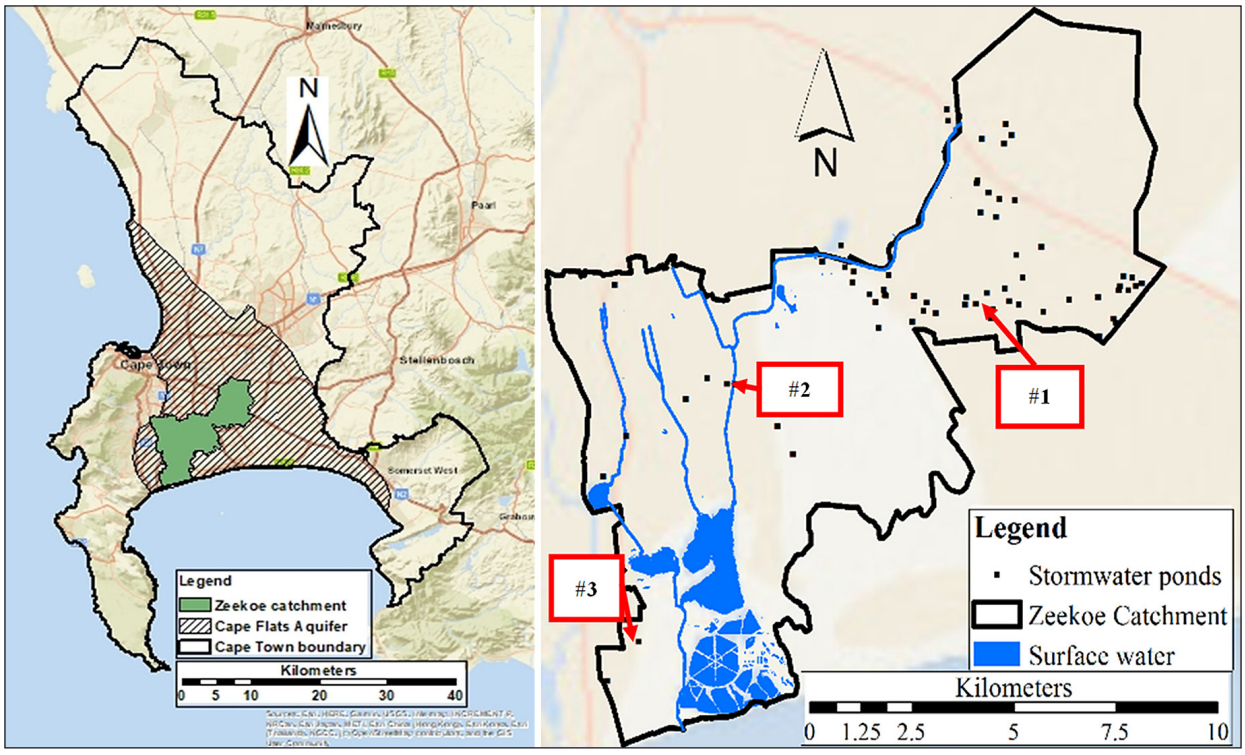

Figure 1. Location of Zeekoe Catchment and the three infiltration test sites (#1 – Pond 1; #2 – Pond 2; #3 – Pond 3)

Table 1. Locations of the selected stormwater ponds

Pond	Pond type	Surface area (m^2)	Suburb name	Road name	Latitude	Longitude	Elevation (m.a.s.l)
1	Detention	32 000	Browns Farms	2309 Msingizane Street	–34.009	18.581	33
2	Retention	10 000	Lotus River	7 Eric Way	–34.025	18.519	15
3	Detention	9 000	Vrygrond	86 Drury Road	–34.087	18.484	8

Table 2. Summary of findings from field and laboratory experiments

Property		Units	Pond 1		Pond 2		Pond 3	
			*Surface	**Below surface	*Surface	**Below surface	*Surface	**Below surface
Soil texture	Fines	%	6.2	7.8	1.7	0.5	0.4	0.6
	Sand		92.4	89.1	98.2	99.1	98.5	98.4
	Gravel		1.4	3.1	0.1	0.3	1.1	1.0
Effective grain size	d_{10}	mm	0.1	0.1	0.15	0.17	0.16	0.14
	d_{30}		0.19	0.19	0.20	0.25	0.21	0.19
	d_{60}		0.35	0.33	0.32	0.39	0.32	0.30
Coefficients of uniformity and curvature (-)	Cu	-	3.53	3.57	2.15	2.32	1.30	1.36
	Cc	-	1.01	1.14	0.85	0.98	0.85	0.86
Soil group		-	SP-SM	SP-SM	SP	SP	SP	SP
Porosity		%	32	33	44	30	43	38
Void ratio		-	47	49	78	43	77	61
Specific gravity		-	2.61	2.60	2.49	2.60	2.56	2.58
Bulk density		kg/m³	1 733	1 889	1 460	1 917	1 635	1 930
Saturated density		kg/m³	2 091	2 074	1 834	2 278	1 892	1 981
Conductivity (K20°C Constant head)		cm/h	4.8	4.8	19.9	11.1	10.5	10.3
Natural moisture content		%	6	8	5	5	13	17

*Depth (<200 mm); **Depth (>200 mm); SP-SM – poorly graded sand with silt; SP – poorly graded sand

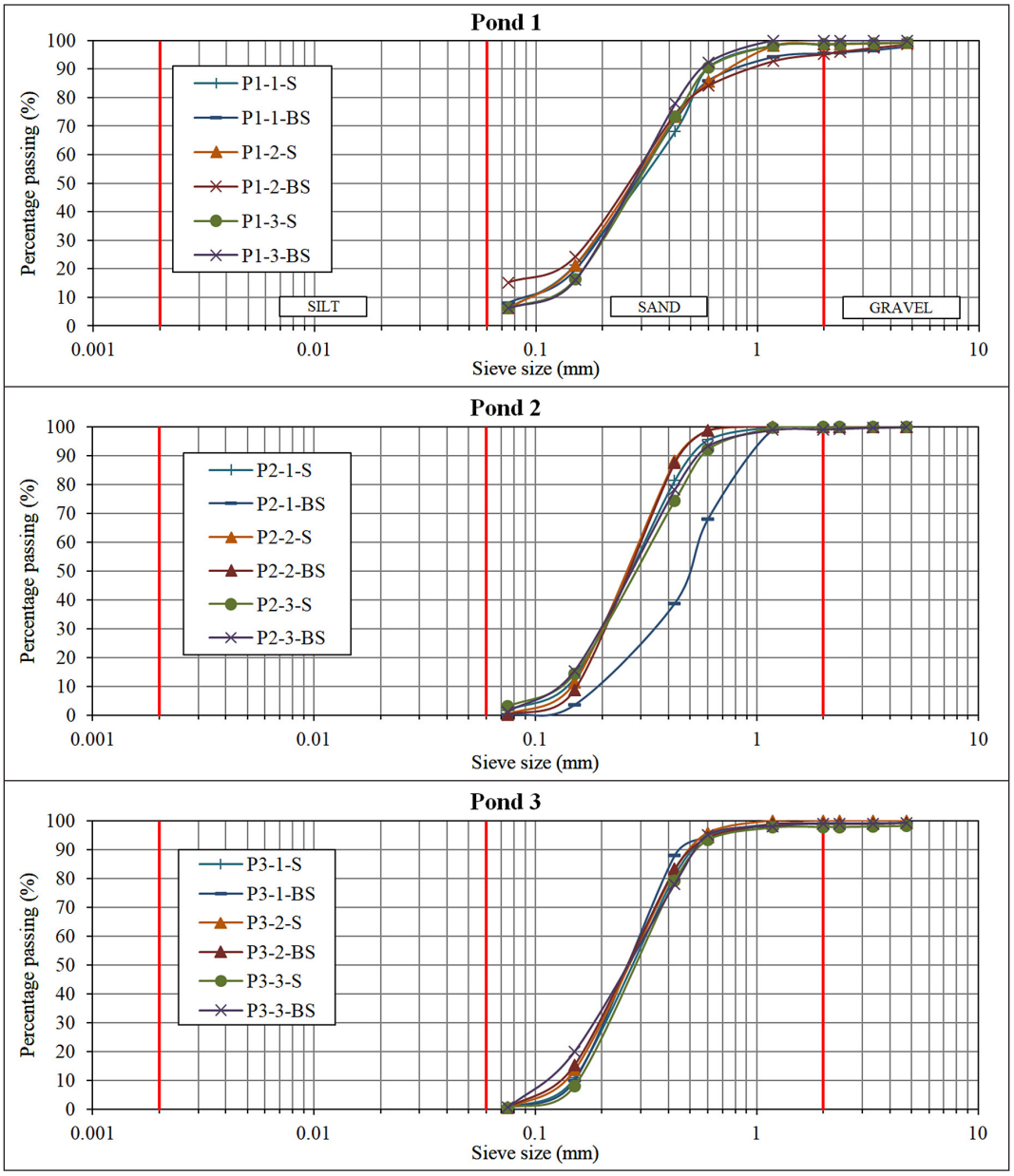

Figure 2. Particle size distributions for the three ponds

In Horton's method, the decay of infiltration rate with time is expressed by the exponential relationship presented in Eq. 1 (Horton, 1933).

$$f = f_c + (f_o - f_c)e^{-\lambda t} \quad (1)$$

where: f is infiltration rate at any time t (cm/h); f_o is initial infiltration rate at t–0 (cm/h); f_c is final infiltration rate (after equilibrium at steady state) at $t = t_c$ (cm/h); λ is Horton's decay coefficient, which depends on soil characteristics and vegetation cover (h^{-1}).

The Horton parameters for the three sites are presented in Table 3.

In the Green-Ampt method, the determination of infiltration rate is based on Darcy's law using Eq. 2 (Green and Ampt, 1911).

$$f = k(1 + \frac{\gamma S_c}{F}) \quad (2)$$

where: f is infiltration rate (cm/h); F is cumulative infiltration (cm); k is hydraulic conductivity (cm/h); S_c is capillary suction at the wetting front (cm); γ is porosity of the soil (%).

The infiltration rates measured in the DRI experiments were compared with values estimated using the Green-Ampt and Horton methods and plotted in Fig. 3. The statistical descriptors of the parameters in Green-Ampt method needed for model development were determined from the experiment and are presented in Table 4.

As shown in Fig. 3, both the Green-Ampt and Horton models visually fit the measured data reasonably well, except in the case of Pond 3. The Nash–Sutcliffe efficiency (NSE) and correlation (R^2) coefficients were used to determine which method provided a better match (Table 5).

Both methods provided reasonably good results, i.e., above 0.5, except NSE for Green-Ampt in Pond 2 and all cases in Pond 3. However, while the plots in Fig. 3 show that the Green-Ampt method better represented the initial infiltration values, the Horton method provided a better estimation of the final infiltration rates. The final selection of Horton method for modelling the infiltration component of the model was based on its superior performance over the longer time periods that might better represent the conditions in stormwater ponds used for aquifer recharge.

The modelling first determined the catchment-scale infiltration component, i.e., the portion of rainfall that is transferred directly to the groundwater aquifer and thus not directly contributing to runoff. The enhanced surface to groundwater transfer was then modelled through the simulation of extended detention in the existing stormwater ponds to enhance the infiltration there. In the model, the stormwater ponds had to be represented as infiltration sources – and not merely temporary storage. The closest available option is 'bio-retention', which allows temporary storage combined with high infiltration rates through a vegetated surface followed by stretches where the surface was allowed to dry out. The model thus considered the stormwater ponds as bio-retention cells on the assumption that they would function in a similar manner. A typical bio-retention cell is composed of 3 horizontal layers, i.e., surface, soil and storage layers, with an underdrain at the bottom as shown in Fig. 4 (Brown et al., 2011):

- **Surface layer** – the top section of the bio-retention cell that receives both direct rainfall and runoff from the catchment. The modelling of water balance in this section is based on the continuity equation (Eq. 3) (James et al., 2010). The surface layer properties are specific to the bio-retention cells' geometric characteristics, i.e., surface area and depth (consistent with the stormwater pond shape) and vegetation cover (100% of the pond surface area).

Table 3. Horton's method infiltration parameters

Statistical measures based on 6 tests per site	Pond 1			Pond 2			Pond 3		
	λ (h^{-1})	f_o (cm/h)	f_c (cm/h)	λ (h^{-1})	f_o (cm/h)	f_c (cm/h)	λ (h^{-1})	f_o (cm/h)	f_c (cm/h)
Mean	1.9	3.6	1.4	0.6	25.8	20.6	0.8	17.80	10.54
Minimum	1.0	0.7	0.3	0.1	9.3	3.8	0.3	5.82	2.22
Maximum	3.0	5.8	2.9	1.3	31.8	28.2	2.4	41.18	22.80

Table 4. Green-Ampt method infiltration parameters

Ponds	Parameters	Units	Mean	Minimum	Maximum
Pond 1	K	cm/h	1.2	0.3	2.3
	Γ	%	31	30	33
	S_c	cm	7.3	0.1	23.1
Pond 2	K	cm/h	22.1	3.8	32.6
	Γ	%	40	30	45
	S_c	cm	31.4	22.7	36.8
Pond 3	K	cm/h	9.6	0.1	21.6
	Γ	%	38	32	50
	S_c	cm	11.1	1.9	30.5

Table 5. Correlation coefficient for measured and calculated infiltration rates

	Pond 1		Pond 2		Pond 3	
	NSE	R^2	NSE	R^2	NSE	R^2
Calculated infiltration rate – Horton	0.73	0.79	0.61	0.77	–2.74	0.09
Calculated infiltration rate – Green-Ampt	0.75	0.92	0.44	0.81	0.005	0.25

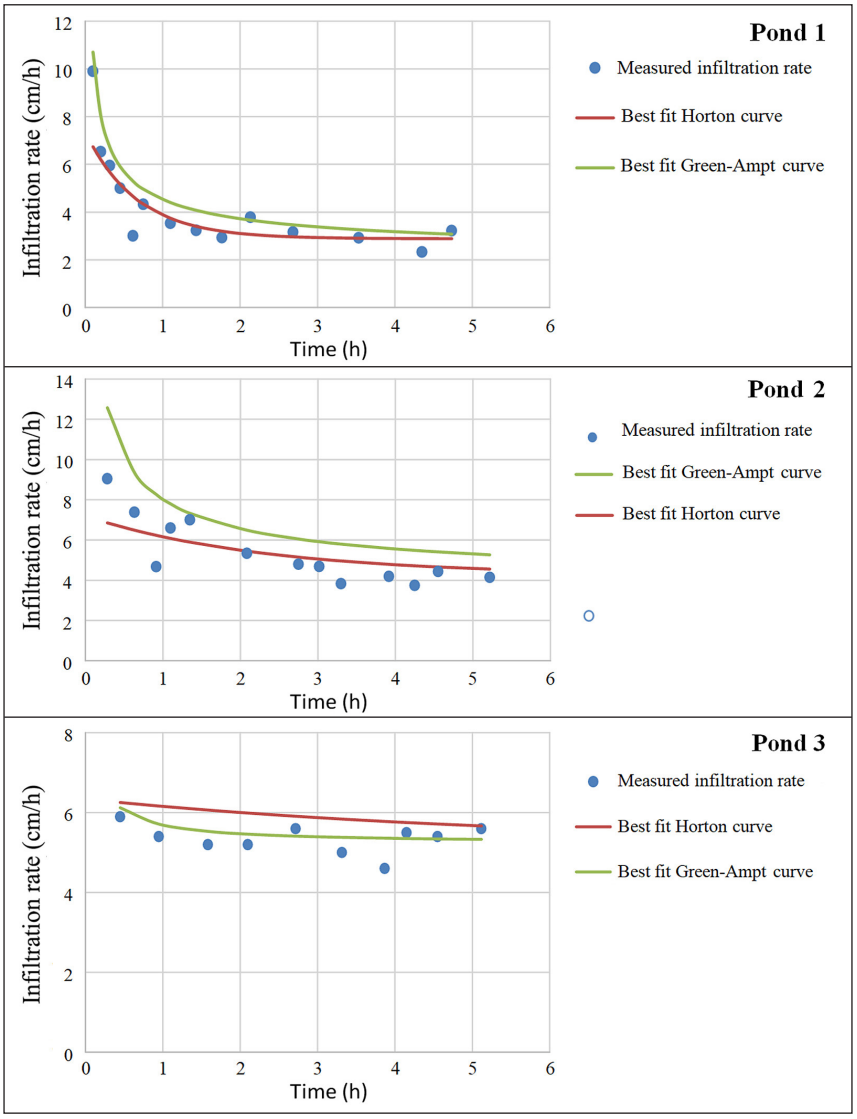

Figure 3. Comparison between measured and best-fit theoretical infiltration rates modelling surface to groundwater transfer

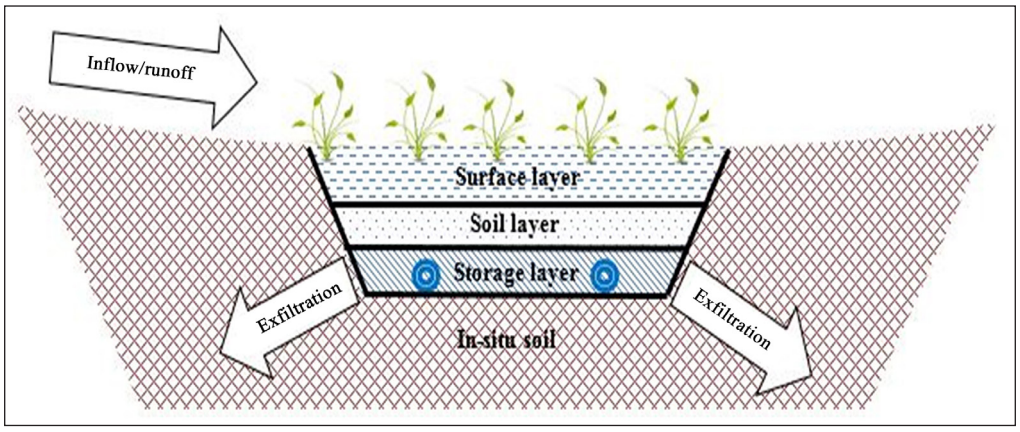

Figure 4. A bio-retention cell (after Brown et al., 2011)

$$\Phi_1 \frac{\partial d_1}{\partial t} = i + q_o - e_1 - f_1 - q_1 \quad (3)$$

where: Φ_1 is fraction of freeboard above the surface not filled with vegetation; d_1 is depth of water in the surface layer (mm); i is rate of precipitation falling directly on the surface layer (mm/h); q_o is inflow to the surface layer from runoff captured from other areas (mm/h); e_1 is surface layer evapotranspiration rate (mm/h); f_1 is infiltration rate of surface water into the soil layer (mm/h); q_1 is surface layer runoff or overflow rate (mm/h).

- **Soil layer** – the middle section of a bio-retention cell generally consists of an engineered soil mixture with organic matter and a thickness of 450–900 mm (James et al., 2010). For the model development and calibration, however, the site-specific soil data presented in Table 2 were used, i.e., porosity (0.30–0.44), field capacity (15.6–17.6%), wilting point (4.4–5.2), conductivity (4.8–19.9 cm/h), conductivity slope (9.7–9.9 cm/cm) and suction head (5.9–114.5 cm). Modelling of the water balance in the soil layer used Eq. 4.

$$D_2\frac{\partial\theta_2}{\partial t} = f_1 - e_2 - f_2 \quad (4)$$

where: D_2 is thickness of the soil layer (mm); θ_2 is soil layer moisture content (fraction); f_1 is infiltration rate of surface water into the soil layer (mm/h); e_2 is soil layer evapotranspiration rate (mm/h); f_2 is percolation rate of water through the soil layer into the storage layer (mm/h).

- **Storage layer** – the bottom of a bio-retention cell generally consists of crushed stone or gravel with thickness from 150–450 mm. In the model development, site-specific data were used, i.e., void ratio (0.47–0.78) as shown in Table 2 and filtration rate (2–10 cm/h) as shown in Fig. 3. The modelling of the storage layer was based on Eq. 5:

$$\Phi_3\frac{\partial d_3}{\partial t} = f_2 - e_3 - f_3 - q_2 \quad (5)$$

where: Φ_3 is voids fraction of storage layer (fraction); d_3 – depth of water in the storage layer (mm); f_2 is percolation rate of water through the soil layer into the storage layer (mm/h); e_3 is storage layer evapotranspiration rate (mm/h); f_3 is exfiltration rate of water from the storage layer to native in-situ soil (mm/h); q_2 is layer runoff or overflow rate (mm/h).

Various values were allocated to the surface, soil, and storage layers based on the field and laboratory tests and supplemented by recommendations from various publications (e.g. James et al., 2010; Brown et al., 2011). The following assumptions were made in the modelling:

- **Surface layer** – the plan area was assumed to be constant for the entire depth, the inflow was assumed to be uniformly distributed over the entire surface area, and water movement inside the bio-retention cell was assumed to be one-dimensional in the vertical direction.
- **Soil layer** – the moisture content was assumed constant throughout the soil layer.

The modelled mean annual water balance values in PCSWMM for evaporation, evapotranspiration, surface runoff and infiltration for the existing land uses with an average catchment imperviousness of 45% are presented in Fig. 5.

As shown in Fig. 5, there was significant infiltration even before the modelling of extended detention in the stormwater ponds. This can be attributed to large sections of the study area having rural/farmland characteristics where natural recharge takes place. Furthermore, the study area possesses physical characteristics that support natural infiltration, including, inter alia, sandy soils (pervious) and reasonably flat terrain. However, with population growth and the associated land-use change, natural 'greenfield' areas are being converted to impervious surfaces in the absence of sustainable drainage systems (SuDS), and hence extended detention in ponds would be important in enhancing surface to groundwater transfer.

Modelling groundwater flow field

In this study, generalised groundwater flow field due to abstraction, and also pollution transport, was modelled from first principles using the hybrid optimization approach presented in Mahinthakumar and Sayeed, (2005; 2006) following the steps presented in Fig. 6.

The approach combines genetic algorithms (GA) with local search methods to solve the groundwater flow equations that were further developed with assistance of the principal author. They solve the two-dimensional steady-state partial differential equation with a time-step component commonly known as Richards' equation (Richards, 1931) (Eq. 6).

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{1}{K(x,y)}\frac{\partial h}{\partial t} \quad (6)$$

where: v_x and v_y are velocity (flux) in x-direction and y-direction, respectively; $K(x, y)$ is hydraulic conductivity in 2 dimensions; dh is hydraulic head; dx and dy are spatial steps in x and y directions, respectively.

In the model, Eq. 6 was represented in a finite difference form (Eq. 7) with discrete nodes defined along a grid covering the study area. The hydraulic head (h) was represented in both the 2-dimensional spatial domain and time interval, i.e., ($h_{i+1,j,t}$, $h_{i,j,t}$, $h_{i-1,j,t}$); ($h_{i,j+1,t}$, $2h_{i,j,t}$, $h_{i,j-1,t}$); ($h_{i,j,t}$, $h_{i,j,t-1}$), and estimated using algebraic equations containing finite differences and values from nearby points.

$$\frac{h_{i+1,j,t} - 2h_{i,j,t} + h_{i-1,j,t}}{(\Delta x)^2} + \frac{h_{i,j+1,t} - 2h_{i,j,t} + h_{j-1,t}}{(\Delta y)^2} = \frac{1}{K(x,y)}\frac{h_{i,j,t} - h_{i,j,t-1}}{\Delta t} \quad (7)$$

The simulation was initially undertaken on a trial section (1.44 km^2 with a single pond) and then finally at the catchment scale (89 km^2 with 61 ponds). Likely groundwater abstraction rates and suitable locations of the boreholes relative to the infiltration basins were estimated through a particle tracking model of the groundwater flow paths in the aquifer. The aim was to ensure that the stormwater ponds were the origin of the groundwater flow fields.

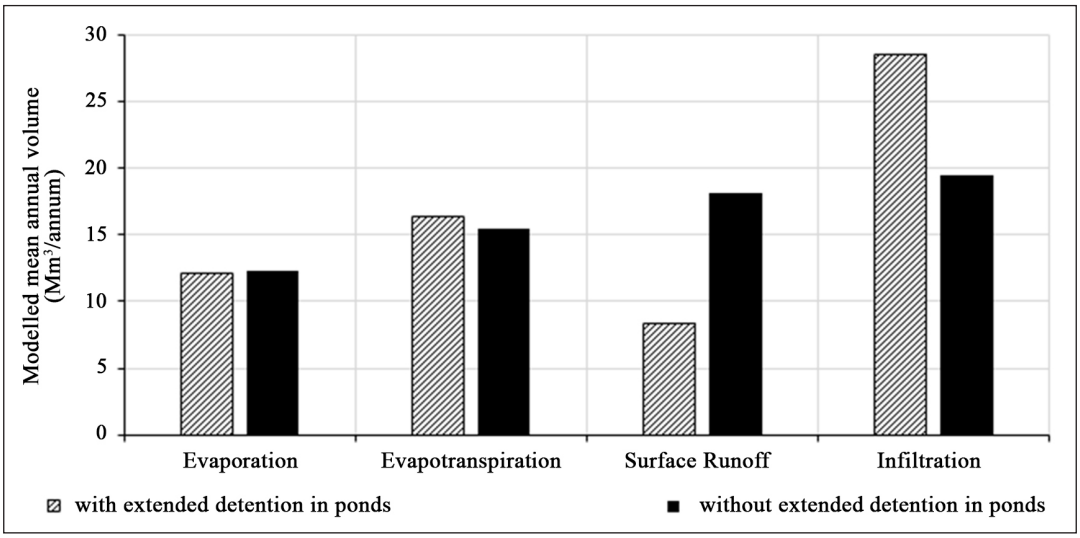

Figure 5. Summary results of modelled water balance (pre-extended detention on pond)

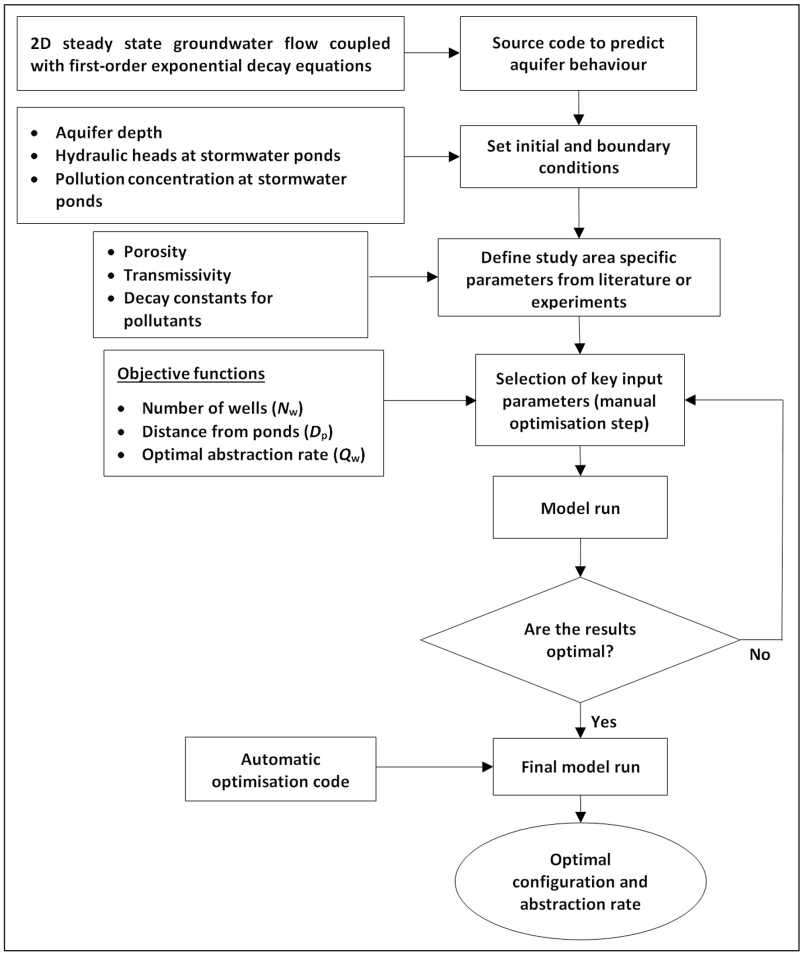

Figure 6. Groundwater abstraction model structure

To minimise simulation run-time, discrete nodes were placed in the centre of 1 x 1 km resolution squares of constant size covering the entire catchment, as shown in Fig. 7. To further reduce simulation run-time, the catchment was subdivided into 4 rectangular domains / computational areas (CA) (labelled CA1, CA2, CA3 and CA4 in Fig. 7) that approximated the extent of the four discrete study areas. The groundwater abstraction modelling aimed to determine the appropriate number of abstraction boreholes (N_w), distance of the boreholes from stormwater ponds (D_p), and abstraction rates (Q_w) for the study areas that would maximise the quantity of water abstracted from the supplementary groundwater resource, assumed to be equal to the stormwater transferred to the aquifer through the infiltration process, i.e., SWH. Furthermore, the managed extraction of groundwater from the vicinity of the ponds should hopefully reduce the risk of subsidence resulting from a general drop in the groundwater table.

Modelling water quality improvement within the aquifer

It was also desirable that the aquifer provides sufficient improvement of the quality of the stormwater, to minimise the subsequent treatment process. One significant advantage of storing stormwater underground is that aquifers act, to a large extent, as sand filters. There is improvement through infiltration, adsorption (the process whereby pollutants bind to the surface of fine sand particles), biodegradation and volatilisation (the conversion of some compounds to gases or vapour). There is a trade-off between maximising the quantity of the harvested stormwater by extracting from the regions closest to the ponds and enhancing the water quality improvement for pathogens by extending the flow path and residence time. The pollution decay associated with groundwater transport from the stormwater pond to abstraction boreholes was thus assessed using the first-order relationship presented in Eq. 8 (Delleur, 2007) for *E. coli* (an indicator organism for faecal pollution) using a decay rate informed by the published values listed in Table 6.

$$C_t = C_o\, e^{-\lambda t} \tag{8}$$

where: C_t is concentration or quantity at time t; C_o is initial quantity at the start of assessment ($t = 0$); λ is pollution decay rate (day^{-1}). The units of C_t and C_o depend on the pollution.

Equation 8 is a simplification of the process, as *E. coli* removal typically depends on various factors including, inter alia, the availability of nutrients in the water, the exposure to UV radiation and temperature (Delleur, 2007). Nevertheless, the simplification was deemed adequate for the study, as the goal was to demonstrate the potential of water quality improvement from the process of stormwater recharge and recovery.

Determination of borehole distribution and determination of abstraction rates

The ideal borehole site selection and determination of the recommended abstraction rates was based on the following criteria:

- Visual inspection of the particle tracks provided by the model was used as guidance to ensure that the groundwater flow paths originated from stormwater ponds.
- The mean groundwater levels are generally deepest at the end of the dry summer, then rise to the surface in many areas with the natural recharge from winter rainfall. Physical data on the seasonal groundwater level fluctuations provided the basis for the setting of the initial conditions and hydraulic heads.

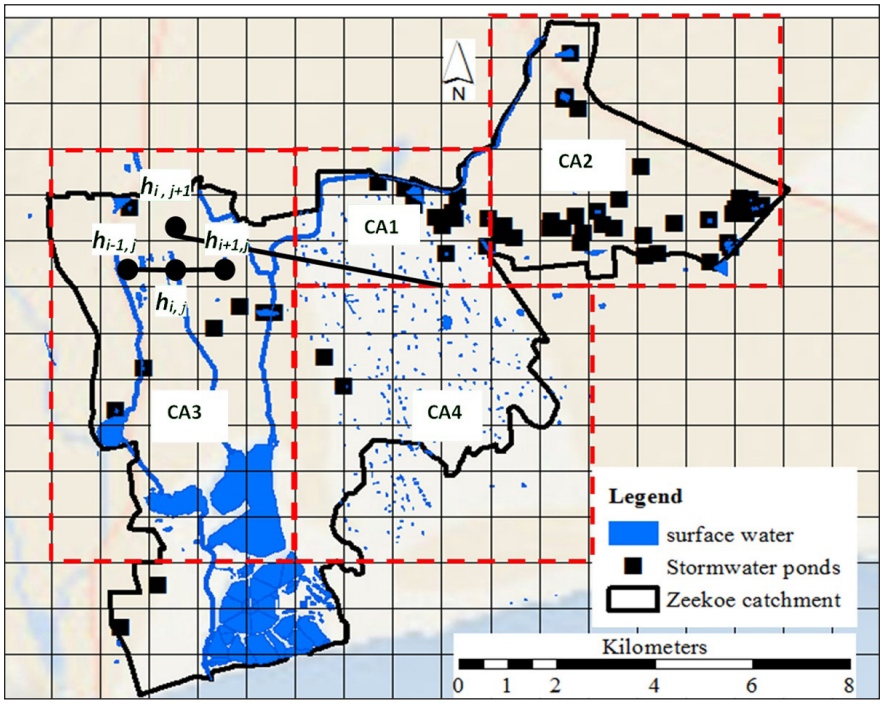

Figure 7. A discretised section of Zeekoe Catchment (CA1 – Computational Area 1; CA2 – Computational Area 2; CA3 – Computational Area 3; CA4 – Computational Area 4)

Table 6. Various published *E. coli* decay rates

Description of conditions	Decay rate	Source
Laboratory condition, light exposure, seawater	14.7–107	Chan et al., 2015
Laboratory condition, darkness, seawater	0.85–1.5	Chan et al., 2015
Literature study	0.025–0.051	Engelbrecht, 1998
Laboratory, groundwater	0.046–0.092	Filip et al., 1988
In-situ diffusion chamber, groundwater	0.42	Page et al., 2010
In-situ diffusion chamber, groundwater	0.691	Sidhu et al., 2012
Field experiment, groundwater	0.15	Toze et al., 2002

- The location of wells and groundwater abstraction rates were set such that the interference between the various drawdown curves was minimised.
- The total abstraction quantity was made approximately equal to the anticipated infiltration with the modified ponds as estimated in PCSWMM.
- The retention time of the water in the aquifer was kept at around 1 year to ensure that pathogenic organisms, indicated by *E. coli*, would be largely eliminated.

RESULTS AND DISCUSSION

Edith Stephens

Initially, a stormwater recharge and recovery model was made of a trial section incorporating only one stormwater pond – the Edith Stephens Wetland (Figs 8 and 9). Examples of the borehole model simulation are presented in Fig. 10.

An initial abstraction rate of 1.2 L/s per borehole was implemented in the model (Fig. 10 left). With this, all flow fields originated from the Edith Stephens Wetland. The borehole abstraction rates were then increased stepwise until 5.8 L/s (Fig. 10 right), which was determined to be the optimal abstraction rate with the flow fields visually observed to originate mainly from the pond. When the abstraction rate was increased above 5.8 L/s per borehole, the flow fields increasingly originate from areas beyond the stormwater pond.

A decay rate of 0.025 – the smallest value of those listed in Table 6 – was selected as a conservative value associated with slow organism inactivation and prolonged survival times, i.e., worst-case conditions. Simulations were undertaken in the model with Eq. 8 to determine transport and decay of the *E. coli* as an indicator organism, using the estimated abstraction rate of 5.8 L/s per borehole. The model was run with an initial mean value of 12 000 CFU/100 mL at the pond, based on the monthly grab samples collected by CCT from various locations in Edith Stephens Wetland over the period 2006–2017 (Fig. 11).

The very high initial *E. coli* values are consistent with major pollution sources, such as on-site sanitation, upstream of the Edith Stephens Wetland, and direct discharge of grey- and blackwater into the drainage channel from informal settlements. Since the grab samples were not collected at regular intervals (i.e., the sample collection date in the month was inconsistent, and some values were missing), the data could only provide an indication of the contamination in the stormwater drainage and values for modelling purposes. The results of the water quality modelling are presented in Fig. 12. The results from the trial section with a single pond (Edith Stephens Wetland), using *E.coli* as an indicator organism for faecal pollution, showed that the sandy aquifer in the study area had the potential to remove very high levels of *E.coli*, i.e., from between 1 x 10^3 and 1 x 10^5 counts per 100 mL to values below 1 count per 100 mL (Fig. 12).

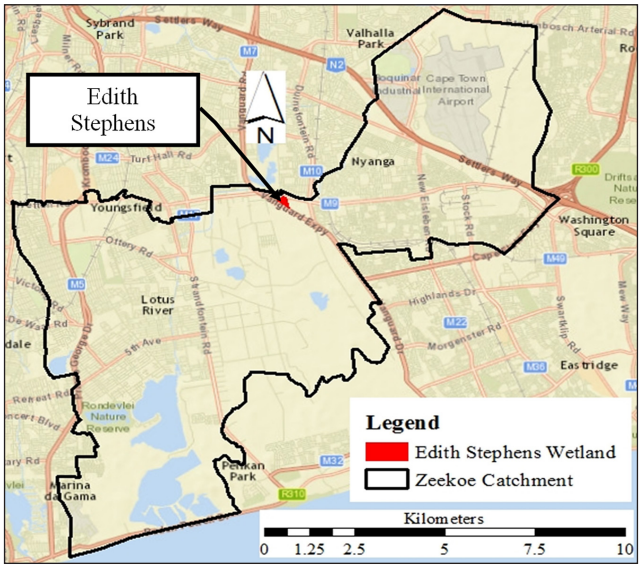

Figure 8. Location of the Edith Stephens Wetland (after CCT, 2015)

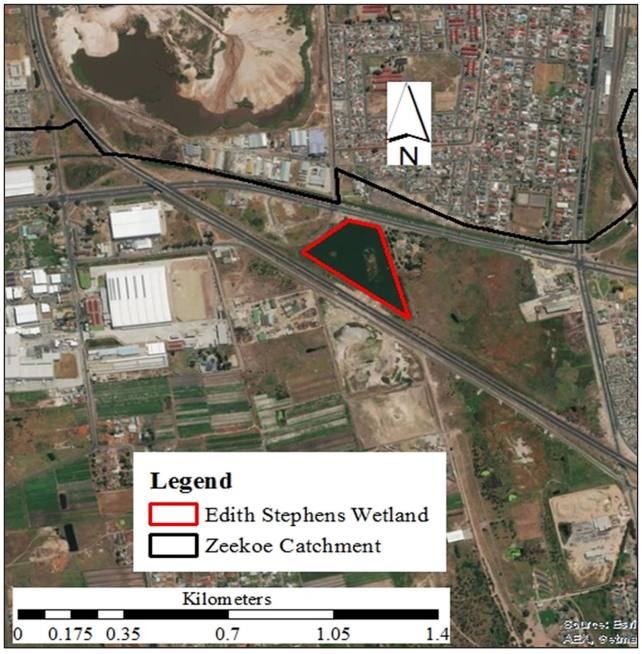

Figure 9. Aerial view of the Edith Stephens Wetland (after CCT, 2015)

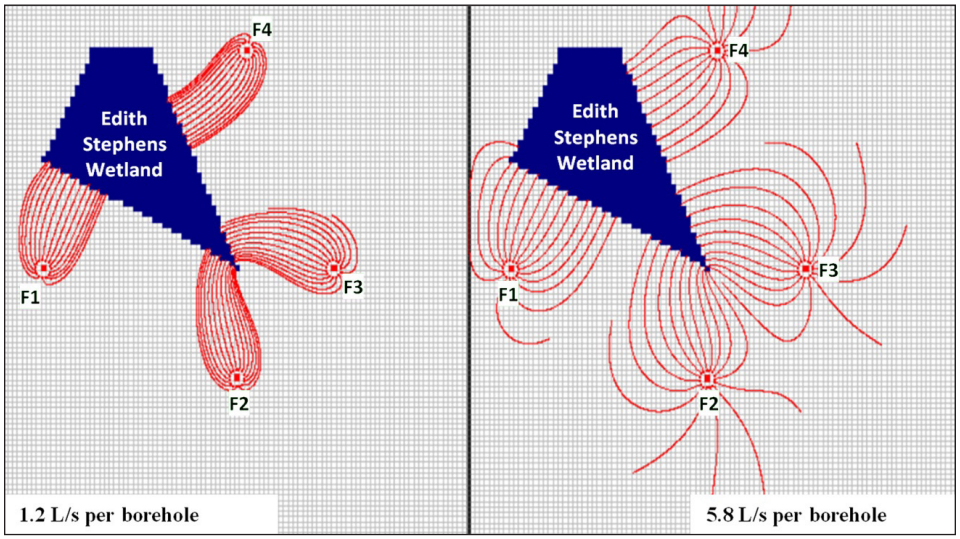

Figure 10. Modelled groundwater flow fields (F1, F2, F3, F4) from 4 abstraction wells near the Edith Stephens Wetland (initial abstraction rate of 1.2 L/s (left) and optimal abstraction rate of 5.8 L/s (right)

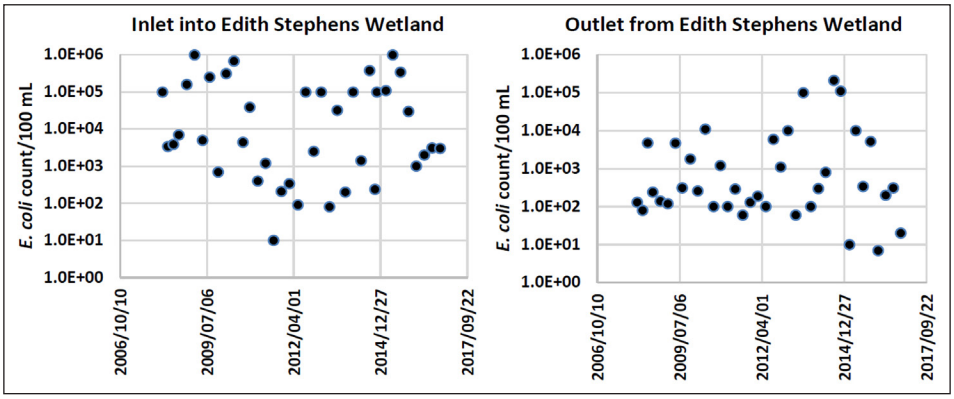

Figure 11. *E. coli* measured at Edith Stephens Wetland (CCT, 2017)

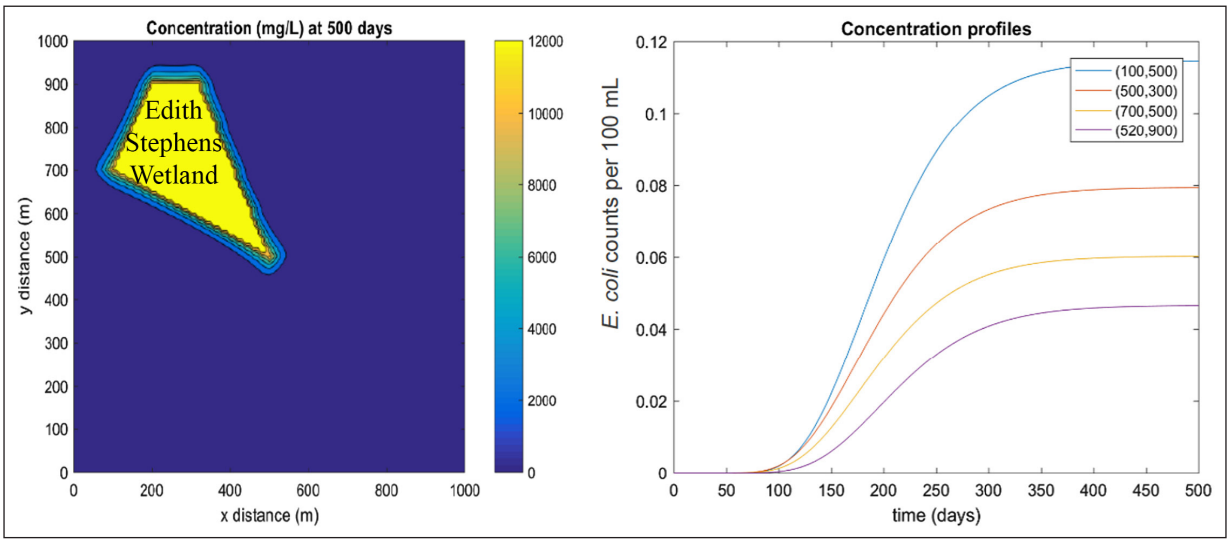

Figure 12. *E.coli* counts with boreholes abstracting at 5.8 L/s

The South African National Standard for drinking water (SANS 241-1:2015, SABS, 2015) requires zero *E.coli* count; however it was evident from the model that stormwater harvested from groundwater storage would be suitable for potable water uses with minimal additional disinfection treatment.

Zeekoe Catchment

The findings from the trial section model and additional information from literature were then used to develop the catchment-scale model. Vandoolaeghe (1989) had determined that a total of 10 Mm^3/yr could be abstracted, with 27 boreholes each pumping at an abstraction rate of 12 L/s from the CFA, while Fraser et al. (2001) suggested a total groundwater yield of 18 Mm^3/yr in the same area. Abstraction rates of 6 L/s per borehole were determined to be most suitable, with higher values potentially extending the groundwater cone of depression to the coastline and resulting in possible seawater intrusion (DWA, 2008). In a more recent study, 6 scenarios were assessed, consisting of 3 arrangements of 9, 18 and 27 boreholes with abstraction rates of 3 L/s and 5 L/s (Mauck, 2017). One of the key aims of that study was flood mitigation through drawdown of the water table to values lower than a pre-determined threshold of 1.5 m below the surface through groundwater abstraction (Mauck, 2017). Mauck (2017) determined that an abstraction rate of 3 L/s would not draw down the water table to below the 1.5 m threshold for flood mitigation in all three borehole arrangements. With the borehole pumping rates increased to 5 L/s, the simulated groundwater drawdown exceeded the 1.5 m threshold only 5% of the time for the 18 boreholes and completely for the 27 boreholes (Mauck, 2017).

The various recommended abstraction rate values were used to guide the borehole abstraction rates in each of the four rectangular computational areas (CA), CA1, CA2, CA3 and CA4 presented in Fig. 7. Four boreholes were randomly placed around the stormwater ponds in each of the computational areas and initially simulated using an abstraction rate suggested in Fig. 13.

The number of boreholes and abstraction rates were then adjusted to ensure that the flow fields originated from the nearest stormwater ponds (i.e., harvesting 'stormwater' from the ponds). The assumption was that infiltration rates were not diminished by high water tables, i.e., abstraction rates lowered groundwater levels to sufficient depth such that the pond floor was above capillary fringe (i.e., the zone of saturated soil directly above the water table where groundwater is pulled upwards from the saturated zone by capillary action). A summary of the key parameters, the final optimised modelled number of boreholes, the abstraction rates per borehole and the mean annual groundwater yields for each computational area, are presented in Table 7.

The modelling suggested that the likely optimal abstraction rates per borehole range from 3.5–8.1 L/s if the flow was to be restricted to that from the ponds. When the abstraction rates were increased beyond these values, the origin of the groundwater flow fields was increasingly from outside the pond area, i.e., not a consequence of MAR at the ponds.

A further assessment was undertaken to determine the likely water quality improvement associated with stormwater recharge and recovery. The CCT collects grab samples from various locations in the study area indicated in Fig. 14.

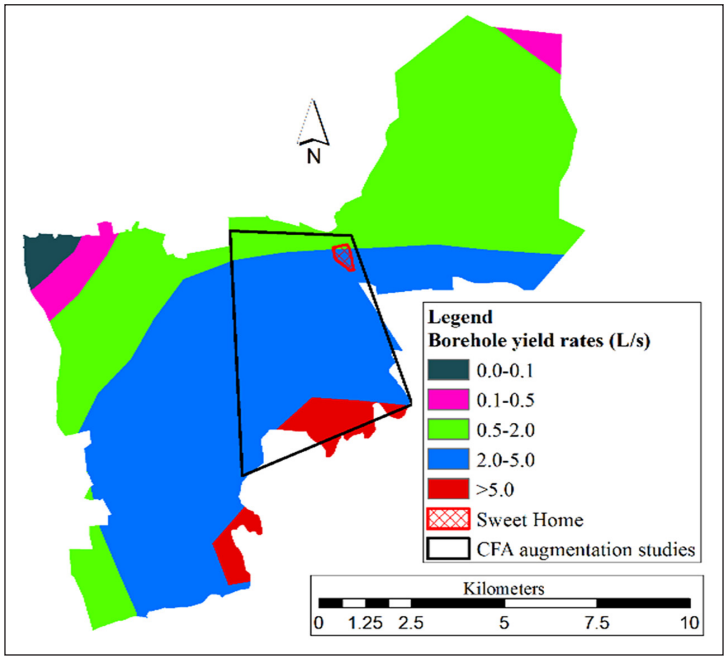

Figure 13. Borehole yield rates in the study area (after CCT, 2005)

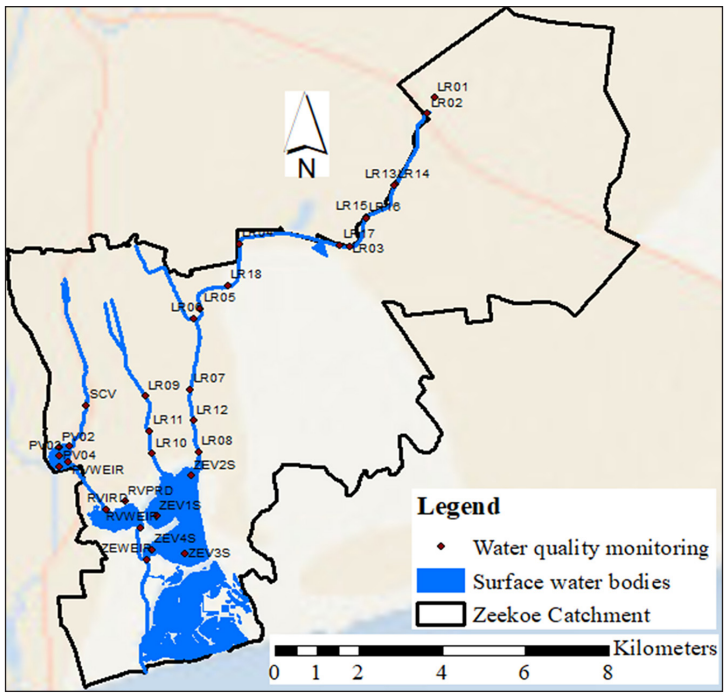

Figure 14. Locations of water quality motoring in the study area (after CCT, 2017)

Table 7. Model domain parameters and potential groundwater yield

Parameters	Computational area			
	CA1	CA2	CA3	CA4
Domain size (km^2)	12	36	45	36
Conductivity (cm/hr)	4.8	11.1	11.1	10.3
Porosity (%)	33	37	37	40
Aquifer depth (m)	30	20	40	50
Number of boreholes	20	20	40	60
Distance of well from ponds(m)	400	400	400	400
Mean abstraction rate per borehole (m^3/day)	300	500	500	700
Mean abstraction rate per borehole (L/s)	3.5	5.8	5.8	8.1
Potential total annual groundwater yield (Mm^3/year)	2	4	7	15

A theoretical assessment of stormwater quality improvement, with *E.coli* as the indicator organism for pathogens, was undertaken for CA1, CA2, CA3 and CA4 based on the CCT data, using Eq. 8 to estimate the likely decay with time. The modelled values for CA1 (Fig. 7) with 10 stormwater ponds and 20 abstraction boreholes suggest that the sandy aquifer in the study area has the potential to remove very high levels of *E.coli*, i.e., between 1 x 10^{-6} counts per 100 mL and less than 8 counts per 100 mL. In CA1 and CA2, *E.coli* counts were detected at boreholes after about 100 days in the model – with the count increasing rapidly over a 200-day period. The counts stabilised in the range of 1 to 8 counts per 100 mL at about 350 days (about 1 year). In CA3 and CA4, *E.coli* counts were detected at boreholes after about 200 days in the model, and increased rapidly over a 400-day period before stabilising after about 600 days (a little less than 2 years).

In summary, with the South African National Standard for drinking water (SANS 241-1:2015, SABS, 2015) requiring a zero count of *E.coli* per 100 mL, the findings from the catchment-scale model show that the stormwater harvested from groundwater storage would theoretically be adequate for potable water uses with minimal additional disinfection treatment. The abstracted water would not require additional treatment for non-potable water demands, i.e., irrigation of urban agriculture, public open parks and residential gardens. Lim et al. (2015) reported similar results, i.e., that microbial pollution in stormwater from groundwater storage was significantly reduced to levels where the water could be directly used for some indoor residential needs with a limited level of contact, e.g., machine washing and toilet flushing. Vanderalm et al. (2010) showed that stormwater recovered from an aquifer after a mean residence time of 240 days was suitable for non-potable water applications. Continuous monitoring would be necessary while post-recovery disinfection and aeration for iron removal might be required.

CONCLUSIONS

In this study, it was determined that the Zeekoe Catchment has the potential for relatively high borehole abstraction rates compared with other areas in Cape Town. The mean annual natural infiltration for the 89 km^2 was estimated to be in the range of 20–21 Mm^3. With the 61 stormwater ponds available in the study area adapted to function as bio-retention cells, the mean annual infiltration could likely increase the groundwater resource to 29–33 Mm^3. The actual additional groundwater resource due to stormwater infiltration could thus be 9–12 Mm^3. The impact of land-use change was also assessed with a hypothetical future general catchment imperviousness of 75%. It was determined that this could decrease the natural mean annual infiltration volume to 10–13 Mm^3. Managed aquifer recharge with stormwater to enhance groundwater augmentation could, however, increase the groundwater resource to about 21 Mm^3. The results from modelling various potential groundwater abstraction scenarios in the Zeekoe Catchment show that, depending on the aquifer parameters – i.e., conductivity, porosity and aquifer depth – suitable borehole pumping rates for later abstraction typically range from 3.5–8.1 L/s for the anticipated 140 boreholes in the 89 km^2 catchment. MAR provides water quality improvement benefits. The study area contains several informal settlements (slums, shanty towns), that generate wastewater and litter discharges into the drainage channels, particularly in the upper reaches of the catchment, and the CCT monthly grab samples of stormwater quality showed that the drainage system in the study area is highly impacted by pollution. MAR could substantially improve the water quality. A preliminary assessment suggested that a residence time of about a year should provide die-off of pathogens in the abstracted water to values less than 10 *E.coli* counts/100 mL.

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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