Hydrogeology Journal (2020) 28:2009–2023
https://doi.org/10.1007/s10040-020-02188-w

REPORT

Scenarios analysis using water-sensitive urban design principles: a case study of the Cape Flats Aquifer in South Africa

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Received: 29 May 2019 / Accepted: 19 May 2020 / Published online: 1 June 2020

Abstract

A feasibility assessment was undertaken on the application of water-sensitive urban design (WSUD) for the Cape Flats Aquifer in Cape Town, South Africa, at the local scale. The study contributes towards the planning of water-sensitive cities in the future. A three-dimensional steady-state groundwater flow model was applied to the Cape Flats Aquifer to predict WSUD scenarios by incorporating managed aquifer recharge (MAR). Analysis of the scenarios of varying recharge estimates and groundwater abstraction rates, predicted using the model, indicated that the water-table distribution and outflows from identified groundwater balance components show direct proportionality to the varying recharge scenarios. A notable increase in these outflows was observed when the recharge rate was increased by 50%. Varying groundwater abstraction scenarios indicated that with increasing abstraction rates, water levels and outflows from groundwater balance components also decreased accordingly. A notable decline in water levels and outflows was established at an abstraction rate of 2.5 and 5 L/s, respectively. Similar to the previous regional studies in the area, the results from the predicted scenarios show that there is a potential for applying WSUD, particularly MAR, at site-specific scale within the Cape Flats Aquifer. However, shallow groundwater levels during wet seasons limit the opportunities for application of WSUD in the area. This finding would provide an important reference to the ongoing debate on the Cape Town water crisis and similar environmental conditions where WSUD is considered.

Keywords South Africa · Conceptual model · Groundwater abstraction · Numerical modelling · Groundwater flow

Introduction

Water-sensitive urban design (WSUD) as defined by Wong (2006) is an approach that integrates urban planning with the management, protection and conservation of the urban water cycle. The approach is aimed at ensuring that water is given due prominence during the urban design process, through the integration of interlinked approaches functioning to achieve the objective of water conservation, wastewater minimisation and stormwater quality improvement, as well as flow control in an urban area (Ward et al. 2012). Water conservation is achieved through potable-water demand management using an alternative water source for different purposes, stormwater or rain water reuse, aquifer storage and recovery, and greywater reuse. Wastewater minimisation is achieved through demand management, grey water reuse and effective infiltration inflows. The stormwater quality improvement and flow controls are achieved through the use of bio-retention ruts to treat stormwater and storing the treated stormwater in the underlying aquifers for future use, and rainwater harvesting and reuse is achieved through rainwater harvesting structures on the roof tops of buildings. The philosophy of WSUD started at Murdoch University in Perth, Australia, and served as a guide on how to advance water infrastructure design in natural and built environments. The focus was on stormwater management design, and by now it has been expanded to include all the components of the urban water cycle. Due to the effectiveness of WSUD in managing urban water cycles in Australia, the approach had been adopted in various countries including Malaysia (in Singapore), England (UK), and South Africa (Ward et al. 2012). In Singapore, two separate systems are used to collect rain and used water. The rainwater is collected through a system of interconnected canals, rivers and stormwater collection ponds before being channelled to Singapore's 17 storage dams (Yang and Soraya 2013). In

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England, WSUD is at an infancy stage, where building regulations have been modified to provide baseline compliance for water efficiency (Yang and Soraya 2013). This forms part of water demand management suggested by WSUD principles. From the South African context, WSUD is well documented in studies by Fisher-Jaffes et al. (2017); Armitage et al. (2014); Lottering et al. (2015) and ROHR (2012), and some methods for urban water cycles management suggested by WSUD had been adopted on various projects like the Atlantis Managed Aquifer Recharge Scheme, and Stellenbosch Lynedoch and Hermanus water demand management projects (Armitage et al. 2014). The research is unclear as to how the concept of water sensitivity links with urban design in the context of peri-urban cities like Cape Town, and how the WSUD approach can be applied to transform the peri-urban settlements in South Africa to green and water sensitive environments (Carden et al. 2017). Modelling approaches and tools can provide a basis to understanding of the benefits and impacts of implementing WSUD principles in greening and creating water sensitive cities of the future in South Africa. The study by Seyler et al. (2016) focused on quantitative assessment of the feasibility of natural systems with a specific focus on impacts and benefits of up-scaled water sensitive design (WSD) on groundwater and surface water in Cape Town and the associated Cape Flats Aquifer. Seyler et al. (2016) quantified the water balance of the Cape Flats Aquifer under ideal implementation of WSD, and also determined the impacts, feasibility, as well as optimal design for up-scaled WSD. The results of the impact and feasibility analysis showed that increased infiltration and MAR is limited by shallow groundwater levels and beneficial only in conjunction with the bulk use of the aquifer. Mauck (2017) tested the applicability of MAR on the Cape Flats Aquifer, with specific focus on the assessment of possible summer groundwater abstraction rates and stormwater storage to the aquifer. The analyses of storage potential and plausible MAR revealed that there is a potential for increased storage and improved water supply using MAR in the Cape Flats Aquifer. In addition, 10 Mm^3 and 7.8 Mm^3/year could be recycled through MAR in the Phillipi and Mitchells plain areas within the southern part of the Cape Flats Aquifer. Seyler et al. (2016) and Mauck (2017) both demonstrated that there is potential and benefits to applying WSUD on the Cape Flats Aquifer. Both studies focused on regional groundwater flow analysis, and there is a need to assess the potential for applying WSUD at local scale. The current study applied a three-dimensional (3D) steady-state numerical flow model at a local scale within the Cape Flats Aquifer to predict WSUD scenarios including MAR. The main aim was to assess the feasibility of applying such WSUD schemes on the Cape Flats Aquifer at the site-specific scale and thus contribute towards the planning of water sensitive cities for South Africa's future.

Study area description

Study area

The Cape Flats Aquifer (33.9249° S and 18.4241° E; Fig. 1) covers an area of approximately 630 km^2 and extends in the northern direction towards the west coast of South Africa. The area represents a central region of the coastal sands between the Cape Peninsula and the mainland (Saayman and Adams 2002). The central sedimentary unit forming Cape Flats Aquifer is characterised by lowland varied terrain ranging between 0 and 110 m above mean sea level (m amsl) with an average elevation of 30 m amsl (Adelana et al. 2010). The main drainages include the Kuils River and Deep River which discharge to the False Bay coast. The Elsieskraal River, Vygekraal River, Black River and Liesbeek River all discharge to Table Bay. A number of wetlands exist in the area, and include the Ramsar protected Zeekoevlei site along the False Bay coast (Meerkotter 2012).

Climate, geology and hydrogeology

The Cape Flats falls within the Mediterranean climatic region with mean annual precipitation of 619 mm (Adelana et al. 2010), which is mostly received during the wet season (April–September). The geology of the area comprises Quaternary sands of marine and aeolian origin overlying the weathered Malmesbury Formation and granite basement rocks that are low in permeability, with average hydraulic conductivity of 3.4 m/day (Scheepers and Schoch 2006). The Malmesbury Formation is characterised by greenschist facies metasedimentary and metavolcanic rocks of Neo-Proterozoic age, with Cape Granite suits intruding the formation in some parts (Scheepers and Schoch 2006). The Quaternary sands overlying the Malmesbury Formation consist of Langebaan, Witzand, Springfontyn, Elandsfontein, Velddrift and Varswater formations. The Langebaan Formation is characterised by very fine to medium calcareous sands containing cross bedding along the coast (Hartnady and Rogers 1990). The Witzand Formation is characterised by very fine to coarse calcareous sand with shells forming vegetation-bound coastal dunes. Velddrift formations are poorly consolidated intertidal sediments which are patchily deposited. Springfontyn Formation varies from fine to medium quartz sands with grain size often increasing with depth. Varswater Formation is of marine deposit with very fine to medium sands and often silty (Vandoolaeghe 1990). Elandsfontein consists of angular, fine to clayey sands (Tredoux et al. 1980). There are two types of aquifer systems found in the area, namely the Cape Flats Aquifer and Malmesbury Aquifer. The Cape Flats Aquifer forms a shallow aquifer system (40–50 m thick) varying from unconsolidated to semi-consolidated sands due to interbedded peat, clay and

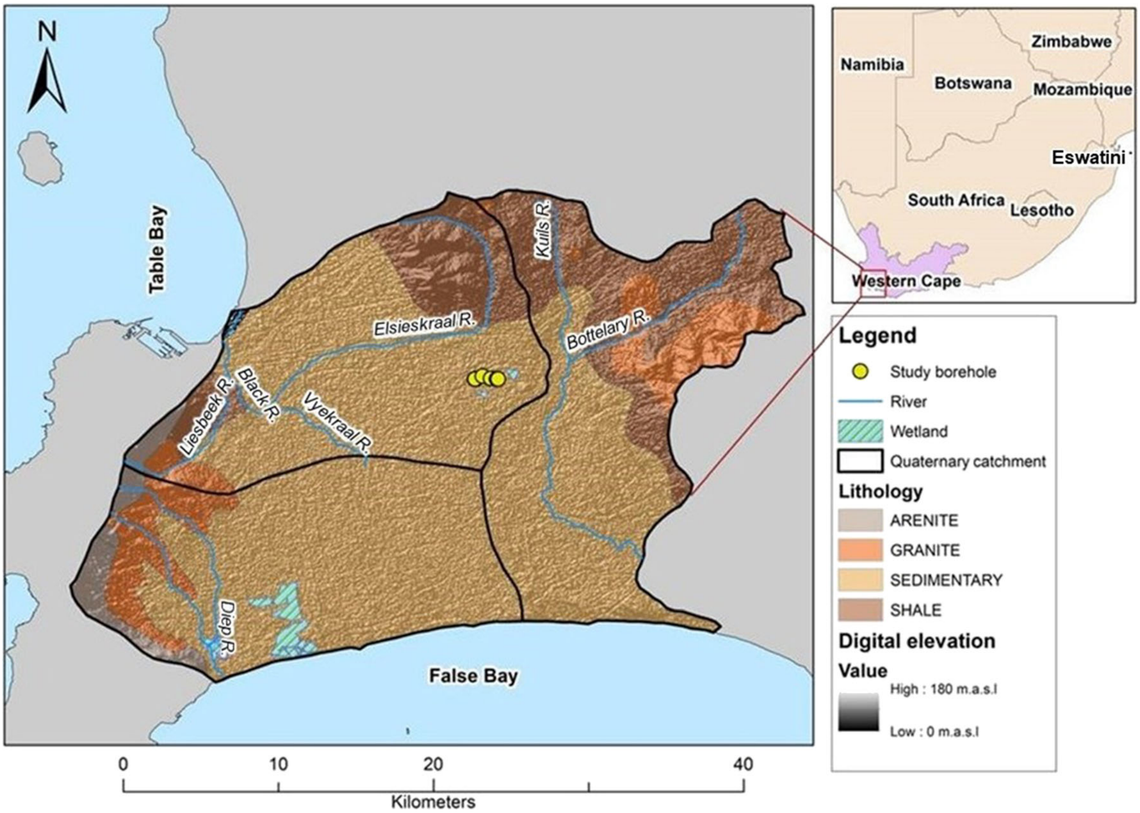


Fig. 1 Location of the Cape Flats Aquifer within the Western Cape Province of South Africa (R River)

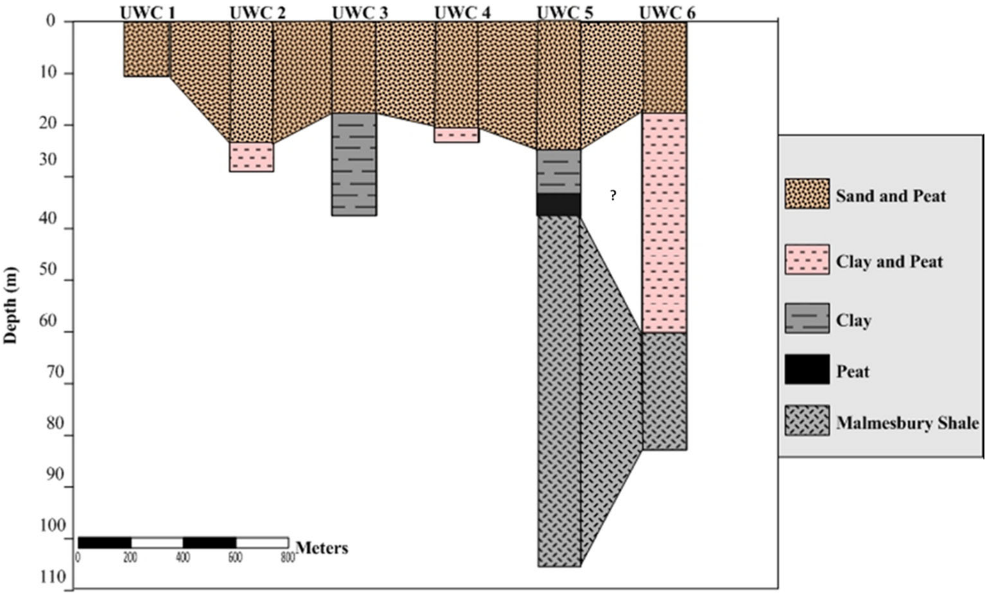
calcrete layers causing the aquifer to be semi-confined in some parts as seen in Fig. 2 (Maclear 1995; Gxokwe 2018). The Malmesbury Aquifer forms a fractured rock system underlying the shallow Cape Flats Aquifer. Due to the low average conductivity, the Malmesbury Formation was considered a no-flow boundary condition in this study.

Methodology

Model conceptualisation

The hydrogeological conceptual model was developed based on data assimilated from previous studies in the area by

Fig. 2 Stratigraphic correlation in a cross-section of the study area



Adelana (2010); Adelana et al. (2010); Mauck (2017); City of Cape Town (2007), DWAF (2008) and from other sources like US Geological Survey, National Groundwater Archives, South African Weather Services and Council for Geoscience in Bellville South Africa. The data collected included geological, lithological, topographical, hydrological and hydrogeological datasets. The geological data included geological maps for the area to understand the surface and subsurface geology. The lithological data included geological core logs for the boreholes in the area to understand the lithological conformation. The topographical data included digital elevations for understanding surface topography. The hydrological data included wetland and river locations, as well as data on weather parameters used for evapotranspiration calculations. Hydrogeological data included aquifer thickness, groundwater levels, borehole locations, borehole depths, screen depths and aquifer boundaries. Figure 3 shows the regional groundwater flow system of the Cape Flats Aquifer. Analysis of regional flow system suggests the flow direction follows a topographical gradient, where the flow direction (yellow arrow heads) is to the south. The highest transmissivity values (15–620 m^2/day) were estimated within the southern part of the area, supporting the proposal that groundwater flow direction is towards that area (Gxokwe 2018). Isotope analysis of deuterium and oxygen-18 (^{18}O and ^{2}H) by Gxokwe (2018) showed that groundwater of the Cape Flats Aquifer is of meteoric origin, and recharge (Re) is diffuse, mostly occurring at the surface of the aquifer during the rainy season. There are other potential sources of groundwater recharge such as urban irrigation return flows, and leakages from water supply pipes and sewage systems, that may also contribute to groundwater recharge in the area. This is evident in the study by the City of Cape Town (2007) which quantified overall fresh and wastewater loss in mains and pipelines. The loss quantified was 186 ML/day (23.3%), which includes losses from leaks in reticulation systems, customer's properties or plumbing leaks, indiscriminate wastage of water and automatic flushing of urinals. The University of the Western Cape (UWC) well field (Fig. 4) represents the local flow system and is modelled in this study. Two formations overlying the Malmesbury Formation are present: the Springfontyn (Qs) and Witzand (Qw) formations. The flow direction at a local scale also follows the topographical gradient, where groundwater flows in the south westerly direction. The shallow Cape Flats Aquifer thickness in the modelled area ranges between 40 and 50 m, with boreholes drilled at the depth of 10–108 m. UWC 5 and UWC 6 are the boreholes with the greatest depth (108 and 84 m) and penetrating through to the Malmesbury

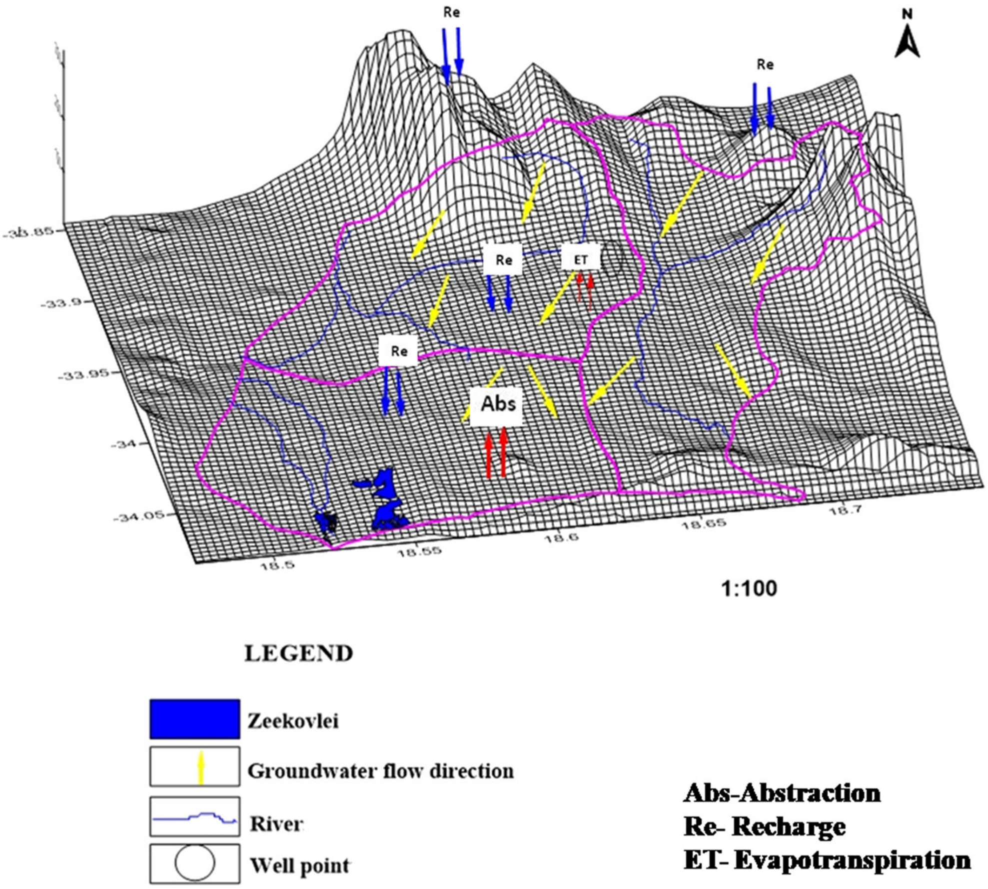


Fig. 3 Regional groundwater flow system of the Cape Flats Aquifer

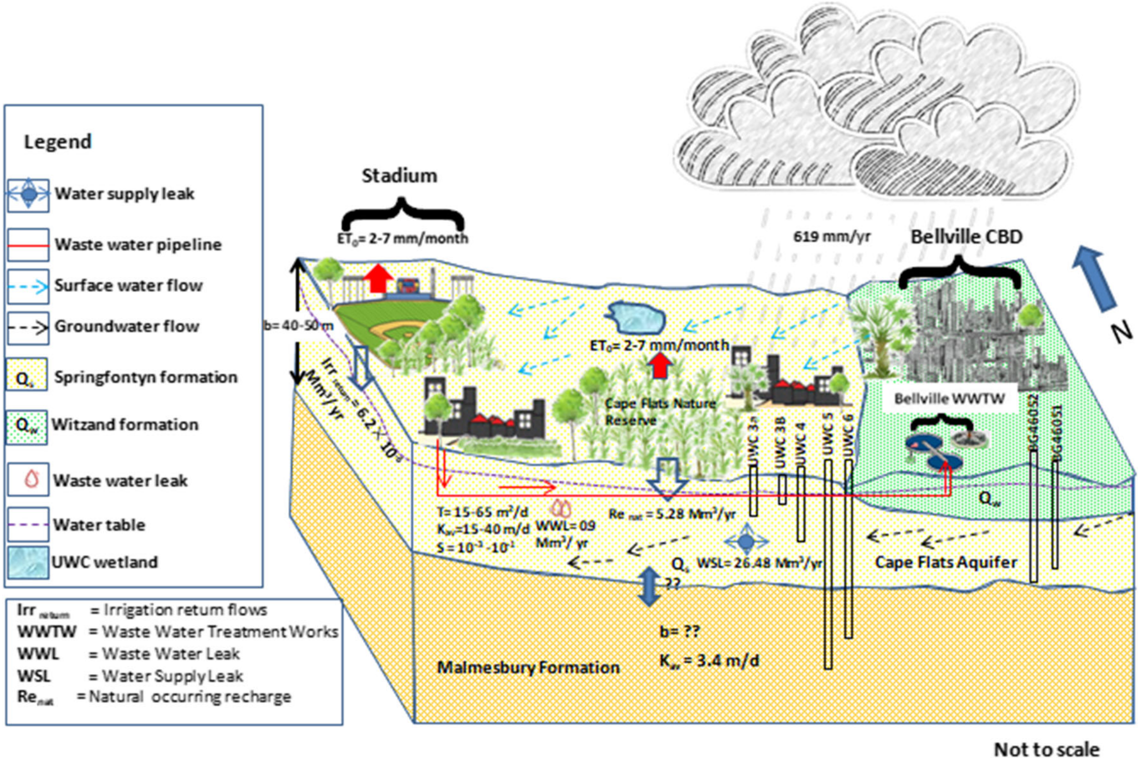


Fig. 4 Local groundwater flow system of the Cape Flats Aquifer

Formation, and boreholes UWC 4, UWC 3, UWC 2 and UWC 1 are only partially penetrating the Cape Flats Aquifer with depths of 22, 37, 30 and 6 m respectively. Groundwater is encountered at mean depth of 5.4 m. The transmissivity, as estimated by Gxokwe (2018) for the Cape Flats Aquifer at UWC, ranges from 15 to 65 m^2/day, and storativity ranges from 10^{-3} to 10^{-1}.

Numerical model design and parameterisation

A 3D steady-state numerical flow model was developed using the MODFLOW 2005 code within ModelMuse graphical user interface software by Winston (2009). The steady-state conditions were simulated based on the equation presented in Anderson et al. (2015). The model consisted of 161 rows and 171 columns making up the grid cells. The grid cell sizes were 100 m × 100 m for the catchment, and further grid refinement was done to 5 m × 5 m grid cells in the area of focus (UWC). Vertically, the model is single-layered, and the top surface elevation was assigned using a 30-m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) sourced from the US Geological Survey's EarthExplore site (USGS 2019). The bottom surface elevation was assigned using the average thickness (50 m) of aquifer within the modelled area specified by Adelana (2010), and this was assumed to be the interface between the Cape Flats Aquifer and Malmesbury Formation.

Input parameters

Recharge (Re)

Groundwater recharge in an urban environment is influenced by the coexisting land use activities in the area; as such estimation of groundwater recharge in these environments requires a complete understanding of each land-cover class and its influence on recharge. To quantify groundwater recharge to the Cape Flats Aquifer, potential sources of groundwater recharge were firstly identified through the review of literature on studies of other urban areas that involve recharge estimations associated with similar hydrogeological, hydrological, geological and land cover characteristics (Xu and Beekman 2003). The identified potential sources included recharge due to leakage of the water supply pipes and sewage pipelines, irrigation return flows from the irrigation of lawns and stadiums in the area, as well as the natural occurring recharge. To estimate groundwater recharge due to leakage of sewage pipelines, the daily total volumes of sewage received in the wastewater treatment works in the area and the volumes of sewage produced by the population of people—3,928,148 according to Stats SA (2011)—living in the area were used. The difference between the wastewater received and the wastewater produced by population in the area (assuming that each person produces 50 L/day of wastewater) gave an indication of what was lost in the system, and it was assumed that this amount had recharged the shallow Cape

Flats Aquifer. The 50 L/day was decided based on the 'Level 6B' water restrictions posed by the City of Cape Town on the 1st February 2018. The Level 6B water restriction means that the maximum daily water consumption per person is 50 L/day (City of Cape Town 2018). The assumption was that each person produces an equal volume of wastewater as the 50 L/day of water used. The estimated value was however used with caution because there is no proper monitoring in place ensuring that each person uses 50 L/day in the area; also using the 50 L/day of water does not necessarily mean that the same volume of wastewater will be produced by each person. The groundwater recharge due to water supply leakage was estimated using the differences between the volume of water that the City of Cape Town releases to the people (331.06 Mm^3/year) from its storage reservoirs obtained from the city's 2014/2015 water budget presented in Ahjum et al. (2015), and the volume of water that the population within the area receives (304.56 Mm^3/year), with the assumption that the difference represents the volume that is lost in pipeline leaks to the Cape Flats Aquifer. The 2014/2015 water budget was used because it is the most recent water budget for the city available. To estimate naturally occurring recharge and recharge due to urban irrigation return flows, land cover classes were established using the 2017 October Landsat 8 image sourced from the US Geological Survey site and using the unsupervised classification technique in ESRI 10.1 ArcGIS. The land cover classes deduced from the image are presented in Fig. 5a, with the proportion of each class to the total area of the catchment modelled shown in Fig. 5b. The naturally occurring recharge was calculated as 20% of the product of mean annual precipitation (619 mm) for the area, and the total area of the open surfaces within the modelled catchment consisted of golf courses, irrigated areas, and dense and sparsely vegetated areas. The recharge due to urban irrigation return flows was calculated from the principle of best practice associated with the irrigation systems' construction and management protocols, rather than a published theory, because data on the volumes of water used for irrigation in the area are not available. The principle of best practice states that every 1,000 m^2 of land uses 4,000 L of water a day. The recharge was therefore calculated as 20% of the total volume of water used to irrigate the total area of the irrigated surfaces consisting of golf courses and other agricultural lands (lawns and stadiums). The 20% proportion for both the naturally occurring recharge and urban irrigation return flows was decided based on the recharge study done in the Atlantis sand dunes, similar to the Cape Flats Aquifer, in terms of lithological conformation, topography and land cover classes. The estimated recharge volumes from all these components are presented in Fig. 6.

The quantitative estimates of groundwater recharge in the area (Fig. 6) indicate a possible net recharge of 32.66 Mm^3/year, with leakages from the water supply pipes as a major contributor to groundwater recharge in the area. The estimated recharge in this study is higher when compared to the recharge value for the Cape Flats Aquifer reported in Hay et al. (2015). The causes of the larger differences could be a miscalculation in the contributions from different sources, especially recharge due to water supply leakages, resulting in the overestimation of the net recharge in the area. It is therefore noted that a more robust study on groundwater recharge estimation is needed to support the modelling of the aquifer. However, based on the estimates and assumptions used, the study specified recharge as 32.66 Mm^3/year over the entire domain area using MODFLOW Recharge package (RCH) (Winston 2009).

Evapotranspiration (ET_0)

Evapotranspiration was estimated from the Hargreaves and Samani (1985) equation. Figure 7 shows the estimated monthly evapotranspiration rates against the monthly rainfall for the year 2016. The monthly ET_0 pattern shows that the range was 2–7 mm/month; the highest ET_0 values were observed during the period of low flows (September–April), and the lowest during the period of high flows (May–August). The evapotranspiration was specified over the entire domain area as average evapotranspiration using the evapotranspiration package in ModelMuse packages and programmes.

Hydraulic conductivity (K)

The hydraulic conductivity values were estimated based on data from the pumping tests conducted in 2015–2017, using Eq. (1). Pumping test analysis applied the Theis solution to derive transmissivity (T) values, and the aquifer thickness (b) values were obtained with reference to the geological cross-sections of the area by Theron et al. (1992) sourced from the Council for Geosciences in Bellville South Africa. Table 1 shows the estimated hydraulic conductivities of the area based on the drawdown data collected from three boreholes in the area. The hydraulic conductivity values were averaged to assign a homogenous K value in all the active cells within the domain area.

$$T = Kb \tag{1}$$

where T is transmissivity in m^2/d, K is hydraulic conductivity in m/d and b is aquifer thickness in m.

Boundary conditions

The boundary conditions identified in this study are presented in Fig. 8. The no flow boundaries were identified as the catchment boundary from the northern part towards the south through the eastern part of the catchment, and the Malmesbury Formation beneath the Cape Flats Aquifer. The

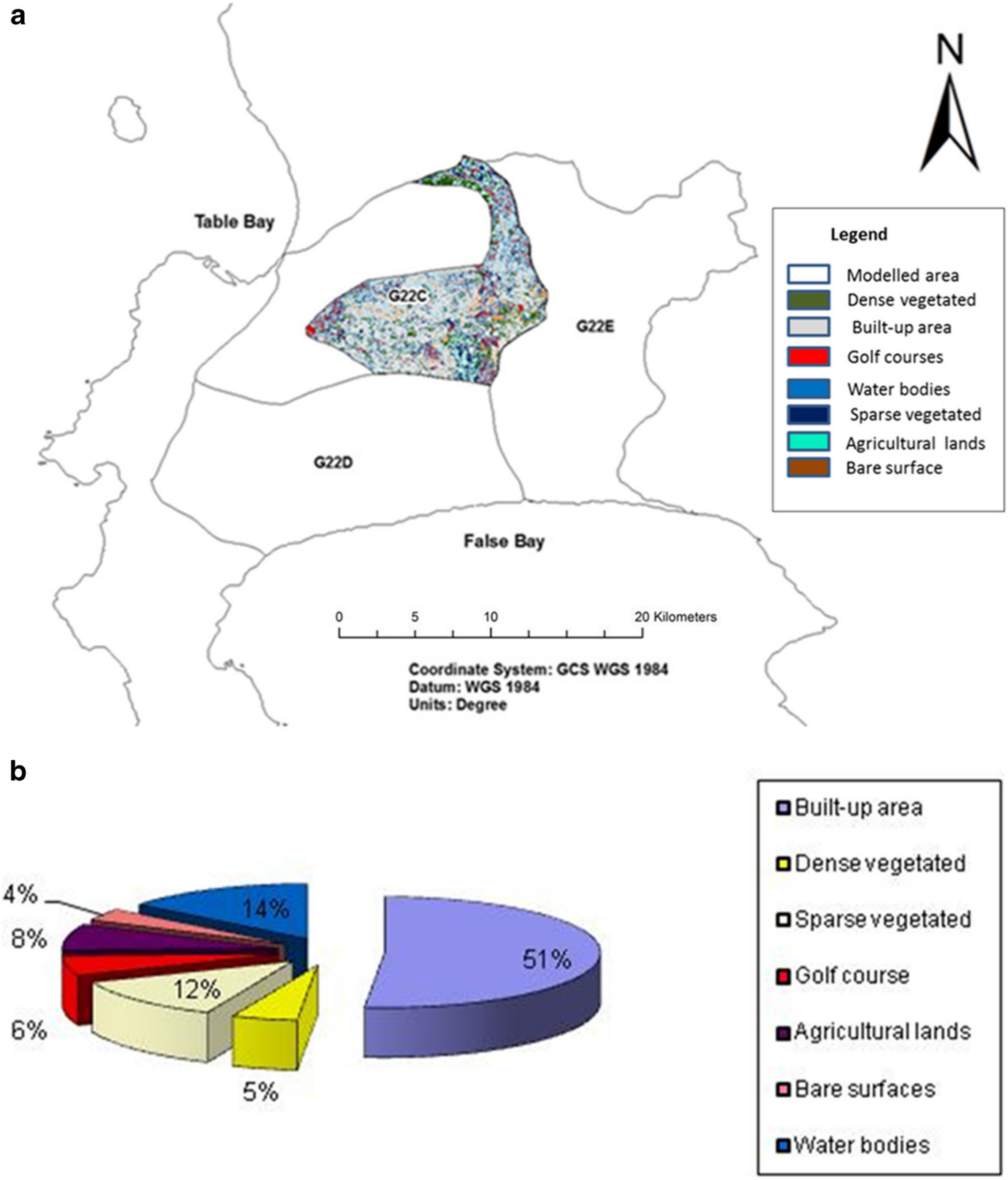


Fig. 5 **a** Land cover classes and **b** the proportion of each class within the modelled area

modelled site covers 17% of the total Cape Flats Aquifer area. These no flow boundaries were specified simply by inactivating the grid cells outside the domain area and activating the cells inside. The head-dependent boundaries were identified as wetlands and rivers. The wetlands were specified using the General-Head Boundary package. The package requires computation of the conductance, which is defined as the degree to which the aquifer and the external source/sink are connected (Winston 2009). Due to the unavailability of conductance data and head stage data for the wetlands, conductance was assigned using the hydraulic properties of the Cape Flats Aquifer and head stages were assigned as groundwater heads measured during the dry season from boreholes closest to these wetlands. The heads used were 52.88 m and 54.74 m measured from boreholes UWC 3a and UWC 4. The two rivers were specified as drains using the MODFLOW Drain package, stagnant water pools within certain sections of the rivers were assumed to be points of depression within the rivers, and conductance was also assigned based on hydraulic properties of the Cape Flats Aquifer.

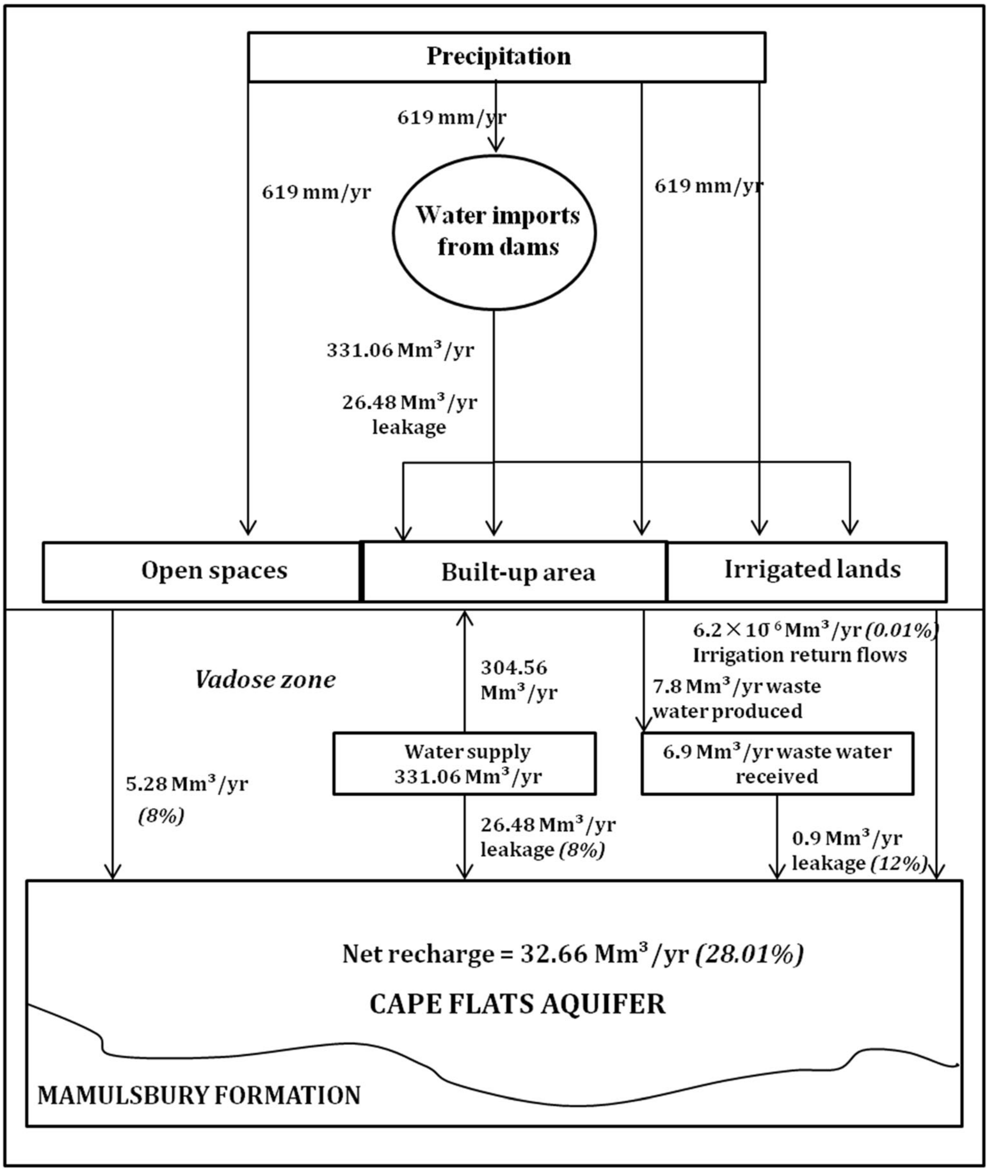


Fig. 6 Estimated groundwater recharge from different components

Model calibration and sensitivity analysis

Calibration

Calibration according to Anderson and Woessner (2002) refers to the process of demonstrating the capability of the model to produce the field measured heads and flows. This is achieved by finding input parameters, stresses or boundary conditions which produce simulated heads or fluxes similar to the observed heads or fluxes. Calibration can be approached in two ways, through forward modelling and inverse problem solution. In this study, forward modelling was used through the conventional trial and error technique, where the recharge was manually adjusted to match the simulated and observed heads. Recharge was the only parameter that was adjusted during the calibration process because it was estimated to be higher than the typical Cape Flats Aquifer recharge estimates presented in Hay et al. (2015). The other parameters, such as hydraulic conductivity and evapotranspiration, were estimated to be within the range of the Cape Flats Aquifer presented in Adelana et al. (2010). The calibrated recharge value was 5.23 Mm^3/year. This value is significantly lower than the initial recharge value presented in the box model (Fig. 6). Justification for the larger difference between the initial and the calibrated recharge values lies with the data used in estimation of the initial recharge components. The current study noted that other groundwater recharge studies on the Cape Flats Aquifer disregarded components like water supply leaks, irrigation return flows and wastewater leaks which also contribute to groundwater recharge in an urban environment

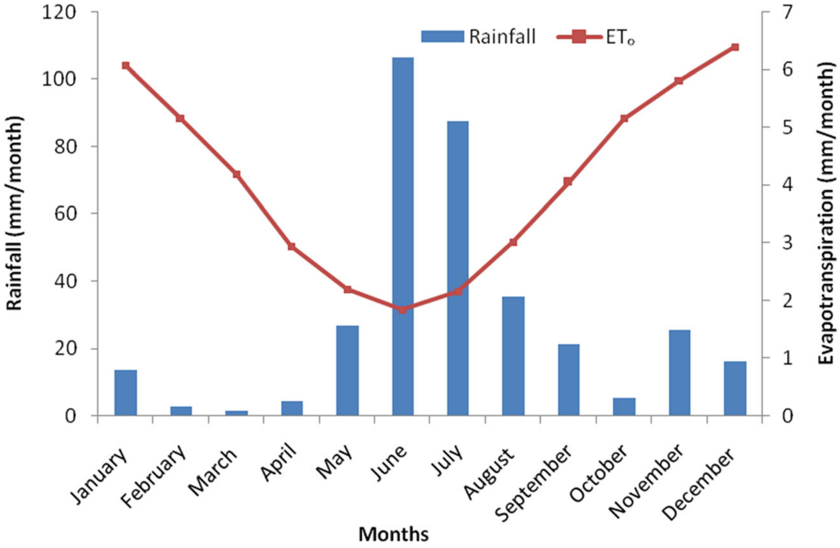


Fig. 7 Monthly evapotranspiration (ET_0) rates against rainfall for the year 2016

(Lerner 2002). Therefore, the initial conceptualisation of the study included these components. However, the estimation of each component relied solely on the assumed measurements rather than the actual measured data. This was due to the unavailability of data for the quantification of these components and thus led to net recharge being biased to higher recharge values. The numerical model calibration assisted in verifying the initial recharge components, and thus proved that the initial recharge value was over estimated. The calibrated model results are presented in Fig. 9.

The results of the calibrated model are presented as a comparison of the simulated and observed heads in Fig. 9. The comparison was done through visual matching of the observed and simulated head contours from five boreholes in the area and the use of the R^2 determinant. The assumption was that the calibration is achieved when there is a good agreement between the simulated and the observed head contours, and there is a R^2 determinant of at least 0.9. The results in Fig. 9 show a good agreement between the simulated and observed groundwater head contours, and a R^2 determinant of 0.988 was observed. This indicates a strong positive relationship between the simulated and the observed heads of the calibrated model thus suggesting that the calibration was achieved.

Table 1 Hydraulic conductivity values of the model domain

Borehole	$K_{\text{March 2015}}$ (m/day)	$K_{\text{September 2015}}$ (m/day)	K_{June2016} (m/day)
Bellville BG46052	0.25	0.37	0.29
UWC 3a	0.36	0.75	0.24
UWC3b	0.37	0.70	0.25

Sensitivity analysis

Sensitivity analysis was performed to understand uncertainty in the calibrated model caused by limitations in the estimates of aquifer parameters and stresses. Groundwater models tend to be sensitive to different model input parameters, and a small change in such parameters will result in larger differences between simulated and observed heads and fluxes (Zhou and Li 2011). In this study, hydraulic conductivity, recharge and general head boundaries were varied by 10, 25 and 50% during successive runs to test the sensitivity of the model to these parameters. A total of 24 runs were simulated by varying the selected parameters within the specified proportions from the calibrated values and the respected root mean square error (RMSE). These parameters were changed uniformly for the entire area and other model parameters. During simulations, when the effect of one parameter was tested, the other parameters were kept to the steady-state calibrated values. The root mean square head change was used to measure the sensitivity of the model to the particular parameter, and the results are presented in Fig. 10.

Results from the sensitivity analysis (Fig. 10) are presented as the root mean square head changes between the simulated and the observed heads. The results indicate that the model is less sensitive to 10 and 25% changes in recharge and hydraulic conductivity values. Root mean square head changes of less than 6 m were observed at 10% variations of both parameters, with head residuals ranging between −4 and 5 m. When the recharge and hydraulic conductivity values were varied by 50%, increases in root mean square head change by up to 8 m were observed, thus indicating that the model is sensitive to 50% variations in these two tested parameters. The variations in general head boundaries demonstrate that the model is sensitive to all the changes in this parameter. The root mean square head changes were all greater than 8 m; however, it

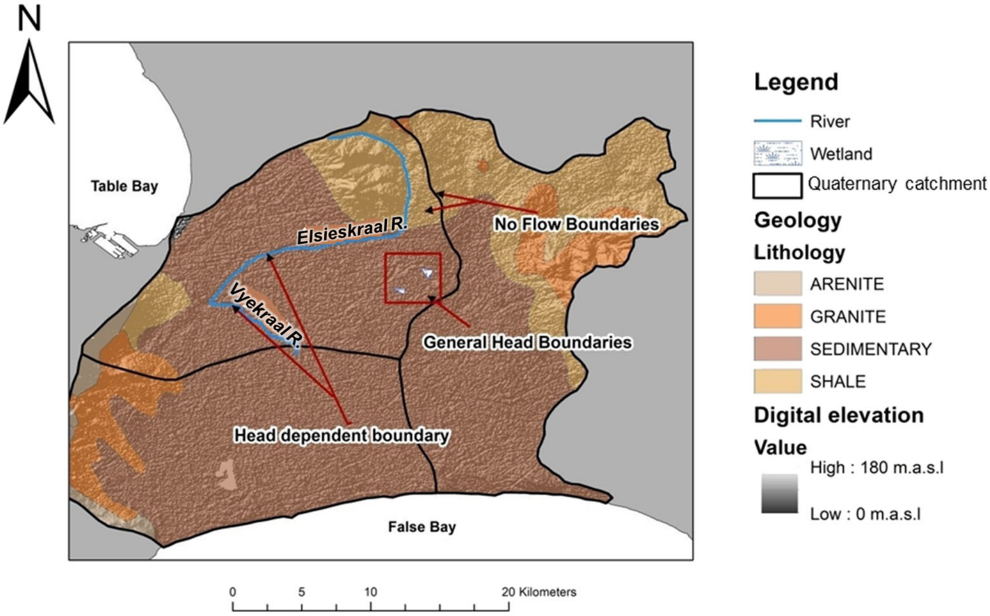


Fig. 8 Boundary conditions for the modelled area

was challenging to establish the areas within the domain area where the model is sensitive, due to the limited number of monitoring points.

Scenarios assessment and analysis results

Table 2 shows the site-specific WSUD scenarios predicted from the numerical model developed for the area. These scenarios were decided based on the regional WSUD feasibility study by Seyler et al. (2016) and Mauck (2017). The chosen scenarios were also related to the suggested methodologies by WSUD principles. The WSUD principles suggested approaches like permeable paving for stormwater attenuation and improvement of aquifer recharge, as well as stormwater flooding minimisation. Furthermore, the use of alternative sources of water, such as grey water reuse and groundwater to minimise the demand for potable water supply, is also suggested, as well as using aquifers for storage of treated effluents and harvested rain water. The results for the predicted scenarios are presented in Tables 3 and 4 as well as Figs. 11 and 12.

Figure 11 shows the results of water level response to varying groundwater recharge scenarios at three selected observation boreholes at UWC. The varying recharge rates were

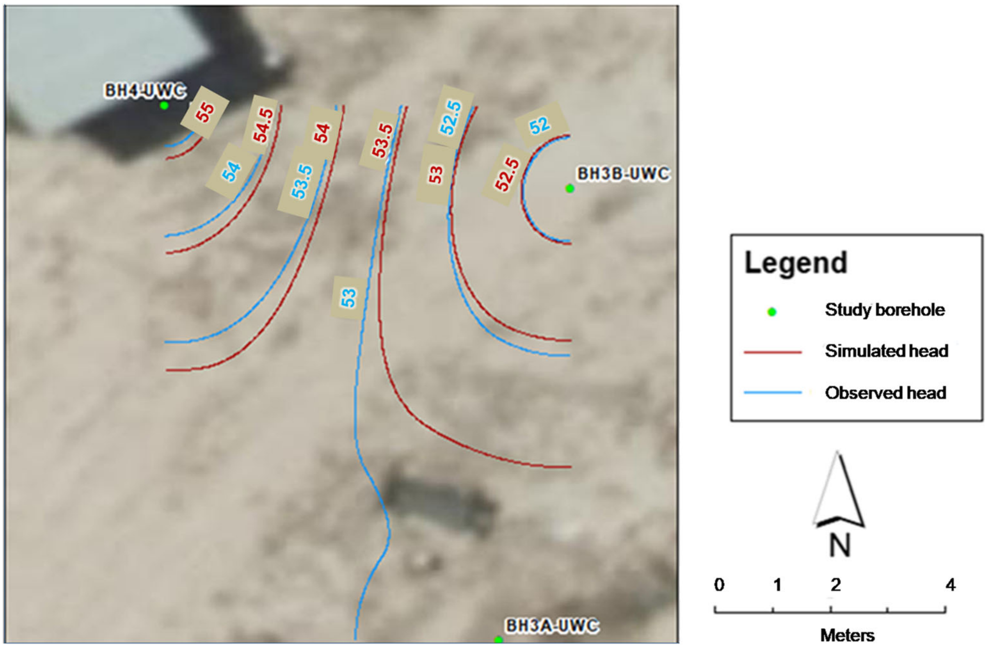


Fig. 9 Comparison between observed and simulated groundwater heads under steady-state calibration

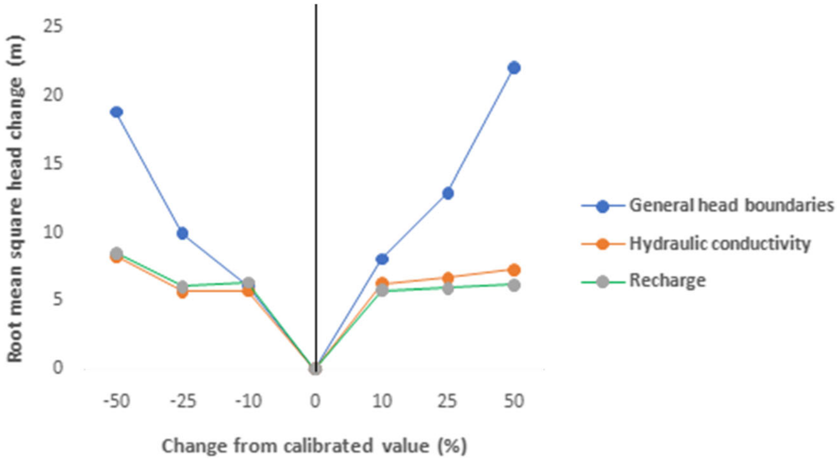


Fig. 10 Sensitivity analysis results

assumed to represent the predicted scenarios in Table 2, about the use of permeable paving at UWC for stormwater attenuation and managed aquifer recharge of treated effluent and stormwater from the university buildings, as suggested by WSUD principles. These results illustrate that the groundwater levels of the Cape Flats Aquifer at UWC are directly proportional to the varying recharge scenarios. A substantial increase in groundwater levels was observed when the recharge rate was increased by 50%, which thus indicates that localised managed aquifer recharge of the treated wastewater effluent from UWC, as well as attenuated stormwater, are likely to significantly increase the water levels within the area. However, recharge may need to be managed to avoid problems associated with shallow water tables during the wet season, as the water table tends to be as shallow as 2 m below the ground level (Adelana et al. 2010). The results also indicate that subsequent pumping of water from the aquifer for flushing toilets and watering lawns and stadiums will need to be implemented during the rainy season as water levels become shallow due to the quick response of the aquifer to recharge from the surface.

Table 3 shows the water budget response to varying recharge scenarios. The results indicate that changes in the water balance components show direct proportionality to the varying recharge scenarios. A notable increase in outflows from ET, drains and head-dependant boundaries was observed at 50% increased recharge rate, and decrease also in outflows from the same water balance components at 50% decreased recharge rate. The results indicate that localised managed aquifer recharge and stormwater attenuation through permeable paving has the potential of increasing outflows and inflows to the system. There is a potential for storing reclaimed wastewater and stormwater in the Cape Flats Aquifer at UWC; however, constant monitoring of groundwater levels and remedial infrastructure are needed to avoid a problem like groundwater flooding.

Figure 12 illustrates the water-level response to variable groundwater abstraction scenarios from four theoretical boreholes placed further down-gradient from the observation boreholes. The scenarios represent the predicted scenarios of groundwater abstraction for irrigating lawn and sports fields and flushing toilets at the university, as presented in Table 2. The results indicate that groundwater levels within the site are inversely proportional to the varying abstraction rates. A notable decline in groundwater levels was observed at an abstraction rate of 2.5 and 5 L/s, by up to 60% from the calibrated model. The results indicate that there is a potential for groundwater abstraction to irrigate sports field and lawns as well as flushing toilets at UWC, thereby reducing the demand for potable water supply and increasing the storage for treated effluent and stormwater attenuation. However, groundwater abstraction should be at a controlled rate to avoid aquifer

Table 2 Predicted scenarios and influence on groundwater recharge

Scenario	Benefits of the groundwater system
Use of permeable paving at UWC for stormwater attenuation	Increase in recharge by up to 50%
Small managed aquifer recharge of the treated effluent from the UWC buildings	Increase in recharge by up to 25%
Groundwater abstraction for irrigating lawns, stadiums and flushing toilets at UWC	Lowering of the water table for stormwater attenuation
Changes in climate (rainfall pattern)	Reduced/increase in groundwater recharge
Retrofitting for stormwater management	Reduced groundwater recharge
Recharging of stormwater to the Cape Flats Aquifer through bio-retention area	Increase in groundwater recharge by up to 50%

Table 3 Water budget response to varying recharge scenarios

Scenario	Water balance component	Inflow (m^3/day)	Outflow (m^3/day)	Change in outflows with respect to the calibrated value	Percentage change with respect to the calibrated value
Calibrated value	Constant heads	0	0	–	–
	ET	0	2,636.93	–	–
	Drains	0	2,894.4	–	–
	Head Dep Bounds	417.66	489.89	–	–
	Recharge	5,611.68	0	–	–
50% recharge increase	Constant heads	0	0	0	–
	ET	0	3,991.68	1,354.75	51.38
	Drains	0	5,659.2	2,764.8	95.52
	Head Dep Bounds	2,177.28	1,002.24	512.35	104.58
	Recharge	8424	0	0	–
25% recharge increase	Constant heads	0	0	0	–
	ET	0	3,352.23	715.3	27.13
	Drains	0	3,438.7	544.3	18.8
	Head Dep Bounds	324	588.4	98.51	20.1
	Recharge	7050	0	0	–
50% recharge decrease	Constant heads	0	0	0	–
	ET	0	1,382.4	−1254.53	−47.56
	Drains	0	1,840.32	−1054.08	−36.42
	Head Dep Bounds	712.8	293.76	−196.13	−40.04
	Recharge	2808	0	0	–

ET evapotranspiration, *Head Dep Bounds* head-dependent boundaries

depletion, whereby the recommended abstraction rate based on this scenario would be 2.5 L/s.

Table 4 shows water balance changes in response to varying groundwater abstraction rates. The varying abstraction scenarios indicate that outflows are inversely proportional to varying abstraction rates. A notable decline in ET, and at drains and head-dependant boundaries, was observed at an abstraction rate of 2.5 and 5 L/s respectively. These results indicate that the abstraction of groundwater is feasible at a managed rate of 2.5 L/s. This would be beneficial to small MAR of the treated effluent and stormwater in terms of the lowering of the water table to increase the aquifer storage. However, the abstraction needs to be monitored to avoid problems like aquifer depletion, as current groundwater abstraction in the vicinity of the site could not be established due to limited data.

Discussion

The most established role of groundwater systems with respect to water-sensitive urban design (WSUD) is storage of the attenuated stormwater, treated wastewater effluent and harvested rain water (Mauck 2017). The use of groundwater systems as storage for attenuated stormwater and treated effluents presents benefits like improved groundwater recharge and minimisation of stormwater flooding. However, the use of groundwater systems for storage of stormwater and wastewater effluents presents risks like groundwater contamination from the untreated stormwater attenuated, excessive increase in groundwater levels, and compromised soils and aquifer structure, e.g. pore clogging resulting in decrease in the hydraulic conductivity (Armitage et al. 2014). The results from the predicted scenarios indicate that there is a potential for application of WSUD on the Cape Flats Aquifer at local scale, with possibilities of stormwater attenuation through the use of permeable paving, thus improving groundwater recharge to the aquifer by up to 50%. Furthermore, groundwater abstractions up to 2.5 L/s are feasible for flushing of toilets at the university buildings and irrigation of stadiums and laws, thus reducing the demand for potable water supply as stipulated by WSUD principles. In addition, it would be possible to increase aquifer storage of treated wastewater effluent and harvested rainwater. The findings of this study corroborate the findings of Mauck (2017) and Seyler et al. (2016) on the regional flow analysis on Cape Flats Aquifer suggesting that WSUD is feasible on the system at all scales. However, shallow groundwater levels during the wet season limit the potential of the storage of treated wastewater effluent and harvested rain water. The development of water-sensitive

Table 4 Water budget response to varying groundwater abstraction rates

Scenario	Water balance component	Inflow (m^3/day)	Outflow (m^3/day)	Change in outflows with respect to 1 L/s abstraction	Percentage change with respect to 1 L/s
Abstraction at 1 L/s	Constant heads	0	0	–	–
	ET	0	1,252.80	–	–
	Drains	0	1,753.92	–	–
	Wells	0	3,456	–	–
	Head Dep Bounds	783.65	236.74	–	–
	Recharge	2,808	0	–	–
Abstraction at 2.5 L/s	Constant heads	0	0	0	–
	ET	0	1,080	−172.8	−13.8
	Drains	0	1,615.68	−138.24	−7.9
	Wells	0	864	−2592	−75
	Head Dep Bounds	907.20	158.98	−77.76	−32.85
	Recharge	2,808	0	0	–
Abstraction at 5 L/s	Constant heads	0	0	0	–
	ET	0	832.03	−420.77	−33.58
	Drains	0	1,434.24	−319.68	−18.23
	Wells	0	1728	−1728	−98.52
	Head Dep Bounds	1,296	74.48	−162.26	−68.53
	Recharge	2,808	0	0	0

ET evapotranspiration, *Head Dep Bounds* head-dependent boundaries

cities requires the integration of water resources during the planning and designing phase of such cities (Lottering et al. 2015). This ensures the protection of water resources in terms of the quality and quantity during the functioning of the city. The results from this report inform the planning phase of water-sensitive cities in terms of how groundwater systems can be used in managing urban water systems such as stormwater and wastewater. In addition, the study also proved the benefits—e.g. storage and recovery associated with the use of groundwater systems—on WSUD implementation.

Conclusions and recommendations

The developed conceptual and numerical flow model facilitated a better understanding of the hydrogeology of the Cape Flats Aquifer at a site-specific scale. Furthermore, the scenarios predicted from the calibrated model proved the feasibility of applying water-sensitive urban design (WSUD) on the Cape Flats Aquifer at a local scale. The initial intent of the study was to assess the feasibility of applying WSUD on the Cape Flats Aquifer at a local scale and thus contribute

Fig. 11 Water-level response to varying recharge scenarios

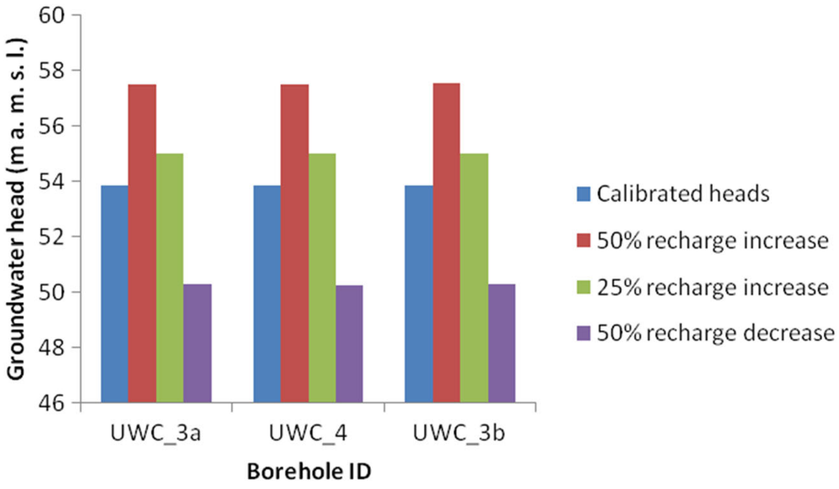
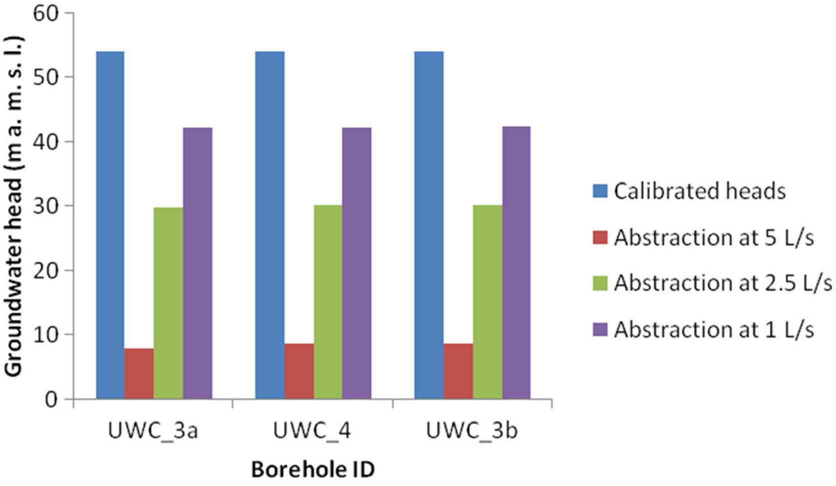


Fig. 12 Water-level response to varying abstraction rates



towards the planning of the water-sensitive cities of the future. The results of the predicted scenarios demonstrate that WSUD methodologies like managed aquifer recharge (MAR) are feasible on the Cape Flats Aquifer through the conventional use of permeable paving for stormwater attenuation to improve groundwater recharge to the aquifer, and to minimise stormwater flooding. The predicted scenarios also indicated that abstraction of groundwater for irrigation of lawns and flushing of toilets is possible, and this can reduce the demand for potable water supply as suggested by WSUD principles, concurrently lowering the water table for increased storage of treated wastewater and MAR implementation. The shallow groundwater levels during the wet season limit the potential for application of MAR and storage of treated wastewater in the aquifer. These findings will provide an important reference to the ongoing debate about the Cape Town water crisis and to similar environments where WSUD is considered. It is recommended that the transient state condition be simulated for the area to assess the WSUD impacts and benefits over time. In addition, accurate quantification of all the components of groundwater recharge at site-specific scale are needed to better inform the WSUD implementation; furthermore, additional groundwater monitoring points are recommended to improve the ongoing model calibration.

Acknowledgements The authors would like to express gratitude to the anonymous reviewers for their valuable input to this report. The authors would also like to thank the collaborative partners from the University of Cape Town (UCT) Department of Civil Engineering, Council for Scientific and Industrial Research (CSIR), as well as Department of Water and Sanitation (DWS), for project formulation and assistance with secondary data. Finally, the authors would like to thank Dr. Richard Winston for ModelMuse software provision and introduction, Dr. Sumaya Israel, Ms. Zanele Ntshidi, and Mr. Bhongolethu Mtengwana for their input.

Funding information This project was funded by the Water Research Commission (WRC) of South Africa.

References

Adelana S (2010) Groundwater resource evaluation and protection in the Cape Flats, South Africa. PhD Thesis, University of the Western Cape, Cape Town, South Africa

Adelana S, Xu Y, Vrbka P (2010) A conceptual model for the development and management of cape flats aquifer. Water SA 36(4)

Ahjum F, Hughes A, Fant C (2015) Climate, land, energy and water strategies in the City of Cape Town. Report, University of Cape Town, Cape Town, South Africa

Anderson MP, Woessner WW (2002) Applied groundwater modelling: simulation of flow and advective transport. Academic, San Diego

Anderson MP, Woessner WW, Hunt RJ (2015) Applied groundwater modelling: simulation of flow and advective transport, 2nd edn. Academic, San Diego

Armitage N, Fisher-Jeffes L, Carden K, Winter K, Naidoo V, Spiegel A, Mauck B, Coulson D (2014) Water sensitive urban design (WSUD) for South Africa: framework and guidelines. WRC Report no. TT 588/14, Water Research Commission, Pretoria, South Africa

Carden K, Armitage N, Fisher-Jeffes L, Winter K, Mauck B, Sanya T, Bhika P, Mallett G, Kanyerere T, Gxokwe S (2017) A feasibility study to evaluate the potential of using water sensitive design to strengthen planning for water sensitive cities of the future. WRC report no. K5/2412, Water Research Commission, Pretoria, South Africa

City of Cape Town (2007) Long term water conservation and water demand management strategy. WC/WDM Report (April 07), City of Cape Town, Cape Town, South Africa

City of Cape Town (2018) Water outlook 2018 report. https://resource.capetown.gov.za/documentcentre/Documents/City%20research%20reports%20and%20review/Water%20Outlook%202018%20-%20Summary.pdf. Accessed 25 June 2018

DWAF (2008) The assessment of water availability in the Berg catchment (WMA 19) by means of water resource related models: groundwater model report, vol 5—Cape Flats Aquifer Model. Report no. P WMA 19/000/00/0408, Department of Water Affairs and Forestry, Pretoria, South Aftrica

Fisher-Jaffes L, Carden K, Armitage N (2017) Water sensitive urban design frame work for South Africa. University of the Free State. Journals.ufs.ac.za/index.php/trp/article/view/3320. Accessed 5 November 2019

Gxokwe S (2018) Conceptualization of urban hydrogeology within the context of water sensitive urban design: case study of the Cape Flats Aquifer. MSc Thesis, University of the Western Cape, Cape Town, South Africa

Hargreaves GH, Samani ZA (1985) Reference crop evapotranspiration from temperature. Appl Eng Agric 1(2):96–99

Hartnady C, Rogers J (1990) The scenery and geology of the Cape Peninsular guidebook. Geocongress '90 Geological Society South Africa, Cape Town, South Africa, July 1990

Hay R et al (2015) Cape Flats Aquifer and opportunities to change. https://www.imesa.org.za/wp-content/uploads/2015/11/Paper-16. Accessed 05 November 2019

Lerner DN (2002) Identifying and quantifying urban recharge: review. Hydrogeol J 10:143–152

Lottering N, du Plessis D, Donaldson R (2015) Coping with drought: the experience of water sensitive urban design in the George municipality. Water SA 41(1):1–7

Maclear LGA (1995) Cape Town needs groundwater: a note on the potential of the Cape Flats Aquifer unit to supply groundwater for domestic use in the Cape Town Metropolitan area, Cape Town. Geohydrology Directorate, Department of Water Affairs and Forestry report no. Gh3868, DWAF, Pretoria, South Africa

Mauck B (2017) The capacity of the Cape Flats Aquifer and its role in water sensitive urban design. PhD Thesis, University of Cape Town, Cape Town, South Africa

Meerkotter M (2012) Sources of heavy metals in vegetables in Cape Town, and possible methods of remediation. PhD Thesis, University of the Western Cape, Cape Town, South Africa

Rohr HE (2012) Water sensitive planning: an integrated approach towards sustainable urban water systems planning in South Africa. Masters Thesis, University of North West, Potchefstroom, South Africa

Saayman IC, Adams S (2002) The use of garden boreholes in Cape Town, South Africa: lessons learnt from Perth, Western Australia. Phys Chem Earth 27(11–22):961–967

Scheepers R, Schoch AE (2006) The Cape Granite suite. In: Johnson MR, Anhaeusser CR, Thomas RJ (ed) The geology of South Africa, 1st edn. CTP, Cape Town, South Africa, pp 421–432

Seyler H, Bollaert M, Witthüser K (2016) Regional water sensitive design scenario planning for Cape Town using urban geohydrology model. WRC report no. TT 708/16, Water Research Commission, Pretoria, South Africa

Stats SA (Statistics South Africa) (2011) Statistics by place, population census, census 2011, Western Cape. http://www.statssa.gov.za/?page_id=964. Accessed 4 January 2018

Theron JN, Gesse PG, Siegfried HP, Rogers J (1992) The geology of the Cape Town area. Explanation on sheet 3318, Geological Survey, South Africa, Johannesburg, South Africa, 140 pp

Tredoux G, Ross W, Gerber A (1980) The potential of the cape flats aquifer for the storage and abstraction of reclaimed effluents. Zeitshr dt geol Gessell 131(2):1–25

USGS (2019) EarthExplore. https://earthexplorer.usgs.gov. Accessed 26 May 2019

Vandoolaeghe M (1990) The Cape Flats Aquifer. Directorate Geohydrology technical report no. Gh3687, DWA, Pretoria, South Africa

Ward S, Lundy L, Shaffer P, Wong T, Ashley R, Arthur S, Armitage NP, Walker L, Brown R, Deletic A Buttler D (2012) Water sensitive urban design in the city of the future. http://hdl.handle.net/10036/4288. Accessed 5 November 2019

Winston RB (2009) ModelMuse: a graphical user interface for MODFLOW: 2005 and PHAST. US Geol Surv Tech Methods 6-A29. http//pubs.usgs.gov/tm/tm6A2. Accessed 1 May 2019

Wong TFH (2006) Water sensitive urban design-journey thus far. Australasian J Water Resour 10(3):213–232

Xu Y, Beekman HE (2003) Groundwater recharge estimation in Southern Africa. UNESCO IHP, Paris

Yang N, Soraya M (2013) Water by design: a shifting paradigm in urban built environment. Proceedings of the SB 13 Singapore—Realising Sustainability in the Tropics, Singapore, 2013

Zhou Y, Li W (2011) A review of regional groundwater flow modelling. Geosci Front 2(2):205–214