Water SA 50(4) 365–383 / Oct 2024
https://doi.org/10.17159/wsa/2024.v50.i4.4015

Research paper

Improving the water quality in the Zandvlei Estuary, Cape Town, by retrofitting sustainable drainage systems in the Diep River catchment

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The Zandvlei Estuary is the only functioning estuary along the False Bay coastline of Cape Town and is therefore of extreme local ecological importance. The most significant problems are eutrophication and siltation caused by the increased total inorganic nitrogen (TIN) and soluble ready phosphorus (SRP) levels due to urban development and the associated increased impervious surface area in the catchment that drains into it. In South Africa, stormwater drainage systems conventionally channel everything they collect into receiving water bodies without significant treatment. Sustainable drainage systems (SuDS) provide an alternative approach to managing stormwater runoff. They are designed to manage both stormwater quality and quantity while potentially improving biodiversity and amenity. This project modelled the potential improvement in the quality of the water entering Zandvlei Estuary resulting from the implementation of selected SuDS control measures in Zandvlei's Diep River catchment using the software program, PCSWMM. SRP, TIN, total phosphorus (TP) and total suspended solids (TSS) were selected as pollutant indicators. Treatment trains that included a large, constructed wetland at the bottom of the catchment will likely provide the greatest improvements to the water quality entering Zandvlei – potentially reducing SRP, TIN, TP and TSS by approximately 59%, 53%, 53%, and 66%, respectively – as well as potentially reducing the runoff by 48%.

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DATES
Received: 30 August 2022
Accepted: 11 October 2024

KEYWORDS
sustainable drainage systems
stormwater
eutrophication
PCSWMM
treatment train
wetlands

INTRODUCTION

The Zandvlei Estuary, located in the Southern Suburbs of Cape Town, South Africa, provides 80% of the estuarine area in False Bay, making it by far the largest of the eight estuaries found along the False Bay coastline (Brown and Magoba, 2009). It is bordered by the suburbs of Lakeside, Muizenberg, Marina da Gama and Steenberg. Its three main catchments – Diep, Keysers and Westlake (Fig. 1) – support multiple land uses with the Diep River catchment being the most urbanised, including commercial and industrial zones (Coastal & Environmental Consulting, 2010).

Litter, hydrocarbons, heavy metals, excess nutrients, and sediments associated with urban development have been allowed to flow directly into the estuary. As the degree of urbanisation has increased, so too have the loads received by the estuary, resulting in eutrophication, loss of habitat, and excess sedimentation to the detriment of its functionality (Thornton et al., 1995). *Potamogeton pectinatus*, commonly known as pondweed, and the accompanying epiphytic algae, *Cladophora/ Enteromorpha* spp., are commonly observed. The National Biodiversity Assessment (Van Niekerk and Turpie, 2012) assigned Zandvlei a 'D' Present Ecological State rating in 2011, which was confirmed in 2018 (Van Niekerk et al., 2018). Meantime, Zandvlei Estuary has also been given an 'Important' Biodiversity Importance Rating with recommendations that it be re-established to a more functional state. However, the enormous impact of urban development makes this challenging (Thornton et al., 1995).

In South Africa, most stormwater drainage systems contribute to the physical degradation and ecological destruction of rivers and receiving water bodies through a singular focus on removing stormwater runoff as quickly as possible through concrete pipes and channels with little to no regard for the runoff quality. Pollutants and contaminants are swept from impermeable surfaces such as roofs, roads, and parking areas and deposited into downstream receiving water bodies without significant intervention to remove harmful substances. Nutrients are washed from fields and gardens. Raised flood peaks cause erosion and subsequent deposition (Armitage et al., 2013).

Sustainable drainage systems (SuDS) provide a different approach to stormwater drainage. They are designed to manage both stormwater quality and quantity while potentially improving biodiversity and amenity (Armitage et al., 2013). There is a growing awareness of their potential in South Africa (Nyawo and Tanyimboh, 2018). This project thus investigated how selected SuDS treatment trains may improve Zandvlei Estuary's water quality through the development and use of a coupled hydraulic/water quality model in PCSWMM – a customised version of the freely available EPA SWMM software (CHI, 2020).

METHOD

Several stormwater modelling software packages were investigated and PCSWMM (CHI, 2020) was selected based on its availability, functionality and applicability, and to maintain continuity with similar investigations elsewhere. The research framework is presented in Fig. 2.

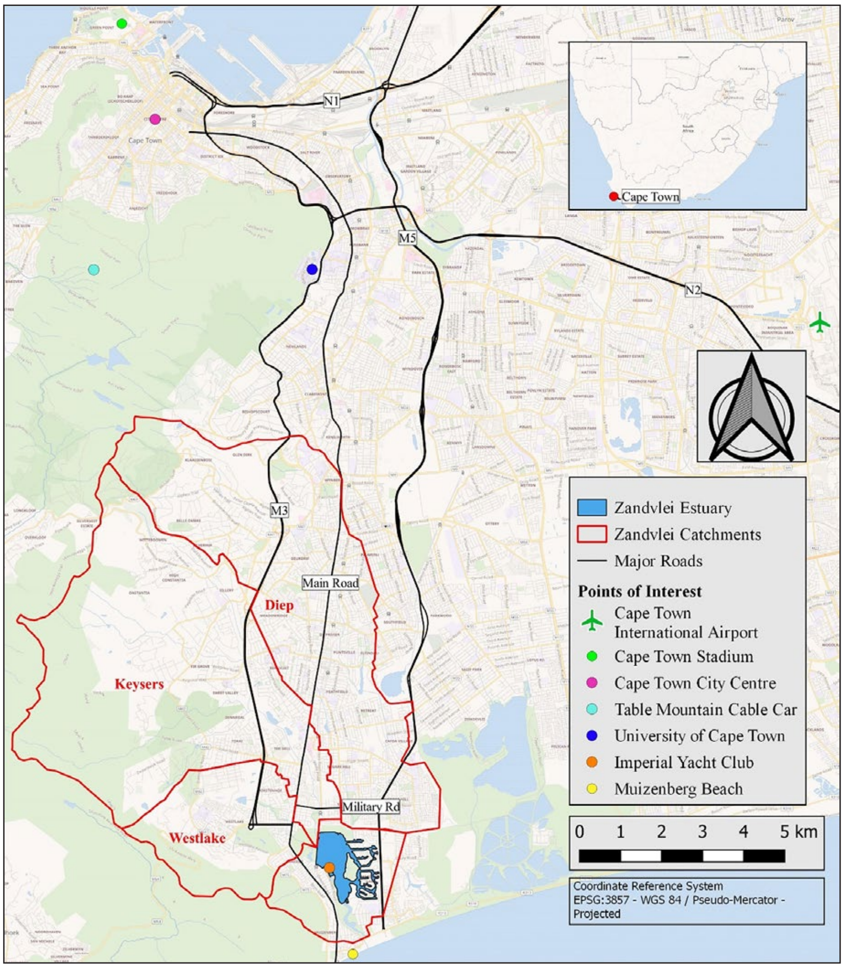

Figure 1. Zandvlei Estuary locality map showing principal catchments – adapted from Wikimedia Maps (Wikimedia, 2021)

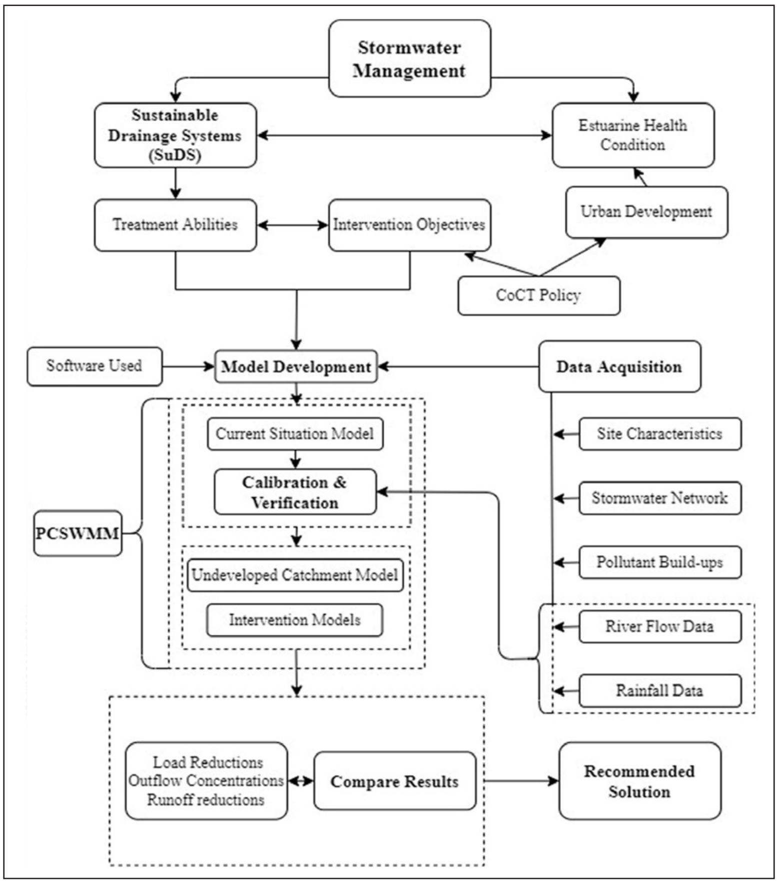

Figure 2. Research framework

The following steps were followed:

- A coupled hydraulic/hydrological model was set up to represent the Diep catchment in its current state. The principal stormwater conveyance network was based on shapefiles obtained from the City of Cape Town (CCT) that described the open watercourses, stormwater pipes, manholes and catchpits.
- A digital elevation model (DEM) from the UCT Geographic Information Systems (GIS) Unit was used to model surface elevations and delineate the Diep catchment into sub-catchments. Various parameters such as land use, soil types and infiltration and runoff properties were assigned to each sub-catchment.
- Five rain gauges were linked to the PCSWMM model (Fig. 3), each with a unique time series. The rainfall records were assessed to ensure they met various requirements pertaining to record duration, data consistency, and data reliability. All records suitable for use in the model were measured at daily intervals and had to be disaggregated to 15-min intervals.
- The model was calibrated and verified using observed data from CCT flow gauges. The final calibrated and verified model included 3 stormwater bodies, 291 junctions, 294 channels (open watercourses, conduits, and pipes), 5 rain gauges, 229 sub-catchments and a single outfall at the end of the stormwater conveyance network (Fig. 3).
- A water quality model was developed to simulate 4 stormwater constituent indicators: soluble ready phosphorus (SRP), total inorganic nitrogen (TIN), total phosphorus (TP), and total suspended solids (TSS). SRP and TIN were modelled as they are the primary causes of eutrophication in water bodies (DWAF, 1996), while TP and TSS were included as they are good indicators of pollution and the CCT requires their loads to be reduced when new SuDS developments are implemented (CCT, 2009). The indicators were simulated using event mean concentrations (EMC) that are widely used for modelling stormwater constituents. Published data were used to provide preliminary EMC values which were then adjusted using water quality data from the CCT for the Diep catchment.
- The calibrated and verified hydraulic and water quality model that broadly represented the Diep catchment in its current state was then used as the baseline for:
    - A pre-development model scenario that was created to give an indication of the situation before urban development began.
    - Five SuDS scenarios that were created to test various treatment train designs.

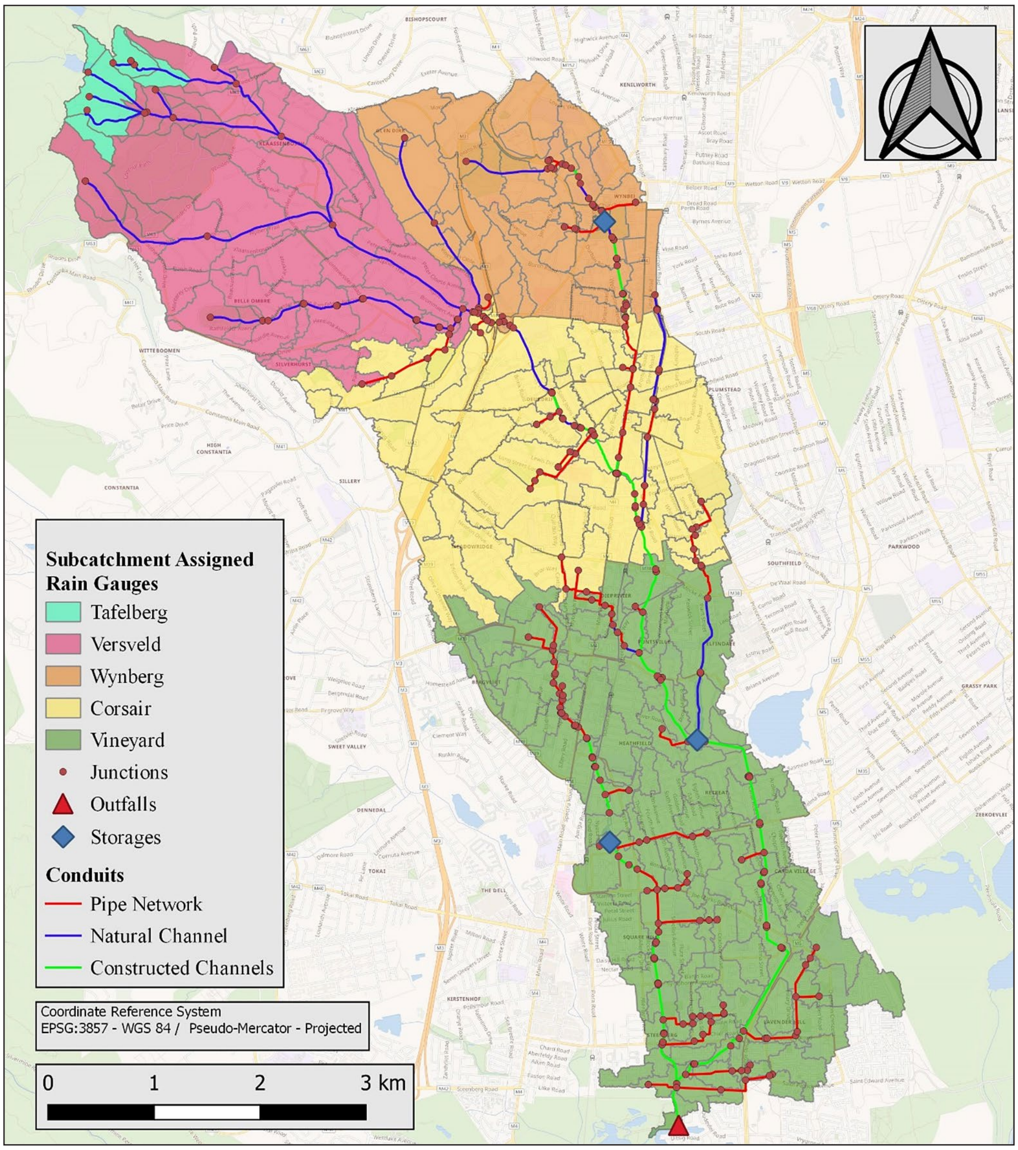

Figure 3. Model network showing rain gauge sub-catchments, conduits, storages, and outfall – adapted from Wikimedia Maps (Wikimedia, 2021)

Constructing the model

Land-use and drainage properties

Land use played a critical role in the development of the hydrological model as it directly impacts runoff volumes, runoff rates, and indicator build-up and wash-off throughout the catchment.

The CCT (2018) provided a GIS shapefile of the land use in the city and its surrounding areas. Some land uses had to be corrected, and duplicate entries removed. The land uses were verified through site visits and satellite imagery (Fig. 4 and Table 1).

The impervious percentage of an area affects the volume and speed of surface runoff with more impervious surfaces generally resulting in larger runoff volumes and flow rates. (Li et al., 2021). Brabec et al. (2002) reported on impervious surface percentages from several literature sources, and these values were then refined by overlaying the land-use zones on satellite imagery of the Diep catchment in QGIS (QGIS, 2022) and estimating impervious percentages.

PCSWMM calculates the average velocity of overland flow using the Manning Equation. A Manning's roughness coefficient, n, was determined for both the pervious and impervious sections of each land use.

A CCT (2018) GIS shapefile provided the upper soil types for the entire city, and this was used to identify the dominant soils within the Diep catchment, which are sand, loam, and sandy loam. The Green-Ampt infiltration method was used for this research as the soil parameters required for this method are widely available in literature.

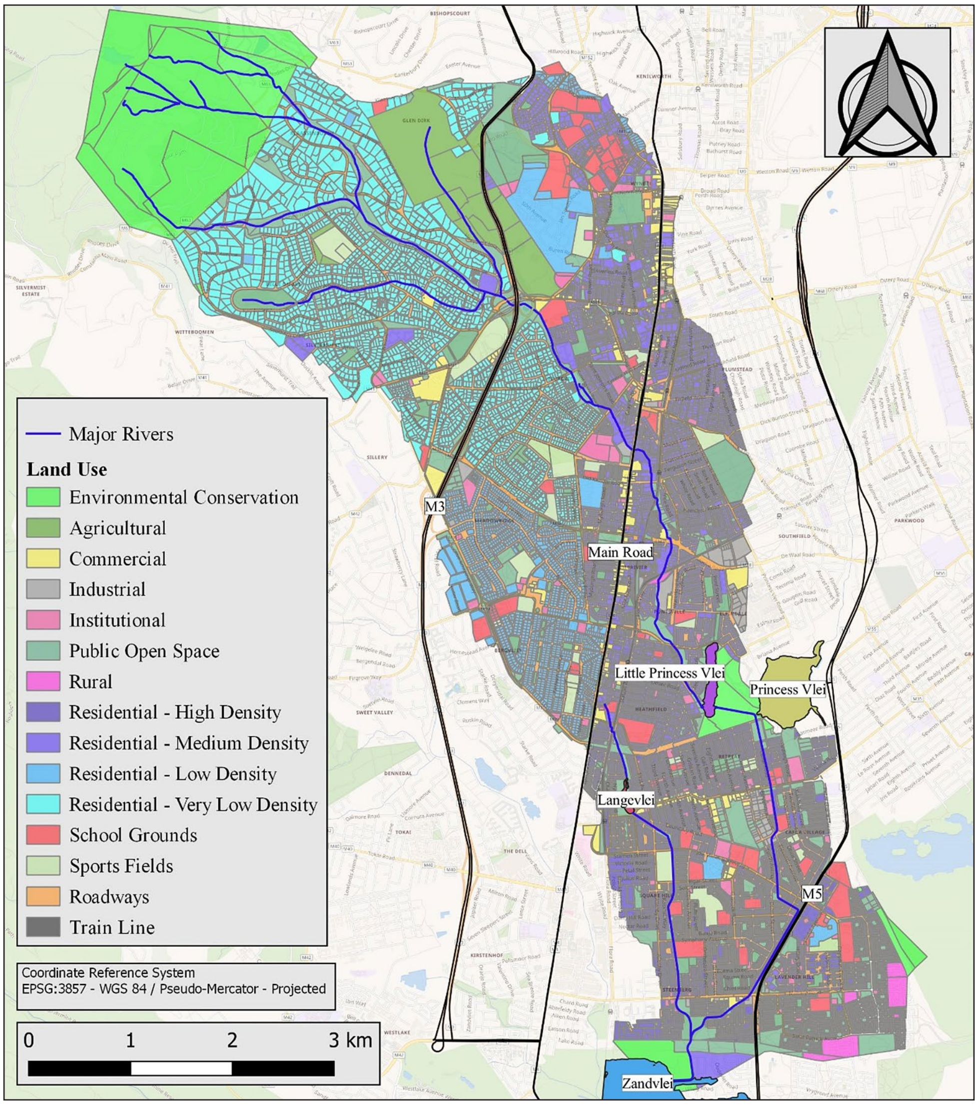

Figure 4. Adjusted land use map – adapted from Wikimedia Maps (Wikimedia, 2021)

Table 1. Land-use categories used in this research

Land uses		
Agricultural	Public open space	Rural
Commercial	Residential – high density	School grounds
Environmental conservation	Residential – medium density	Sports fields
Industrial	Residential – low density	Roadways
Institutional	Residential – very low density	Train line

Streamflow data

Continuous flow data were used to calibrate the hydrological model. The CCT has several streamflow monitoring stations throughout the city, three of which are located within the Diep catchment (Fig. 5): DIEP05CS (Doordrift Road), LPVL05AS (Little Princess Vlei) and WYNB05BS (Maynardville Park). However, only DIEP05CS provided reliable data – and then only from the middle of 2013. Sadly, this is situated in the upper reaches of the catchment area and thus could only be used to calibrate those portions of the catchment.

The CCT streamflow sensors measure streamflow as water depth (m). The depth readings had to be converted to flow rates (m^3/s) for the calibration process. This was achieved using a rating curve devised by Rohrer (2017) based on a calibration table received from the CCT.

Rainfall data

Cape Town has a Mediterranean climate and experiences mild, wet winters and warm, dry summers. However, due to the mountain ranges in and to the east of the city, there are numerous micro-climates that cause significant areal variation in rainfall (World Weather Online, 2021). The Diep catchment, located at the foot of the Peninsula Mountain Chain experiences mean annual precipitations ranging from 800 to 1 400 mm/year. In a bid to capture this variation, 21 rainfall records for the catchment were collected from the CCT, South African Weather Service, Department of Water and Sanitation (DWS), UCT's Climate System Analysis Group, and private citizens. The 21 records were then checked for duration, consistency, and data reliability. Mitchell et al. (2008) recommend that rainfall time series should ideally have a minimum duration of 10 years if they are to be used in a continuous stormwater system simulation, as this allows the capture of both intra- and inter-annual variation. Those records with substantially less than the recommended 10 years, with large data gaps or unreliable data, were thus excluded – leaving 12 records. A suitable timeframe for the hydrological model simulations was then determined by searching for the period exceeding 10 years that encompassed the largest number of rainfall station records. 16 January 2003 – 6 December 2015 was chosen as it was covered by the maximum number of 5 stations (Fig. 5).

The modelling time-step was also an important consideration. Daily time-step intervals significantly underestimate stormwater runoff volumes (Coombes and Barry, 2007). The ideal time-step for continuous rainfall model simulations is often considered to be 5 min to account for the response time of small sub-catchments. However, given the relatively large sub-catchment areas, the lack of sufficient data sets with 5-min intervals, and the limited disaggregation abilities of PCSWMM, 15-min time-steps were deemed to be a reasonable compromise. The five selected rainfall gauges all recorded at daily intervals and the data thus had to be disaggregated to 15-min intervals.

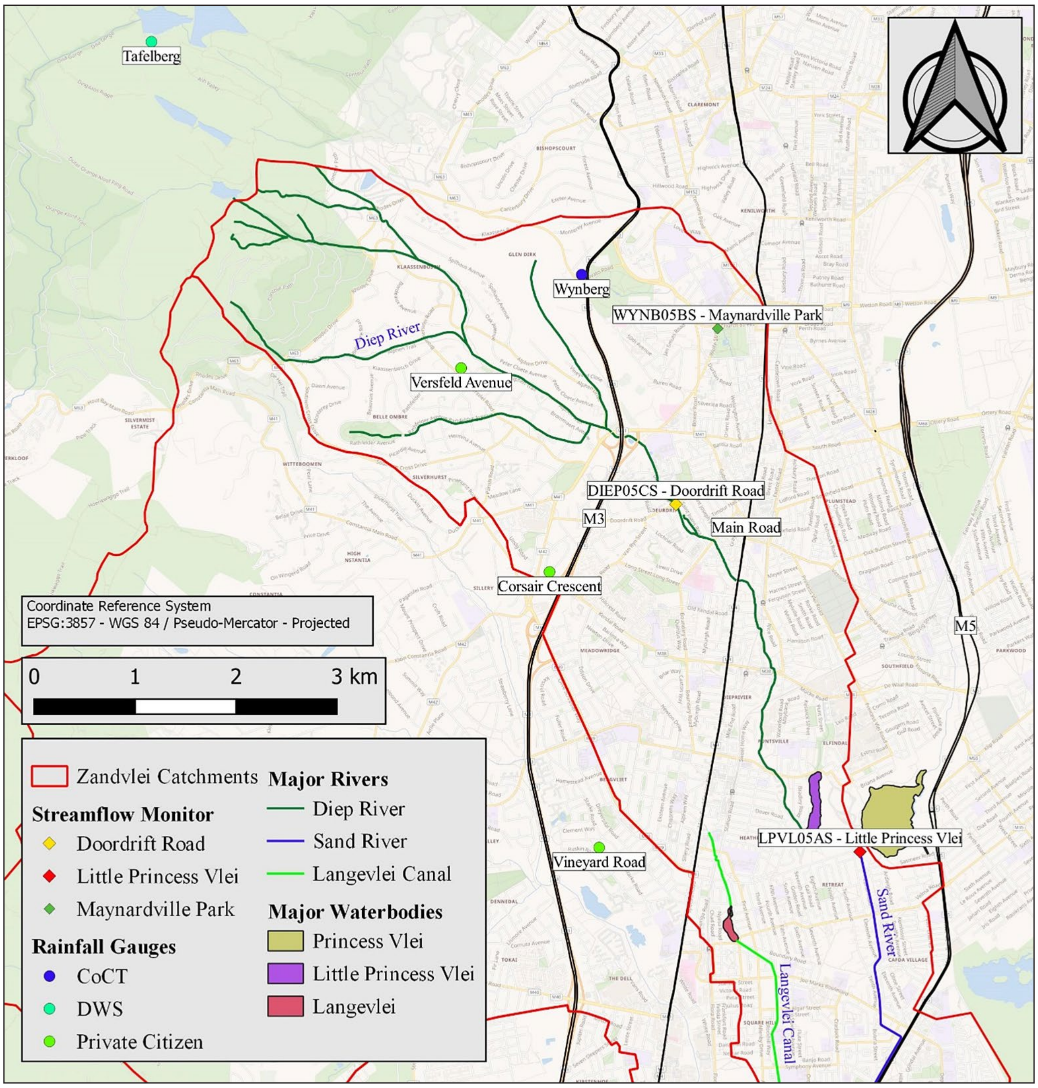

Figure 5. Streamflow monitors and rainfall gauges – adapted from Wikimedia Maps (Wikimedia, 2021)

The disaggregation process consisted of 2 steps. Firstly, NetSTORM was used to transform the rainfall records from daily to hourly intervals using rainfall data with hourly or sub-hourly interval data from nearby stations. Secondly, PCSWMM was used to disaggregate the hourly data into 15-min data. The disaggregation process is based on sampling event distributions from nearby high-resolution rainfall records within the same climatic region. While the disaggregation process cannot recreate the actual rainfall events it generates stochastic rainfall data with the same underlying statistics. No sensitivity analysis was conducted. The rain gauge data were assigned to 5 separate sub-catchments according to their proximity (Fig. 3).

Sub-catchment delineation and development

Sub-catchments provide the base computational unit for the hydrological processes in PCSWMM with each having a single outlet point determined by their topography (Rossman, 2015). PCSWMM offers several tools to aid in model development. The Watershed Delineation tool was used to delineate the entire catchment into sub-catchments using a 1 x 1 m DEM developed by the UCT GIS Unit using light detection and ranging (LiDAR) data obtained from the CCT. Small errors that might have been introduced into the model resulting from the automated delineation process not being able to identify local deviations in surface level were accounted for during the calibration and verification processes.

PCSWMM's Area Weighting tool was used to create weighted averages for runoff and infiltration properties for each sub-catchment based on the land uses and soil types present within the sub-catchment. Each sub-catchment was defined in terms of 3 separate subareas (pervious, impervious, and impervious with no depression storage) that, by default, are drained independently by the sub-catchment outlet. PCSWMM allows users the option of routing a percentage of the runoff to a separate pervious subarea to model potential infiltration. The sub-catchment outlet then drains any surplus runoff. This approach was used for the agricultural, public open space, environmental conservation, and sports field land uses.

Stormwater conveyance network

The Diep catchment stormwater conveyance network (Fig. 3) comprises natural channels, closed conduits, and open constructed channels. It was initially modelled using the GIS shapefiles from the CCT open data portal (CCT, 2018) but, given the large extent of the study site and the absence of detailed data on the smaller diameter conduits, it was then decided to exclude closed conduits with a diameter of 675 mm or less. Sub-catchments that would have been drained by the removed conduits had their outlets assigned to the points where they would have connected to included conduits (in Fig. 3 these sub-catchments do not appear to be connected to the system as the removed conduits are not indicated). Inaccuracies introduced by this approach were accounted for through the calibration and verification of the model.

Many larger conduits were missing diameter, invert, and/or slope data. These were estimated using standard design procedures such as those found in the *Neighbourhood Planning and Design Guide* (CSIR, 2019) on the assumption that this is likely how they were designed.

The open watercourse shapefile includes all the natural and altered waterways interconnecting the conveyance network. Natural channel sections were incorporated into the model using the DEM and PCSWMM's Transect Creator tool. Constructed channels with regular sections were measured on site.

Three existing large stormwater ponds were included in the model: Little Princess Vlei, Langevlei, and the Maynardville Park Pond.

Calibration and validation

Calibration and validation of the model were undertaken to reduce the uncertainty of crucial estimated parameters within the model (James, 2005). PCSWMM's Sensitivity Radio Tuning Calibration (SRTC) tool was utilised to calibrate the model. The parameters calibrated included: the sub-catchment properties, the Manning's coefficients, the depression storage depths, the percentage of impervious areas with no depression storage, the percentage of runoff routed to pervious areas, and the Green and Ampt parameters. The sub-catchment parameters were a particular focus of the calibration process as they significantly impacted the model output, but published data were initially used for most as they could not be measured on site.

PCSWMM calibrates and validates models on storm events: 26 storm events were identified from the observed rainfall data. They were split roughly 2:1, with 17 events used to calibrate the model and the remaining 9 used to validate the calibrated parameters following methods used in similar studies (Mancipe-Munoz et al., 2014). DIEP05CS was used for the flow data. Although DIEP05CS only accounted for the upstream portions of the catchment, the calibrated parameters were adjusted equally in both the gauged and ungauged sections on the assumption that the behaviour of each would be similar. At the end of the calibration and verification process, the model was deemed an acceptable representation of the physical catchment.

Table 2 presents the model errors after calibration and validation. Values were determined for: the total flow volume, max flow rates, and comparison with measured flow hydrographs; and 3 error functions were used: integral square error rating (ISE), Nash-Sutcliffe efficiency (NSE), and coefficient of determination (R^2). Although the minimisation of model error is of the utmost importance, there is no generally accepted standard for what might be considered acceptable (James, 2005). Moriasi et al. (2007) and Golmohammadi et al. (2014) suggest an NSE value between 0 and 1 and an R^2 of greater than 0.5, while Santhi et al. (2001) recommend an NSE value greater than 0.5 and an R^2 value greater than 0.6. The calibration was considered acceptable for this study as both NSE and R^2 were significantly greater than 0.5 for all parameters measured.

Figure 6 presents storm event hydrographs of observed and modelled data for a typical storm event (27–30 August 2013) after the completion of the calibration and validation processes. As the rainfall data had to be disaggregated through a stochastic process, the modelled runoff does not visually match the observed hydrograph particularly well; however, the error measurements nevertheless indicate that the storm is calibrated to an acceptable standard as both the NSE and R^2 values exceeded 0.5.

Table 2. Model errors

Parameter	Error function	Calibrated	Validated
Total flow volume	ISE rating	Good	Fair
	NSE	0.883	0.842
	R^2	0.943	0.935
Max flow rates	ISE rating	Fair	Fair
	NSE	0.701	0.707
	R^2	0.748	0.747
Hydrograph	ISE rating	Fair	Fair
	NSE	0.685	0.64
	R^2	0.724	0.721

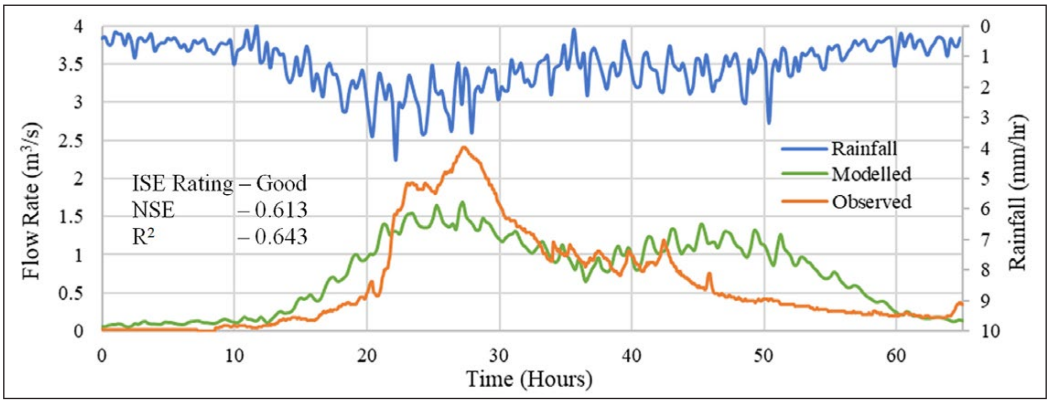

Figure 6. Modelled and observed hydrographs of a typical storm event (27–30 August 2013)

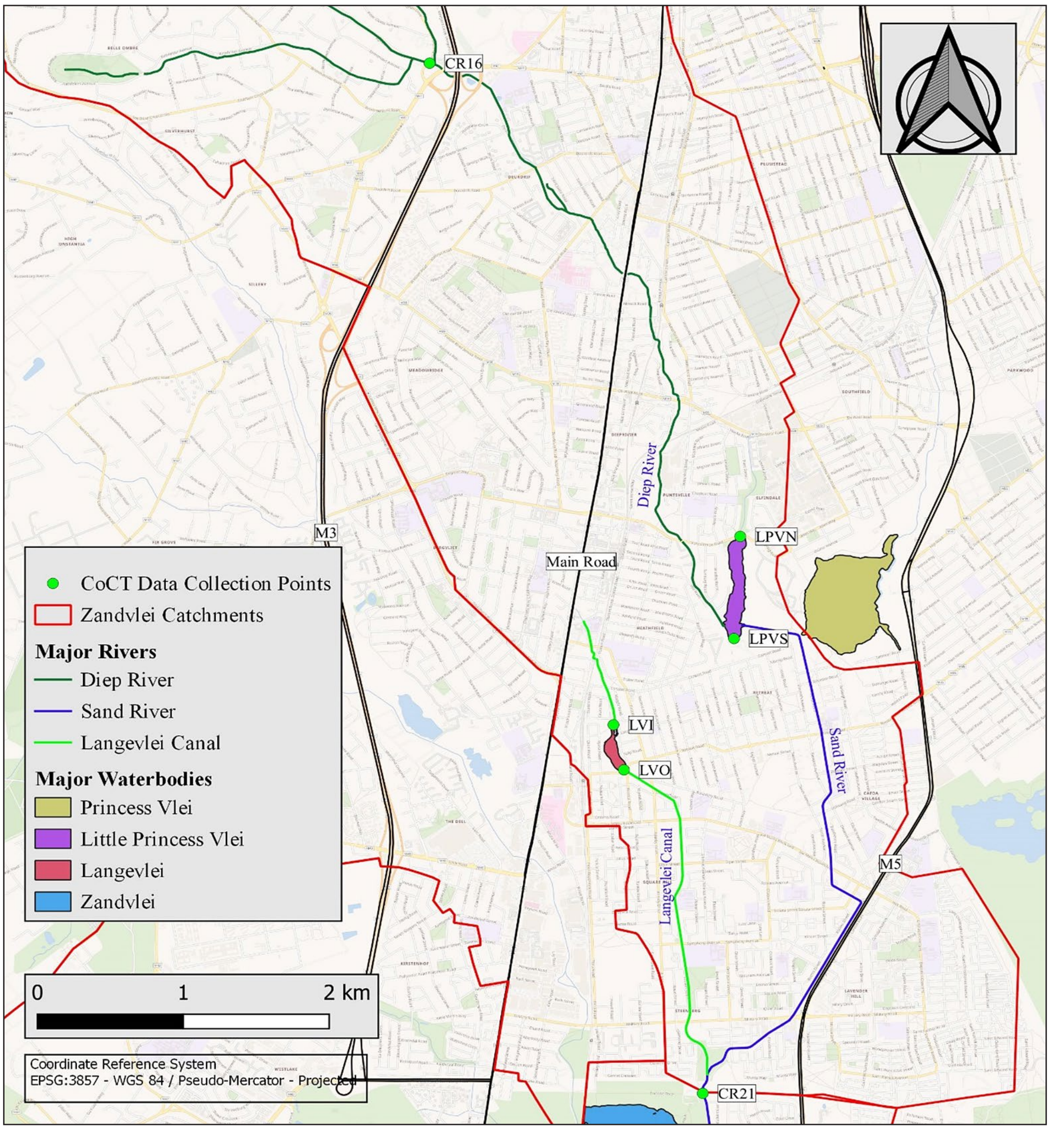

Figure 7. Water quality sampling locations

Development of the water quality model

The CCT Scientific Services Branch has been monitoring the water quality of many of Cape Town's rivers for decades. Monthly grab samples are taken and dissolved oxygen, temperature, salinity, pH, suspended solids, conductivity, total phosphates, orthophosphates, nitrites and nitrates, ammonia, and *E. coli* measured. These data were obtained from the CCT for the period from 2000 to 2020 for 12 locations within the catchment. After analysing the data, it became apparent, however, that many of the sampling points were inappropriate for this project due to missing stormwater water quality measurements and a low number of data entries, leaving only 6 suitable sampling points (Fig. 7): CR16 (Fig. 8), Little Princessvlei North (LPVN) (Fig. 9), Little Princessvlei South (LPVS), Langevlei Inflow (LVI) (Fig. 10), Langevlei Outflow (LVO) (Fig. 11) and CR21 (Fig. 12).

Figure 8. CR16 sampling point (outflow of Alphen Drive culvert)

Figure 9. Little Princessvlei North (LPVN) sampling point

Figure 10. Langevlei Inflow (LVI) sampling point

Figure 11. Langevlei Outflow (LVO) sampling point

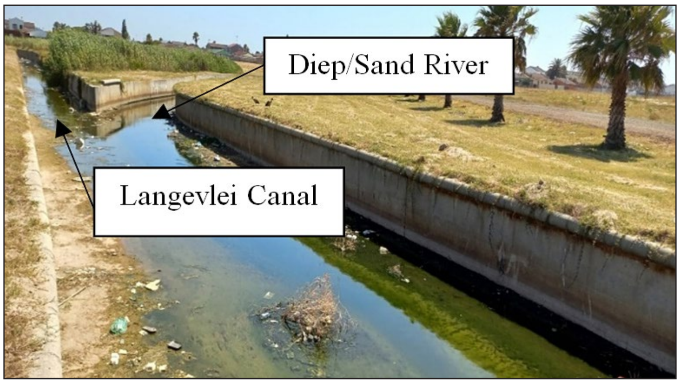

Figure 12. CR21 sampling point

While the CCT grab samples were useful for locating areas of high pollutant concentrations and guiding SuDS deployment, they were not directly usable in PCSWMM. Instead, EMCs were used to model stormwater pollutant wash-off and transportation as EMC values are readily available in literature and PCSWMM can easily accommodate them (Lin, 2004).

Preliminary EMC values were developed for the land uses in the catchment using published data (District Department of the Environment, 2014; Järveläinen et al., 2017; Kayhanian et al., 2007; Mitchell, 2005; Nordeidet et al., 2004; Song et al., 2019; Tuomela et al., 2019; USEPA, 1983; Wicke et al., 2021). However, these were all European or American studies and EMC values vary with location (Tuomela et al., 2019). The published values thus had to be adjusted for the Cape Town context. The values that were selected were for SRP and TIN as they are the primary causes of eutrophication, and TP and TSS as the CCT Management of Urban Stormwater Impacts Policy (CCT, 2009) requires developers to achieve TP and TSS reductions of 45% and 80%, respectively. The current situation (As-is) model was run using the preliminary EMC values as input and the modelled indicator concentrations as outputs at the CCT sampling points obtained. The EMC input values were then manually adjusted for each land use by comparing the modelled output concentrations to those measured by the CCT until a reasonable match was achieved. The final input EMC values used in the model are presented in Table 3.

Table 3. EMC input values used in the model simulations

Land use	SRP	TIN	TP	TSS
	mg/L			
Agricultural	0.300	1.284	1.05	30.0
Commercial	0.150	1.500	0.15	23.0
Environmental conservation	0.080	0.420	0.05	12.0
Industrial	0.110	0.804	0.10	6.5
Institutional	0.110	0.918	0.165	8.96
Public open space	0.080	1.188	0.20	10.0
Residential – high density	0.140	1.500	0.45	7.0
Residential – medium density	0.042	0.400	0.25	10.0
Residential – low density	0.041	1.000	0.05	6.0
Residential – very low density	0.160	1.600	0.40	22.0
Rural	0.029	0.675	0.10	8.0
School grounds	0.123	0.600	0.25	7.0
Sports fields	0.022	0.500	0.165	7.17
Roadways	0.011	1.446	0.10	8.5
Train line	0.022	1.200	0.05	7.39

Modelling SuDS in PCSWMM

SuDS may be implemented in PCSWMM using the 'LID Control' tools. The tools offer 9 SuDS Stormwater Control Measures (SCM) (Table 4). Pollutant removal in them is closely associated with stormwater removal through infiltration. Unfortunately, no 'regional controls', i.e., ponds and wetlands (Armitage et al., 2013), are included among the tools; however, it is possible to model regional controls by inserting conduits, junctions, and storage units. New sub-catchments were created in the PCSWMM model to represent individual SuDS SCMs (Fig. 13). This allowed for the creation of treatment trains as the outflow of one SuDS SCM can be directed into others downstream.

The pollutant removal abilities of regional controls may be modelled in PCSWMM by assigning treatment functions for each pollutant. This could be a fixed percentage removal or a decay function that indicates the pollutant removal by the SuDS SCM over time (CHI, 2021). In this project, first-order decay functions were derived for ponds and wetlands with hydraulic retention time (HRT) as the independent variable based on published experimental data. Decay functions ideally require data specific to each intervention site. Climatic factors, such as temperature, have a significant impact on the treatment ability of SuDS, with higher temperatures generally correlating with higher removal efficiencies (Akratos and Tsihrintzis, 2007). Therefore, published data on the performance of wetlands and ponds from systems with similar climates to that of Cape Town were prioritised. Since PCSWMM requires that treatment equations be defined in terms of fractional removal the decay function curves were used in the form:

$$R = 1 - e^{-k \times HRT} \qquad (1)$$

where: R = removal fraction of the target pollutant; k = decay coefficient associated with the target pollutant; HRT = hydraulic retention time (h).

The inevitable variability in wetland and retention pond efficiencies caused by environmental and hydrological factors was catered for by establishing both high- and low-level treatment equations for each indicator to provide potential treatment ranges. The removal efficiency curves for SRP, TIN, TP and TSS for retention ponds and wetlands are presented in Figs 14 to 17 and the equations listed in Table 5.

Table 4. SuDS readily available in PCSWMM (CHI, 2019)

Available in the 'LID Control' tools		Excluded regional control SuDS
Source control	Local control	
Rain gardens	Bio-retention cells	Detention ponds
Green roofs	Infiltration trenches	Retention ponds
Rain barrels	Vegetative swales	Constructed wetlands
Rooftop disconnection		
Permeable pavements		

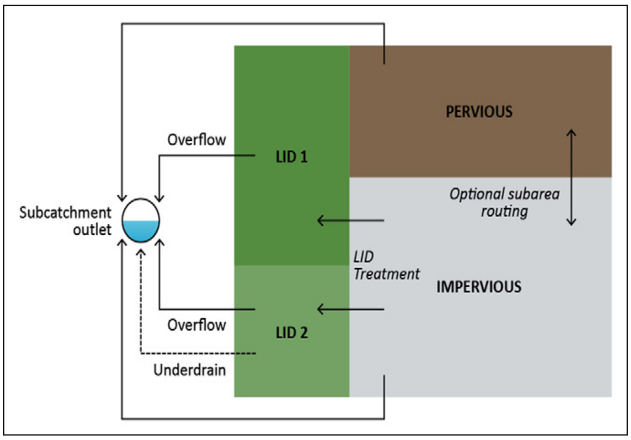

Figure 13. SuDS (LID) placement approach (Computational Hydraulics Inc., 2024; used with permission)

Table 5. Treatment equations for retention ponds and wetlands – derived from experimental data collected by Abbassi et al. (2011); Akratos and Tsihrintzis (2007) and Kabenge et al. (2018)

Indicator	Treatment equations	
	High-level removal	Low-level removal
SRP	$R = 1 - e^{-0.016 \times HRT}$	$R = 1 - e^{-0.0048 \times HRT}$
TIN	$R = 1 - e^{-0.012 \times HRT}$	$R = 1 - e^{-0.004 \times HRT}$
TP	$R = 1 - e^{-0.007 \times HRT}$	$R = 1 - e^{-0.0043 \times HRT}$
TSS	$R = 1 - e^{-0.03 \times HRT}$	$R = 1 - e^{-0.013 \times HRT}$

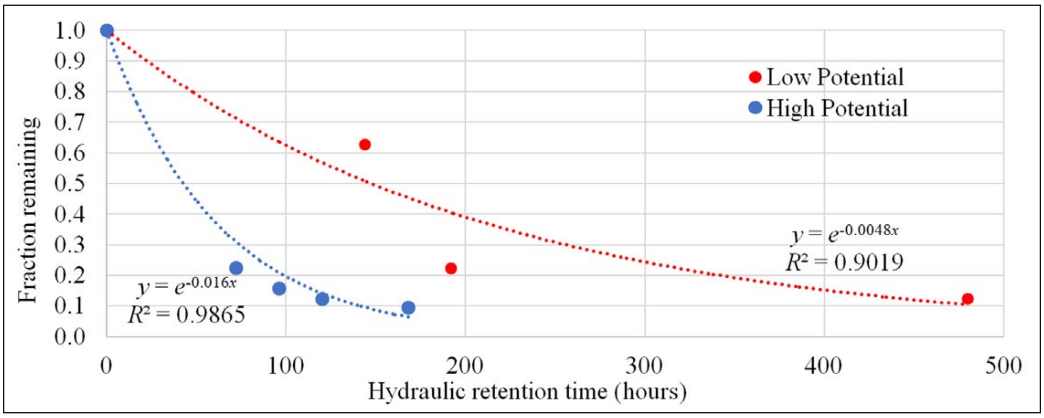

Figure 14. SRP removal efficiency curves for retention ponds and wetlands

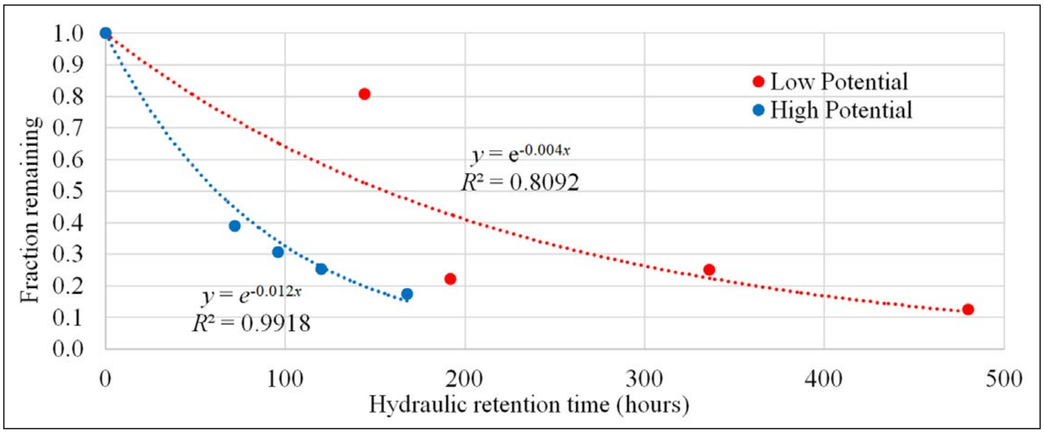

Figure 15. TIN removal efficiency curves for retention ponds and wetlands

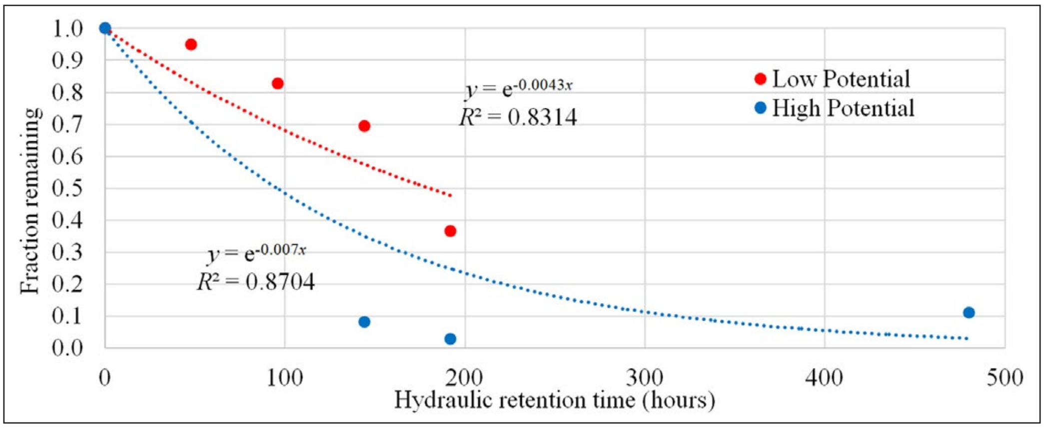

Figure 16. TP removal efficiency curves for retention ponds and wetlands

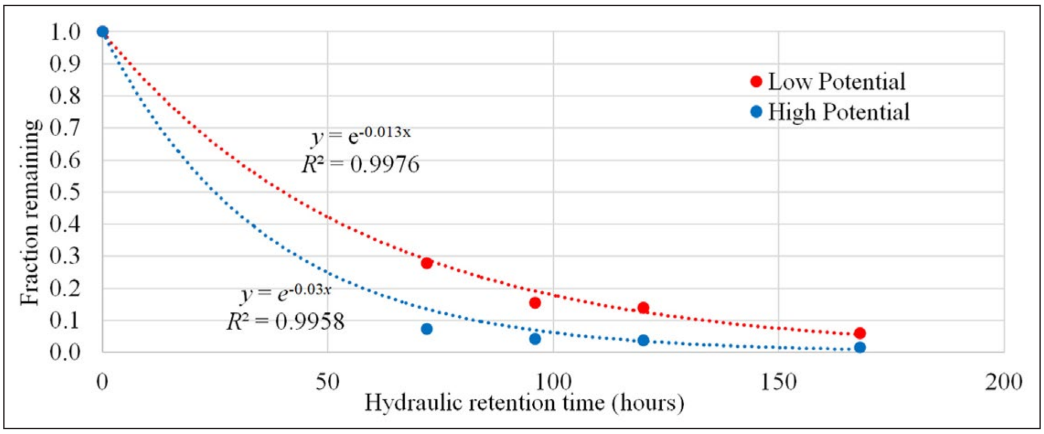

Figure 17. TSS removal efficiency curves for retention ponds and wetlands

Model scenarios

As-is

The As-is Scenario was developed to represent the Diep catchment in its current state. It included the topography, current land uses and stormwater drainage networks of the catchment. The calibrated and validated model was then used as a baseline for all subsequent models.

Pre-development

The Pre-development Scenario was developed to estimate the natural pollutant indicator loads and flow rates that probably best represent sustainable conditions in the Diep catchment. The following changes were made to the As-is Scenario: all land-uses were set to 'Environmental conservation', the pipe network was removed, constructed conduits were altered to represent more natural channels, and culverts under roads were replaced with open channels. The scenario could not be calibrated as no flow data were available for any period prior to urbanisation.

Scenario 1 – source controls

Scenario 1 assumed various source controls – SuDS SCMs that manage stormwater runoff at or near the source – to reduce runoff volumes from sites and reduce the pollutant loads received downstream. It illustrated the effect these may have on reducing pollutants in areas with open pervious spaces. Since designing and modelling these systems for every site in PCSWMM would have been highly intensive and would have introduced additional uncertainty into the model through the need for additional parameter estimation, an alternative approach was used. PCSWMM's subarea routing function was used to route runoff from impervious to pervious areas in each sub-catchment. The treatment range was established using high and low sub-area routing percentages for each land use (Table 6) producing high and low reduction potentials, respectively.

The agricultural areas (A1, A2, A3 and A4) on either side of the M3 Freeway produce crops that often require fertilisers, pesticides and other products that may result in poor quality runoff. Large SuDS are not viable in these areas as they would reduce the productive agricultural area, thus swales were deemed the most effective interventions. Four large swales were placed along the contours to reduce the slope, and as close to boundaries as possible to reduce the intrusion into productive agricultural land (Fig. 18).

Table 6. Subarea routing percentages for Scenario 1

Land use	Subarea routing (%)	Land use	Subarea routing (%)
Agricultural	60–70	Residential – low	75–85
Commercial	0	Residential – very low	90–100
Environmental conservation	90–100	Rural	0
Industrial	0	School grounds	50–60
Institutional	40–50	Sports fields	90–100
Public open space	60–70	Roadways	0
Residential – high	0	Train line	0
Residential – medium	60–70		

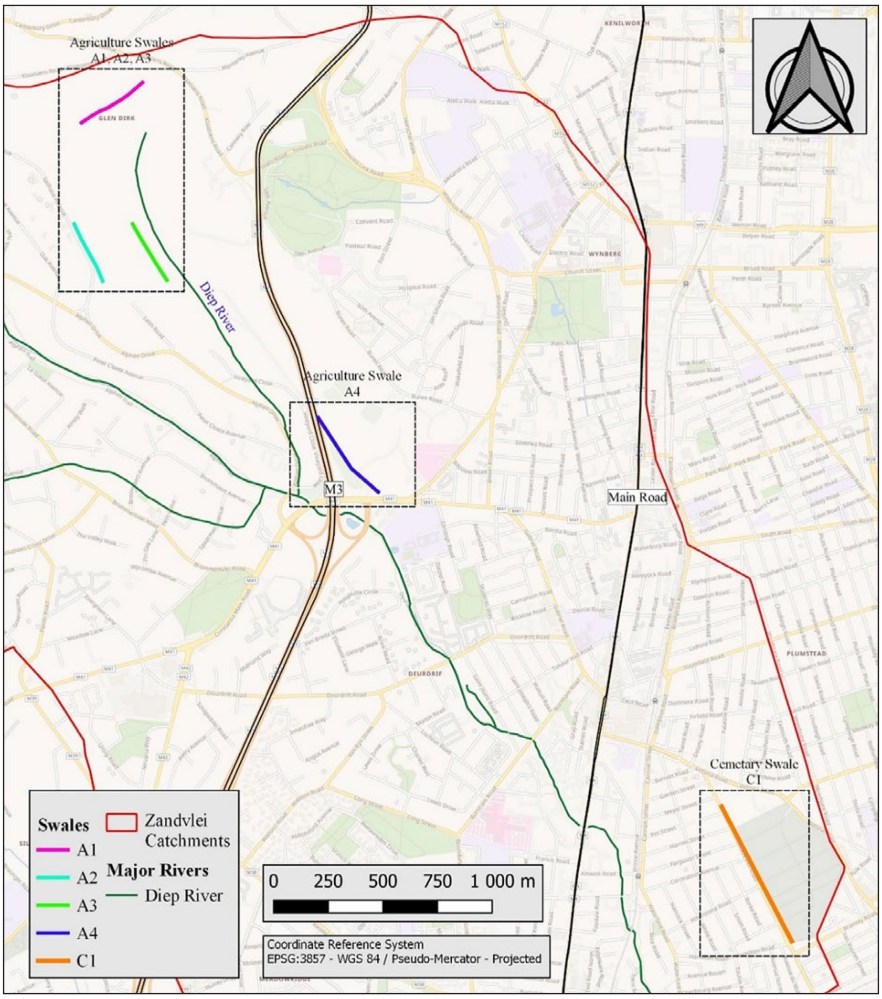

Figure 18. Scenario 1 swale locations – adapted from Wikimedia Maps (Wikimedia, 2021)

A single swale was modelled along the lower boundary of the Plumstead Cemetery (C1). This area produces large volumes of runoff due to its size. It is neighboured by a sports club that may utilise nutrient-based fertilisers to maintain the playing fields and the cemetery swale also collects the runoff from this site. Runoff exiting the swale may be directed towards the existing stormwater network, or a small irrigation dam may be constructed to capture runoff and allow the sports club and the cemetery to water their extensive open areas during dry periods.

Scenario 2 – historic wetlands and ponds

Zandvlei and its catchments have experienced a long history of modification (Jack, 2006). The relatively flat topography of the Diep catchment, especially in the lower reaches, used to support an extensive floodplain wetland but urban development has reduced the extent of the large floodplain wetland to small, isolated wetland areas scattered around the catchment (Obree, 2004). Some of these provide attenuation storage during large storm events, while others are entirely disconnected from the system. Scenario 2 thus reincorporated four small existing wetlands and an existing overflow retention pond into the formal stormwater drainage system. An existing detention pond was converted into a retention pond. These were all modelled as storage units in PCSWMM (Fig. 19). Practically, reincorporation of the wetlands and the existing overflow pond would be accomplished by removing the berms/walls that prevent direct flow into them.

One example of the wetlands that could be re-introduced into the main river channel is at Ian Taylor Road. It was disconnected from the Diep River when the river section was channelised (Figs 20 and 21). The concrete walls of the channel currently do not allow stormwater to enter the wetland, while an adjacent berm further separates the two systems.

As the area utilised by the wetland is small, the flow into the system should be limited to protect the wetland from damage and reduce the risk of flooding to the medium-density residential areas surrounding the site. However, low flows from smaller, more frequent storms are the primary target for SuDS as they transport the bulk of the contaminant load.

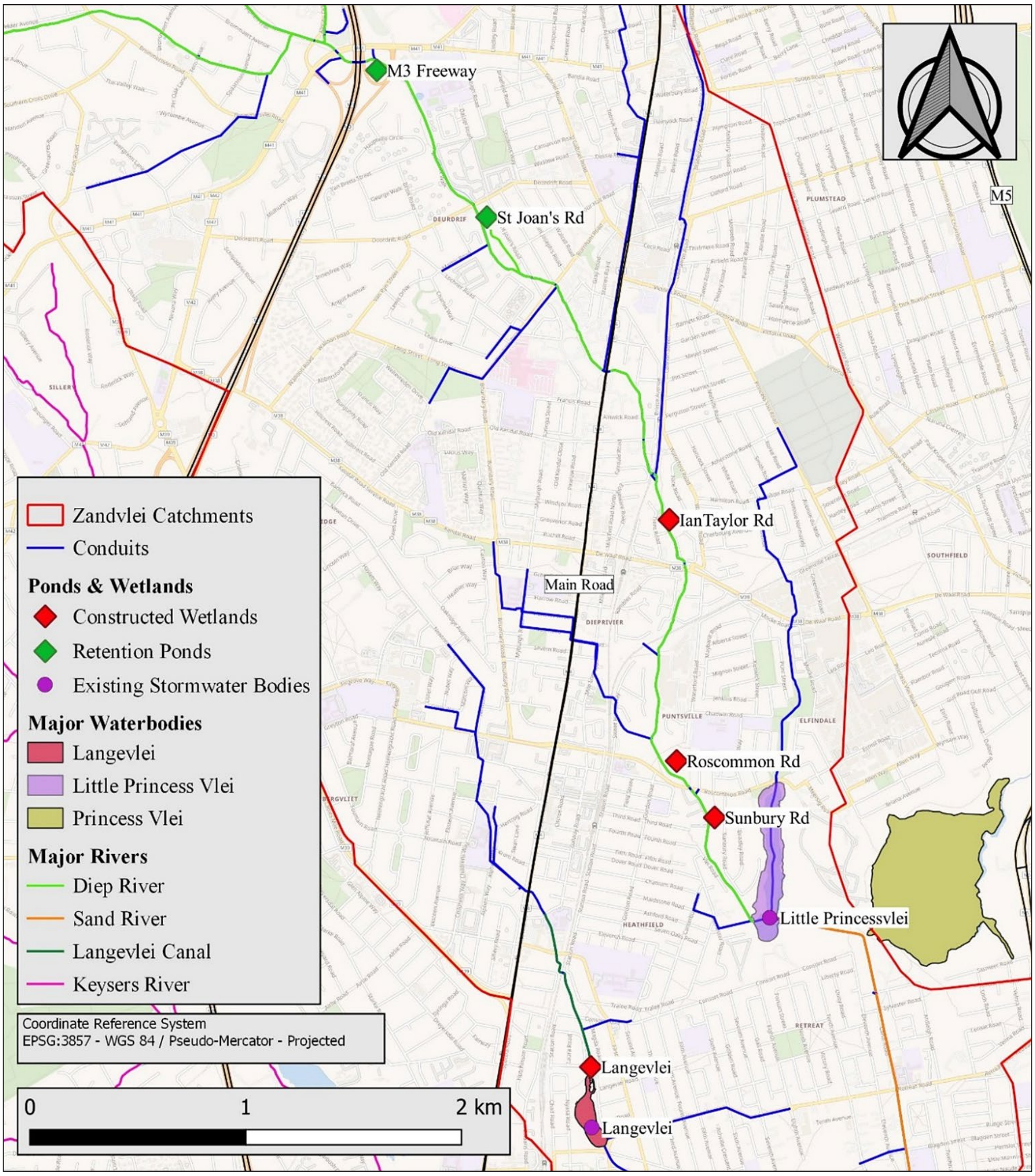

Figure 19. Existing ponds and wetlands reincorporated into the drainage system

Figure 20. Existing overgrown marsh/wetland area on Ian Taylor Road

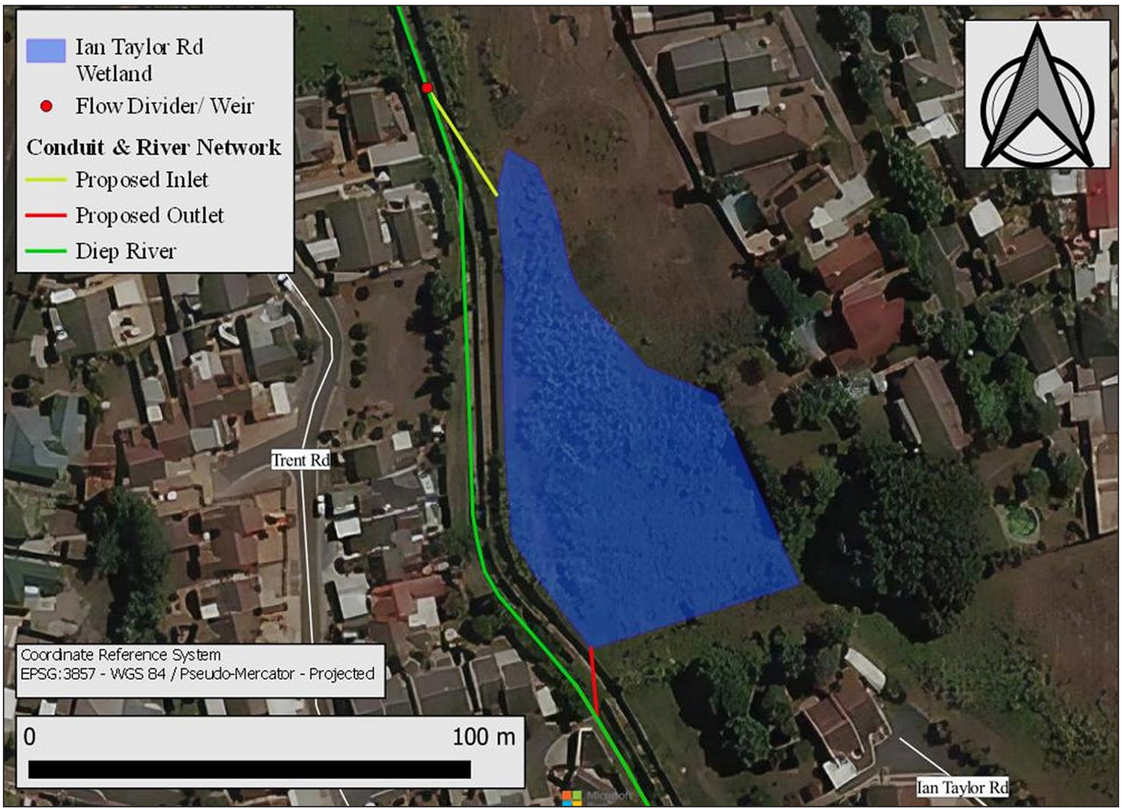

Figure 21. Proposed layout of the Ian Taylor Road wetland

Scenario 3 – new confluence wetland

A single, large-scale regional control at the confluence of the Sand River and the Langevlei Canal was developed for Scenario 3. Currently, this is a large unused open area bounded by the two rivers, making access for recreational activities difficult. The small triangular marsh area currently does not receive any runoff from the concrete-lined canals. A constructed wetland that would receive all the runoff from both river systems was thus included for this 0.5 km^2 area (Fig. 22).

Owing to height differences, the entire site would need to be excavated for the wetland. As all the runoff from the entire catchment would be channelled towards this system, an emergency overflow would be required to protect it during high flows. As there is considerable open apace on either side, there is also a significant opportunity to expand the wetland or utilise this space. Additionally, as the runoff collects large volumes of sediment and litter, a sediment basin and litter trap should be installed immediately upstream.

Scenario 4 – source controls and confluence wetland

The fourth scenario combined Scenarios 1 and 3 to create a more holistic treatment train. It thus included the source controls of Scenario 1 with the proposed large wetland at the confluence of the Langevlei Canal and the Sand River.

Scenario 5 – existing and confluence wetlands

The final scenario combined two existing wetlands and a retention pond (only) from Scenario 2 with the proposed new wetland at the confluence of the two rivers (Scenario 3). The regional controls would not target specific areas of high indicator inflow but rather treat the entire system at locations where large areas are available. This scenario would likely have a large impact on the water quality

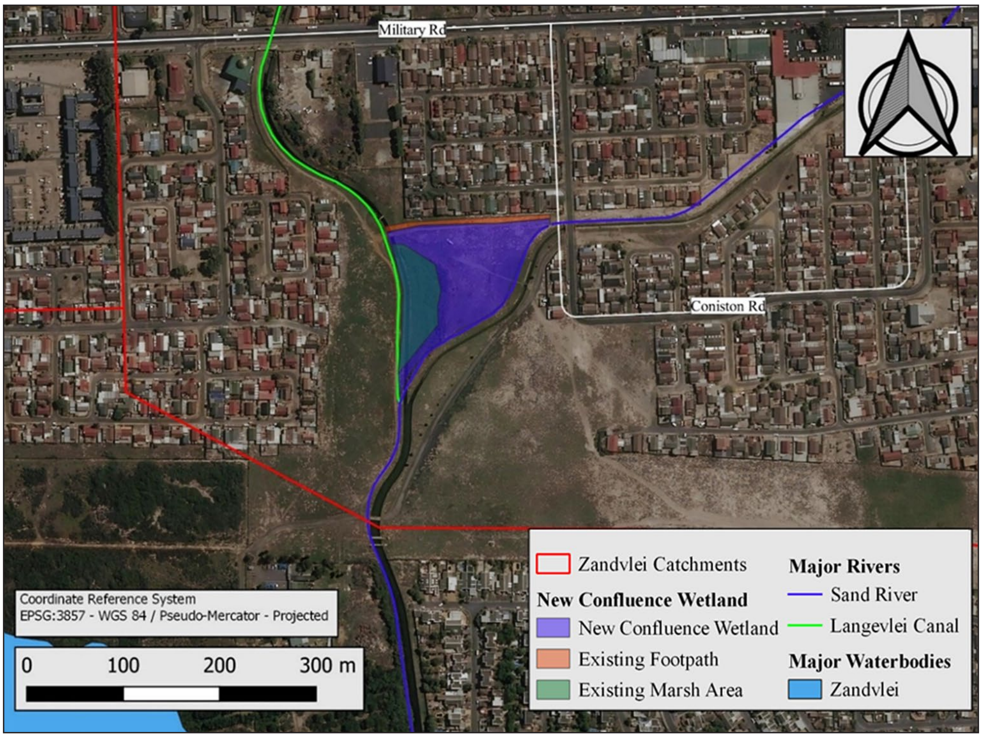

Figure 22. New confluence wetland location – adapted from Bing Maps (Microsoft Bing, 2021)

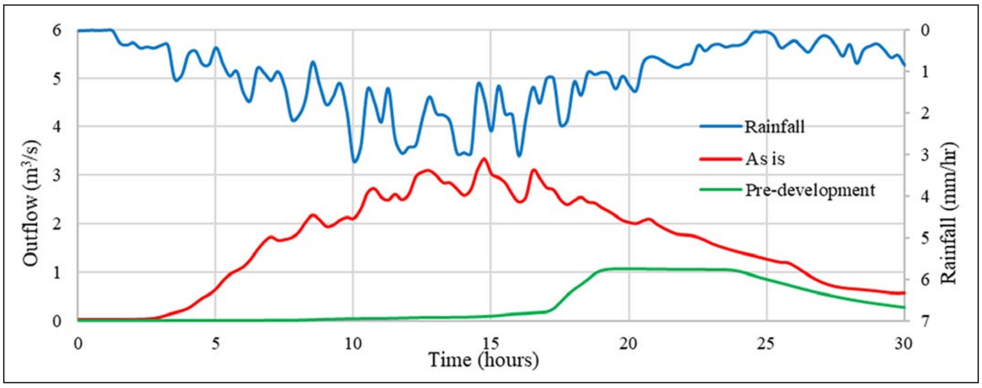

Figure 23. As-is Scenario and Pre-development Scenario outflow rates during a 6-month storm event (16–17 August 2005)

Table 7. As-is Scenario indicator quantities and runoff volumes (12 years and 11 months)

Runoff volume (10^6 m^3)	Total SRP load (tonnes)	Total TIN load (tonnes)	Total TP load (tonnes)	Total TSS load (tonnes)
61.8	4.4	49.9	11.1	541

received by Zandvlei but may leave isolated areas in the catchment with poor water quality. The wetlands and ponds incorporated in this scenario include:

- Existing:
  - Ian Taylor Road wetland
  - Sunbury Road wetland
  - M3 Freeway retention pond
- New confluence wetland

RESULTS AND DISCUSSION

As-is Scenario

Table 7 provides the cumulative quantities produced by the As-is Scenario at the outfall to Zandvlei between 16 January 2003 and 6 December 2015.

Pre-development Scenario

The outflow rates experienced by the As-is and Pre-development Scenarios are compared in Fig. 23 for a 6-month return period storm event (16–17 August 2005). This figure illustrates the extent to which urban development has reduced the infiltration ability of the catchment and significantly increased the outflow rates – and thus volumes – experienced in the lower reaches.

SuDS load reductions

The outputs of the SuDS scenarios are compared to those obtained from the As-is Scenario in the form of percentage reductions (Fig. 24), as this is required by the CCT (2009) stormwater impact policy. The indicator loads deposited into Zandvlei from each of the SuDS scenarios are presented in Figs 25 to 28.

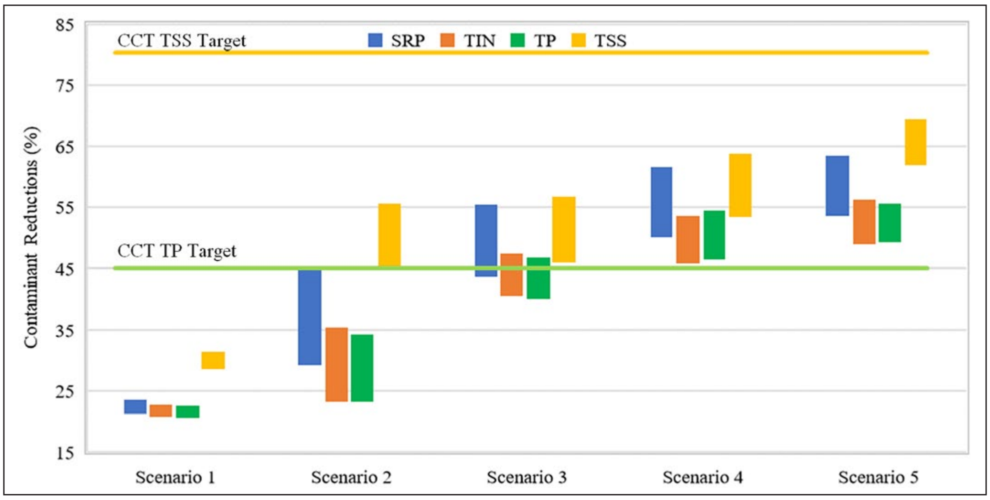

Figure 24. Indicative removal percentages compared with current levels as modelled in the five SuDS scenarios (the area covered by the bars indicates the range of uncertainty)

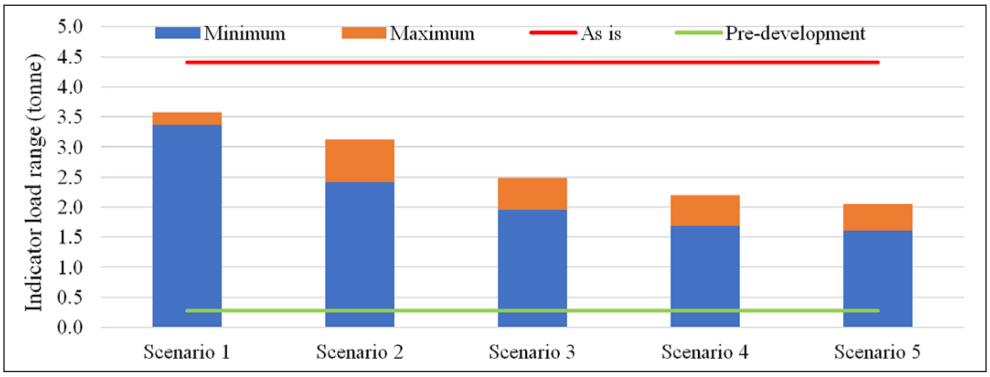

Figure 25. SRP load ranges from SuDS scenarios (16 January 2003 to 6 December 2015); orange bars represent the range

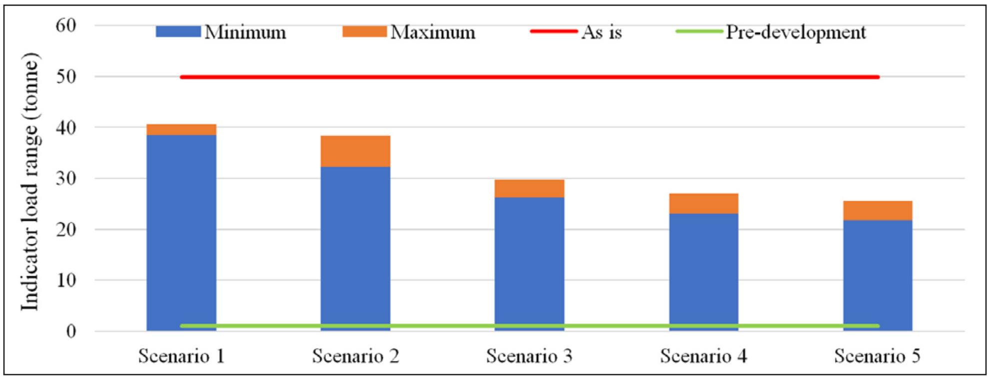

Figure 26. TIN load ranges from SuDS scenarios (16 January 2003 to 6 December 2015); orange bars represent the range

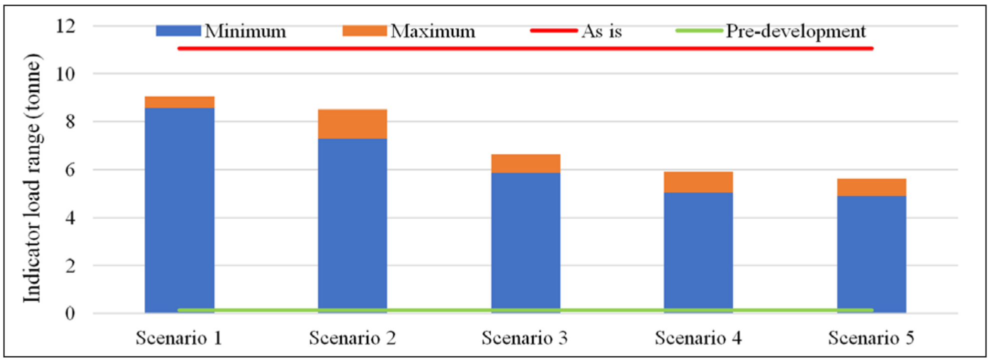

Figure 27. TP load ranges from SuDS scenarios (16 January 2003 to 6 December 2015); orange bars represent the range

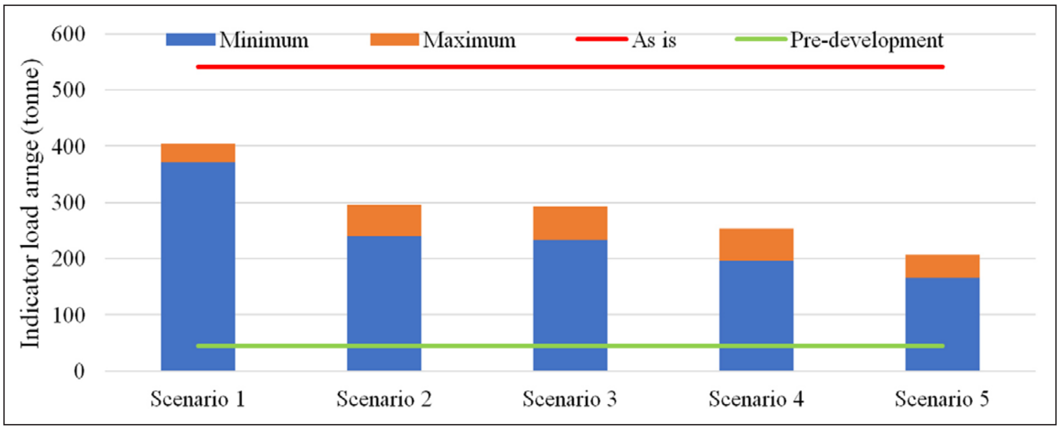

Figure 28. TSS load ranges from SuDS scenarios (16 January 2003 to 6 December 2015); orange bars represent the range

Scenario 1 (source controls) provided some level of improvement; however, this scenario presented the lowest removal percentages for all 4 indicators. This is likely due to the land uses targeted by the SuDS; as this scenario required permeable areas for the source controls, land uses with minimal pervious areas were largely untreated. Unfortunately, these are often the sites that produce the highest wash-off concentrations. The reductions obtained from Scenario 1 did not meet the TP and TSS reductions of 45% and 80%, respectively, required by the CCT.

Scenario 2 (reincorporation of historic ponds and wetlands) provided larger indicator reductions than Scenario 1, albeit with the greater degree of uncertainty associated with the wide range of treatment potential associated with ponds and wetlands. This scenario also fell short of the CCT recommendations, with maximum reductions of TP and TSS of 34% and 56%, respectively.

Scenario 3 (new confluence wetland) provided bigger reductions than Scenarios 1 and 2 for all pollutant indicators except TSS. The CCT 45% reduction requirement for TP was met for by the upper – but not the lower – treatment potential. Unfortunately, Scenario 3 did not meet the TSS reduction requirement.

As expected, Scenarios 4 (source controls and confluence wetland) and 5 (existing and confluence wetlands) provided the most significant reductions. These scenarios incorporated SuDS from the first three scenarios to develop treatment trains and create more robust systems. Both Scenario 4 and 5 completely met the CCT TP requirement, with Scenario 5 providing the greatest reduction. Unfortunately, neither Scenarios 4 nor 5 met the targeted TSS reduction of 80%. As the TSS targets were not met in any of the five SuDS scenarios, the rate of siltation within the estuary will not be satisfactorily decreased.

The likely sustainable indicator loads from the Pre-development Scenario were not obtained in any SuDS scenario (Figs 25 to 28). Scenario 5, providing the lowest loads for each indicator, presented the closest results to that of the Pre-development Scenario.

SuDS outflow concentrations

Excessive SRP and TIN concentrations are responsible for the overgrowth of plants and cause eutrophication in water bodies. The concentrations of these entering Zandvlei must therefore be reduced. Figures 29 and 30 present the mean outflow concentrations at the model outlet from each SuDS scenario and the concentration range in which eutrophication may occur, as specified by DWAF (1996).

The SRP outflow concentrations are still within the eutrophic range for each SuDS scenario (0.025–0.25 mg/L); thus, eutrophication will likely continue. The mean SRP concentration obtained from the As-is Scenario would likely be reduced in four of the five SuDS scenarios (Fig. 29) with Scenario 2 (reincorporation of historic ponds and wetlands) and Scenario 5 providing concentrations well below those of the As-is Scenario. The TIN concentrations are all well below the eutrophic range (2.5–10 mg/L).

Scenario 1 (source controls) presented a slightly increased mean SRP outflow concentration. This is likely due to the areas targeted by the SuDS; the targeted pervious areas are associated with lower mean wash-off concentrations than the impervious areas. The large impervious areas in the middle and lower reaches of the catchment were not significantly affected in Scenario 1, thus the runoff from these areas continued to flow into the river networks without treatment. Scenario 3's large confluence wetland reduced both the SRP load and runoff volume by approximately 45%, resulting in a mean SRP outflow concentration similar to that of the As-is Scenario.

SuDS runoff

Urban development has significantly increased the impervious surfaces within catchments resulting in hugely increased runoff volumes. Furthermore, the channelisation of the river network has increased runoff flow rates. The likely reduction in runoff volumes and flow rates due to the implementation of SuDS was thus assessed. Runoff reductions are provided as percentage decreases from the As-is runoff volume (Fig. 31). Additionally, the runoff flow rates experienced at the outfall of each scenario during a typical storm event (18–21 April 2010) are presented in Fig. 32.

Table 8 presents the predicted total runoff from the Diep River catchment over the 12 years and 11 months modelling period.

Scenario 1 (source controls) predicted a moderate runoff reduction with a range of 21–26%. As this scenario targeted land uses with pervious areas, the sites with large impervious areas providing large runoff volumes were not impacted.

Scenario 2 (reincorporation of historic ponds and wetlands) produced a small runoff reduction of 11%. The reintroduced systems targeted low flows from smaller storms. The larger flows bypass the new systems and continue down the existing channels until they reach Zandvlei.

The large confluence wetland system at the discharge point into the estuary receives the entirety of the flows from the Diep/Sand River and Langevlei Canal systems and provides considerable attenuation storage that slows runoff and allows infiltration. As expected, the scenarios that included this wetland (Scenarios 3, 4, and 5) produced the most significant drops in runoff volumes with all three producing runoff decreases of over 40%.

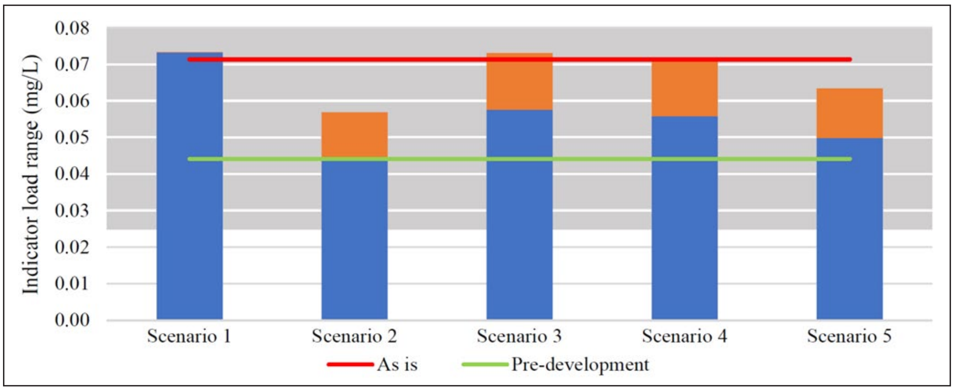

Figure 29. SRP model outflow concentrations; grey band represents the eutrophic range (0.025–0.25 mg/L); orange bars represent the concentration range due to high and low treatment potentials

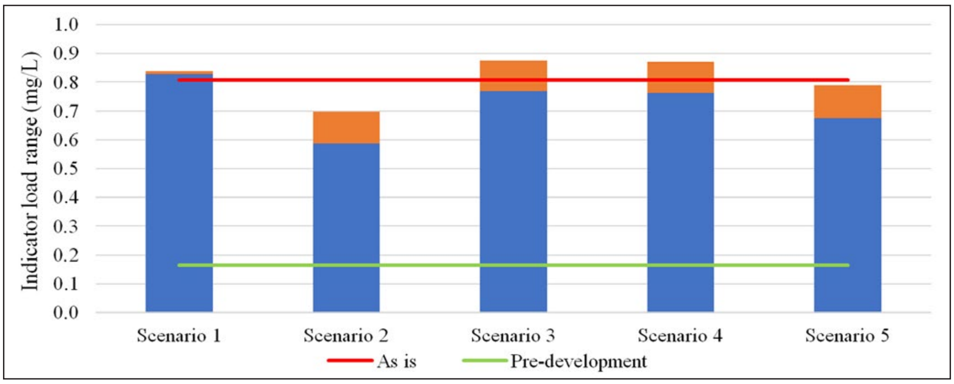

Figure 30. TIN model outflow concentrations; eutrophic range of 2.5–10 mg/L; orange bars represent the concentration range due to high and low treatment potentials

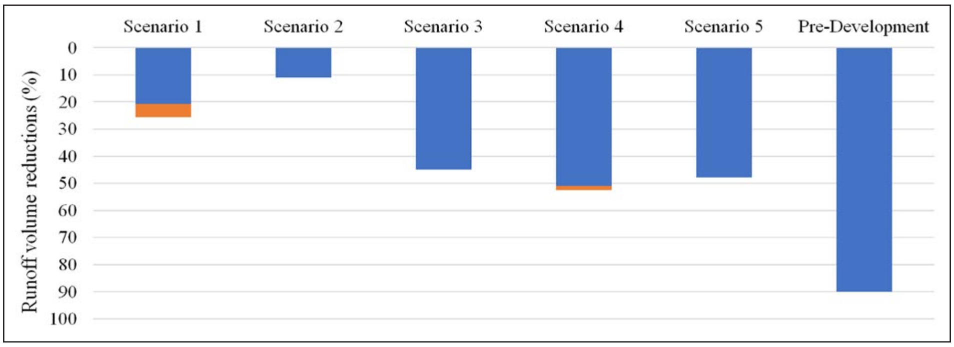

Figure 31. Runoff volume reduction percentages; orange bars represent the range

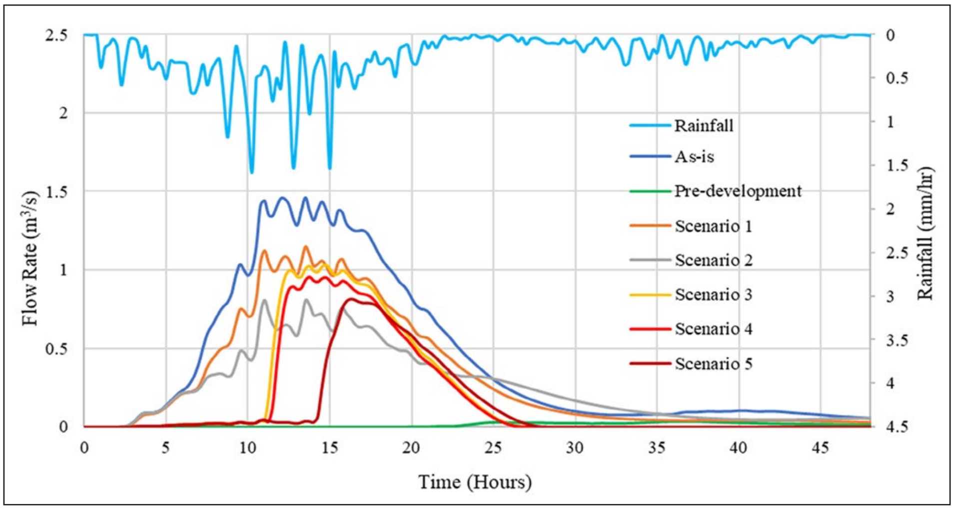

Figure 32. Outfall flow rates during a typical storm event (18–21 April 2010)

Table 8. Total runoff volumes (12 years and 11 months) for different scenarios

Scenario	As-is	Pre-development	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total runoff volume (10^6 m^3)	61.8	6.2	46.0–48.9	54.9	34.0	30.3–31.2	32.3

As Scenario 4 (source controls and confluence wetland) includes elements from Scenario 1, this resulted in two separate runoff values. Table 8 presents the runoff volumes received by Zandvlei over the entire simulation period.

The Pre-development Scenario suggests a total runoff volume decrease of approximately 90% compared with the As-is Scenario. The magnitude of this reduction is to be expected as the catchment would have had significantly less impervious area allowing much more infiltration. The reduction is over 35% more than the best performing SuDS scenario, Scenario 4.

CONCLUSIONS

The City of Cape Town (2009) Management of Urban Stormwater Impacts Policy requires that new developments should decrease TP and TSS loads by at least 45% and 80%, respectively. Additionally, the South African Water Quality Guidelines for Aquatic Ecosystems (DWAF, 1996) state that SRP and TIN are responsible for the eutrophic states in estuaries, a significant problem for Zandvlei (Thornton et al., 1995). Therefore, the Diep catchment – the most urbanised contributor to the flow into Zandvlei – was modelled to see the likely impact of various SuDS scenarios using SRP, TIN, TP and TSS as the stormwater constituent indicators.

Various SuDS scenarios were tested under conditions of both high and low treatment to determine the likely pollutant reduction ranges for SRP, TIN, TP and TSS. The results were compared to those obtained from As-is and Pre-development Scenarios. Scenarios 1 (source controls) and 2 (reincorporation of historic ponds and wetlands) did not meet either CCT target. Scenario 3 (new confluence wetland) partially met the CCT TP reduction target at the top end. Scenarios 4 (source controls and confluence wetland) and 5 (existing and confluence wetlands) fully met the TP reduction target. None of the five SuDS scenarios met the 80% TSS target. As a result, sedimentation may occur in Zandvlei at a rate faster than that experienced before urbanisation began; however, the rate will be lower than that currently experienced.

None of the scenarios resulted in mean outfall SRP concentrations below the eutrophic range, thus eutrophication may still occur in Zandvlei. However, Scenarios 2, 3, 4 and 5 will all likely result in lower mean SRP concentrations than the As-is Scenario.

The Pre-development Scenario indicated a 90% decrease in runoff volume compared with the As-is Scenario and was over 35% better than the best SuDS scenario. The modelled runoff received by Zandvlei from the Diep catchment was reduced between 10% and 55% in the various SuDS scenarios, with Scenario 2 and Scenario 4 providing the lowest and highest reductions, respectively.

Based on the results obtained from the various scenarios, the implementation of Scenario 5 would provide the most significant improvement to Zandvlei's water quality. However, while this scenario would likely surpass the CCT 45% TP reduction target it would not meet the 80% TSS reduction target. Many of the wetlands and ponds utilised in the scenario already exist; however, rehabilitation, remediation and maintenance of these sites are required before they may be used effectively. Currently, the location proposed for the large, confluence wetland is unused.

Unfortunately, the indicator loads from Scenario 5 were substantially larger than the likely sustainable results obtained by the Pre-development Scenario. Therefore, the overall objective of improving the water quality within Zandvlei Estuary using SuDS in the Diep catchment is achievable, but improving the water quality to the sustainable conditions observed in the Pre-development model would require additional interventions.

AUTHOR CONTRIBUTIONS

Geordie Thewlis was responsible for the collection of the data, the construction and running of the various models, the analysis of the model outputs, and 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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