Water SA 51(4) 326–336 / Oct 2025
https://doi.org/10.17159/wsa/2025.v51.i4.4179

Research paper

Evaluating the impact of indigenous ground cover categories in reducing stormwater runoff within bioswales in South Africa

Gavin Melvin Oberem[1], J Snyman[1] and EA Burger[1]

[1]*Department of Civil Engineering, Faculty of Engineering and the Built Environment, Tshwane University of Technology, Pretoria, South Africa*

Urbanization has placed pressure on urban stormwater infrastructure. Previously implemented stormwater master planning had become inadequate in managing floods. Research has shown that the use of sustainable drainage systems (SuDS) assists in mitigating the effects of the change in impervious areas brought about by urbanisation. While research on the usage and functions of SuDS is widely available, there is a lack of literature on the impact of indigenous ground cover categories in reducing stormwater runoff within bioswales in South Africa. The aim of this study was to evaluate the impact of indigenous ground cover categories on the hydrological performance of a bioswale in reducing stormwater runoff volume and peak. A physical simulation model was constructed to assess the water balance of the bioswale, taking into account the soil water content of the engineered soil medium. The effects of the inflows in the simulation model were addressed by mimicking the 1-in-10-year post-development return period stormwater runoff scenario, within the Gauteng Province, South Africa, during the summer rainfall pattern. The lawn category (kweek /*Cynodon* grass) demonstrated an average volume reduction of 54.7%, with a peak flow reduction of 49.9%. Ornamental grasses and veld grasses also exhibited a volume reduction (42.2% and 38.0%, respectively) and peak flow reduction (40.4% and 38.3%, respectively). Additionally, these grass categories influenced the soil water content. Overall, these findings demonstrate that there is potential for various grass types to mitigate stormwater runoff.

CORRESPONDENCE
Gavin Melvin Oberem

EMAIL
oberemgm@gmail.com

DATES
Received: 1 November 2024
Accepted: 18 September 2025

KEYWORDS
stormwater runoff
ground cover
sustainable drainage systems
hydrological performance
soil water content
infiltration
bioswales
macropores

COPYRIGHT
© The Author(s)
Published under a Creative Commons Attribution 4.0 International Licence (CC BY 4.0)

INTRODUCTION

Urbanization has made managing stormwater drainage systems more complex (Fletcher, et al., 2015), creating more impervious surfaces like roads and buildings, which replace natural infiltration areas. As a result, there is a rapid surface runoff response for both time concentration and peak flow (Xiao et al., 2017), influencing the quality and quantity of stormwater runoff (Brabec et al., 2002). In South Africa, traditional materials like concrete and paving contribute to this issue. Sustainable drainage systems (SuDS) offer a sustainable approach to managing stormwater, promoting infiltration to replenish underground water tables. Conventional civil engineering techniques prioritize quickly discharging stormwater, while SuDS methods focus on reducing runoff volume and peak flow through rainwater harvesting, infiltration, and other techniques that mimic the natural hydrological cycle. Municipalities have realised the impact of increased runoff, leading to ongoing erosion and degradation of watercourses, as well as posing a potential danger to people and low-lying properties (Gauteng Provincial Government, 2020; Brabec et al., 2002).

A study was conducted on traditional bioswales to explore the use of diversifying vegetation to enhance infiltration through root channels, improving the soil's ability to absorb water. The study aimed to expand knowledge on bioswales, focusing on the impact of indigenous South African ground cover categories on reducing stormwater runoff volume and peak flow. A bioswale is a shallow, vegetated channel designed to slow down, filter, and absorb stormwater runoff. Bioswales use plants and soil to remove pollutants and support infiltration. Bioswales are a key part of SuDS and are designed to handle stormwater from minor events up to a 1-in-10-year return period (Armitage et al., 2013). The effectiveness of a bioswale depends on the type and density of vegetation used, such as trees, shrubs, wildflowers, or grass. Thicker grass is better at filtering pollutants, while deep-rooted native plants are preferred for infiltration and require less maintenance (Dinić-Branković et al., 2018; Armitage et al., 2013).

The aim of this study was to investigate how different indigenous ground cover categories affect the hydrological performance of a bioswale. The study measured reductions in stormwater runoff volume and peak flow for post-development 1-in-10-year storm events. These reductions were based on the bioswale's water balance and soil water content, monitored as the root structures of the plants matured. Based on the findings, a recommendation combining SuDS and ground cover is provided to offer an alternative stormwater management strategy optimized for new, existing, or redevelopment projects. An environmentally friendly layout could enhance biodiversity, increase property value, and benefit the local economy (Woods Ballard et al., 2015). At the same time, the research could provide valuable insights for planning future developments and contribute to guidelines for using bioswales effectively, helping to reduce stormwater volume and peak flow while considering local and regional control implemented by SuDS.

METHODS

A physical simulation model was developed to support experimental investigations into bioswale performance, which was duplicated to, incorporate various categories of indigenous ground cover. Constructed as a full-scale, tangible section of a bioswale within a controlled water flow environment, the simulation models were designed to replicate real-world conditions. It was carefully monitored over a 5-month period, with data collected through direct observation and measurement to ensure accuracy and reliability in assessing the impact of different ground covers on stormwater runoff volume and peak flow.

The experiments were conducted outdoors to evaluate the hydrological performance of indigenous ground cover types under natural environmental conditions. This setup allowed for the influence of biodiversity, temperature fluctuations, sunlight exposure, and rainfall to be observed. V-notch weirs were used to quantify the water balance of the simulation models, specifically measuring infiltration and surface flow. Additionally, sensors were employed to monitor the infiltration rate of the engineered soil medium, providing detailed insights into the bioswale's water retention capabilities.

The key considerations for the simulation models included the following:

- Site placement
- Simulated inflow rate and sizing of bioswales
- Engineered soil medium characteristics and placement depth
- Indigenous ground cover categories
- Data collection
- Data analysis

Site placement

The study was conducted in Centurion, Pretoria, a residential area within the Gauteng Province of South Africa. This site was selected due to its representation of an urbanized area, availability of space for the simulation models, and adequate sunlight exposure, which were critical for the study. Additionally, weekday accessibility was essential for continuous assessments. The simulation models were constructed with a 2% gradient, ensuring the bioswales were positioned according to the specified design slopes and optimum infiltration (Morbidelli, et al., 2016). The paved area received sunlight throughout the day with minimal shadow interference, providing optimal conditions for ground cover growth.

Simulated inflow rate and sizing of bioswales

A physical rainfall simulator was used to create controlled water flow over the bioswale model. The inflow rate was calculated using the Rational Method, which is widely used for estimating stormwater runoff from small areas (Smithers, 2012). Rainfall intensities were based on Gauteng Province's average annual rainfall of about 700 mm (SANRAL, 2013). Maximum stormwater discharge calculations were determined using post-development data and a 1-in-10-year recurring storm event for local controls, as specified for minor system designs by Armitage et al. (2013). A runoff coefficient of 0.8 was considered to account for the highly impervious areas influenced by urbanization (Rujner et al., 2016). Stormwater runoff was calculated for a post-development 1-in-10-year recurring storm event, using the appropriate runoff coefficient for a peak duration of 30 min within a 1-h duration, as compared to field evaluations by the Gauteng Provincial Government (2020), Rujner et al. (2016), and Rujner et al. (2018).

To accurately calculate the stormwater inflow rate, a surface area of approximately 150 m² draining into a bioswale from a nearby road was analysed. The surface area calculation for the bioswale was based on its capacity to manage stormwater runoff from a 15 m section of a 7.4 m wide road, including 3 parallel parking spaces each measuring 2.5 m in width and 5 m in length. The time of concentration was calculated based on overland flow, as stormwater runoff from the road surface area discharges into the bioswale as sheet flow, subsequently flowing through the bioswale (SANRAL, 2013). The inflow rate calculation is crucial for determining the volume and flow of stormwater in the simulation model, ultimately impacting the water balance of the bioswale. The reduction of stormwater runoff volume and peak is based on the simulated inflow rate of 4.1 L/s.

The simulation model's cross-sectional profile was trapezoidal, typical for swales, bioretention swales (Woods Ballard et al., 2015), or enhanced dry swales (Armitage et al., 2013). This shape increases the wetted perimeter, enhancing stormwater treatment. The trapezoidal cross-sectional shape sizing was based on the simulated inflow rate from the assumed road catchment. Using the calculated simulated inflow rate and Manning's equation (Eq. 1) as indicated by Armitage et al. (2013 p. 16), open channel flow parameters and dimensions were determined to handle a stormwater discharge of 4.1 L/s, as shown in Table 1.

Manning's Equation:

$$Q = \frac{A^{5/3} S^{1/2}}{n P^{2/3}} \quad (1)$$

The final dimensions of the simulation model were determined by considering critical factors such as roughness coefficient, water depth, and velocity. These calculations, presented in Table 1, account for both pre- and post-vegetation scenarios. Ground cover significantly slows overland flow, enhancing soil infiltration (Ahmed et al., 2015). To ensure optimal conditions for germination and prevent soil erosion, the stormwater flow velocity was restricted to not exceed 1.0 m/s until the ground cover

Table 1. Open channel flow and cross-sectional parameters

Parameter	Channel design (little to no growth)	Channel design (growth completed)
Discharge (*Q*)	4.1 L/s	4.1 L/s
Roughness coefficient (*n*)	0.025 s/m$^{1/3}$	0.350 s/m$^{1/3}$
Energy slope (*S*)	0.020 m/m	0.020 m/m
Side slope	1:5 or 0.2 m/m	1:5 or 0.2 m/m
Bottom width	0.600 m	0.600 m
Top width	0.607 m	0.630 m
Cross-sectional area (*A*)	0.010 m²	0.046 m²
Wetted perimeter (*P*)	0.635 m	0.751 m
Velocity	0.395 m/s	0.090 m/s
Depth of water	0.017 m	0.074 m

was established. Post-establishment, the velocity was maintained below 0.3 m/s to ensure adequate stormwater runoff infiltration, as recommended by Woods Ballard et al. (2015).

The roughness coefficient was determined using 2 values: 0.025 s/m$^{1/3}$ for a gravelly earth channel with no vegetation (The Engineering ToolBox, 2004) and 0.350 s/m$^{1/3}$ for an established ground cover. According to Woods Ballard et al. (2015), the flow depth in a grassed swale should not exceed 100 mm, corresponding to Manning's *n* value of 0.350 s/m$^{1/3}$.

The bioswales within the model, based on Table 1, were sized to be 3.0 m in length and 1.2 m in width. They featured a trapezoidal profile with a bottom width of 0.6 m and side slopes of 1:5 (Department of Human Settlements, 2019, p. L.52), designed to handle a water depth of approximately 100 mm. The dimensions were selected to optimize the precision of a bioswale that would be encountered during field assessments (Shafique et al., 2018; Rujner et al., 2016).

Engineered soil medium characteristics and placement depth

In the urban environment, the unsaturated zone plays a crucial role in facilitating the healthy growth of ground cover, promoting infiltration, and maintaining soil water content within a bioswale. Classified as a bio-cell or bioretention system, the engineered soil medium is a vital component of the water balance in a bioswale. The characteristics of the engineered soil medium layers enhance infiltration rates and improve soil water content, although these rates can be influenced by macropores, mesopores, and micropores. This is due to the ability of plant growth to channel water across the unsaturated zone through preferential flows along root channels and root penetration into urban subsoil drainage systems (Jarvis and Larsbo, 2023; Beven and Germann, 1982). The engineered soil medium, when compared to a bio-cell as presented by Meneghelli (2019), has been shown to effectively reduce stormwater peak runoff volume and flow, while maintaining water quality, amenity, and biodiversity relative to SuDS (Armitage et al., 2013). The optimal characteristics for the soil within a bioswale's engineered soil medium are classified as sandy loam. The placement of the engineered soil is depicted in Fig. 1.

To ensure optimal drainage around an underlying drain in an urban environment, a 300 mm thick layer of clean, washed gravel with a particle size of 19 mm was placed at the base of the bioswale to support drainage and filtration. The gravel should be free of clay and organic matter to maintain its effectiveness. This grading meets commercial standards and is widely accepted in urban settings. The gravel layer facilitates efficient drainage and promotes greater infiltration compared to the growth medium, without hindering the infiltration rate. Additionally, a geofabric with a high infiltration rate can be used to separate the gravel layer from the growth medium.

The growth medium used in the experimental setup was designed to replicate the properties of sandy loam soil. It had a porosity factor of 0.5 and a sandy loam texture, composed of less than 3% clay, up to 70% sand, and up to 30% silt. The medium was placed in a 300 mm thick layer, consistent with the ideal characteristics outlined by Meneghelli (2019).

Indigenous ground cover categories

The study aimed to identify suitable grasses for indigenous ground cover categories native to the Gauteng region of South Africa, specifically for use in bioswales within urban environments, such as new developments or redevelopments (Armitage et al., 2014).

Three types of indigenous ground cover categories were identified as suitable options for bioswales. These categories include multiple plants of the same type that complement each other, rather than a single plant species. The selections, detailed in Table 2, were chosen for their ability to work synergistically, creating a cohesive and visually appealing landscape. Additionally, they provide essential bioswale functions such as erosion control, water absorption, and pollutant removal. The use of multiple plant species within each ground cover type ensures diversity and resilience, enhancing the bioswale's effectiveness in managing stormwater runoff and supporting local biodiversity.

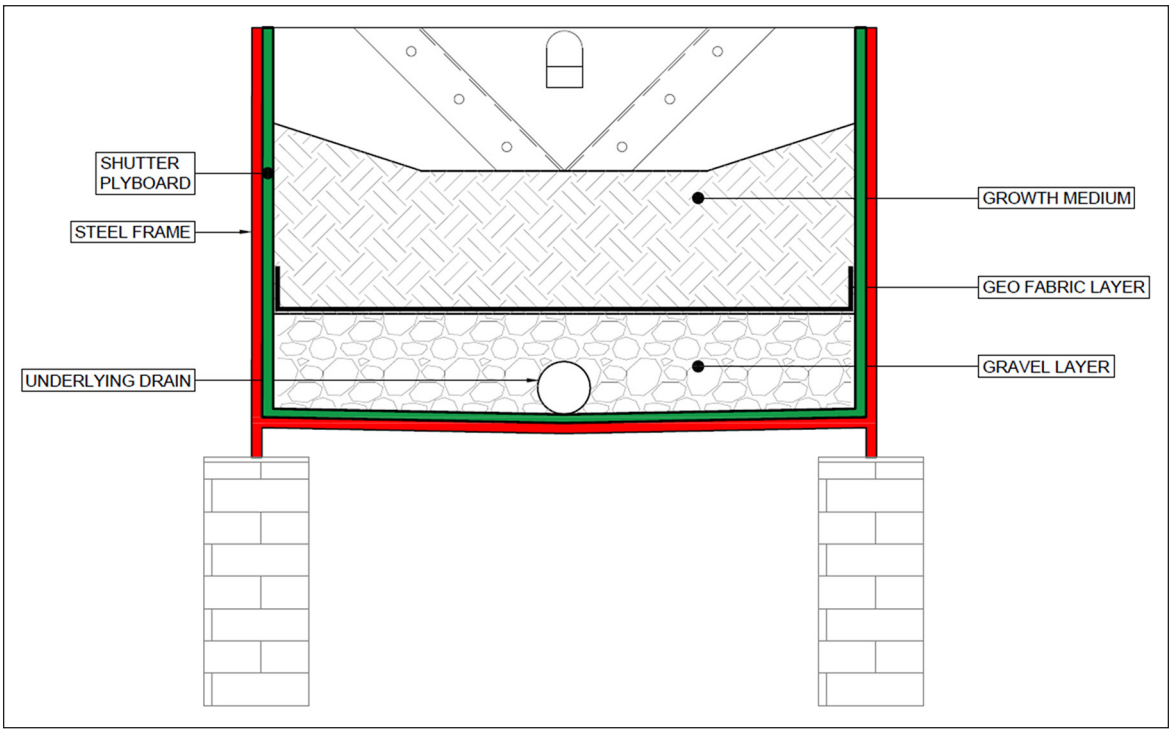

Figure 1. Section of the engineered soil medium

Table 2. Species selection for ground cover categories (sourced from Botha and Van der Walt, 2018)

Category	Scientific name	Common name	Plant No.
Lawn selection (3.6 m² area)	*Cynodon dactylon*	Bermuda / kweek / cynodon grass	
Ornamental grass selection (3.6 m² area)	*Eragrostis capensis*	Heart seed love grass	4
	Eragrostis planiculmis	Broom love grass	3
	Harpochloa falx	Caterpillar grass	4
	Pennisetum thunbergii	Fountain grass	3
	Schizachyrium sanguineum	Red autumn grass	4
Veld grass selection	*Andropogon eucomus*	Snowflake grass	3
	Aristida junciformis	Ngongoni three-awn	3
	Eragrostis capensis	Heart-seed love grass	3
	Eragrostis gummiflua	Gum grass	3
	Pennisetum thunbergii	Fountain grass	3
	Setaria incrassata	Vlei bristle grass	3

The identified categories are as follows:

Lawns: These species are commonly used as ground cover in gardens, parks, sports fields, and residential areas. When mowed and maintained, they form dense, even turf, making them ideal for grass swales and bioswales in Gauteng, South Africa. Their versatility and adaptability make them popular for various landscaping applications.

Ornamental grasses: These species are valued for their resilience to temperature changes, wetness, and drought. Landscapers appreciate their aesthetic appeal, and they are widely used for ornamental purposes. Native to Gauteng, these grasses are readily available and desirable for bioswales and other landscaping projects.

Veld grasses: Native to Africa and cultivated in their natural environment, these grasses are used in urban settings to promote indigenous biodiversity. Indigenous to Gauteng, they are commercially available and well-suited for bioswales.

Based on Botha and Van der Walt (2018), a selection of native species was made (Table 2) to ensure the effectiveness and sustainability of bioswales in urban environments.

Data collection

Data were collected from October 2023 to March 2024, during the summer season, which featured high temperatures, rainfall, and varying soil water content – ideal conditions for studying bioswale effects. This allowed for a quantitative approach to assess the impact of indigenous ground cover on reducing stormwater runoff peak and volume in bioswales. Measurements were taken weekly, including inflow and overflow volume and peak, infiltration volume and peak, and soil water content of engineered soil medium. This weekly data collection helped categorize antecedent moisture conditions as dry or wet, in relation to vegetation growth within the bioswale, using soil moisture sensors (Nishat et al., 2010).

Inflow volume and peak

The upstream flow and volume of water discharged into the bioswale were measured according to the calculated post-development 1-in-10-year stormwater runoff, while maintaining sub-critical water flow. These measurements were recorded as the inflow to the bioswale's water balance.

Two methods were employed for data collection: a 90-degree V-notch weir and a depth sensor. The 90-degree V-notch weir, selected for recording low flow rates, was used in conjunction with a liquid level sensor, allowing for the determination of water height with an accuracy of 0.005 m (Placidi et al., 2021). The dimensions of the 90-degree V-notch weir were 0.6 m wide by 0.3 m high, enabling the calculated water height to discharge as indicated in Table 3. These calculations (Eq. 2) of the water height were based on hydraulic methodologies by Shen (1981). Measurements were logged at 5-min intervals over a 1-h monitoring duration per assessment run, as documented by the Gauteng Provincial Government (2020 p. 13)

Table 3. Maximum sizing of 90-degree V-notch weir sizing

Parameters	Input values
Discharge (*Q*)	4.1 L/s
Gravity (g)	9.81 m/s²
V-notch weir angle (ø)	90°
C_d	0.59
Height of water	0.097 m
Freeboard allowed	0.100 m
Final depth of V-notch	0.197 m

$$Q = \frac{8}{15} C_d \sqrt{2g} \tan\left(\frac{ø}{2}\right) h^{5/2} \quad (2)$$

Based on Chadwick et al. (2004 p. 440), it was suggested that the Cd value for the angle of weir should be approximately 0.59 as a starting point. However, it is important to note that this value can be affected by several factors, such as the Reynolds number, Weber number, V-notch weir angle, and the height of the water.

Overflow water

The overflow from the bioswale that was measured represented the reduction of the simulated inflow rate of 4.1 L/s, based on the calculated post-development 1-in-10-year storm event. This reduction occurred either through absorption into the engineered soil medium or, if not absorbed, through infiltration.

These data were essential for determining the water balance of the bioswale concerning the discharge volume and peak of overflow. The primary objective was to evaluate the impact of indigenous ground cover categories on reducing stormwater runoff volume and peak. Data were recorded following the guidelines of the Gauteng Provincial Government (2020), at 5-min intervals over a 1-h monitoring duration. This approach was particularly relevant in Gauteng, where rainfall events are typically short and intense. The sensors facilitated the comparison of inflow and overflow data, enabling the creation of hydrographs.

Infiltration

The inflow water passes through the bioswale, where it is absorbed into the engineered soil medium via infiltration. Any overflow discharges out of the bioswale, while the infiltrated water percolates into the underdrain at varying infiltration rates, influenced by root structures. The water in the underdrain is then discharged into a centralized sump.

Measuring of the underdrain volume and peak was conducted before the centralized sump. This involved using a combination of liquid level sensors and a 90-degree V-notch weir. Water liquid level sensors were installed before the 90-degree V-notch weirs to accurately measure the water height with a precision of 0.005 m (Placidi et al., 2021).

These infiltration data contribute to the outcome of the total outflow volume for the water balance of the bioswale. The data collected were recorded at 5-min intervals over a 1-h monitoring duration following the guidelines of the Gauteng Provincial Government (2020).

Soil moisture content

Soil moisture content sensors were positioned at 2 locations along each 3.0 m bioswale, using a DFM 40 cm continuous logging soil moisture probe. Data were recorded every 15 min over a 1-h monitoring period during each water balance assessment.

These sensors, based on frequency domain reflectometry (FDR)/capacitance, measured the relative average soil volumetric water content (m^3 of water per m^3 of soil) over the probe's length (Rujner et al., 2016). They were placed at 0.75 m and 2.25 m along the bioswale to determine average moisture content across its length. These data helped assess the soil water content conditions of the engineered soil medium, in relation to root structures and soil temperature.

The probes were inserted at a 45° angle, 30 cm into the soil, to minimize flow obstruction within the planter tank, as suggested by Rujner et al. (2016). All data were logged and uploaded to a PC. The sensors also checked antecedent moisture conditions (AMC) relative to initial soil moisture content, determining if conditions were dry or wet (Nishat, Guo, and Baetz, 2010).

Environmental conditions

For each indigenous ground cover category, environmental conditions were recorded, including surface temperature, plant growth, and visual biodiversity influences that could promote the formation of macropores, mesopores, or micropores (Berland et al., 2017; Ow and Chow, 2021). These influences included insects and plant root growth, which could increase the infiltration rate. Visual conditions were documented for every assessment run to coincide with the water balance analysis.

Data analysis

The data analysis aimed to evaluate the impact of 3 indigenous ground cover categories – lawns, ornamental grass, and veld grass – on reducing stormwater runoff volume and peak. Data were collected using 90-degree V-notch weirs, ultrasound water level sensors, and soil moisture content sensors.

The analysis compared the effects of each ground cover on soil properties and hydrological effects in the bioswale. The focus was on the water balance, and soil moisture content, analysed in relation to the infiltration rate to understand the bioswale's performance.

Water balance analysis

The water balance analysis evaluated the hydrological performance of each bioswale with a pre-selected ground cover type, indicating necessary stormwater reductions for a post-development 1-in-10-year storm event.

Each run of the model used a calculated inflow rate to discharge into the bioswale, with a 30-min peak and a total monitoring duration of 1 h. Hydrological data for the inlet, underdrain, and overflow weirs were analysed for the following criteria: total inflow volume (V_{in}), overflow volume ($V_{overflow}$), underdrain volume ($V_{underdrain}$), total outflow volume (V_{TOut}), inlet peak flow rate (Q_{in}), overflow peak flow rate ($Q_{overflow}$), relative bioswale flow volume reduction (ΔV), and relative bioswale flow peak reductions (ΔQ_{pk}).

The data were based on 5 sensors measuring water height, working with corresponding 90-degree V-notch weirs. Sensors were placed in the stilling tanks at the start of each simulation model, as well as in the overflow and underdrain diversion channels before the weirs drained into the centralized sump. The volume passing each weir was determined using flow rate data at 5-min intervals to ensure consistent determination without overloading the sensor battery (Purvis et al., 2019).

The volume was calculated by considering the volumes corresponding to each individual weir for inlet, overflow, and infiltration (Eq. 3).

$$V = Q \times t \tag{3}$$

V represents volume (m^3); Q corresponds to the flow rate (m^3/s), t denotes the time interval, recorded every 300 s (5 min) to match the ultrasound depth sensor measurements. The total outflow volume (V_{TOut}) is the sum of the volumes from the underdrain ($V_{underdrain}$) and overflow ($V_{overflow}$) weirs (Eq. 4).

$$\text{Total outflow volume } (V_{TOut}) = V_{overflow} + V_{underdrain} \tag{4}$$

To determine the bioswale inlet volume reduction (ΔV) due to infiltration, the overflow volume ($V_{overflow}$) is subtracted from the inflow volume (V_{in}) (Eq. 5). This value represents the water that has entered the engineered soil medium, accounting for losses through evapotranspiration during the observation period. This information is crucial for assessing the effectiveness of bioswale networks in managing stormwater runoff (Purvis et al., 2019)

$$\text{Inlet volume reduction } (\Delta V) = \left(\frac{V_{in} - V_{overflow}}{V_{in}}\right) \times 100\% \tag{5}$$

To determine the relative bioswale peak flow reduction (ΔQ_{pk}) due to infiltration abstraction, one must first calculate the peak outflow of the overflow. This value is then subtracted from the inflow volume to obtain the volume reduction (Eq. 6)

$$\text{Peak flow reduction } (\Delta Q_{pk}) = \left(\frac{Q_{in} - Q_{over}}{Q_{in}}\right) \times 100\% \tag{6}$$

Soil water content analysis

An assessment was conducted to evaluate the impact of ground cover categories on the initial soil water content ($SWC_{initial}$) of the engineered soil medium and to understand dynamic changes in soil water content.

Two soil moisture probes were strategically placed within a planter box at 0.75 m and 2.25 m from the stilling tank (Fig. 2). Continuous monitoring was conducted every 15 min during the 1-h assessment. The collected data were analysed to determine the high (SWC_{high}) and mean (SWC_{mean}) soil water content values for each ground cover type. These values represent soil moisture levels relative to dry and wet antecedent moisture conditions (Nishat et al., 2010) at the start of a storm event. Measurements were taken as average soil volumetric water content in m^3 of water per m^3 of soil over the length of the soil moisture probe.

The study examined the relationships between initial soil water content ($SWC_{initial}$) and the water balance, considering the growth

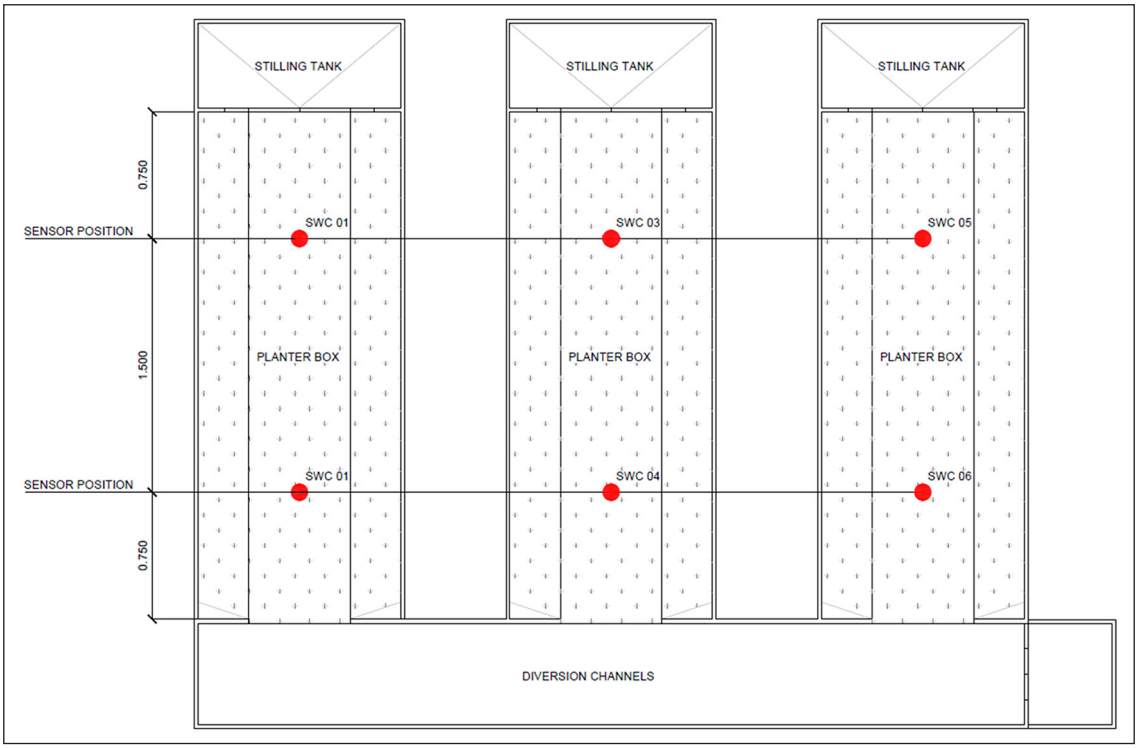

Figure 2. Sensor placement within planter boxes

Figure 3. Growth of veld grass category

of ground cover types and their influence on reducing stormwater peak and volume. It was reasonable to subdivide the initial soil water content ($SWC_{initial}$) into SWC_{high} and SWC_{mean} based on the statistical values acquired from the soil moisture probes.

RESULTS AND DISCUSSION

Field observation

The study investigated 3 ground cover categories: lawns, ornamental grasses, and veld grasses. These categories were monitored throughout the study to assess their effect on reducing stormwater runoff within bioswales. The ground cover was established using sods or seedlings specified in Table 2.

The progression and establishment of the veld grass category, as illustrated in Fig. 3, were achieved under natural conditions without the use of artificial lighting. Sunlight and surrounding biodiversity, including birds, insects, and worms, supported the growth process. This approach aimed to replicate field study conditions while maintaining control over the bioswale environment.

Figure 4 and Figure 5 indicate the growth and establishment of the ornamental grass category and lawn category, respectively. As illustrated in the figures, the ornamental grass category was established using sods, whereas the lawn was initiated from seedlings. As a result, data collection for the lawn category was postponed for a duration of 2 weeks as a consequence of the germination phase.

Two aspects were deliberately not controlled in order to assess their impact on the bioswale's ability to reduce stormwater runoff. Firstly, maintenance was not performed, simulating a scenario of neglect where plants grew naturally. Secondly, cross-contamination was allowed, as the indigenous ground cover was planted in an open environment, permitting natural biodiversity to cause unmonitored species cross-contamination.

Indigenous ground cover categories

The primary objective of this study was to evaluate the effects of 3 indigenous ground cover categories – lawns, ornamental grasses, and veld grasses (Table 2) – on the reduction of stormwater volume and peak flow within bioswales. To achieve this objective, the study focused on analysing water balance and soil water content for each bioswale.

Data collection and analysis were conducted from September 2023 to March 2024, coinciding with the South African summer season in the Gauteng region. The weather conditions during this period were predominantly hot, with limited rainfall until December, followed by heavier rainfall until February. Observations were made 24 h post-rainfall to minimize wet antecedent conditions.

Figure 4. Growth of ornamental grass category

Figure 5. Growth of lawn category

The following were observed during the study:

- **Ground cover establishment**: The indigenous ground covers established and thrived with minimal intervention, except for irrigation during each run of the model and natural precipitation. Consistent sunlight, with occasional cold weeks, supported plant growth. Initial growth was slow but accelerated significantly with the onset of summer rainfall.
- **Growth rates**: Among the ground covers, lawns established the fastest, followed by ornamental grasses and veld grass. Root structures of all categories extended to the geofabric without penetration. Lawns exhibited the highest root volume, while ornamental and veld grasses had comparable root volumes.
- **Infiltration rates**: The root structure of lawns initially enhanced infiltration rates but eventually became too dense, negatively impacting infiltration. Conversely, the root structures of ornamental and veld grasses grew at a slower pace, maintaining consistent infiltration rates throughout the study without becoming overly dense.
- **Biodiversity**: Biodiversity within each bioswale was rapidly established, with the presence of birds, bees, other insects, and worms contributing to the formation of macropores and enhancing infiltration. Birds also facilitated weed dispersal and thus contamination of bioswales with weed species, which further increased root structures within the bioswales.

Water balance analysis

A water balance analysis was conducted on 3 types of indigenous ground cover: lawns, ornamental grasses, and veld grasses. A total of 38 assessment runs were performed to evaluate the ground cover's effectiveness in reducing stormwater runoff. The objective was to assess the hydrological performance of each ground cover type and to identify any significant trends or differences in their ability to mitigate stormwater volume and peak flow.

Table 4 summarizes the recorded data for the three ground cover types, showing the hydrological performance of each bioswale in terms of water balance and soil water content throughout the study.

Table 4. Summary of water balance and soil moisture analysis by simulation and grass category

Category	Date	$SWC_{initial}$	SWC_{high}	SWC_{mean}	Temp. (°C)	V_{in} (m^3)	$V_{underflow}$ (m^3)	V_{TOut} (m^3)	ΔV	Q_{in} (L/s)	$Q_{overflow}$ (L/s)	ΔQ_{pk}
Lawn	2023/10/19	56.23	72.58	65.69	27	7.428	1.336	6.427	31.5%	2.94	2.94	29.9%
	2023/10/27	45.61	79.30	64.82	35	3.927	1.624	3.223	59.3%	2.15	0.94	56.0%
	2023/11/02	60.28	73.76	68.79	23	6.690	1.130	5.230	38.7%	3.88	2.44	36.9%
	2023/11/10	59.16	79.17	70.68	30	6.917	1.633	5.214	48.2%	3.78	2.08	45.0%
	2023/11/20	47.59	80.17	69.90	33	7.233	2.697	5.695	58.6%	4.08	1.94	52.5%
	2023/11/30	30.86	77.28	63.29	23	7.413	5.060	6.579	79.5%	4.08	0.99	75.8%
	2023/12/07	44.65	79.26	68.03	23	7.198	4.484	6.576	70.9%	3.98	1.50	62.3%
	2023/12/18	61.60	80.20	74.40	30	5.654	3.828	6.576	75.0%	3.02	0.81	72.9%
	2024/01/01	63.11	79.94	74.62	31	7.527	2.508	5.700	57.6%	4.08	2.01	50.9%
	2024/01/15	57.20	80.90	71.50	29	7.179	2.401	5.668	54.5%	3.98	1.51	49.6%
	2024/02/04	59.72	80.60	78.11	27	7.624	1.558	5.774	44.7%	4.08	2.52	38.2%
	2024/02/11	67.55	80.08	76.22	22	7.467	0.893	5.619	36.7%	4.19	2.77	34.0%
Ornamental grasses	2023/10/08	47.45	66.89	61.01	32	9.523	0.738	7.468	29.3%	5.47	3.88	29.1%
	2023/10/18	47.31	61.84	54.96	24	7.323	0.526	5.222	35.9%	4.19	2.77	34.0%
	2023/10/26	45.55	70.67	60.97	30	7.007	0.875	5.092	39.8%	3.88	2.44	36.9%
	2023/11/03	48.08	66.70	57.78	25	6.991	1.120	5.119	42.8%	3.98	2.37	40.5%
	2023/11/12	48.25	69.07	57.76	30	7.376	1.489	5.469	46.0%	4.19	2.44	41.7%
	2023/11/23	49.63	68.81	60.77	35	7.374	0.768	5.224	39.6%	4.08	2.60	36.3%
	2023/12/01	50.05	73.76	65.01	31	7.694	1.411	5.373	48.5%	4.08	2.29	43.9%
	2023/12/14	48.53	75.85	65.22	25	7.390	2.087	5.459	54.4%	4.08	2.15	47.4%
	2023/12/18	58.25	79.74	71.56	32	7.185	1.690	5.175	51.5%	3.98	2.08	47.8%
	2024/01/07	44.39	81.16	68.58	32	7.197	1.943	5.361	52.5%	4.08	2.15	47.4%
	2024/01/21	58.35	81.53	73.90	26	7.411	0.893	5.143	42.6%	4.08	2.52	38.2%
	2024/02/04	55.71	81.60	73.84	29	7.427	0.932	5.090	44.0%	4.08	2.44	40.1%
	2024/02/11	50.51	80.94	70.12	23	7.377	1.117	5.254	43.9%	4.08	2.44	40.1%
Veld grasses	2023/10/08	55.26	67.93	63.10	31	9.342	0.792	7.567	27.5%	5.85	4.75	18.9%
	2023/10/17	58.66	70.49	66.08	22	6.752	0.528	5.638	24.3%	3.78	2.94	22.2%
	2023/10/25	56.49	77.14	69.86	31	6.192	0.954	5.067	33.6%	3.48	2.44	29.8%
	2023/11/03	60.85	77.84	73.48	25	7.087	1.471	6.560	28.2%	4.08	3.02	26.0%
	2023/11/12	59.36	81.18	72.98	33	6.935	1.184	5.138	43.0%	3.88	2.44	36.9%
	2023/11/24	60.07	79.27	72.42	36	7.769	1.408	6.970	28.4%	4.41	3.29	25.3%
	2023/12/04	57.13	76.71	69.62	35	7.274	1.751	6.105	40.2%	4.08	2.60	36.3%
	2023/12/14	62.48	79.65	74.71	29	7.348	1.949	6.046	44.2%	4.08	2.52	38.2%
	2023/12/21	65.73	81.54	76.72	31	7.427	2.047	6.387	41.6%	4.08	2.60	36.3%
	2024/01/07	56.50	81.11	72.83	33	7.458	3.437	6.583	57.8%	4.08	2.08	49.2%
	2024/01/21	63.59	80.86	75.69	28	7.398	2.130	6.467	41.4%	4.08	2.52	38.2%
	2024/02/04	64.82	80.86	75.46	29	7.395	1.707	6.156	39.8%	4.08	2.60	36.3%
	2024/02/11	63.09	80.55	76.14	24	7.408	2.140	6.244	44.6%	4.08	2.44	40.1%

*SWC: soil water content

Inlet volume reduction

Inlet volume reduction (ΔV) is the decrease in water volume flowing through the bioswale and is calculated by comparing the inflow volume (V_{in}) to the overflow volume ($V_{overflow}$). This helps estimate the amount of water that would either be directed to local or regional control systems (like an attenuation pond) or absorbed into underdrains or the water table.

The reduction in volume is influenced by factors such as increased infiltration rates due to the capillary effect of the ground cover and water movement through root channels. Equation 5 was used for each run, and a monthly average was calculated to show the impact of indigenous ground cover growth, as detailed in Table 5.

Table 5 show that lawns had the most significant impact, reducing inlet volume by an average of 54.7% during the summer.

Lawns reduced inlet volume by 45.4% to 75%, with the highest reduction occurring in the first 3 to 4 months, especially during a 1-in-10-year storm event. After this period, their performance decreased, possibly due to root density, soil clogging, or capillary action. Lower rainfall in the early summer months also contributed to higher reductions, with soil water content increasing from December to March.

In comparison, ornamental grasses and veld grasses showed increases in inlet volume reduction of 42.2% and 39.1%, respectively. Ornamental grasses achieved monthly reductions of between 35.0% and 46.4%, while veld grasses' performance ranged from 23.6% to 43.7%.

Peak flow reduction

Peak flow reduction (ΔQ_{pk}) indicates the decrease in stormwater peak flow during an event. It depends on the extent to which the bioswale and ground cover can reduce the peak flow rate over a 3 m length, via infiltration, which is enhanced to vary degrees by the ground cover type. The reduction is greater due to the growth of the ground cover, increased roughness, and the ability of the ground cover to hold water in the unsaturated zone and engineered soil medium.

Equation 6 was used to determine ΔQ_{pk} for each run, and a monthly average was calculated to show the impact of plant growth on peak flow reduction for each ground cover type, as shown in Table 6.

Table 6 show that lawns achieved the highest peak flow reduction (ΔQ_{pk}), averaging 49.9% during the summer for a 1-in-10-year storm event. However, factors like increased soil water content, root growth, lack of maintenance, seasonal rainfall, and soil clogging caused the lawn's performance to decline over time. Monthly reductions ranged from 36.1% to 67.6%.

Ornamental grasses and veld grasses showed peak flow reductions of 40.4% and 34.4%, respectively. Ornamental grasses had monthly reductions between 33.3% and 46.4%, while veld grasses performance ranged from 23.6% to 43.7%.

Soil water content analysis

To assess the impact of indigenous ground cover on bioswales' hydrological performance in reducing stormwater runoff volume and peak flow, we monitored soil water content. This aimed to understand the effect of ground cover growth on the engineered soil medium, considering both the water within the soil and the amount held by plants through root capillary action and evapotranspiration.

Soil water content was analysed for each bioswale during each run using moisture sensors, as summarized in Tables 7 to 9. This analysis was conducted only when the antecedent moisture content was very low, as recommended by Nishat et al. (2010). This section compares soil water content and elaborates on findings and general observations.

The soil water content parameters considered were:

- Initial soil water content ($SWC_{initial}$)
- Highest soil water content (SWC_{high})
- Mean soil water content (SWC_{mean})

Based on the analysis in Tables 7 to 9, the study tracked the establishment of various ground cover categories and noted an

Table 5. Inlet volume reduction per month

Category	Average monthly reduction in inlet volume						Average reduction for the study period
	September	October	November	December	January	February	
Lawn	-	45.4%	56.2%	75.0%	50.2%	40.7%	54.7%
Ornamental grasses	-	35.0%	42.8%	46.4%	42.8%	44.0%	42.2%
Veld grasses	-	28.5%	33.2%	42.0%	49.6%	42.2%	39.1%

Table 6. Peak flow reduction per month

Category	Average monthly reduction in peak flow						Average reduction for the study period
	September	October	November	December	January	February	
Lawn	-	43.0%	56.2%	67.6%	50.2%	36.1%	49.9%
Ornamental grasses	-	33.3%	39.5%	46.4%	42.8%	40.1%	40.4%
Veld grasses	-	23.6%	29.4%	36.9%	43.7%	38.3%	34.4%

Table 7. Increase in $SWC_{initial}$ per category

Category	Average monthly $SWC_{initial}$						Overall increase in $SWC_{initial}$ for the study period
	September	October	November	December	January	February	
Lawn	-	50.9%	49.5%	53.1%	60.1%	63.6%	20.0%
Ornamental grasses	-	46.8%	48.7%	52.3%	51.4%	53.1%	11.9%
Veld grasses	-	56.8%	60.1%	61.8%	60.0%	64.0%	11.2%

Table 8. Increase in SWC_{high} per category

Category	Average monthly SWC_{high}						Overall increase in SWC_{high} for the study period
	September	October	November	December	January	February	
Lawn	-	75.9%	77.6%	79.7%	80.4%	80.3%	5.4%
Ornamental grasses	-	66.5%	68.2%	76.5%	81.2%	81.3%	18.2%
Veld grasses	-	71.9%	79.4%	79.3%	81.0%	80.7%	11.0%

Table 9. Increase in SWC_{mean} per category

Category	Average monthly SWC_{mean}						Overall increase in SWC_{mean} for the study period
	September	October	November	December	January	February	
Lawn	-	65.3%	68.2%	71.2%	73.0%	76.8%	15.0%
Ornamental grasses	-	59.0%	58.8%	67.3%	68.6%	72.0%	18.1%
Veld grasses	-	66.3%	73.0%	73.7%	74.3%	74.3%	12.1%

increase in soil water content over time.

- **Initial soil water content** increased by 20% for lawns, 11.9% for ornamental grasses, and 11.2% for veld grasses.
- **Soil saturation (SWC_{high})** increased by 5.4% for lawns, 18.2% for ornamental grasses, and 11.0% for veld grasses.
- **Mean soil water content** increased by 15.0% for lawns, 18.1% for ornamental grasses, and 12.1% for veld grasses.

These increases impacted the engineered soil medium as the ground cover established, due to the plants' ability to hold water through capillary action. The findings also considered the water balance criteria, such as inlet volume reduction (ΔV) and peak flow reduction (ΔQ_{pk}), in relation to the initial soil water content.

CONCLUSION

After conducting 38 simulation runs, the study found that indigenous ground cover categories positively impact the hydrological performance of bioswales by reducing stormwater runoff volume and peak flow. Each ground cover type improved inlet volume reduction (ΔV) and peak flow reduction (ΔQ_{pk}), showing that selecting the right ground cover can maximize stormwater control and provide economic and environmental benefits.

The study revealed that the infiltration rate of bioswales is significantly influenced by different indigenous ground covers, provided they are constructed and maintained according to standards like the 'South African guidelines for sustainable drainage systems' (Armitage et al., 2013) and the 'SuDS manual' (Woods Ballard et al., 2015). Increased infiltration is likely due to root structures creating preferential flow channels, increased soil porosity, and enhanced biodiversity.

Key findings include:

Lawn: Highest average inlet volume reduction (54.7%) and peak flow reduction (49.9%) during summer, but performance declined after 3 months without maintenance. The soil water content of the soil increased by 15%.

Ornamental grasses: Consistent inlet volume reduction (42.2%) and peak flow reduction (40.4%), requiring less maintenance than lawns. The soil water content of the soil increased by 18.1%.

Veld grasses: Steady increase in inlet volume reduction (39.1%) and peak flow reduction (34.4%). The soil water content of the soil increased by 12.1%.

Lawns had a significant impact on stormwater system sizing and flash flooding mitigation but required more frequent maintenance. Ornamental and veld grasses showed more consistent performance with lower maintenance needs, though with a smaller impact on stormwater infrastructure costs.

These findings highlight the importance of selecting appropriate ground cover types to optimize the performance and cost-efficiency of stormwater management systems. Incorporating a monitoring plan into the design is essential to determine the best timing for maintenance, enhancing the effectiveness of bioswales in reducing stormwater runoff peaks and volumes.

In conclusion, indigenous ground covers in bioswales can significantly reduce stormwater volume and peak discharge. Lawns had the most significant impact but required more maintenance, while ornamental and veld grasses offered more stable performance with less maintenance. These insights can help design engineers optimize bioswales for stormwater management, cost efficiency, and improved downstream control.

RECOMMENDATIONS

Long-term studies should be conducted on the effect of various ground covers on bioswales, due to limited literature on the use of indigenous ground covers in optimising bioswales, particularly in developing countries.

These studies should consider the effects of various seasons, include comparison of multiple years, and determine the perfect mixture of vegetation to optimise the infiltration rate, assessing the impact at various locations in South Africa and globally, and for multiple different storm occurrences, using characteristics specific to each province or geographic location.

Additional factors that could be studied for bioswales are the water balance and infiltration rate under different ground cover categories, effects of soil water content on each ground cover type, and various soil applications and their potential advantages. It is also recommended that maintenance of bioswales should be studied based on stormwater control versus the impacts of the ground cover type, design specifications, and the economics or reasonability of upkeep.

Development of a South African guideline on bioswales relative to various design parameters and specifications would aid in the enhancement of stormwater management, while mitigating the impact of urbanization. A guideline should be developed which would expand on design principles and practical implementation strategies to suit various environmental, geological, and topographical situations.

ORCIDS

Gavin Melvin Oberem
https://orcid.org/0009-0006-6611-8310

J Snyman
https://orcid.org/0000-0003-2309-4153

EA Burger
https://orcid.org/0000-0002-4645-2075

REFERENCES

AHMED F, GULLIVER J and NIEBER J (2015) Field infiltration measurements in grassed roadside drainage ditches: Spatial and temporal variability. *J. Hydrol.* **530** 604–611. https://doi.org/10.1016/j.jhydrol.2015.10.012

ARMITAGE N, VICE M, FISHER-JEFFES L, SPIEGEL A and DUNSTAN J (2013) Alternative technology for stormwater management: South African Guidelines for Sustainable Drainage Systems. WRC Report No. TT 558/13. Water Research Commission, Pretoria. 57 pp.

BERLAND A, SHIFLETT SA, SHUSTER WD, GARMESTANI AS, GODDARD HC, HERRMANN DL and HOPTON ME (2017) The role of trees in urban stormwater management. *Landscape Urb. Plann.* **162** 167–177. https://doi.org/10.1016/j.landurbplan.2017.02.017

BEVEN K and GERMANN P (1982) Macropores and water flow in soils. *Water Resour. Res.* **18** (5) 1311–1325. https://doi.org/10.1029/wr018i005p01311

BOTHA W and VAN DER WALT I (2018) *A Practical Grass Selection Guide (South Africa)* (1st edn) Diverse Ecological Solutions, Pretoria. 184 pp.

BRABEC E, SCHULTE S and RICHARDS PL (2002) Impervious surfaces and water quality: a review of current literature and its implications for watershed planning. *Journal Plann. Lit.* **16** (4) 499–514. https://doi.org/10.1177/088541202400903563

CHADWICK A, MORFETT J and BORTHWICK M (2004) *Hydraulics in Civil and Environmental Engineering* (4th edn) Spon Press, London. 644 pp.

DINIĆ-BRANKOVIĆ M, BOGDANOVIĆ-PROTIĆ I, MITKOVIĆ P, IGIĆ M and ĐEKIĆ D (2018) Bioswales as elements of green infrastructure – foreign practice and possibilities of use in the district of the City of Niš, Serbia. Presented at: ICUP, 14–17 November 2018, Niš.

FLETCHER TD, SHUSTER W, HUNT WF, ASHLEY R, BUTLER DS, ARTHUR S, TROWSDALE S, BARRAUD S, SEMADENI-DAVIES A, BERTRAND-KRAJEWSKI JL and MIKKELSEN PS (2015) SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. *Urb. Water J.* **12** (7) 525–542. https://doi.org/10.1080/1573062x.2014.916314

GAUTENG PROVINCIAL GOVERNMENT (2020) Literature review on SuDS: definitions, science, data, policy and legal context in South Africa. GT/GDARD/094/2018 ed. Gauteng Provincial Government, Johannesburg.

JARVIS N and LARSBO M (2023) Macropores and macropore flow. In: Goss MJ and Oliver M (eds) *Encyclopedia of Soils in the Environment* (2nd edn). Academic Press. 306–313. https://doi.org/10.1016/B978-0-12-822974-3.00098-7

MENEGHELLI J (2019) SUDS for the City of Johannesburg: Engineered soil filter media function and design. SAICE CoJ Stormwater Manual Conference, 25–26 June 2019, University of the Witwatersrand.

MORBIDELLI R, SALTALIPPI C, FLAMMINI A, CIFRODELLI M, PICCIAFUOCO T, CORRADINI C and GOVINDARAJU RS (2016) Laboratory investigation on the role of slope on infiltration over grassy soils. *J. Hydrol.* **543** 542–547. https://doi.org/10.1016/j.jhydrol.2016.10.024

NISHAT S, GUO Y and BAETZ B (2010) Antecedent soil moisture conditions of different soil types in South-western Ontario, Canada. *Hydrol. Process.* **24** (17) 2417–2424. https://doi.org/10.1002/hyp.7647

OW L and CHOW D (2021) Urban stormwater management: can tree roots and structural soils improve hydraulic conductivity into compacted soils? *Arboricult. Urb. For.* **47** (2). https://doi.org/10.48044/jauf.2021.007

PLACIDI P, MORBIDELLI R, FORTUNATI D, PAPINI N, GOBBI F and SCORZONI A (2021) Monitoring soil and ambient parameters in the IoT precision agriculture scenario: An original modeling approach dedicated to low-cost soil water content sensors. *Sensors* **21** (15) 5110. https://doi.org/10.3390/s21155110

PURVIS RA, WINSTON RJ, HUNT WF, LIPSCOMB B, NARAYANASWAMY K, MCDANIEL A, LAUFFER MS and LIBES S (2019) Evaluating the hydrologic benefits of a bioswale in Brunswick County, North Carolina (NC), USA. *Water* **11** (6) 1291. https://doi.org/10.3390/w11061291

RUJNER H, GÜNTHER L, PERTTU AM, MARSALEK J and VIKLANDER M (2016) Advancing green infrastructure design: Field evaluation of grassed urban drainage swales. In: *Proc. Novatech 2016 9th International Conference on Planning and Technologies for Sustainable Urban Water Management*, 28 June – 1 July 2016, Lyon.

RUJNER H, LEONHARDT G, MARSALEK J, PERTTU AM and VIKLANDER M (2018) The effects of initial soil moisture conditions on swale flow hydrographs. *Hydrol. Process.* **32** (5) 644–654. https://doi.org/10.1002/hyp.11446

SANRAL (2013) *Drainage Manual* (6th edn.) South African National Roads Agency Ltd., Johannesburg.

SHAFIQUE M, KIM R and KYUNG-HO K (2018) Evaluating the capability of grass swale for the rainfall runoff reduction from an urban parking lot, Korea. *Int. J. Environ. Res. Public Health* **15** (3) 537. https://doi.org/10.3390/ijerph15030537

SHEN J (1981) Discharge characteristics of triangular-notch thin-plate weirs. United States Department of the Interior, Geological Survey. https://doi.org/10.3133/wsp1617b

SMITHERS J (2012) Methods for design flood estimation in South Africa. *Water SA* **38** (4) 633–646. https://doi.org/10.4314/wsa.v38i4.19

THE ENGINEERING TOOLBOX (2004) Manning's roughness coefficients. URL: https://www.engineeringtoolbox.com/mannings-roughness-d_799.html (Accessed 18 June 2023).

WOODS BALLARD B, WILSON S, UDALE-CLARKE H, ILLMAN S, SCOTT T, ASHLEY R and KELLAGHER R (2015) *The SuDs Manual.* Version 6. CIRIA, London. 888 pp.

XIAO Q, MCPHERSON EG, ZHANG Q, GE X and DAHLGREN R (2017) Performance of two bioswales on urban runoff management. *Infrastructures* **2** (4) 12. https://doi.org/10.3390/infrastructures2040012