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Green roofs and stormwater runoff quality in the urban landscape in South Africa

Arisha Sucheran[1], Reshma Sucheran[2*]

Engineering Unit, eThekwini Municipality, Durban, South Africa
Faculty of Management Sciences, Durban Univerity of Technology, Durban, South Africa

Corresponding author. E-mail : reshma@dut.ac.za

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Abstract

A number of sustainable urban drainage systems (SuDS), such as green roofs, are being developed and implemented in cities around the world to help reduce stormwater runoff and improve stormwater runoff quality. This study compares the water quality of green roofs with that of conventional roofs in the eThekwini region, South Africa. Samples of stormwater runoff from the different green roof systems on the eThekwini Green Roof Pilot Project were collected to test their level of contaminants and pollutants. The tests focused on all physical, aesthetic, chemical, and microbiological determinants pertaining to stormwater runoff. For all tests, the level of contaminants and pollutants were measured against the South African Water Quality Guidelines Volume 7 for Aquatic Ecosystems. The data revealed significant variations in pollutant concentrations between the green roofs and the conventional roof. Moreover, runoff water quality varied across the various roof types, which may indicate that the substrate composition has the greatest impact on green roof performance regarding rainwater quality. Overall, the results suggest that these green roof systems do not have the ability to filter pollutants out of stormwater runoff, but rather increase their levels of concentration.

Keywords: *green roofs, water quality, stormwater, urban areas, environment*

1. Introduction

The urgency to implement environmental policies and practices has emerged from the realization that urbanization is taking place far more rapidly than planning solutions are to deal with the problem of rapid urbanization [1]. Major land-use changes in built-up urban environments have altered natural landscapes leading to disastrous consequences to urban ecosystems. In particular, inappropriate urban development has resulted in increased runoff and contaminant loads, and therefore, urban storm water often results in a significant deterioration of receiving freshwater systems due to pollution, unnatural flow regimes and habitat disturbance [1, 2]. With the continued rapid rate of urbanization, the pressure on urban water demand will also escalate, causing stress on the current water systems. Cities around the world are facing severe storm water related issues such as water scarcity, degraded waterways, increased flooding, degradation of the quality of water bodies that receive surface run-off and ageing infrastructure [1-4].

These impacts are estimated to increase with climate change. Urban areas are further challenged by extensive impervious surfaces, damaged soils, and little room for green spaces or for storm water management facilities [1]. In response to these impacts, a number of sustainable urban drainage systems (SuDS) have been developed and put into operation in numerous cities in the last three decades. SuDS allows storm water to infiltrate, evaporate, run off, and/or be used on-site [4-6]. Examples of SuDS include green roofs, rainwater harvesting, soakaways, permeable pavements, filter strips, swales, detention ponds, retention ponds, and constructed wetlands [7].

Green roofs in particular, have the capability to filter storm water through their soil and vegetation layers, and are based on the idea that the green space consumed by the footprint of buildings should be replaced [8]. There are a number of environmental benefits associated with green roofs which include stormwater management, the lowering of building temperatures, the insulating of buildings, and a positive contribution to human well-being [1, 7, 8]. Green roofs are further known to offer an array of advantages in terms of stormwater runoff, including their ability to temporarily and permanently store runoff, and improve runoff quality [4, 9]. Water quality is defined as the chemical, physical and biological constituents of a specific water sample, and the implementation of green roofs allows for the filtration of stormwater runoff and therefore, the improvement of the quality of water entering our waterways and water sources. During a rainfall event, stormwater runoff that travels through a green roof system can either be filtered or contaminated by the different plant types or by the constituents of the substrate layer. Studies have also demonstrated that green roofs can act as a filter for pollutants and have the capability of improving stormwater runoff quality [10, 11].

Green infrastructure within the South African context involves many green agendas but places more emphasis on the preservation of biodiversity within the country [12]. Implementing green roofs in South Africa has not been seen as a priority, with the only motivation for the implementation being the additional points allocated by the Green Building Council of South Africa (GBCSA) when a building is being assessed [13]. The poor integration of storm water management with the rest of the urban water cycle implies the lack of a holistic approach by South African municipalities in covering all aspects of water services [14]. Storm water is often managed as a potential flood hazard and disposed of as rapidly as possible. This approach focuses on managing water quantity and ignores the management of water quality. It is against this background that the study assessed the potential of stormwater runoff from green roofs in enhancing water quality. The study analysed and compared the quality of stormwater runoff from the eThekwini Municipality Green Roof Pilot Project with that of freshwater body standards. In particular, the study examined the quality of stormwater runoff data captured from the green roofs in terms of physical, chemical, microbiological and organic determinants, that affect stormwater discharge into freshwater ecosystems.

1.1 Literature Review

The demands of an escalating urban population have reduced the available land for green spaces in urban areas [15, 16], which in turn has led to an increase in impervious surfaces [1, 4]. Pavement and paved areas reduce the infiltration of groundwater, and increase the proportion of water going to surface overland flow. When surfaces are paved, vegetation that originally provided interception and evapotranspiration is removed, and natural depressions in the landscape, which normally detain up to 50% of the runoff, are eradicated. This substantially increases the volume and rate at which the runoff is delivered to the receiving water bodies, resulting in a greater recurrence of floods [4]. In addition to exacerbating flooding, erosion and sedimentation, urban runoff is also high in pollutants such as pesticides and petroleum residues which harm wildlife habitats and contaminate drinking supplies, and this poses a great challenge for urban stormwater systems. Essentially, the urban water cycle has replaced the natural water cycle, which adds to water stress and water insecurity.

Municipal stormwater managers now have to contemplate various management and engineering options that consider these environmental impacts in urban areas. In particular, the creation of more green spaces is crucial for greener urbanization [1]. Sustainable drainage systems (SuDS) are therefore now favoured, as they mimic the hydrological process that would have taken place, had the site not been developed [6]. The increasing interest in green infrastructure is due to the need to improve water management as a result of the growing demand for freshwater and the impacts of climate change. Green infrastructure is therefore seen as an environmentally appropriate solution to water infrastructure solutions. New approaches to green infrastructure in stormwater management include the principles and applications of Sustainable Urban Drainage Systems (SuDS), Low Impact Development (LID) or Water Sensitive Urban Design (WSUD) [16]. The natural vegetation in SuDS helps to attenuate water flow, trap pollutants, promote infiltration, enhance evapotranspiration and reduce the urban heat island effect. However, limited land space and the high land prices in urban areas has made the creation of green spaces rather expensive or virtually impossible [17].

Given that between 40% to 50% of impermeable spaces in urban areas consists of unused roof areas [8], green roofs are considered as an appropriate alternative towards sustainable urban stormwater. Green roofs are becoming increasingly popular in SuDS and are regarded as a suitable technology as there is limited space to implement other types of stormwater controls in urban areas [7]. Land values are often too high in urban areas to allocate much surface area to stormwater control devices. Through green roofs, the impervious area is decreased when planted roofs are installed on, or retrofitted to buildings, as they contribute to the reduction of peak flow rates and runoff volumes collected by drainage systems [15]. Moreover, green roofs are considered favourable for SuDS as they do not require any further land-take requirements, apart from the footprint of the building.

Research confirms that while green roofs can act as pollution absorbents and filters and provide benefits in terms of stormwater quantity (7, 16, 18-21], they can also potentially contribute to the degradation of the quality of receiving waters with pollutants released from soil, plants and fertilizers (3, 17, 22-24]. Some studies cite an improvement in water quality [3, 22], as green roofs help neutralize acidic rain and reduce the amount of pollutants [11, 23], which results in the production of better quality stormwater runoff. Similarly, Palla et al. [16] found that green roofs are able to lower pollutant loads associated with the early stages of rainfall, whilst Van Seters et al. [23], in their study of runoff samples from an extensive green roof in Toronto, found that concentrations of most pollutants were lower in the runoff from the green roof relative to that from the conventional roof with the exception of Ca, Mg, and total P. Conversely, several investigations confirmed that runoff from green roofs have a higher concentration of most nutrients [10, 15, 17, 21]. Moran et al. [18] undertook a study of green roofs in Northern Carolina and found that, water quality data revealed higher contaminants and nutrient concentrations in the green roof runoff than those in the rainfall and control roof runoff. Common contaminants in urban stormwater runoff include heavy metals, petroleum hydrocarbons, pesticides, suspended solids, nutrients, and pathogenic micro- organisms. Vijayaraghavan and Joshi [10] observed that runoff comprises significant quantities of Na, K, Ca, Mg, NO3 and PO4. Teemusk and Mander [24] maintain that the slower the runoff rate, the higher the concentration of total N, NH4-N and organic material (BOD and COD) in the runoff water. Research therefore corroborates that green roofs may have different effects on stormwater quality with the possibility of both filtration and contamination.

1.2 Stormwater pollutants

Generally, rainwater contains a small amount of phosphorous. Contamination of urban runoff with phosphorous may come from fertilizers, bird droppings and animal excreta. Several studies have concluded that green roofs are a source of phosphorous in runoff (22, 24, 25, 26], with varying concentrations of phosphorous in green roof runoff [17] ranging from 0.006mg/L [27] to 66.0mg/L [28]. Other researchers reported phosphorus concentrations ranging from 0.012 mg/L to 0.09 mg/L for a 1–2-year-old green roof [24], and higher concentrations of 0.23–0.45 mg/L [23], 0.6–1.5 mg/L [18], 0.31 mg/L [26], 0.6–1.4 mg/L [25] and 2–3 mg/L [29]. Conversely, a study undertaken by Zhang et al. (8) in China claimed that the average total phosphorous concentration of the rainwater (0.035 mg/L) samples was significantly lower than that of the green roof runoff (0.113 mg/L), and asphalt roof runoff (0.091 mg/L).

Nitrogen in soil is found as NO3-N and NH4-N. Excess nitrogen levels in natural water bodies can speed up the growth of algae and other aquatic plants, which leads to unpleasant odours and lowered dissolved oxygen levels which is detriment to marine life [30]. Some studies have reported decreased total nitrogen in green roof runoff [8, 20, 27] and other studies have shown unchanged concentrations (24, 26, 31]. Teemusk and Mander [24] also found that green roofs released more NH4+-N after heavy rain-storms. Zhang et al (8) reported that the green roof increased the concentrations of total nitrogen, NH4+-N, NO3−-N in stormwater runoff, which are believed to be released from the roof substrate, whilst Berndtsson [17] maintains that concentrations of nitrogen in green roof runoff can be attributed to the type of soil, the age of the green roof and maintenance of the roof.

Anything that changes the chemical balance of waterways may be detrimental to aquatic plants and animals. pH is an indicator of this imbalance and improving water quality by buffering pH is one of the most important effects of green roofs [15, 16, 29]. Berghage et al. [15] found that green roofs increased the pH of runoff compared to flat asphalt roofs, and reported that the pH of runoff from the asphalt roofs ranged from 4 to 7, while runoff from the green roofs was consistently above 6.4. Zhang et al. (8) conducted a study on the capacity of green roofs to reduce stormwater runoff and pollutants in a typical area of acid rain in China. The study identified the mean pH of rainfall as 5.61. However, the pH value increased to a mean value of 6.84 when the rain-water flowed through the green roof, confirming the potential of green roofs to neutralize local rainwater. Zhang et al. (8) also found that the average pH was significantly higher for the asphalt roof (pH 7.35) compared to the green roof runoff (pH 6.84).

Suspended solids form the largest pollutant constituents in stormwater. The accumulation of suspended solids leads to negative impacts on the environment, including: an increase in turbidity, making it difficult for aquatic ecosystem to function normally; a decrease in light for photosynthesis; the contamination of gills in fish and aquatic species; the reduction in spawning of fish and general survival; and an increase in the transportation of heavy metals, phosphorous and other pollutants through waterways as they attach to the sediment particles and harm water quality [8]. Suspended solids are defined as particles that cannot pass through a 2-micron filter (EPA Method 340), and comprise clays, silts, fine organic debris and other suspended particulate matter. Turbidity is one of the first measurements of water quality, and is a measurement of the amount of light that can pass through the water sample without being scattered by particles. Green roofs can increase suspended solids and turbidity after installation. Morgan et al. [32] found high TSS values (1050 to 250 mg/L) after the first watering event as compared to the second (300 to 75 mg/L) of a newly installed green roof. Gnecco [33] reported that green roof substrate only slightly contributes to the delivery of solids into the drainage network, and Morgan et al. [32] therefore concluded that TSS and turbidity decrease over time after installing green roofs.

Heavy metals are normally present in stormwater runoff, as a result of passing over polluted surfaces. They are not biodegradable and are therefore harmful to aquatic life. Metals that are usually measured for stormwater quality include zinc, cadmium, lead, copper, manganese, nickel, cobalt, vanadium, and chromium. Large proportions of these are found in stormwater, especially the runoff collected from roofs and street surfaces. The assessment of heavy metals in stormwater is very important due to their toxicity for living organisms and the fact that heavy metals cannot be easily transformed or removed from water. The content of heavy metals in stormwater varies depending on the site, rain intensity and rain duration [34], and Berndtsson et al. [22] claim that any concentration of heavy metals in green roof runoff usually corresponds to that of moderately polluted natural water. Zhang et al (8) found that the average F−, Cl−, SO42−, K+, Ca2+, and Si4+ concentrations of the green roof runoff samples were considerably higher than those of the asphalt roof runoff. In particular, Copper (Cu) and Zinc (Zn) have been the two metals most commonly found in green roof runoff [15, 26]. However, Gnecco et al. [33] reported that the water quality data of Cu, Fe, and Zn confirmed that the concentration of heavy metals in green roof outflows was generally lower in comparison to urban impervious areas. Van Seters et al. [23] undertook a study on the green roof at York University in Toronto and reported that higher detection frequencies of lead, nickel, cadmium, and beryllium were found in green roof samples whilst runoff from the conventional roofs revealed higher mean concentrations of copper, zinc and manganese. Vijayaraghavan et al. [28], found that for conductivity and salinity, green roofs act as a source by increasing the concentration of ions in the runoff. Runoff from green roofs were found to contain high concentrations of light metals such as Na, K, Ca and Mg. Release of heavy metals such as Fe, Cu and Al was also observed in green roofs on several instances. Gnecco et al. [33] found that the green roof substrate was the main source of calcium and potassium, and concluded that potassium behaves as a pollutant source in green roofs while zinc and copper was retained by the green roofs. Gregoire and Clausen [31] observed that total nitrogen and NO3+NO2–N concentrations were not significantly different between green roof runoff and precipitation. The green roof acted as a sink for NH3–N, Pb and Zn, and was a source of NO3+NO2–N, total phosphorous, PO4–P, and Cu. The likely source of Cu was attributed to the type of fertilizer that was used.

Generally, stormwater harvested on green roofs has some level of faecal contamination, the main sources of which are animal faeces, vegetation and air pollution. Factors that determine the microbiological quality of stormwater include: type of roof materials, roof contamination, rain intensity and the length of dry periods between rain events. Microbiological contamination tends to increase with the increased intervals between rainfalls events. Common indicators to assess the microbiological components of stormwater are faecal coliform, faecal streptococci and E. coli [34].

Overall, a number of studies have focused on the runoff quality from green roofs and have shown that green roofs can filter and absorb pollutants [26]. However, in the long-term, green roofs can also contribute to the deterioration of runoff water quality by releasing fertilizers regarded as pollutants [17, 24). The differences in runoff quality as indicated by various studies are largely attributed to variations in green roof construction and maintenance. Other factors that further affect green roof runoff quality include the type of material used in green roof construction (soil, drainage material or hard roof material), soil thickness, type of drainage, vegetation type, dynamics of precipitation; source of local pollution and physio-chemical properties of pollutants [17], composition of the substrate; age of the green roof; and maintenance [10, 11]. In terms of the age of a green roof, Vijayaraghavan and Joshi [10] also conclude that the quality of runoff in the first year of a green roof may not be representative of the runoff from a much older and established green roof.

2. Materials and Methods

2.1 Study Area and Site

The eThekwini region, or Durban, is located on the south-eastern coast of South Africa, in the province of KwaZulu-Natal (KZN) (Fig.1). The region covers approximately 98 km of coastline, along with 18 river catchments, 16 estuaries, and over 4 000 kilometres of rivers. The eThekwini region has a population of 3.9 million people, accounting for 34.7% of the total population of the KwaZulu-Natal Province. eThekwini's population is estimated to grow at a steady rate over the next few decades with a projected population size of between 4.1 and 4.5 million by 2035 [35]. The region receives an average of 828 millimetres (mm) (32.6 inches) of rainfall per year. The driest weather is in October when an average of 9 mm (0.4 in) of rainfall (precipitation) occurs. The eThekwini Climate Change Strategy has identified a positive rise in temperature and rainfall into the year 2065 and a 500mm increase in rainfall between 2065 and 2100. This means that more intense and frequent storms are expected, and are evident in the weather patterns seen in eThekwini Municipality in the past decade [35].

The study experiment was conducted on the eThekwini Green Roof Pilot Project under natural weather conditions. The Green Roof Pilot Project is part of the eThekwini Municipality’s Municipal Climate Protection Programme. This programme was initiated by the eThekwini Municipality’s Environmental Planning and Climate Protection Department and was launched on 22 May 2009. The aim of the project was to understand the city’s resilience to climate change, based on projections of increased levels of surface runoff and flooding that result from the increase of non-permeable surfaces in the city, and to explore the extent to which green roof habitats can assist in reducing temperatures and stormwater run-off, thereby enhancing the city’s adaptive capacity [35]. In particular, the Green Roof Pilot Project aimed to test green roofs in terms of their stormwater and temperature benefits [36]. The project site is on the roof of a building within the eThekwini Municipality’s Old Fort Complex in the city. This particular roof was selected for the project due to the fact that it is flat, easily accessible, and located within a secure complex. Structural engineers confirmed that the roof is capable of withstanding the additional loading from the retrofitted green roof systems [37]. The physical address of this Green Roof Pilot Project is 166 KE Masinga Road, and Fig. 1 illustrates the location and characteristics of the study site.

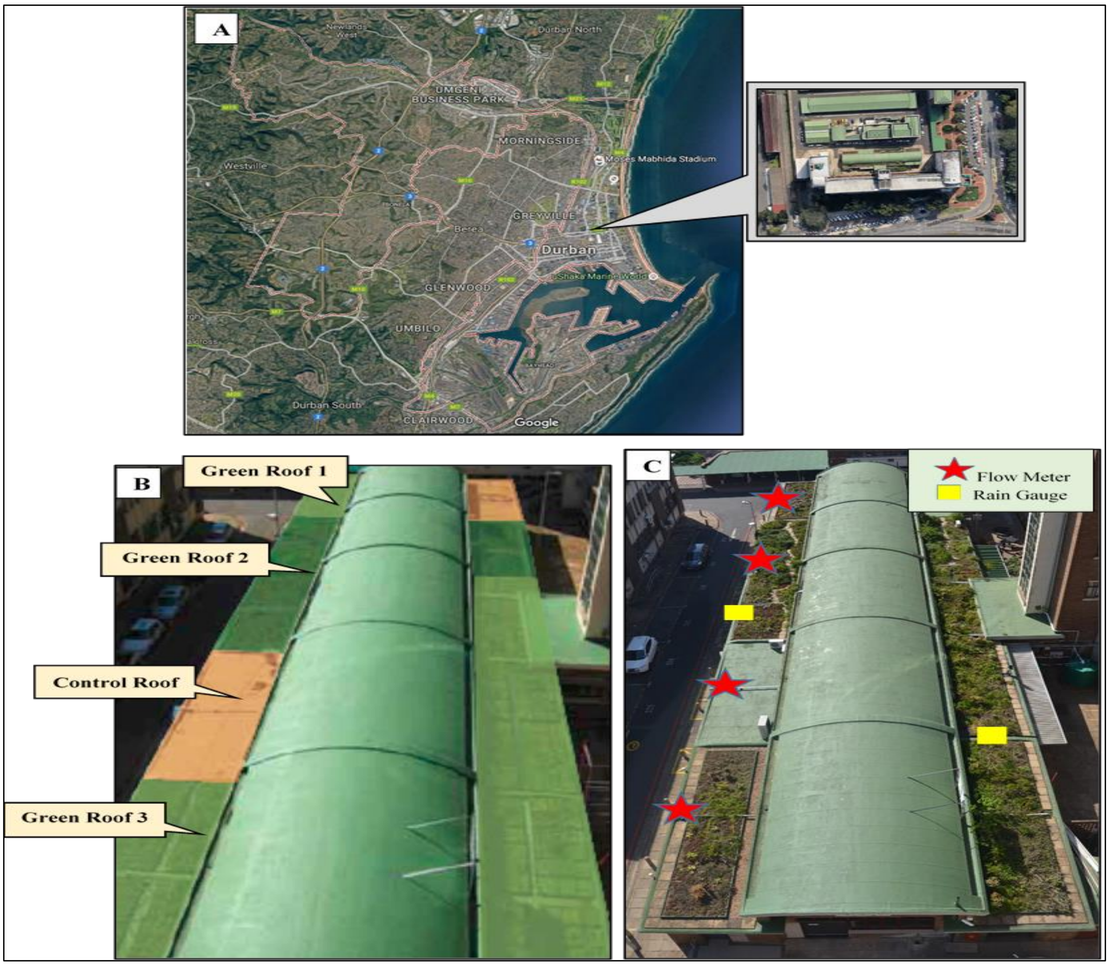

Fig. 1 Study area and site: (A) location of the Green Roof Pilot Project in relation to Durban, (B) plan view indicating initial demarcated roof areas, and (C) location of green roof monitoring apparatus on the Green Roof Pilot Project

As depicted in Fig. 1, two adjoining flat topped roofs at the eThekwini Engineering Services building have been planted with twelve varieties of vegetation. The roof used for the Green Roof Pilot Project consists of two flat slabs on either side of a raised arch. The Green Roof Pilot Project comprises both modular and in-situ approaches to green roof installation, in an attempt to draw a comparison between the two, as well as a conventional control roof to use as a reference [37]. The roof was subdivided into three portions, namely an in-situ green roof system, a modular green roof system and a control roof [36]. The total area allocated to the project is 550m2, with each roof variation comprising approximately 50m2 [37]. The different sections are depicted in Figure 2, where the dark green areas represent the in-situ systems, the light green areas represent the modular systems, and the red areas represent the control roofs [36].

The properties of the Green Roof Pilot Project and the substrates comprise as follows:

- Green Roof 1: Covers an area of 46.8m2 and has a depth of 3cm. The substrate type is made up of 55% crushed brick, 23% decomposed granite, 11% fine decomposed compost, and 11% dark building sand.
- Green Roof 2: Covers an area of 43.6m2 and has a depth of 10cm. The substrate comprises of 50% Light Expanded Clay Aggregate, 15% decomposed granite, 10% dark building sand, 10% fine decomposed compost, 10% vermiculite, and 5% perlite.
- Green Roof 3: Extends over an area of 47.2m2 and has a depth of 10cm. The substrate is made up of 50% Light Expanded Clay Aggregate, 15% decomposed granite, 10% dark building sand, 10% fine decomposed compost, 10% vermiculite, and 5% perlite.

2.2 Data Collection and Apparatus

Samples of the stormwater runoff from the different green roof systems, as well as the control roof, were collected to test their level of contaminants and pollutants. In particular, five sets of stormwater runoff samples were collected from five different rain events between the period of March 2017 and September 2017, as reflected in Table 1. The stormwater runoff was collected in containers that were supplied by the Council for Scientific and Industrial Research (CSIR), who were also responsible for the analyses of the samples. The samples were collected at the base of the pipe connected to the flow meters, the positioning of which is shown in Fig. 1. These pipes are also an extension of the roof gutter pipes. Both pipes are made from polyvinyl chloride (PVC). The containers were filled to the brim with no head space, as required by the CSIR. All sets of samples were tested for the quality of stormwater runoff entering freshwater ecosystems. The tests focused on all physical, aesthetic, chemical, and microbiological determinants pertaining to stormwater runoff discharging into a freshwater ecosystem.
The apparatus installed in the Green Roof Pilot Project to measure rainfall depth and stormwater runoff flow rates included a system of electronic tipping rain gauges, flow meters and data loggers. This system was able to measure the amount of stormwater runoff from the different areas of the project, and the rate of flow of the stormwater runoff (van Niekerk et al., 2009). Figure 3.14 illustrates the location of the various apparatus on the roof.

Table 1. Test days and rainfall information

Test #	Date	Time	Peak rainfall in ten minutes	Day before	Time before collection
Test 1	24 April 2017	09h00	3.4mm	No rainfall	7hrs 10min
Test 2	12 May 2017	17h30	6.8mm	Light rainfall	10hrs 45min
Test 3	14 May 2017	12h30	1.4mm	Heavy rainfall	15hrs 50min
Test 4	15 May 2017	21h30	1.4mm	Heavy rainfall	1hr 25min
Test 5	16 May 2017	09h30	4mm	Heavy rainfall	2hrs 30min

2.3 Data Analysis

For all tests, the level of contaminants and pollutants were measured against the South African Water Quality Guidelines Volume 7 for Aquatic Ecosystems. The guideline lists the determinants and corresponding target water quality range that should be achieved, in order for the water sample to be deemed acceptable for entering a freshwater aquatic ecosystem [38]. The target water quality ranges set out by the Guideline are tabulated in Table 2. Some of the constituents do not have a target water quality range set out in the South African Water Guidelines for Aquatic Ecosystems, but rather have a percentage limit in relation to their historic concentrations. This is because these constituents are site and time specific, implying that they do not have a set target value but rather a target value for different seasons and locations. All sets of samples for water quality testing were handed over to the laboratory at the Council for Scientific and Industrial Research (CSIR) within 24 hours after collection, in order to accurately account for all the pollutants present. The CSIR laboratory is equipped to test water samples for an extensive set of quality parameters and harmful impurities, including bacteria, viruses, minerals, chemicals and organic substances. The laboratory offers advanced testing and analytical facilities as well as specialized knowledge and technical services. The laboratory is accredited (ISO 17025) with the South African National Accreditation System which ensures that the analytical methods used by the laboratory, and the results achieved from the analyses, are traceable to international standards [39].

The results from the CSIR were analysed for this study, using Microsoft Excel to compile graphs for each determinant. A comparison was then drawn up between the test results and the target ranges set out by the South African Water Quality Guidelines. Another objective of the compilation of the graphs was to illustrate the difference in pollutant levels between the different green roof systems, as well as a comparison to the pollutant level of the control roof. Tests were not conducted on the rainwater before it fell on any of the roofs, therefore the researcher could not draw a comparison between the level of pollutants in the actual rainwater and the level of pollutants in the stormwater runoff from the green roofs as well as from the control roof.

Table 2. Target water quality ranges set by the South African Water Quality Guidelines Volume 7 for Aquatic Ecosystems

Constituent	Target Water Quality Range	Unit of measurement
Aluminium – pH < 6.5 – pH > 6.5	≤ 5	µg/L
	≤ 10	µg/L
Ammonia	≤ 7	µg/L
Arsenic	≤10	µg/L
Cadmium – in soft water	≤ 0.15	µg/L
Chlorine	≤ 0.2	µg/L
Chromium	≤ 7	µg/L
Copper – in soft water	≤ 0.3	µg/L
Cyanide	≤ 1	µg/L
Dissolved Oxygen	*80% - 120% of historic concentration	mg/L
Fluoride	≤ 750	µg/L
Iron	*≤ 10% of historic concentration	mg/L
Lead – soft water	≤ 0.2	µg/L
Manganese	≤ 180	µg/L
Mercury	≤ 0.04	g/l
Nitrogen	*≤ 15% of historic concentration	mg/L
pH	≥ 6 and ≤ 8 *≤ 5% of historic values or ≤ 0.5 pH units	pH units
Phenols	≤ 30	µg/L
Phosphorous	*≤ 15% of historic concentration	mg/L
Selenium	≤ 2	µg/L
Temperature	*≤ 10% of historic values or ≤ 2˚C	˚C
Total Dissolved Solids	*≤ 15% of historic concentration	mg/L
Total Suspended Solids	*≤ 10% of historic concentration	mg/L
Zinc	≤ 2	µg/L

3. Results and Discussion

Stormwater runoff from the three different green roof systems, as well as the control roof was sampled and analysed for all determinants contributing to the quality of stormwater runoff entering freshwater aquatic systems. Results were compared to the target water quality ranges set out by the South African Water Quality Guidelines for Aquatic Ecosystems, drafted by the Department of Water Affairs and Forestry [38]. Figures 2, 3, 4 and 5 displays the data on the level of various physical, chemical, microbiological and organic determinants in the sampled stormwater runoff, and Table 3 illustrates the summary of results of stormwater runoff quality.

3.1 Physical and Aesthetic Determinants

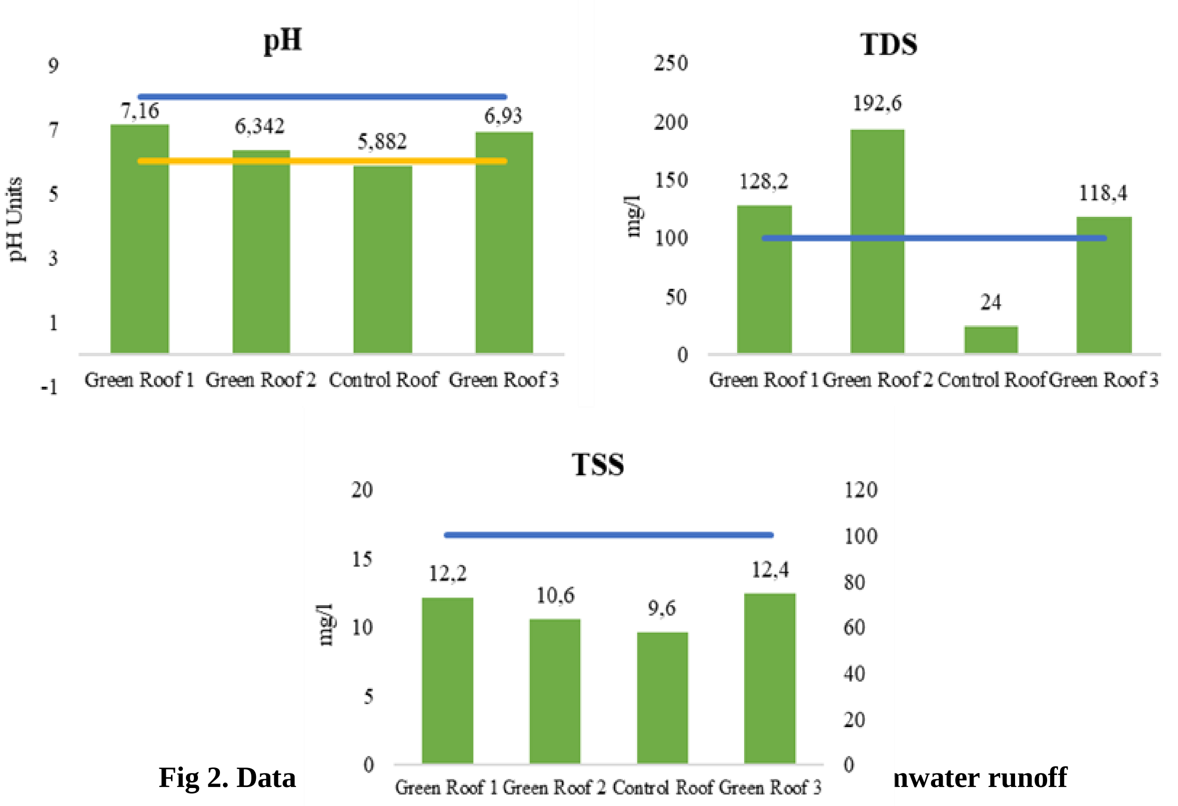

Fig 2. Data **nwater runoff**

3.1.1 pH levels

According to Fig. 2, the control roof revealed the lowest average pH level, whilst green roof 1 showed the highest pH level. The average level of a pH value of 5.882 from the conventional roof was the only result that did not conform within the target quality range of 6-8 pH units [38]. In general, green roofs have been proven to reduce the acidity of stormwater runoff from between 5 and 6 in rainwater, to between 7 and 8 in runoff from a green roof [17], and this correlated with the findings of this study. This increase in the pH level indicates that green roofs have the ability to neutralize acid rain [10] and therefore protect the receiving water bodies from acidification [40]. Test results indicated that green roof 1 proved to neutralize the runoff the most. Green roof 1 has a different substrate mix and thickness in comparison to the other two green roofs, and this can be attributed to its higher average pH level. Green roof 2 and green roof 3 had the same substrate mix and thickness, but varied in vegetation type and the amount of vegetation. The finding leads to the conclusion that the diverse vegetation can result in differing pH levels.

3.1.2 Total Dissolved Solids (TDS)

The test results indicate a range of between 24-192.6mg/L of TDS in the water samples (Fig. 2). The lowest level of TDS was from the control roof, and the highest level was from green roof 2. Although green roofs 2 and 3 have the same substrate mixture and depth, green roof 2 produced runoff with a higher average TDS concentration, which is possibly due to the plant type. Only TDS levels from the control roof was within an acceptable range as per the target water quality ranges prescribed by the South African Water Quality Guidelines for Aquatic Ecosystems (Table 2).

3.1.3 Total Suspended Solids (TSS)

Stormwater runoff from the control roof contained the lowest average concentration of TSS. Amongst the green roof systems, green roof 2 produced the lowest concentration of TSS, and green roof 3 produced the highest concentration of TSS (Fig. 2). Moreover, the data indicated that TSS levels in runoff from all the roof systems were found to be below the target water quality minimum of 100mg/L (Table 2). These results are inconsistent with findings by Zhang et al. (2015), that showed the TSS levels in a green roof system were lower than that from a conventional roof. Other studies propose that a common range of TSS from a green roof is 6mg/L to 482mg/L [32, 41], which is supported by the findings of this study.

3.2 Chemical Determinants

3.2.1 Free Chlorine

The control roof revealed the lowest average concentration of free chlorine from all the roof systems, and the highest average concentration originated from green roof 2. In particular, green roof 2 produced an average concentration of almost 1.5 times higher than that from the control roof (Fig. 3). The average levels of free chlorine from all roof types, were found to be above the target water quality range of 0.0002mg/L (Table 2). Contrary to the findings of this study, Zhang et al. (8) found no significant difference in the chlorine concentrations originating from a green roof and a conventional roof. Higher concentrations of free chlorine can hinder the growth rate, reduce reproductive activity, affect survival skills, upset the blood chemistry, and cause damage to gills in freshwater fish species [38].

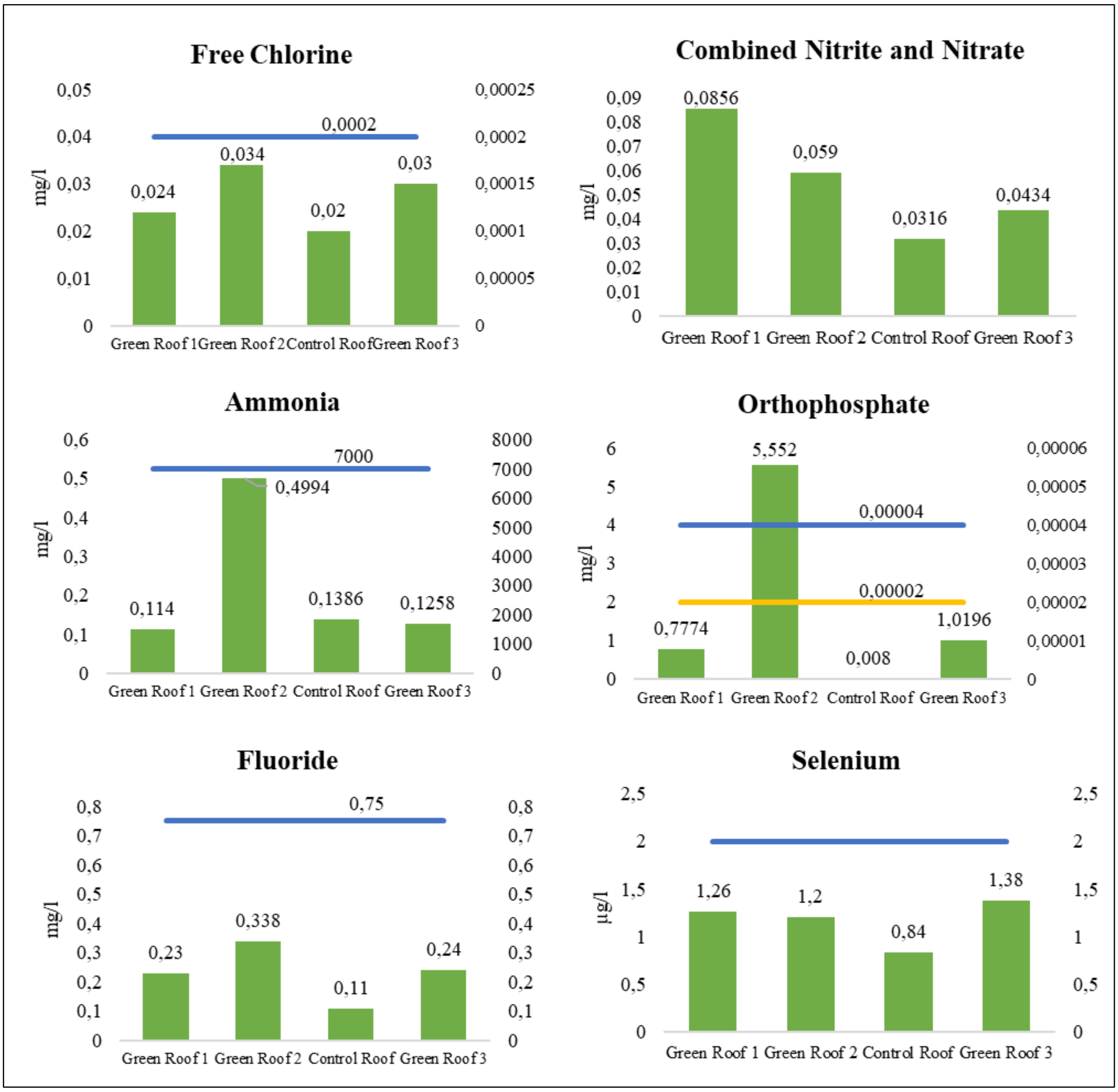

Fig 3. Data on chemical determinants in stormwater runoff

3.2.2 Nitrogen and Orthophosphates

Based on average concentrations, Fig. 3 confirms that the lowest level of nitrite and nitrate concentrations was from the control roof. Amongst the green roof systems, green roof 1 produced the highest average concentration, and green roof 3 produced the lowest average concentration. The characteristic that sets green roof 1 apart from the other systems is the substrate mixture, and substrate thickness. This mixture contains 55% crushed brick, 23% decomposed granite, 11% compost and 11% building sand, and has a substrate thickness of 3cm. Results were consistent with findings of similar studies which confirmed that nitrate and nitrite concentrations were higher in green roof runoff than in runoff from a conventional roof [8]. The results confirm that green roofs do not have the ability to retain nitrogen [26, 42].

3.2.3 Ammonia

Test results for all roof types revealed levels of ammonia that is below the maximum target water quality range value of 7000mg/L (Table 2). In particular, Fig. 3 indicates that the runoff from green roof 1 contained the lowest average ammonia concentrations, and green roof 2 produced runoff with the highest average ammonia concentrations. Green roofs 1 and 3 produced similar average ammonia concentration, despite their substrate depths being different. Green roof 2 had the same substrate depth as green roof 3, but showed a result which was more than 4 times greater than the lowest result. Green roof 1 had a depth of 3cm, and green roofs 2 and 3 had a depth of 10cm. Green roofs 1 and 3 both had vegetation that was similar in type and density. Green roof 2 consisted of very dense vegetation. Considering that green roofs 1 and 3 had similar average concentrations, and green roof 2 had a higher average concentration, the findings show that the vegetation type and density is a possible reason for these varying levels of ammonia. Overall, the ammonia level found in all roof types were within an acceptable limit per the target water quality ranges prescribed by the South African Water Quality Guidelines for Aquatic Ecosystems (Table 2).

3.2.4 Orthophosphate

Orthophosphate concentrations found in runoff from the control roof were at a constant level of 0.008mg/L over the 5 tests (Fig. 3). Green roof 2 showed the highest average concentration of orthophosphate, whereas green roof 1 showed the lowest average concentration of orthophosphate. The data confirms that the average orthophosphate levels were found to be above the target water quality range of 0.00002mg/L – 0.00004mg/L as per the target water quality ranges prescribed by the South African Water Quality Guidelines for Aquatic Ecosystems (Table 2), and were not at acceptable levels for all roof types (Table 3). Contradictory to the research by Beecham and Razzaghmanesh [40], which indicated that green roofs with lower plant density, produce runoff with higher orthophosphate concentrations, Green roof 2 in this study had the highest plant density amongst the green roof types, yet produced the highest average concentration of orthophosphate. However, Beecham and Razzaghmanesh [40] also found that green roofs with a crushed brick substrate gave off lower concentrations of orthophosphate in their stormwater runoff. Green roof 1 in this study showed the lowest orthophosphate levels, with a substrate mixture consisting of 55% crushed brick, demonstrating that this result was consistent with the findings made by Beecham and Razzaghmanesh [40]. Although green roofs 2 and roof 3 have the same soil mixture and depth, they recorded varying results for orthophosphate, ammonia, and nitrate. The difference in plant types may be the reason for this difference, as confirmed by Aitkenhead-Peterson et al. [43] that different plant species in the same substrate showed varying nitrogen and phosphorous amounts in runoff. Moreover, varying concentrations of nitrogen have been proven to be a result of soil mixture, age of the green roof, maintenance practices, and the types of fertilizer used [31].

3.2.5 Fluoride

When compared to the control roof, fluoride levels in the runoff from the green roof systems were found to be significantly higher (Fig. 3). Green roof systems indicated average levels ranging from 0.23mg/L from green roof1, to 0.338mg/L from green roof 2. Overall, the lowest average level of fluoride was from the control roof, with a value of 0.11mg/L. Similarly, Zhang et al. (8) showed that fluoride levels are greater in runoff from a green roof than from a conventional roof. All test results were found to be below the maximum target water quality level of 0.75mg/L [38]. When comparing average concentrations amongst the green roofs, green roof 1 and green roof 3 yielded similar results, whereas green roof 2 produced a higher average concentration. This discrepancy could be a result of the higher volume of vegetation present on green roof 2, leading to increases in the concentration of fluoride in the stormwater runoff. On the whole, all roof systems in his study exhibited acceptable levels of fluoride (Table 3), as per as per the target water quality ranges prescribed by the South African Water Quality Guidelines for Aquatic Ecosystems (Table 3).

3.2.6 Selenium

Fig. 3 confirms that amongst all the green roof systems in this study, green roof 2 produced the lowest average selenium concentration, whilst green roof 3 produced the highest. Compared to all roof types, the control roof produced the lowest average concentration of selenium. Green roofs 2 and 3 contained the same substrate mixtures and depths, but different plant types and plant densities. A difference of 0.18µg/L is therefore more likely to be a result of the variation in plant type and density, rather than substrate composition or depth. Overall, selenium concentrations for all roof types were found to be below the maximum target water quality range of 2µg/L (Table 2), which constitutes acceptable levels (Table 3).

3.3 Metals

3.3.1 Arsenic

Average arsenic concentrations were found to range from 0.012mg/L to 0.106mg/L (Fig. 4). Overall, green roof 2 produced the highest level of arsenic, whilst green roof 1 produced the lowest level of arsenic. All average levels recorded were found to be higher than the maximum target water quality range (Table 2), with acceptable levels found in all roofs except green roof 2 (Table 3). Also, green roofs 2 and 3 showed varying results despite having the same substrate depth and composition. This implies that the different plant type and density could be responsible for the noticeable difference in the average arsenic concentration. Exposure to increased levels of arsenic could result in a reduction in growth and reproduction, and a reduction in migration behaviour in various aquatic organisms [38].

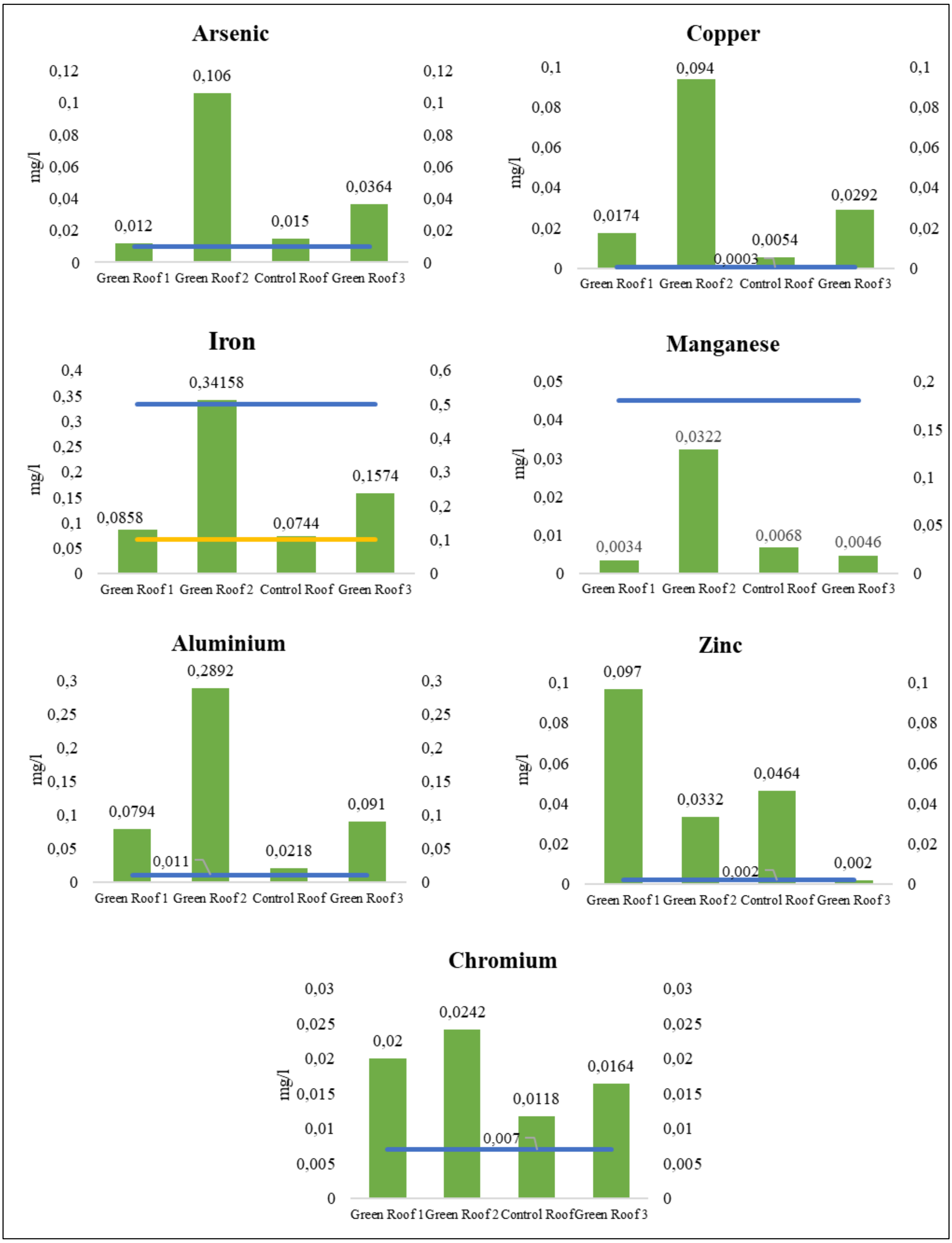

Fig 4. Data on metal determinands in stormwater runoff

3.3.2 *Copper*

Levels of copper in the stormwater runoff were found to range from 0.0054mg/L on the control roof to 0.094mg/L on green roof 2 (Fig. 4). Green roof 1 produced stormwater runoff with the lowest level of copper of 0.0174mg/L. All roof types displayed acceptable levels of copper (Table 3). Overall, the data confirms considerably higher concentrations of copper from the green roof systems than from the control roof. Similarly, Grzegorz et al. [9] found the content of metals in runoff from the green surfaces revealed several times higher concentrations of copper in comparison to those determined in rainwater. Conversely, Zhang et al. (8), discovered no substantial difference between the copper concentrations found in runoff from a conventional roof and a green roof. Differences in the green roof properties in this study suggest that the type and density of vegetation present on green roof 2 resulted in the higher copper concentrations. In higher concentrations, copper has been known to be responsible for brain damage in some mammals close to aquatic ecosystems [38].

3.3.3 *Iron*

According to Fig. 4, the control roof revealed the lowest average iron concentrations, whereas green roof 2 showed the highest level. The green roof with the lowest iron concentrations was green roof 1. As seen in previous results, the reason for the higher concentrations in green roof 2 could be a result of the vegetation types and density. Green roof 2 produced an average iron concentration that was higher than the target water quality maximum (Table 2). Overall, green roof 1 and the control roof showed acceptable levels of iron (Table 3).

3.3.4 *Manganese*

Fig. 4 confirms that the concentrations of manganese in all types of roof systems were below the maximum target water quality level of 0.18mg/L, and all were within the acceptable levels (Table 3). Green roof 1 showed the lowest concentration of manganese, and green roof 2 showed the highest average concentration. Green roofs 1 and 3 exhibited a similar average level of manganese and is possibly due to these roofs having similar plant types and density. Contrary to the findings of this study, Zhang at al. (8) found no noticeable difference in the manganese levels found in runoff from a control roof and that from a green roof.

3.3.5 *Aluminium*

The data presented in Fig. 4 reveals that the concentration of aluminium in the stormwater runoff from all roofs fall outside the target water quality range of 0.005mg/L – 0.01mg/L (Table 2), and were not within the acceptable levels (Table 3). The lowest concentrations were found in runoff from the control roof, whereas the highest concentrations were found in runoff from green roof 2. Vijayaraghavan and Raja [44] found that substrates containing vermiculite produced stormwater runoff with a higher aluminium concentration level, which corroborates with the findings of this study.

3.3.6 *Zinc*

The average concentration of zinc levels in this study ranged from 0.002mg/L to 0.097mg/L (Fig. 4), which was greater than the maximum target water quality range of 0.002mg/L (Table 2). Moreover, only green roof 3 had a zinc concentration at an acceptable level of 0.002mg/L (Table 3). Gregoire and Clausen [31] claimed that usually a green roof acts as a sink for Zinc,thereby reducing the amount present in runoff, which is consistent with the findings of this study. However, the average concentration from green roof 1 proved to be higher than that from the control roof, indicating that it acted as a source of zinc. Similar findings were made by Grzegorz et al. [9] where green surfaces revealed several times higher concentrations of zinc in comparison to those determined in rainwater.

3.3.7 Chromium

The data presented in Fig. 4 confirms that the chromium concentrations in the stormwater runoff was greater than the maximum target water quality range of 0.007mg/L (Table 2), and was not at an acceptable level for all roof types (Table 3). Chromium can be especially harmful to mammals in terms of retarding bone repair [38].

Although it has been proven that certain metals are present in higher quantities in runoff from a green roof than from a conventional roof, no study has confirmed that green roofs are a source of metal pollutants [28]. Vijayaraghavan and Raja [44] found that aluminium and iron concentrations in runoff from green roofs containing vermiculite were higher than in other substrate compositions. This is consistent with the findings of this study, in which the highest levels of aluminium and iron were present in runoff from green roof 2, which consists of a substrate mixture containing 10% vermiculite.

3.4 Organic Determinands

Phenols

Fig. 5 confirms that the average concentrations of phenols from the stormwater runoff was the lowest, and at an acceptable level for the control roof (Table 3), and was the highest for green roof 2. According to the Department of Water Affairs and Forestry [38], the maximum target water quality range is 30µg/L. The control roof in this study revealed phenols level below this target. Phenols are known to cause an increase in respiratory rates, a reduction in growth, and imbalance in some fish species, as well as a reduction in the rate of photosynthesis in some aquatic plant species [38].

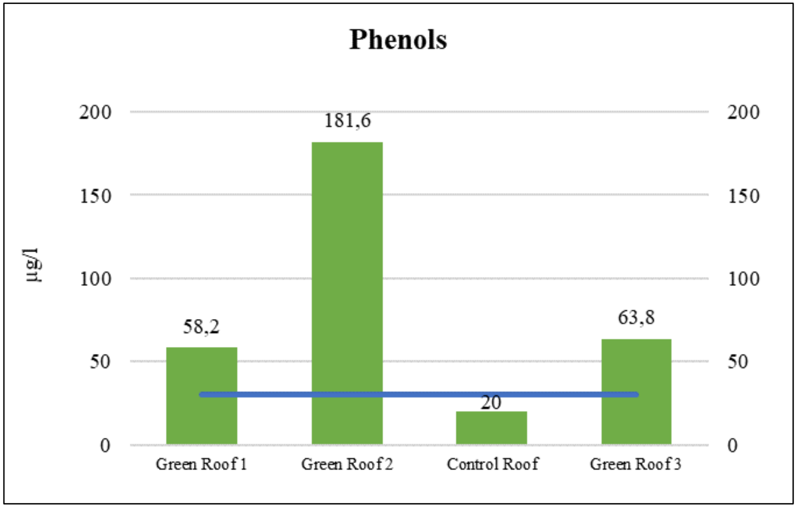

Fig 5. Data on organic determinants (phenols) in stormwater runoff

Table 3. Summary of stormwater quality results

Determinants	Unit	Green Roof 1	Green Roof 2	Control Roof	Green Roof 3	Max Value	Min Value
TDS	mg/L	128.2	192.6	24	118.4	100	
TSS	mg/L	12.2	10.6	9.6	12.4		
Free Chlorine	mg/L	0.024	0.034	0.02	0.03	0.0002	
Nitrogen	mg/L	0.0856	0.059	0.0316	0.0434		
Ammonia	mg/L	0.114	0.4994	0.1386	0.1258	7000	
Orthophosphate	mg/L	0.7774	5.552	0.008	1.0196	0.00004	0.00002
Fluoride	mg/L	0.23	0.338	0.11	0.24	0.75	
Selenium	µg/L	1.26	1.2	0.84	1.38	2	
Arsenic	mg/L	0.012	0.106	0.015	0.0364	0.1	
Copper	mg/L	0.0174	0.094	0.0054	0.0292	0.0003	
Iron	mg/L	0.0858	0.34158	0.0744	0.1574	0.1	
Manganese	mg/L	0.0034	0.0322	0.0068	0.0046	0.18	
Aluminium	mg/L	0.0794	0.2892	0.0218	0.091	0.01	
Zinc	mg/L	0.097	0.0332	0.0464	0.002	0.02	
Lead	mg/L	0.0178	0.0268	0.0158	0.0158	0.0002	
Chromium	mg/L	0.02	0.0242	0.0118	0.0164	0.007	
Phenols	µg/L	58.2	181.6	20	63.8	30	

Acceptable levels

Not acceptable levels

4. Conclusion

Data from tests for seventeen different pollutants were analysed. The study found that most pollutants had increased in concentration after passing through the various green roof systems, in comparison to the readings obtained from the control roof. Green roof 1 acted as a source for all pollutants except ammonia and manganese, whilst green roof 2 was a source for all 17 pollutants, except zinc. The results also confirmed that green roof 2 acted as a source for all pollutants except ammonia, manganese and zinc. Physical and aesthetic determinants which showed an increased level in runoff from all green roof systems were TDS and TSS. Chemical determinants which increased in concentration comprised free chlorine, nitrogen, orthophosphate, fluoride, selenium, arsenic, copper, iron, aluminium, lead, and chromium. Results indicated that levels of ammonia and manganese increased for tests done on green roof 2 only, whereas zinc results showed increased levels for green roof 1 only. Lastly, the organic determinants which increased in concentration after passing through all green roof system was Phenols.

The only pollutants that showed reduced levels in comparison to the control roof were that of ammonia and manganese for green roof 2, and zinc for green roof 1. This indicates that green roof 2 acted as a sink for ammonia and manganese, and green roof 1 acted as a sink for zinc. Green roof 2 differed from the other green roof systems in terms of vegetation type and density, leading to the suggestion that the type of plants used in green roof 2 may have led to a decrease in the ammonia and manganese concentrations in stormwater runoff. The main characteristics that were different in green roof 1 were the substrate depth and the substrate mix. A substrate depth of 3cm and a substrate mix of primarily crushed brick and granite, are two possible reasons for the decrease in the zinc concentration found in the stormwater runoff from green roof 1. Having lower concentration levels of these determinants in stormwater runoff would be an added benefit for any green roof system. Runoff water quality varied across the various roof types, which may indicate that the substrate composition has the greatest impact on green roof performance regarding rainwater quality. Overall, the results from the study suggest that these green roof systems do not have the ability to filter pollutants out of stormwater runoff, but rather increase their levels of concentration. Green roof water quality controlling effects are significant but are affected by many factors, such as the depth and type of the growing medium layer, the slope of the roof, the type of rainfall, the seasonal climate, and the planting time.

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