Journal of Environmental Science and Management 26-1: 72-84 (June 2023) ISSN 0119-1144

Long-term Environmental Performance of Stormwater Biofiltration Sorption Media in Sustainable Drainage Systems (SuDS)

ABSTRACT

In this climate impacted world, there is an increasing need for countries facing potential water extremes to improve the reuse potential of grey water and storm water. By implementing best management practices for the treatment of stormwater and urban run-off, contaminants can be removed, and the water recycled and reused. The effectiveness of stormwater treatment is impacted by the clogging of equipment or where contaminant storage exceeds performance design. Poorly or untreated stormwater runoff can impact the environment through the release of total dissolved solids (TDS), suspended solids (turbidity), phosphate, ammonia, and elevated chemical and biochemical oxygen demand (COD and BOD, respectively). This study evaluated the hydraulic and environmental performance of gravity flow stormwater filters over a three-year period with the average filter life cycle four months. Six bespoke gravity stormwater filters employing sorbent pillows, and including peat moss, were tested for their effectiveness, including for nitrite and nitrate. An improvement in water quality of 80-98% was recorded. Oil and grease were managed effectively (peat moss and sorbent pillows reduced BOD, COD, color, and turbidity) but not significantly when compared to conventional filter media. The findings demonstrate that stormwater biofilters can be an innovative, low-cost, and sustainable solution for both urban and sub-urban runoff management, addressing water quality and resource quantity challenges.

Keywords: *stormwater filtration, sustainable drainage systems (SuDS), organic loading, sorption, filter media, water circularity, water sensitive urban design (WSUD)*

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INTRODUCTION

In the past, stormwater was allowed to flow directly into the nearest receiving water body to be dispersed by nature. Today, recognition of the environmental impacts of untreated stormwater runoff generally prohibits release into natural hydrosystems. The treatment of stormwater runoff from urban areas is constrained by geography and infrastructure and by finances (*Abbott and Comino-Mateos 2003; Tota-Maharaj et al. 2012*). There are a diverse number of filter media and treatment techniques available under best management practice (BMP), sustainable drainage system (SuDS) or water sensitive urban design (WSUD) (*Susdrain 2013; Broughton 2015*). That said, a new alternative cost-effective filter media are being developed. Filtration is effective for purifying water for the control of microbiological contaminants and was first used for domestic applications using wool, sponges, and charcoal (*Enzler 2020*). According to *Huisman and Wood* (*1974*), John Gibb designed the first slow sand filtration system in 1804 and later constructed a water filtration system for the Chelsea Water Company in 1829. Stormwater filters employing biofilters and/or conventional engineered systems were appropriate management solutions for urban runoff, until the 1970s, when improvements in the efficacy of control of microbiological water contaminants unknown in Gibb's time were gradually introduced (*Coerver et al. 2021*). Due to rapid urbanization, there is now an increased need for stormwater collection, treatment, and recycling. Runoff from roofs and other impermeable surfaces has increased threefold over the past 30 years (*Tony 2010; Jordan 2013*) and the development of e.g., SuDS and other management solutions has led to water storage and treatment for use for public and commercial uses. Urban runoff from highly trafficked areas has potential to be harvested but is dependent upon the extent of pollution and available treatment options (*Way and Thomas 2005*). SuDS service delivery can be specifically designed to facilitate local water conservation and supply, and (for surface water) the interception of runoff, its volume reduction and quality enhancement (*Tony*

2010). SuDS filtration systems can be beneficial by; accommodating a building's water demand; delivering sustainable and climate resilient gains; reducing the volume of runoff from a specific site; and reducing the volume of attenuation storage required at a specific site.

Although stormwater filters are often regarded as a SuDS BMP, they are constrained by dry weather domestic water reuse, as they are susceptible to local rainfall and precipitation patterns. Therefore, systems need to enable stormwater storage above a set threshold, with an ability to drain (the excess) slowly downstream or via soakaways. At present time, performance data is lacking particularly during significant rainfall events and no guidance on the engineering design and storage volumes are available (*Hackney 2013*). Collected and treated stormwater can generally be used for a range of non-potable purposes, such as for flushing toilets, charging washing machines and for external uses such as car washing, and irrigation (*Jason 2011*). In the UK, stormwater management and rainwater harvesting systems (RWH) are rarely used to provide potable water for consumption or bathing. Moreover, in the United Kingdom, private water utilities and suppliers for locations not connected to main water supply networks must comply with the Private Water Supplies Regulations 2009 (*Environment Agency 2010, 2019; Ballard et al. 2015*). According to *Di Bernado and Isaac* (*2001*), gravitational flow filters (down-flow filters) can get quickly clogged requiring regular maintenance. Stormwater pre-treatment by e.g., biofilters increase the treatment options available and the range of potential contaminants that can be mitigated. The inclusion of layered filter media within the filter bed can improve the management of synthetic organic and inorganic pollutants (*Rybarczyk et al. 2019*). For low turbidity stormwater, gravity-flow filters are defined in structure and layout and the choice of filter media can enable a quality treated effluent. Moreover, *Butler and Davies* (*2011*) describe urban stormwater filters as offering control over; drainage of surface runoff; groundwater recharging and use for irrigation or for household water; the quality of very early-stage stormwater; and infrastructure damage and flood prevention.

The pre-treatment of grey water and wastewater can be managed economically and in doing so protects water quality, amenity, and biodiversity but is contingent upon the effective operation of stormwater filters. A key operational parameter is ensuring filters do not clog to ensure there is no loss of head (*Pratap et al. 2007*). The appropriate choice of filter media can lead to an optimal resistance to head loss and high efficiency treatment, providing maintenance regimes (including periodic backwashing) are employed. As such, the effectiveness of filtration for the treatment of highly turbid stormwater is maintained (*Cornwell et al. 1984*). In recognition of the need for effective alternative filter systems, the objectives of this study were to evaluate alternative ecological filter media to provide experimental and performance data and review the operational and maintenance requirements of biofilters within a SuDS framework Low-cost filter media can have enhanced sorption characteristics and potential to deliver environmental benefits and meet water quality goals (*Maryland State Highway Administration 2010*). With the increasing impacts of urbanization and intensification of land use, stormwater runoff has become a major environmental challenge, significantly contributing to water pollution. SuDS is an effective and proven green infrastructure for managing urban and sub-urban stormwater runoff.

This study aims to explore the utilization of stormwater biofiltration units, as a SuDS technique for the reduction of urban runoff pollution. Stormwater management is crucial for maintaining water quality and minimizing the adverse impacts of urbanization and farming on natural water bodies. There are possibilities that graywater from households, commercial buildings and the farming sector mix with stormwater runoff when there is a lack of proper drainage infrastructure. Similar practices occur with agricultural/farm runoff. Stormwater biofilters have emerged as an effective tool to treat stormwater runoff, addressing various parameters such as total dissolved solids (TDS), turbidity, color, ammonium (NH_4^+), phosphates, chemical oxygen demand (COD) and biochemical or biological oxygen demand (BOD). This research project aims to evaluate the removal rates of these physicochemical parameters in stormwater biofilters, while considering accepted values and their implications for stormwater treatment. To achieve research objectives, this study employed various filter media at pilot-scale to investigate stormwater treatment potential, hydraulic performance, and potential for field application in urban and sub-urban environments. The materials used for the filter media included gravel, sand, peat moss, sorbent pillows and geotextiles.

MATERIALS AND METHODS

Two designs of novel stormwater filtration systems were tested at laboratory scale for their performance. They were also examined for their strengths and weaknesses for stormwater treatment and reuse adapting the research and experimental studies of *Paul and Tota-Maharaj* (*2015*); *Ajibade and Tota-Maharaj* (*2018*) and *Monrose et al.* (*2021*).

Design and Construction

Six plastic containers (300 × 300 × 700 mm) were filled with layered filter media. Stormwater sampling pipes were placed within the bottom filter layer which consisted of an equal mix [percent (%) w/w, total weight] of 6-10 mm and 20 mm gravel. To reduce the risk of clogging, a sampling pipe with 15-mm diameter was selected. The key components of filter rigs 1 and 2 include geotextile (**Table 1**). The base filter media was composed of a mix of 6-10 mm and 20-mm gravel and was 300 mm thick. This was followed by a medium sand layer with a thickness of 250 mm. The filter rigs were constructed in pairs, one with and one without the use of geomembrane between the filter media and 50 mm thick top dressing, comprising sorbent pillows or peat moss. The geotextile was a violet light-balanced, high steadiness product made from woven polypropylene.

Filter Sorption Media

Peat Moss has strong credentials for replacing conventional filter media in SuDS structures, such as swales, bioswales and bio-slopes. Despite being a perishable material, *Koob and Barber* (*1999*) reported that peat moss is one of the best stormwater filters for treating urban rformed by plant decay in de-oxygenated or anoxic water. The physical structure and peat composition is controlled by its constituent plant-matter originating from sedge, moss, and other wetland plants. Peat is physically and biologically complex being primarily composed of humic, folic acids, and cellulose. Peat placed on the top zone of a stormwater filter system moss can be used to reduce influent pH.

Sorbent Pillows are often used in stormwater treatment systems to trap floating oils and greases. They can also further enhance the removal of floatable hydrocarbons and additional volatile compounds which originate especially in urban areas and fuel stations (*Pitt et al. 1995*) and can absorb up to 25 times of their own weight. Sorbent pillows are lightweight, easy to handle and have a superior sorption speed. The sorbent pillows employed in in this study were 200 mm × 460 mm and were placed as the top filter media layer, specifically to buffer oils and hydrocarbons present in the stormwater.

Sand is one of the widely used finer aggregates for the purification of water. The use of sand is only recently becoming widely accepted as a structural best management practice (*Kandasamy et al. 2008*) despite its use in water and wastewater treatment for >150 years. Sand is an effective for treating Total Suspended Solids (TSS), heavy metals, fecal coliforms, other bacteria, and viruses. The percentage of pollutants removed by sand increases with depth, however, sand must be periodically back-/pressure- washed to prevent clogging (*Pratap etal. 2007*).

Gravel is a commonly used filtration medium in SuDS. Gravel rapidly impacts water clarity and quality. The use of gravel filter media within SuDS, BMPs or WSUD reduces the effective impermeable zones and provides stormwater infiltration and detention whilst also preserving the natural hydrology of an area. In general, gravel is often used as a top filter layer, to prevent debris from entering the filter system, and its efficacy is related to particle size and bed thickness. In this study, the gravel mixture chosen was used as a base filter layer. As with other filter media, gravel requires routine maintenance to reduce the risk of clogging and a reduction in performance (*Hatt et al. 2007; Tota-Maharaj, et al. 2021*).

Geotextile membranes are mainly used in reinforcement, filtration, drainage and as a barrier within urban drainage designs (*Tota-Maharaj and Paul 2015*), but their application for stormwater treatment is still somewhat under development (*Khambhammettu 2005*). Geotextiles enable a stable permeable interface between an engineered channel and soil and impede the development of fine particles (*Korkut et al. 2006*), partially through the production of a converse channel on the adjoining (inner surface) of the geotextile (*Koerner et al. 1994*).

Construction of the Test Filter Rigs

Each filter layer was placed to the required depth and hand compacted with and without the application of geomembrane. The geomembrane was 400 mm × 400 mm with an additional 50 mm (side uplift) to facilitate stormwater flow. Geotextile was used as an upper membrane in filter rigs 1 and 6, and as both lower and upper membranes in rigs 3 and 4. Sorbent pillows of 50 mm x 200 mm × 460 mm were placed on top of the compacted upper sand filter layer or membrane in filter rigs 1, 2 and 3. Filter rigs 4, 5 and 6 used 50 mm of peat moss as top dressing (**Figures 1 -6**).

Experimental Methodology

Influent properties. Stormwater inflow and outflow samples were analyzed in triplicate for: Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Dissolved Solids (TDS), Turbidity, Colour, Phosphates (PO_4) and Ammonium (NH_4). hese physicochemical parameters are important water quality parameters of stormwater i.e., pH, temperature, turbidity,

Table 1: Stormwater filter rigs media components, characteristics and dimensions.

Rigs 1 and 2 Components and Characteristics			
Depth (mm)	**Filter Media**	**Thickness (mm)**	**Aggregate Size (mm)**
50	Sorbent Pillows	50	-
52	Geotextile Membrane	2	0.0625 to 2
302	Sand	250	Medium
Rigs 3 and 4 Components and Characteristics			
Depth (mm)	**Filter Media**	**Thickness (mm)**	**Aggregate S (mm)**
20	Peat Moss	20	-
50	Sorbent Pillows	30	-
300	Sand	250	Medium
302	Geotextile Membrane	2	0.0625 to 2
602	Gravel	300	20

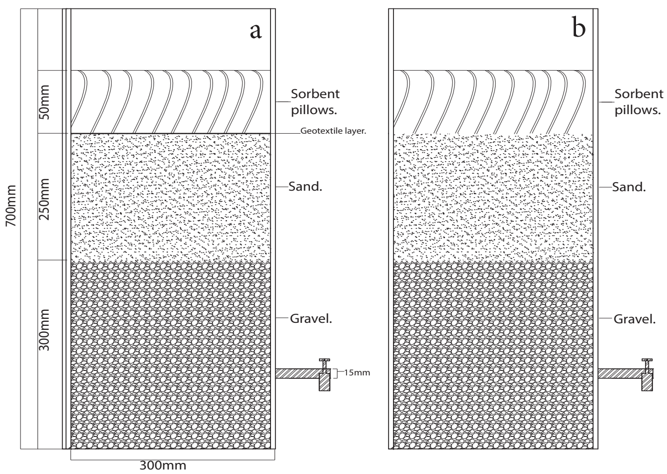

Figure 1. Experimental Rigs 1 (a) and Rig 2(b)

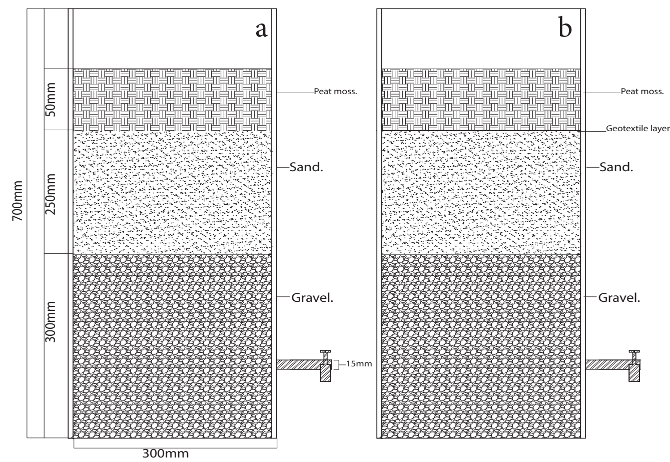

Figure 3. Experimental Rigs 5 (a) and Rig 6 (b)

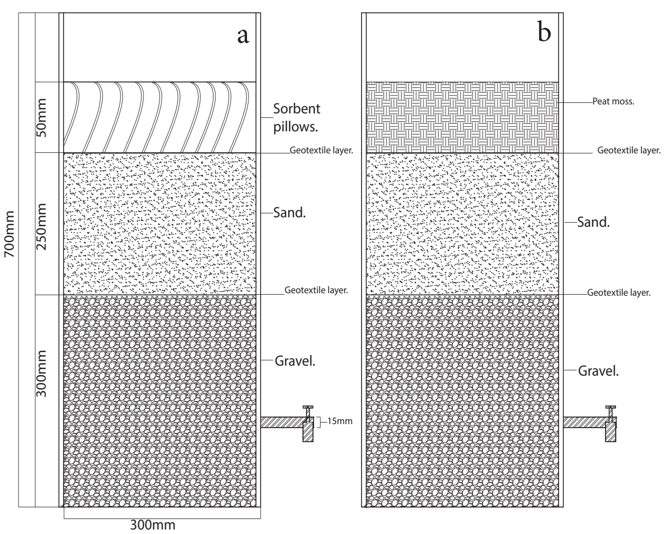

Figure 2. Experimental Rigs 3 (a) and Rig 4(b)

conductivity, total dissolved solids, total suspended solids, total alkalinity, sulfates, nitrates, heavy metals, and phosphates. However for this study, stormwater influent and effluent samples were analysed in triplicate for Chemical Oxygen Demand The period of sampling extended from March 2016 to August 2019, with an average sampling number (n) = 430, for each water parameter. A standard influent stormwater volume of 5 L was used per rig. The treatment of wastewater influent is guided by international/national standards including those of the *World Health Organization* (*2004; 2017*), the European Union (urban wastewater treatment directive) (*EU Directives 1991*), Environment Agency (*Environment Agency 2019*) and the US EPA (Drinking Water Standards and Health advisories (*US EPA 2013; 2018*). The minimum effluent concentration or value has been taken from the guide available (**Table 3**).

Filter Operation and Water Sampling. Stormwater runoff and gully pot liquor was collected twice weekly in Chatham Maritime, Kent, United Kingdom, in the vicinity of the University campus. All stormwater was obtained from rainwater storage tanks and gully pots. The rainwater originating from a roof was channeled to a receiving tank (**Figure 6**).Prior to application, the influent was tested for key physicochemical properties in triplicate (**Table 2**). Then the collected stormwater was uniformly applied to

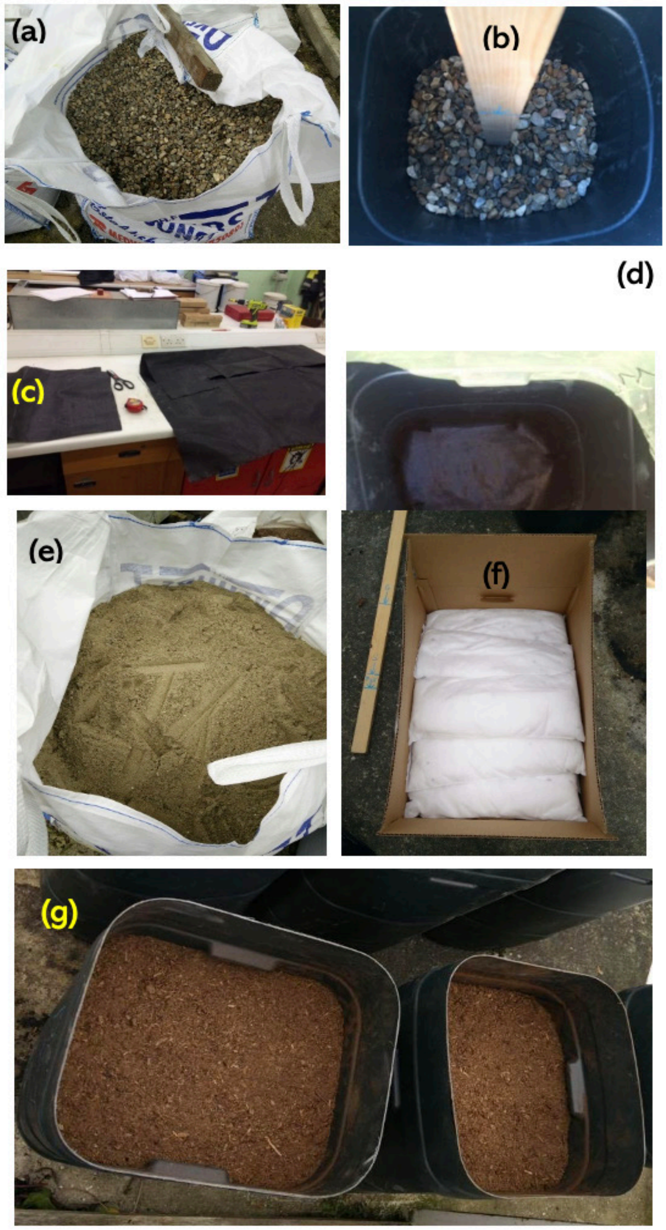

Figure 4. Construction materials and filter media (a)-mixes 6-10 mm and 200 mm Gravel, (b) Wooden Ruler for filter media depth and measurements (c) Preparation of geotextile membrane (d) Placement of a 'lower' membrane (e) Medium sand (f) Sorbent Pillows, and (g) Peat Moss

Figure 5. Filter media (a) Medium sand, (b) Geotextile (upper layer), (c) Peat moss, and (d) Sorbent pillows

the top surfaces of each Test Rig twice weekly in shares of 5 L volumetric loads. To prevent clogging of the test filter rigs, backwashing was undertaken once every three months to prevent the head loss observed in earlier trials (*Ahsan and Alaerts 1997*).

Total Dissolved Solids (TDS). Total Dissolved Solids (TDS) were determined using a HM digital COM-100: Waterproof Professional Series EC/TDS/TEMP meter (which is also capable of measuring electrical conductivity (EC) and temperature). The TDS was measured by simply inserting the instrument in the water samples after periodic calibration.

Turbidity. It is essentially the 'cloudiness' in water and is controlled by drinking water standards. It is a measure of the clarity of water, primarily caused by suspended particles. The commonly used standard for turbidity in water and wastewater is 4 NTU (Nephelometric Turbidity

Table 2. Operational characteristics of stormwater filters as a Sustainable Drainage System (SuDS).

Water Quality Parameter	Drinking Water Guidelines and International Standards	Standards for Wastewater Treatment and Discharge Effluent
Total Dissolved Solids (TDS)	500 $mg.l^{-1}$	500 $mg.l^{-1}$
Biochemical Oxygen Demand (BOD)	< 0.20 $mg.l^{-1}$	< 10$mg.l^{-1}$
Chemical Oxygen Demand (COD)	< 4.5 $mg.l^{-1}$	< 20$mg.l^{-1}$
Turbidity	< 2 NTU	5 NTU
Color	5 PCU	20 PCU
Phosphates	< 0.5 $mg.l^{-1}$	< 0.5 $mg.l^{-1}$
Ammonium	< 0.5 $mg.l^{-1}$	< 5.0 $mg.l^{-1}$

Figure 6. Rainwater and Gully Pot Mixing Tank, for concentrating stormwater influent

Table 3. Guidelines and Standards for Drinking Water Quality and Wastewater Discharge.

Operations	Periodic Times & Rates
Hydraulic load	0.15 L m^{-2}
Filtration Rates	0.025 m hr^{-1}
Stormwater above top filter media (ponding)	0.05 m
Retention Times	≈ 30 hrs
Average Filter Cycle Length	≈ 4 mos
Periodic Backwashing when required	10 L m^{-2} (distilled water), when effluent Turbidity > 5 NTU

Units) (*Butler and Davies 2011*). When turbidity levels are greater than 5 NTU, it is visible to the human eye. Turbidity measurements were performed using a microprocessor-controlled Turbidity meter (HANNA Instruments HI 93703) employing 10 mL cuvettes, filled to one-quarter of their capacities.

Color. The color of water indicates the presence of dissolved organic and inorganic material that can impair water quality. Color quantification is commonly measured in platinum cobalt units (PCU), or Hazen Units (HU). A colorimeter (Hanna HI-727) was used with the range 0-500 PCU to measure water color. After each measurement, the colorimeter was recalibrated with distilled water.

Chemical Oxygen Demand (COD) is a measurement of how much organic material is the water which can be chemically oxidized. COD was measured using a spectrophotometer (Hach Lange LT 200). Samples were allowed to react, heated and incubated for 2 hours at 148 ± 2°C prior to analysis, which involved an oxidation step employing potassium dichromate, sulfuric acid, silver sulfate, and mercury sulfate.

Biochemical Oxygen Demand (BOD_5). The determination of Biochemical Oxygen Demand (BOD_5) was performed using an incubator (Lovibond TC135S). BOD_5 in theBOD5 measured for the influent and effluent of all six stormwater biofilter rigs, evaluated the oxygen consuming microbes and bacteria present in the stormwater (*Tebbutt 1998*). Prior to incubating the prepared water samples for 5 days at 20°C, 4 drops of potassium hydroxide (KOH) were placed in the seal gasket of each BOD bottle to prevent accumulation of carbon dioxide (CO_2). The following determination involved adding 10 drops of Allyl Thiourea (ATH) nitrification inhibitor to 428 mL of water in each BOD bottle.

Phosphate in dissolved phosphates, as a dissolved solid can infiltrate, precipitate and adsorb can precipitate and adsorb onto soil particles. Dissolved phosphate was measured using a spectrophotometer (Hach Lange dry thermostat LT 200, Hach Lange DR 1900) using phosphate cuvette test (Hack LCK 348) reagents. Cuvettes containing 0.5 mL of sample mixed with reagent and heated to 100°C for 1 hr using the thermostat. After allowing the temperature of the mixture to reduce to 18 – 20°C, 0.2 mL of LCK solution B was added to the mixture and placed in the spectrophotometer.

Ammonium is generated by the hydrolysis of ammonia following the 'natural' breakdown of urea. Ammonium was tested and included in this study as a key stormwater quality parameter because of possible contamination from agricultural industries and farming. (Equations 1 and 2 below):

$$NH_2CONH_{2(aq)} + H_2O \rightarrow 2NH_{3(g)} + CO_{2(g)} \quad (1)$$

$$NH_{3(g)} + H^+_{(aq)} \rightarrow NH_4^+{}_{(aq)} \quad (2)$$

Ammonium was determined using using a spectrophotometer (Hach Lange DR 1900) employing ammonium cuvette test (Hack LCK 303 and LCK 304). Each cuvette contained a mixture of 0.2 mL water and reagents that was thoroughly agitated for 15 min before the determination was made.

RESULTS AND DISCUSSION

The water quality parameter used in this study included Total Dissolved Solids (TDS), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD); turbidity, color, phosphates and ammonium (**Table 4**).

Total Dissolved Solids

Total dissolved solids (TDS) refer to the inorganic and organic substances present in stormwater, such as salts, minerals, and trace elements, which can negatively impact downstream water quality. The stormwater biofilters significantly reduced TDS concentrations, thereby improving the overall water quality (**Figure 7**).

Accepted values for TDS vary depending on the location and designated water usage. For instance, The Drinking Water Inspectorate in the UK and the United States Environmental Protection Agency (USEPA) recommends a TDS maximum contaminant level of < 500 mg L^{-1} for drinking water. However, for stormwater treatment, specific guidelines may not exist, and comparison with natural water bodies or treated wastewater can provide insights into acceptable levels.

The long-term evaluation for TDS removal rates for this three-year study for the stormwater biofilters showed varying removal efficiencies of 40-90 % for each experimental rig. These removal rates depend on factors such as the filter media composition, hydraulic loading rates, and specific TDS constituents. High removal rates are desirable to minimize the impact of TDS on downstream ecosystems and to ensure water quality in accordance with regional guidelines.

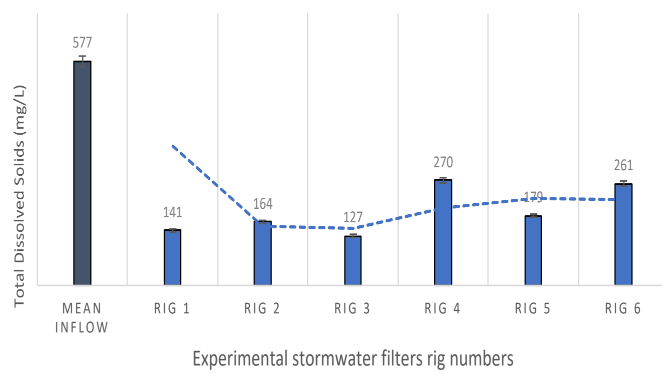

Figure 7. Total Dissolved solids (mg l^{-1}) average influent and effluent (Rig 1-Rig 6) for the stormwater treatment efficiency with moving average and error bars (2.5 % from analysis). Sampling period: March 2016-August 2019. Sample Number 'n'= 430 with average value of inflow and outflow taken from triplicate). The moving average helped to inform the overall picture of each biofilter's performance and inherent or fundamental stormwater discharge standards and values with its real outflow quality due to the fluctuations over the 3-year period

Table 4. Average influent stormwater physiochemical characteristics (March 2016-August 2019; n= 430).

Water Parameter/Pollutant	Mean Value / Quantity ± Standard Deviation
Total Dissolved Solids (TDS)	577 mg L^{-1} ± 39
Biochemical Oxygen Demand (BOD)	181 mg L^{-1} ± 27
Chemical Oxygen Demand (COD)	68 mg L^{-1} ± 23
Turbidity	32 NTU ± 6
Color	398 PCU ± 11
Phosphates	>1.5 mg L^{-1} ± 0.8
Ammonium	>2.7 mg L^{-1} ± 0.3

Filtration was done to remove particles for stormwater filters as stormwater filters are simple in design and have low capital, and operational costs (*Way and Thomas 2005*). The various filter test rigs employed in this study were demonstrated for inorganic, organic and biological particulates. However, with time, a loss of head and an increased turbidity was observed as binding occurred. This loss of 'performance' could be reversed by the periodic backwashing and cleaning of the filter media.

Turbidity

High turbidity levels can reduce sunlight penetration, disrupt aquatic ecosystems, and indicate the presence of other contaminants. Therefore, reducing turbidity is essential for effective stormwater management (*Butler and Davies 2011; Paul and Tota-Maharaj 2015*). The stormwater biofilters have demonstrated promising results in reducing turbidity. For instance, in this study, it can be seen a reported a reduction from 9.7 NTU to 0.54 NTU (**Table 4** and **Figure 8**), showcases the filter'seffectiveness in meeting the standard. The implications of achieving such turbidity reduction in stormwater biofilters are significant. Lower turbidity levels ensure better aesthetics, facilitate ecosystem health, and promote sustainable aquatic environments. Additionally, reduced turbidity positively impacts downstream water and wastewater treatment processes, thereby providing more efficient water treatment and reducing costs. Turbidity varied significantly between each stormwater filter test rig (**Figure 8**). Turbidity substantially decreased during the filtration processes (from 32 NTU to between 9.7 and 0.54 NTU for rigs 1and 4, respectively). The impact of the geotextile was found to be significant (rig 5) when combined with effective filter media composed of sand and gravel.

Color

The color in stormwater as well as suspended particles indicates the presence of dissolved organic substances, which can result from various urban activities. The color range for stormwater varied significantly, e.g., between 398 and 57 PCU (**Figure 9**). Highly colored stormwater can sometimes indicate the presence of pollutants and may pose challenges for effective treatment (*Butler and Davies 2011; Paul and Tota-Maharaj 2015*). Stormwater biofilters, incorporating biofilter media, exhibits a favorable capacity to improve color for the treated stormwater. The implications of color improvement in stormwater biofilters are two-fold. Firstly, visually appealing water enhances the aesthetic qualities of urban environments, contributing to positive community

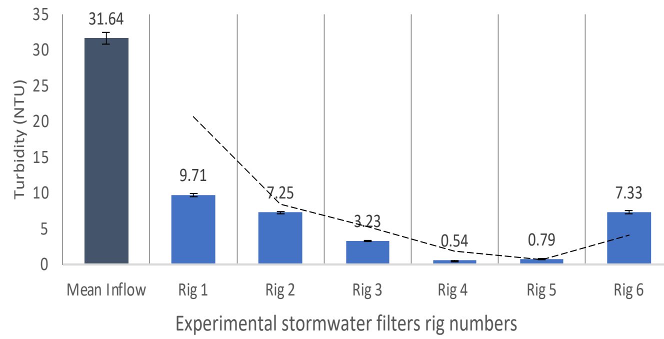

Figure 8. Turbidity (NTU) average influent and effluent (Rig 1-Rig 6) for the stormwater treatment efficacies with moving average and error bars (2.5 % from analysis). Sampling period: March 2016-August 2019. (n= 430 with average value of inflow and outflow taken from triplicate)

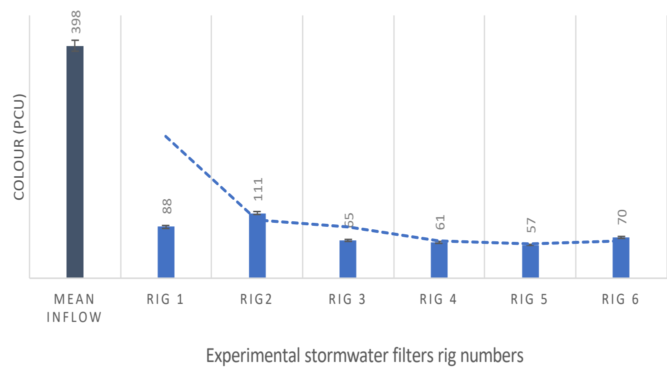

Figure 9. Colour (PCU) average influent and effluent (Rig 1-Rig 6) for the stormwater treatment efficacies with moving average and error bars (2.5 % from analysis). Sampling period: March 2016-August 2019. (n= 430 with average value of inflow and outflow taken from triplicate)

perceptions. Secondly, the reduction of color indicates successful removal of various pollutants and organic substances, thereby assisting in achieving improved water quality standards and protecting downstream ecosystems. The color of the water samples significantly improved during filtration with the decrease being in the range 55 -111 PCU, from an initial value of 398 PCU. It was noticed that periodic backwashing and cleaning of the filter media improved the colour of treated stormwater. The presence of a geotextile membranes did not appear to impact the colour of outflow/effluent.

Phosphates

Phosphates are a major contributor to water pollution, leading to eutrophication and harmful algal blooms in receiving waterbodies. For this laboratory-scaled study, all six stormwater biofiltration systems demonstrated significant potential in removing phosphates from the stormwater runoff collected and analyzed. These biofilter systems utilized a combination of physical, chemical, and biological processes to achieve effective phosphate removal. The stormwater biofilters reduced phosphate concentrations from an inflow level of 1.5 mg L^{-1} to an outflow level as low as 0.07 mg L^{-1}. The biofiltration process which involved the use of special engineered media (geotextile membranes), conventional filter media such as sand, gravel, and biofiltration media (peat moss and sorbent pillows) which acted as a filter to trap and retained phosphates. Phosphorus was present in influent at 1.5 mg L^{-1} and was reduced to 0.16 to 0.06 mg L^{-1} by filtration (**Figure 10**). Additionally, the geotextile membranes within the biofiltration system enhanced the phosphate removal through sorbent pillows and peat moss uptake and microbial activity. Infiltration and percolation treatment-based processes are capable of oxidizing and decontaminating the stormwater inflows (*Mottier et al. 2000; Bali et al. 2010*), with phosphate removal typically occurring in the upper sand layers of filters (*Bali and Gueddair 2019*).

Ammonium

Ammonium is another common pollutant found in stormwater runoff, primarily originating from fertilizers, animal waste, and septic systems. High levels of ammonium in water bodies can be toxic to aquatic life and can also contribute to nutrient imbalances. The SuDS biofilters have proven effective in removing ammonium through various mechanisms in this study. This research has shown that these stormwater biofilters achieved ammonium removal rates from influent concentrations of 2.3 mg L^{-1} to effluent concentrations as low as 0.021 mg L^{-1} and 0.022 mg L^{-1}, respectively (**Figure 11**). The removal of ammonium in biofiltration systems occurs through processes such as adsorption, nitrification, and filter media uptake. The filter media within these systems facilitated these removal and remediation processes, providing an environment conducive to microbial activity and nutrient transformation.

The reduction in ammonium (NH_4^+) in the filter was positively impacted by influent velocity and flow. The influent contained 2 mg L^{-1} of ammonium, which was reduced to less than 0.06 mg L^{-1} in each rig tested. This finding indicated that stormwater filters are beneficial and at operational loading rates, enabling significant degradation of ammonium to take place. However, the degradation of ammonium would also be influenced by dissolved oxygen (DO) content in influent and effluent (> 4 mg L^{-1}) was observed. The study further indicated the natural adsorbent properties of sand, gravel, geotextiles, peat moss and sorbent pillows were efficient adsorbent media. However, this is subject to the concentration of ammonia and filter media particle size, with finer media and geotextiles aiding removal; observations supported by *Hanusová* (*2014*) who reported that specific surface areas and flows can impact influent treatability.

Organic Loading as a Function of BOD and COD

This long-term study explored the performance and behavior regarding removal rates of COD and BOD within these stormwater biofiltration systems.

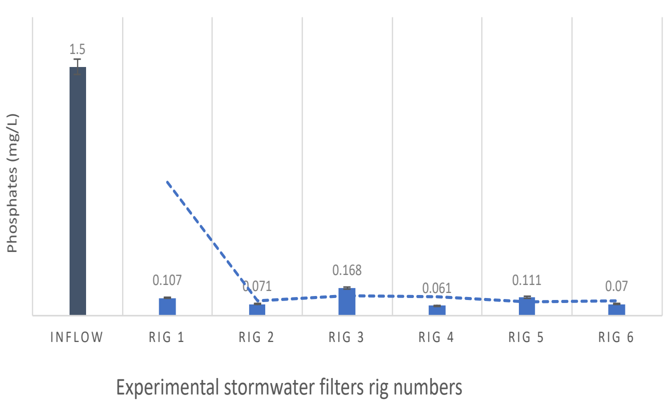

Figure 10. Phosphates (mg L^{-1}) average influent and effluent (Rig 1-Rig 6) for the stormwater treatment efficacies with moving average and error bars (2.5 % from analysis). Sampling period: March 2016-August 2019. (n= 430 with average value of inflow and outflow taken from triplicate)

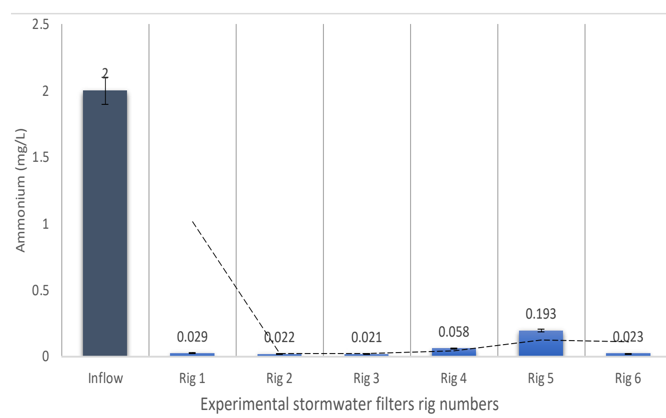

Figure 11. Ammonium (mg l^{-1}) average influent and effluent (Rig 1-Rig 6) for the stormwater treatment efficacies with moving average and error bars (2.5 % from analysis). Sampling period: March 2016-August 2019. (n= 430 with average value of inflow and outflow taken from triplicate)

Stormwater biofiltration systems as SuDS can have a more significant reputation and recognition as a reliable method in managing both organic and inorganic flows. One of their major benefits is the ability to remove various pollutants, including Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD). By efficiently removing organic and inorganic pollutants, these systems contribute to the preservation of ecosystems, support aquatic life, and enhance water quality (*Butler and Davies 2011; Paul and Tota-Maharaj 2015*). High COD removal rates are desirable as they indicate the successful removal of potentially harmful substances from stormwater. One of their major benefits is the ability to remove various pollutants, including COD and BOD. By efficiently removing organic and inorganic pollutants, these systems contribute to the preservation of ecosystems, support aquatic life, and enhance water quality (*Butler and Davies 2011; Paul and Tota-Maharaj 2015*). Lower BOD levels help protect downstream water bodies by reducing oxygen consumption, minimizing the risk of eutrophication, and supporting healthier aquatic ecosystems. The rigs showed significant reductions, suchas COD values decreasing from 68 mg l^{-1} to 2.8 mg L^{-1} and BOD values ranging from 181 mg l^{-1} (inflow) to as low as 17 mg L^{-1} for the effluent.

The COD represents the amount of oxygen required to oxidise organic and inorganic chemical compounds present in water (*Butler and Davies 2011; Paul and Tota-Maharaj 2015*). These stormwater biofiltration systems harnessed natural remediation processes and filter media to effectively reduce COD levels, resulting in improved water quality. The significant decrease in COD from 68 mg L^{-1} to as low as 2.8 mg L^{-1} demonstrates the efficiency of stormwater biofiltration systems. Factors such as the selection of appropriate filter media, residence time, and presence of biofilms contributed to their ability to break down and remove organic and inorganic pollutants. Biological/Biochemical Oxygen Demand (BOD) represents the amount of dissolved oxygen required by microorganisms to decompose organic matter in water. These stormwater biofiltration systems excelled in reducing BOD levels, showcasing their efficacy in treating polluted stormwater. The reduction of BOD values from 181 mg L^{-1} to 17 mg L^{-1} highlights the SuDS' ability to remove organic pollutants. By providing an ideal environment for microbial activity, biofiltration systems foster the degradation of organic matter, leading to a substantial decrease in BOD. High removal rates of BOD are crucial for maintaining water quality standards and preventing negative ecological impacts. Efficient removal of organic matter reduces oxygen depletion in water bodies, promoting a healthy and balanced aquatic environment. Additionally, lower BOD levels signify the successful removal of potential toxins and

For this study, the stormwater biofiltration systems have proven to be highly effective in removing For this study, the stormwater biofiltration systems as SuDS have proven to be highly effective in removing COD, BOD from stormwater runoff. The substantial reductions in COD values, from 68 mg L^{-1} to 2.8 mg L^{-1} (rig 1), 4.3 mg L^{-1} (rig 2), 6.6 mg L^{-1} (rig 3), 7.0 mg L^{-1} (rig 4), 6.1 mg L^{-1} (rig 5), 3.7 mg L^{-1} (rig 6) and the BOD effluent values, ranging from 16.9 mg L^{-1} to 27.3 mg L^{-1}, highlights the significant impact of these systems in improving water quality.

The COD is the readily biodegradable biochemical oxygen demand (BOD) and other refractory organics. The BOD and COD reductions within influent is achieved by the removal of organic particulate matter (and can be correlated to the TSS removal) and the bacterial

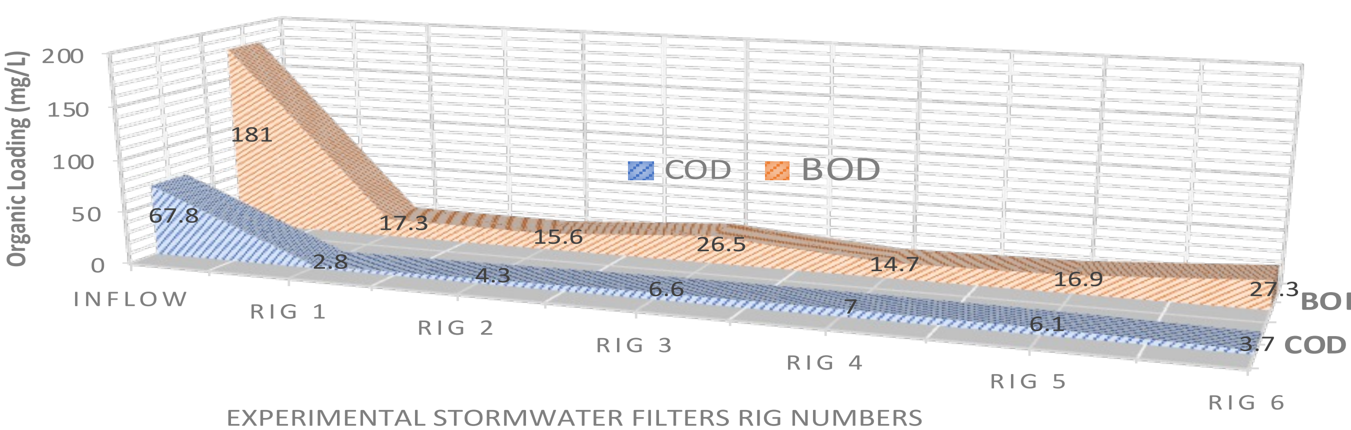

Figure 12. Organic Loading in the form of chemical oxygen demand (COD, mg L^{-1}) and biochemical oxygen demand (BOD, mg L^{-1}) average influent and effluent (Rig 1-Rig 6) for the stormwater treatment efficiency with moving average). Sampling period: March 2016-August 2019. (n= 430 with average value of inflow and outflow taken from triplicate)

oxidation of biodegradable dissolved organics (measured as BOD). Overall, the reduction of BOD and COD in influent the 6 rigs varied from 89-95 % for mean COD, and 84-92% for BOD, with influent BOD ranging from 181 mg L^{-1} and COD being 68 mg L^{-1} (**Figure 12**). The high removal rates of COD and BOD demonstrate the potential of stormwater biofiltration systems to mitigate the impact of urbanization on natural water bodies. By efficientlyremoving organic and inorganic pollutants, these systems contribute to the preservation of ecosystems, support aquatic life, and enhance water quality.

CONCLUSIONS AND RECOMMENDATIONS

Stormwater biofilters prove to be valuable tools for the removal of total dissolved solids, turbidity, color, ammonium (NH_4^+), phosphates, COD and BOD from stormwater runoff in this three-year study. The removal rates of these parameters significantly influence the quality of treated stormwater and its impact on ecosystems. By considering accepted values and guidelines, stormwater biofilters can effectively contribute to sustainable stormwater management, ensuring the protection and preservation of water resources.

The Hydraulic loading rate of approximately 0.15 L m^{-2}, ponding depth above the filter media (0.05 m), retention times of 30 hours, filter run in full cycles of four months in duration before periodic backwashing (**Table 3**) as a direct correlation with organic loading rates, turbidity levels and total dissolved solids (TDS) within the biofilters and respective stormwater filter media. Generally, very good removal rates were measured and observed for TDS, with a mean stormwater inflow of 577 mg l^{-1} and Rig 3 (**Figure 2**) with a 78 % removal efficacy of TDS (**Figure 7**). The turbidity (NTU) levels measured and observed varied from the source of urban stormwater inflows (32 NTU) versus the effluent and engineered outflows ranging from 0.54 for Rig 4 (**Figure 2**) to 9.71 for Rig 1 (**Figure 1**) (**Figure 8**). Periodic measurement of color (PCU) showed relatively high improvements, ranging from 78% for rig 1, 72% for rig 2, 84% for rig 3, 85% for rig 4, 86% for rig 5 and 82% for rig 6 respectively. Rig 4 (**Figure 2**) consisting of peat moss, an upper geotextile layer, sand, a lower geotextile layer and gravel showed the best improvements for the stormwater quality. Phosphates removal rates varied from each experimental rig with very similar performances. While there were no major differences in the stormwater treatability with respect to phosphate entrapment, once again, rig 4 (**Figure 2**) consisting of peat moss, an upper geotextile layer, sand, a lower geotextile layer and gravel showed the highest removal efficacies averaging 96% (**Figure 10**). Ammonium (mg L^{-1}) mean inflow concentrations fluctuated significantly throughout this study at relatively low concentrations which is expected for stormwater runoff (1.5-2.3 mg L^{-1}). There were no significant differences between rigs 1, 2,3 and 6 with respect to ammonium removal. For this three-year experimental study, the most optimal removal of COD occurred with RIG 1 (**Figure 1**) which consisted of sorbent pillows, a geotextile layer / geotextile membrane, sand, and gravel (approximately 96% removal efficacy). BOD removal efficiencies varied slightly across each experimental rig with rig 4 which was constructed of peat moss, a geotextile layer, sand, and gravel (**Figure 3**) reducing it from 181 mg L^{-1} of BOD inflow loading to 14.7 mg L^{-1}.

In practice, the selection of stormwater filters for specific sites requires an understanding of the water quality and quantity, and the drainage characteristics of the site. As such, stormwater filters used for SuDS should be designed, and retrofitted in urbanized areas as they are a BMP that can meet performance criteria for runoff of variable volume and pollutant load, for use over extended timescales. The design of SuDS involves choosing appropriate filter media configurations for use within a stormwater management plan, supported by an appropriate maintenance regime. The informed choice of filter media can have a significant impact on filter performance, as for example, sorbent pillows incorporating geotextile membranes can maintain color in effluent of variable inflow of 86 PCU. In the present work, the six filter designs remained free of clogging/obstruction and maintained their effectiveness in reducing high concentrations of TDS, turbidity, nutrients, and organic compounds in stormwater influent. The designs demonstrated high removal efficacy for phosphates, ammonium, and COD levels of 85-98% and control of turbidity, and that by increasing filter media thickness (from 250-450 mm) further increases in performance could be realized, despite reduced influent flow rates of 20-30%. Future work will involve the use of peat moss in sorbent pillows, including in combination with novel filter media, garnet in combination with conventional filtration materials (sand and gravel) to investigatethe long-term impact of e.g., BOD and dissolved oxygen. The inclusion of a larger catchment for stormwater and an increase in the range and concentration of pollutant 'types' will also be investigated. Further research and continuous monitoring of stormwater biofiltration systems are crucial to optimize their performance and ensure long-term success. Implementing these systems on a larger scale can lead to more sustainable stormwater management practices that protect the environment, reduce downstream pollution, and promote the well-being of surrounding communities.

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ACKNOWLEDGMENT

The authors would like to express their thanks and appreciation for the support of the technical staff and chief engineering technician (Mr. Ian Cakebread), within the School of Engineering, University of Greenwich, Medway Campus, Kent, England, UK. This research was supported by the International Water Security Network and funded by Lloyd’s Register Foundation, a charitable foundation helping to protect life and property by supporting engineering-related education, public engagement, and the application of research.