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Review

High Rate Stormwater Treatment for Water Reuse and Conservation—Review

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Abstract: Effective stormwater management is increasingly vital due to climate change impacts, such as intensified rainfall and flooding. Urban expansion, water scarcity, and intensified agriculture demand innovative solutions like Green Stormwater Infrastructure (GSI), including vegetated biofilters, green roofs, wetlands, bioretention systems, and high-rate filtration. These systems, enhanced by natural and engineered filter materials, improve contaminant removal across diverse contexts. Modern practices prioritize retention, infiltration, and groundwater recharge over traditional rapid drainage, reframing stormwater as a resource amid rising extreme weather events. In water-scarce regions, stormwater management offers dual-use potential for drinking and non-drinking applications, addressing freshwater scarcity exacerbated by population growth and climate change. Targeting the "first flush" of pollutants after rainfall allows for more efficient, cost-effective treatment. This paper identifies three key objectives: addressing GSI limitations and exploring new technologies, evaluating treatment train combinations for cost-effective reuse, and advancing urban stormwater treatment research. Various filter media, such as those in green roofs, bioretention systems, and swales, effectively remove pollutants like nutrients, heavy metals, PAHs, and micropollutants. Granular activated carbon (GAC) filters excel at reducing heavy metals and dissolved organic carbon (DOC), with pre-screening via anthracite filters to extend GAC lifespan by trapping sediments and pollutants. Managing emerging contaminants and microplastics remains underexplored and requires further investigation.

Keywords: Green Stormwater Infrastructure (GSI); stormwater; filter media; harvesting; high rate treatment systems

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1. Introduction

Green Stormwater Infrastructure (GSI) provides a sustainable framework for stormwater harvesting, employing methods like vegetated swales, constructed wetlands, biofilters, etc. These approaches offer multiple advantages, including flood mitigation, water quality improvement, and support for urban ecological systems. GSI is variously referred to in some countries as low-impact development (LID), water-sensitive urban design (WSUD), and sustainable urban drainage design (SUDS). GSI supports the development of cities with diverse water sources and minimal energy reliance, promoting broader social, political, and environmental sustainability. The effects of GSI on urban ecology, public health, and sustainability—both immediate and long-term—are outlined in Table 1. This review focuses primarily on the technical aspects of stormwater reuse. Legal and regulatory considerations are addressed by national water quality guidelines specific to the intended use of the water and are not discussed in detail here. For instance, in Australia, drinking water standards are outlined in the Australian Drinking Water Guidelines [1], while the Australian Guidelines for Water Recycling [2] provide a framework for developing safe and sustainable strategies for recycling water from sources such as greywater and stormwater. Stormwater management is a critical component of water quality efforts at the catchment, waterway, and local levels. The Australian Guidelines for Urban Stormwater Management [3] promote an ecologically sustainable approach to managing stormwater. Similar documents addressing these issues exist in other countries applicable in their jurisdictions.

Table 1. Short- and long-term impacts of GSI systems.

	Short-Term Impacts:	Long-Term Impacts:
Ecological health:	- Improved water quality by reducing pollutants entering water bodies. - Creation of habitats for wildlife through features like vegetated swales and rain gardens. - Reduction of erosion, thus preserving soil integrity.	- Restoration and enhancement of natural ecosystems through the promotion of native vegetation and creation of interconnected green spaces. - Increased biodiversity and resilience to climate change. - Improved soil health over time.
Human health:	- Decreased risk of flooding and erosion, enhancing public safety and reducing property damage. - Provision of recreational opportunities and enhancement of mental well-being through green spaces. - Mitigation of the urban heat island effect, improving overall urban livability.	- Reduction of waterborne diseases and improvement of air quality. - Mitigation of the urban heat island effect, leading to healthier and more livable communities. - Potential economic benefits through reduced stress, depression, anxiety, and property damage.
Environmental sustainability:	- Prevention of pollutants such as sediment, heavy metals, and nutrients from contaminating water bodies. - Protection of aquatic ecosystems by maintaining overall water quality.	- Long-term protection and restoration of aquatic ecosystems. - Cascading effects on entire watersheds, including improved habitat for aquatic organisms. - Minimization of pollution and preservation of water quality through effective stormwater management practices.

Among GSI methods, constructed wetlands and biofiltration systems excel in the treatment of stormwater because of other pollutant removal efficiency and suitability for urban areas. However, achieving disinfection levels that meet potable standards, particularly through UV treatment, necessitates effective pre-treatment to reduce pathogen levels. While wetlands and biofilters provide robust pre-treatment, consistent maintenance is key to maintaining their performance over time. The increasing concern about emerging contaminants and microplastics in stormwater and their fate and impacts on human and environmental health is another aspect of GSIs.

Ongoing maintenance is essential for the reliable operation of stormwater harvesting systems. Without it, blockages may reduce system efficiency and allow pollutants to re-enter the water supply. Regular vegetation management in wetlands and biofilters also helps maintain treatment capacity. A thorough life cycle cost analysis should account for aspects such as planning, design, construction costs, maintenance schedules, pollutant disposal, de-silting of storage areas, corrective measures, and eventual decommissioning. This comprehensive analysis is vital during the planning stages to balance treatment costs with environmental benefits.

GSI offers valuable benefits for ecological, human, and environmental health and sustainability in both the short and long term. However, the success of GSI systems relies on thoughtful design, regular maintenance, and integration with other urban infrastructure. Adaptive management and ongoing monitoring are necessary to ensure that GSI systems meet evolving needs and continue to deliver desired outcomes as conditions shift.

The paper outlines the following main objectives for advancing stormwater management practices:

1. Technological Gaps: Identifying shortcomings in current GSI practices and exploring new technologies with the potential to meet non-potable reuse requirements (Section 2).
2. Detailed review of different new filter media to enhance the removal of specific pollutants (Sections 3 and 4).
3. Pilot-scale Investigation on High-rate Stormwater Technologies: Assessing the feasibility of high-rate filtration and adsorption systems to achieve cost-effective stormwater reuse. This provides insights for future research for the development and validation of stormwater treatment trains in urban areas (Section 5).

Overall, the transition to more sustainable stormwater management practices is not only environmentally necessary but also holds economic and public health benefits, especially in the context of global water scarcity.

2. Research Background

2.1. Stormwater Technologies Rural and Semi-Urban Areas

Stormwater management often employs technologies like bioretention, biofiltration, constructed wetlands, rain gardens, swales, and permeable pavements to address dissolved pollutants [4–7]. These methods work through mechanisms such as plant absorption, enhanced infiltration that reduces runoff, decomposition facilitated by microbes and plant roots, and adsorption. Although systems like constructed wetlands and bioretention rely on nature-based processes, they are best suited to semi-urban or rural areas due to their larger space requirements. Additionally, their treatment consistency measured in terms of suspended solids (SS), total phosphorus (Tot-P), total nitrogen (TOT-N), and *E. coli* varies (see Table 2) and may fall short of standards required for water reuse.

Table 2. Pollutants removal range by different treatment methods (modified from Singh et al. [8]).

Stormwater Treatment Method	SS	Tot-P	Tot-N	*E. coli*
Gross Pollutant Trap (GPT)	0–70%	0–30%	0–15%	Negligible removal
Swale	55–75%	25–35%	5–10%	Negligible removal
Bioretention	70–90%	50–80%	30–50%	−58–95%
Pond	50–75%	25–45%	10–20%	40–98%
Wetland	50–90%	35–65%	15–30%	−5–99%

In rural areas, stormwater treatment primarily focuses on treatment for protection of environmental protection instead of producing water of a quality suitable for reuse [8]. Treatment goals emphasize removal of litter and sediment together with nutrients. Water destined for reuse also requires removal of heavy metals, pathogens, etc., which are generally not prioritized in stormwater treatment systems. In urban water, a study conducted by Russo et al. [9] on the performance of horizontal subsurface flow constructed wetlands showed a BOD_5 and COD removal of 61–63% and 59–66%, respectively.

Constructed wetland: Large-scale stormwater harvesting projects often use constructed wetlands due to their cost-effectiveness in treating substantial volumes of collected stormwater [10]. Unlike biofiltration systems that generally need separate water storage post-treatment, constructed wetlands offer integrated water storage within the wetland itself. These systems efficiently remove suspended solids, metals, and nutrients [11] and help reduce fecal coliform concentrations, though their effectiveness in this regard can be variable.

Sharma et al. [12] reviewed the applicability of wetland systems across many locations in the USA, Australia, New Zealand, Singapore, and Greece. The performance shown highlights high variability in pollutant removal. For instance, total-P removal ranged from 15% to 90%, Tot-N from 10% to 82%, and total SS from 55% to 95%.

Chua et al. [13] conducted a floating treatment wetland (FTW) study on a pilot scale for treating stormwater runoff in Singapore. They observed the removal of 39% and 68%

for total-P and Tot-N, respectively, when *Typha angustifolia* was used as a floating plant. When *Polygonum barbatum* was used as a plant, the removal was reduced to 19% and 41% for total-P and Tot-N, respectively. An in situ study conducted in New Zealand with *Carex virgata* as a plant led to 50% removal for tot-P [14]. A relatively large, controlled outdoor FTW experiment (Mesocosm) conducted in the USA with the *Schoenoplectus tabernaemontani* plant led to higher removal of 50% and 68% for total-P and Tot-N, respectively [15]. Ladislas et al. [16] conducted a full-scale FTW study in France using *Andropogon geradii*, *J. effusus*, *Carex stricta*, and *Hibiscus Moscheutos* as plants and obtained the removal of 78%, 40%, and 49% for SS, total-P, and Tot-N, respectively. A pilot study FTW conducted in Australia with *Carex appressa* as the plant led to a removal of 18% and 53% for total-P and Tot-N, respectively [17]. A field-scale study conducted by Olguin et al. [18] in Mexico showed a Fecal coliform removal of 86%. They used *Pontederia sagitata* and *Cyperus papyrus* as plants. A mesocosm scale FTW study conducted in the USA by Garcia Chance & White [19] using *C. flaccida* as the plant showed 32% and 49% for total-P and Tot-N, respectively. Schwammberger et al. [20] conducted a field-scale study in Australia with *C. appressa* as the plant and observed 15% and 17% for total-P and Tot-N, respectively. Another mesocosm scale FTW study conducted in the USA by Spangler et al. [21] using *J. effusus*, *Spartina pectinata*, and *P. cordata* as plants showed 64% and 26% removal in Tot-N and Tot-P, respectively. Due to the low removal of total-P and Tot-N, constructed wetlands are suitable for use as pre-treatment in stormwater treatment applications. Furthermore, they require a large area.

2.2. Stormwater Technologies in Urban Areas

Wetlands find application in locations where land space is less constrained as they require several hectares to accommodate all their components. This space is not available in more urbanized settings, particularly in inner city areas. The essential features of wetlands have been captured in the form of a vegetated biofilter for application where land space footprint is a constraint.

Vegetated Biofilter: In urbanized areas, biofilters are a more suitable alternative treatment, requiring less land than constructed wetlands and making it particularly suitable for local stormwater harvesting solutions. Laboratory experiments have shown that biofilters are effective at removing significant amounts of suspended solids and metals from stormwater [22,23], and these findings have been largely validated in real-world applications [24,25]. Although the removal of nutrients is another potential benefit [26–28], certain studies report biofilters as net contributors of nutrients, particularly nitrogen [22,23,29]. Tables 3 and 4 outline the main elements of stormwater biofilters and the processes involved in pollutant removal.

Table 3. Two key components of stormwater biofilters and their functions (modified from Payne et al. [30]).

Components	Function
Vegetation	Provides carbon to microbes, reduction of stormwater volume through transpiration, helps to maintain infiltration rates, provides cooling to nearby environment, aesthetic appearance, adsorbs stormwater pollutants, and treats through the microbes in the plant roots.
Filter media	Offers particulate filtration, pollutant removal via adsorption and precipitation, fosters plant growth, and enhances stream health.

Table 4. Key removal processes of stormwater Pollutants (modified from Payne et al. [30], Bodus et al. [31]).

Stormwater Pollutant	Removal Processes
Sediment	• Settling • Media filtration
Nitrogen	• Nitrification and Denitrification • Assimilation by plants and microbes • Decomposition • Adsorption
Phosphorus	• Filtration of particle associated fraction • Adsorption • Assimilation by plants and microbes • Decomposition
Heavy metals	• Adsorption by plants and microbes present in the roots • Filtration of particle associated fraction • Oxidation and reduction
Pathogens	• Adsorption • Media filtration • Microbial Die-off
Micropollutants	• Adsorption • Biological degradation
Antibiotic resistance genes	• Filtration • Sorption • Physico-chemical methods
Microplastics	• Infiltration/filtration with biochar, GAC etc. • Gross Pollutant Traps

Biofiltration works by improving water quality through biological filtering processes (Figure 1). These systems are called by various names, such as biofilters, bioretention systems, and rain gardens, and are integral to GSI as treatment methods that consume little energy and enhance both water quality and volume management. These systems are adaptable to a range of catchment sizes and settings, from small-scale applications like street trees and private gardens to larger installations along streets and in parking areas. A typical biofilter is made up of two layers, i.e., a vegetated basin or swale layered over a porous filter medium, usually sand. These drain into a porous pipe connected to the stormwater system.

There is limited data available on pathogen removal in biofilters. A pilot study assessing vegetated biofilters with various plant species found that they achieved *E. coli* removal rates ranging from 48% to 97% [29]. Additionally, experiments with different biofilter configurations showed pathogen removal of more than two to three log reductions [32]. Small stormwater harvesting systems in Kuring-Gai, New South Wales, Australia showed approximately a 1 log reduction in fecal coliforms. Influent water to this system (pre-treatment) is typically treated by biofilter.

Although both constructed wetlands and biofilters have demonstrated significant potential in reducing pathogen levels, they are not yet recommended for compliance under Australian guidelines [2].

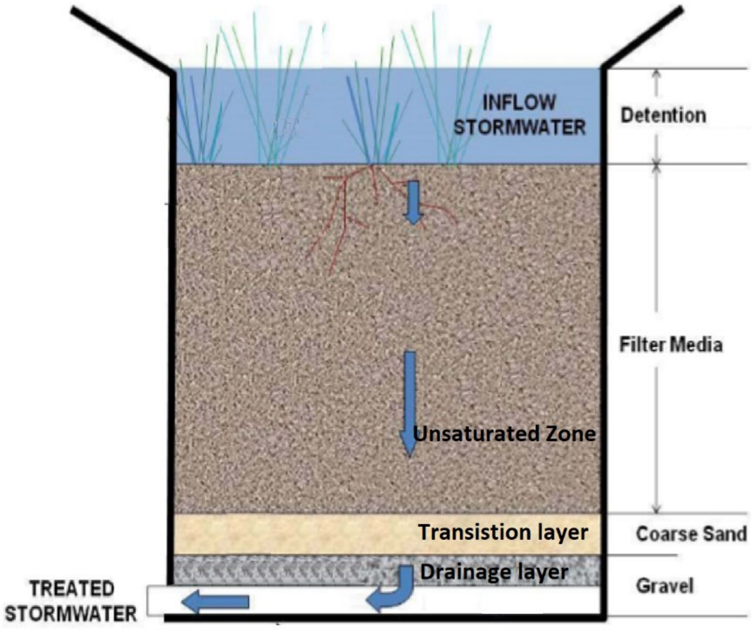

Figure 1. Schematic of biofilter system.

Although vegetated biofilters are a good choice for stormwater pollutants, especially in inner city areas, they are unable to remove all the pollutants, i.e., organic matter and nutrients. There is a need to investigate different filters that can remove such pollutants.

Despite the increasing focus on the presence, fate, and impacts of emerging contaminants, antibiotic resistance genes, and microplastics, related research is scarce. Bodus et al. [31] provide an overview of their fate during various GSI approaches. Most of these pollutants are "forever chemicals" which increases their presence in the environment posing increasing challenges to human and environmental health, thus requiring to be addressed adequately.

3. Removal of Nutrients and Heavy Metals Removal Using Different Filter Materials

Introducing suitable filters or adsorption media is an effective approach to enhancing organic matter, nutrients, and heavy metals removal.

Nutrient Removal: Studies have investigated several filtering materials—namely, calcite, zeolite, sand, and iron filings—to evaluate their effectiveness in removing nitrate and phosphate from simulated stormwater over a 24 h period with varying initial concentrations [33]. Nitrate removal rates ranged from 39–65% for calcite, 42–77% (zeolite), 40–70% (sand), and 74–100% (iron filings). For phosphate, removal efficiencies were 35–41% for calcite, 59–100% (zeolite), 49–100% (sand), and 73–100% (iron filings). Nitrate reduction primarily occurs through electrostatic adsorption, while iron filings also promote removal through electrochemical reduction, ligand complexation, and precipitation. Phosphate removal relies largely on electrostatic adsorption for all materials, though precipitation may become dominant at higher concentrations, except with calcite.

- Iron filings proved to be the most effective medium, achieving maximum removal rates for both nitrate (73–100%) and phosphate.
- A maximum nitrate adsorption capacity of 16 µg/g of dry material was reached by calcite, zeolite, and sand. Iron filings showed a higher capacity, surpassing 30 µg/g for nutrient adsorption.

- Phosphate adsorption was typical for calcite, while zeolite, sand, and iron filings had higher adsorption up to concentrations of 0.5–1 mg/L. Beyond this limit, precipitation played a larger role.

Heavy Metals: Batch tests using synthetic stormwater containing varying concentrations of individual metal pollutants were conducted to evaluate the removal effectiveness of four potential absorption inorganic filter materials (calcite, zeolite, sand, and iron filings) on six common toxic metals (cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni), chromium (Cr), and zinc (Zn)) [34]. The efficiency of metal removal was influenced by the metal type, its concentration, and the choice of filter material. The highest removal efficiencies recorded were 95–100% with calcite, zeolite, and iron filings for Cd, Cu, Pb, and Zn; 90% (zeolite) for Ni; and 100% (iron filings) for Cr. As no single material achieved maximum removal for all metals, enhancing the simultaneous removal of various heavy metals may be achieved by combining multiple filter materials.

Stormwater runoff significantly contributes to heavy metal pollution, transporting contaminants such as Cd, Cr, and Ni, which can adversely affect ecosystem health and human wellbeing. A variety of filter materials were tested for their effectiveness in adsorbing heavy metals from stormwater, typically utilizing methods that are chemically intensive or energy consuming. Byproducts from drinking water purification processes referred to as water treatment residuals (WTR) which are aluminum based are non-toxic and present a cost-effective solution for removing heavy metals. However, WTR's low permeability necessitates blending it with materials like sand and carbon to enhance water flow, which in turn diminishes its capacity to adsorb. In response, a granulated WTR sorbent was created through a low-energy, organic method, demonstrating significant potential as a sustainable filter medium for heavy metal removal from stormwater [35].

Five inexpensive and easily accessible sorbents were evaluated for their ability to remove polycyclic aromatic hydrocarbons (PAHs) like pyrene, phenanthrene, acenaphthylene, and naphthalene from synthetic stormwater. The materials tested included three unprocessed waste products—waste tire crumb rubber (WTCR), coconut coir fiber (CCF), and blast furnace slag (BFS)—as well as two modified substances: biochar (BC) and iron-coated biochar (FeBC) [36]. The findings showed that carbon-based sorbents had high PAH removal efficiency, while BFS was comparatively less effective.

Integrated Pollutant Removal with Multiple Filter Media: While stormwater harvesting can help reduce reliance on other water sources, stormwater typically carries a variety of pollutants that require treatment before reuse or discharge. Ekanayake et al. [37]) conducted lab-based column experiments to assess a soil-based filter medium's effectiveness in removing multiple pollutants from stormwater over short-term tests representing 1–3 years of rainfall. The soil filter efficiently removed PO4-P and NH4-N for up to 8 h at a flow rate equivalent to one year's rainfall in Sydney, Australia. By incorporating 10% zeolite, the filter's saturation time increased to 24 h, achieving over 50% removal of nine heavy metals for up to 4 h, which extended to 16 h with the zeolite mix. The soil + 10% zeolite filter showed high removal efficiencies for Pb, Cu, Zn, and As, with Pb removal reaching the highest percentage. When combined with 0.3% granular activated carbon, the filter achieved 65–99% PAH removal after 24 h.

This study showcases a novel method to assess filter media performance for stormwater treatment, effectively removing various pollutants through a mix of three contrasting adsorbent materials [37].

4. Incorporation of Different Filter Media to Enhance the Removal of Specific Pollutants

Westholm [38] reviewed various stormwater treatment facilities using different filter media in field and pilot-scale applications to address stormwater pollutants (Table 5). These media were implemented in GSI systems, including green roofs, bioretention areas, and swales. They improved the removal of specific pollutants by enhanced adsorption and filtration.

Table 5. Summary of media used in filters (modified from Westholm [38]).

Filter	Reference
Basalt	[39]
Biochar	[40]
Biochar	[41]
Light-weight aggregates (LWA)	[42]
Sand	[41]
WTR	[43]
WTR	[35]
WTR	[44]
Woodchips	[45]
Zeolites	[39]
Zeolites	[46]

In a pilot-scale study by Sountharararajah et al. [39], the removal of heavy metals by a permeable pavement system (PPS) was tested using basalt and zeolite as the filter media. This study examined the removal of cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) from synthetic stormwater over an 80-h period, simulating rainfall in Sydney, Australia over a 10-year period. The results showed that basalt removed between 38% and 67% of the total heavy metals tested by adsorption.

Biochar has proven effective in laboratory studies as a filter medium for removing various stormwater pollutants [47,48]. This solid material, composed of carbon and ash, is produced through the thermochemical treatment of organic matter in an oxygen-limited environment, such as during pyrolysis. Additional research has included pilot-scale and field experiments (Table 6).

Kranner et al. [40] carried out simulated field tests over roughly 14 months using sand alone and a sand-biochar blend to examine *Escherichia coli* removal with natural stormwater. In another pilot study, Teixidó et al. [41] employed biochar in a multi-step treatment system designed to address various pollutants. The process began with a sand filter spiked with iron for phosphate removal, followed by a woodchip bioreactor and an aeration step to eliminate nitrate. This was followed by columns filled with sand amended with iron, biochar, and/or manganese oxides to capture trace metals and other harmful substances. This system was tested with real stormwater runoff over 8 months. Teixidó et al. [41] observed nearly complete nitrate removal in the bioreactor, though phosphate removal in the iron-enriched sand was less effective, resulting in breakthrough conditions. During the first four months, columns containing sand combined with biochar and manganese oxides removed 80% of metals and organic pollutants. The researchers suggested that, in their specific study environment, nutrient removal might be effective for about a decade, while organic compound removal could be less durable. Additionally, lightweight aggregates have been investigated as filter media in green roofs (see Table 6). The removal mechanisms were adsorption and filtration.

Liu & Coffman [42] identified dredged lightweight aggregates (LWA) as an effective filter medium for green roof applications. These aggregates, typically produced from materials that would otherwise end up in landfills, offer a sustainable solution.

Table 6. Different filter materials incorporated on GSI method (modified from Westholm [38]).

Filter Material Used	GSI	Pollutants Removed	References
Lightweight aggregates (LWA)	Green roof	Total-P	[49]
Sand	Swales	Zn, PAHs and glyphosate	[50]
Water treatment residuals (WTR)	bioretention	Different P species, and total-N	[43]
Woodchip with sand, and gravel	Infiltration trench	SS, Different P- species, and total-N	[45]
Woodchip	bioreactor and aeration	nitrate	[41]

Cheng et al. [49] conducted a study involving 32 pilot-scale green roofs in New Jersey, USA from 2017 to 2022, which spanned all four growing seasons and included 38 storm events. The objective was to evaluate phosphorus contributions to roof runoff from sedum-planted roofs. The growing medium consisted of 90% LWA, made using either pumice or expanded clay, with compost being the other alternative. Their findings revealed a decrease in total phosphorus (total-P) concentrations in the effluent over time, indicating green roofs can effectively retain phosphorus within them by filtration. Cheng et al. [49] also explored using permeable reactive barriers and various additives, including zeolites and wood-derived biochar, for use in the substrate component of green roofs. An inclusion of 20% zeolite in the substrate material led to lower total-P concentrations (by in-exchange and adsorption).

In another field study by Fardel et al. [50] in Nantes, France, two swales received stormwater runoff from roofs. Naturally, sources of silt loam soil were used to make one swale. The other consisted of a central sand filtration area surrounded by silt loam embankments. This study aimed to assess the removal efficiencies for four micropollutants, including zinc (Zn), polycyclic aromatic hydrocarbons (PAHs) such as pyrene and phenanthrene, and glyphosate. Fardel et al. [50] found that the standard swale reduced micropollutants in infiltrated water by 35% to 85%, and overflow water concentrations were between 65–100% by adsorption. In contrast, the filtering swale achieved reductions of 67% to 90% for Zn and at least 89% for the other micropollutants, demonstrating that filtering swales were more effective than standard ones.

Water treatment residuals (WTR), produced during the drinking water purification process when aluminum- or iron-based coagulants are used, have emerged as a promising filter medium for removing phosphorus and heavy metals [35]. Several field investigations utilizing WTR in various low-impact development (LID) facilities have been conducted recently, as detailed in Table 6.

In a field study, Ament et al. [43] tested the effectiveness of WTR in a bioretention system over a two-year period. The WTR medium performance was compared to a control setup that included washed gravel, pea stones, sand, and compost. While both media demonstrated reductions in all phosphorus species, the WTR medium consistently showed greater removal rates.

Nagara et al. [35] also examined aluminum-based WTR in a field experiment conducted over 6 months focused on phosphorus and heavy metal removal (Cu, Pb, and Zn) from stormwater that ran off a car park situated in New Jersey, USA. Throughout 12 storm events, WTR granules effectively lowered dissolved phosphorus, copper, and zinc, as well as total concentrations of phosphorus, copper, lead, and zinc. This highlights WTR's potential as a filter medium that can divert waste from costly landfill disposal.

Kuster et al. [44] demonstrated that drinking water treatment residuals (DWTR) are effective in reducing all tested phosphorus species, concluding that DWTR is a viable option for phosphorus removal. Woodchips, produced from tree chipping, have also attracted interest as a filtering material in low-impact development (LID) methods for stormwater treatment (see Table 6).

In a study using stormwater from roads and parking areas, Geronimo et al. [45] observed that pre-treatment effectively captured silt or sand in quantities ranging from 9% to 92%, with nitrogen and phosphorus levels higher in silt than in sand, thereby enhancing nutrient removal. Zeolites were also field-tested for heavy reduction of metal (see Table 6).

In a pilot-scale study in Sydney, Australia, Sounthararajah et al. [39] used natural Australian zeolites along with basalt in a permeable pavement system (PPS). They evaluated the removal of five heavy metals (Cd, Cu Ni, Pb, Zn) from synthetic stormwater. Over an 80-h test, simulating 10 years of rainfall, zeolites achieved cumulative metal removal rates of 41% to 72%. Adding a post-treatment layer with sodium titanate nanofibers (TNF) and granular activated carbon (GAC) further improved metal adsorption and filtration, allowing the effluent to meet regulatory standards.

In another field study, Milovanović et al. [46] assessed zeolites as a filter material for stormwater treatment in an area of Stockholm that included a copper-covered roof and a recreational park. They reported significant reductions in both total and dissolved copper, achieving removal rates of 52–82% and 48–85%, respectively (see Table 6). The removal mechanisms were ion exchange and filtration.

Even GSI with modified filter media may not be suitable for urban areas where there are short intense periods of rain. Intense rain generates large volumes of runoff that cannot be treated all at once in filters. This means that large storage facilities are required, meaning an additional land footprint is required, something not available in urban settings, particularly inner-city areas. In this case, high-rate treatment systems may be a suitable alternative.

5. High-Rate Stormwater Treatment Technologies

Systems such as wetlands, biofilters, and PPS are popular for treating stormwater. However, the existing stormwater treatment systems do not consistently deliver the water quality suitable to meet standards for recycling. Additionally, given the high volume of stormwater discharge, they typically incorporate storage components that occupy significant land areas, which can be limited in urban inner-city environments. An alternative approach involves storing stormwater before treatment, similar to traditional management systems. However, untreated stormwater in storage holds little value and can deteriorate under both anaerobic and anoxic conditions. Incorporating pre-treatment can enhance the quality of stored water, making it more suitable for beneficial reuse.

Physico-chemical treatment systems, including fiber filters, deep bed filters, and granular activated carbon (GAC) filters, can effectively remove pollutants at high rates (see Table 7). High-rate systems are designed to improve water quality to meet at least non-potable standards. A brief overview of these systems is provided below.

Fiber Filter: High-rate fiber filters have been effectively utilized in tertiary wastewater treatment. Unlike traditional sand filters, these systems use filters consisting of fine polyamide fibers shaped in the form of U-shaped bundles. Fiber filters operate at filtration velocities that are over five times faster than conventional rapid sand filters and possess a specific surface area that is more than double that of sand [51–53]. The unique packing of the fibers provides a large specific surface area and is highly porous (exceeding 90%). This means that the pressure drop across the filter is low while maintaining a high removal efficiency, even at elevated filtration velocities [53]. The inline addition of flocculants can further enhance the system's capacity to remove dissolved organics and trace metals.

Deep Bed Filter: Deep bed filtration, also known as media or rapid filtration, is extensively employed in water treatment for particle removal as the last clarification step. This method is effective for eliminating various particles in both water and wastewater. Deep bed filters are particularly suitable for clarifying dilute suspensions with particle concentrations below 500 mg/L and sizes ranging from approximately 0.1 to 50 µm [52]. These filters can operate under pressure or gravity, with filtration velocities typically ranging from 5–20 m/h. Deep bed filters can be configured as either single-media or dual-media systems, with dual-media setups enabling the influent to flow through one type of media before moving on to another.

Membrane Filtration and Hybrid Systems: Pilot studies in low-pressure membrane technologies, including microfiltration (MF) and ultrafiltration (UF), have led to their growing use in stormwater treatment, thanks to their effectiveness, ease of operation, and compact size [52]. Microfiltration membranes usually have pore sizes between 0.1 and 0.2 µm. In comparison, ultrafiltration membranes typically have smaller pore sizes, ranging from 0.005 to 0.05 µm or less. Microfiltration is effective at removing particles, clays, and bacteria, while ultrafiltration is designed to eliminate macro-molecules, proteins, polysaccharides, and viruses. Operating pressures for MF vary from 100–200 KPa, whereas UF generally requires pressures above 200 KPa. Membrane filtration is often preceded by pre-treatment methods (e.g., fiber filters, deep bed filters), resulting in hybrid systems that significantly improve overall removal efficiency and produce good quality water that meets water quality standards for reuse [52].

GAC Biofilter: This is an adsorption biofilter generally consisting of a column packed with support media that promotes microbial growth. During the initial operation phase, the main mechanism is the adsorption of different substances, including microorganisms. As the system develops, microbial activity plays a greater role in breaking down organic matter. The effectiveness of biological filtration in pollutant removal is significantly affected by the actions of the microbes within the system.

Table 7. Indicative percentage of pollution retained in the treatment system and indicative levels of pollutants in the outflow for a range of high-rate treatment measures (modified from Jonasson et al. [52]).

High Rate System	Fiber Filter [1]	Deep Bed Filter [1]	Submerged Membrane Hybrid Systems	GAC Biofilter
Heavy Metals	90%	40–54%	- [2]	90%
Total Phosphorus	90%	50%	- [2]	74%
Total Nitrogen	90%	38%	- [2]	34%
Turbidity [3]	95%	95%	98%	75%
TOC	40%	30–45%	40%	100%
E. coli [3]	93%	80%	99.9%	-

[1] in conjunction with in-line flocculent ferric chloride addition [2] at least equal to fiber filter, deep bed filter, or biofilter depending on the system the membrane filter is coupled to. Usually, membrane systems are coupled with in-line flocculent or adsorbent addition. [3] influent and effluent pollutant concentrations in mg/L except for turbidity (NTU) and *E. coli* (cfu/100 mL).

Applications of High-Rate Filter Systems

High-rate treatment systems present a sustainable solution for urban development by reducing the need for municipal water, lessening pollutants in stormwater, and minimizing the release of stormwater. The byproducts generated from these treatment processes (concentrated pollutants, sludge), are usually routed to the sewer system, helping to solve sludge disposal issues and offering a low-maintenance option. Utilizing water reuse systems like these can effectively reduce the transport of stormwater contaminants from locations to adjacent water bodies.

Table 8 highlights the efficiency of high-rate treatment systems used for stormwater reuse. These systems demonstrate impressive removal rates for physical pollutants (suspended solids, turbidity), heavy metals (including Fe, Mn, and Pb), as well as organic matter. Their small design footprint allows for minimal land use, as there is no need for water storage prior to pre-treatment.

Table 8. Total organic carbon values (modified from Kus et al. [54]).

Treatment Process	Influent (mg/L)	Anthracite (mg/L)	GAC (mg/L)
GAC filter	2.3–6.9 (range) 4.6 (average)		ND-1.0 (range) 0.1 (average)
Anthracite followed by GAC	2.3–6.9 (range) 4.6 (average)	2.3–6.4 (range) 4.1 (average)	ND-1.0 (range) 0.1 (average)

Materials and Methods on high-rate systems: A detailed on-site pilot-filtration study was conducted in Kogarah, Sydney, Australia to evaluate the performance of filters using anthracite coal and granular activated carbon (GAC) at high filtration velocities for the removal of solids, heavy metals, and organic pollutants (Figure 2). Raw harvesting water was stored in a tank (Figure 2). Samples of raw water were sourced from a stormwater harvesting facility in Sydney, Australia. The stormwater primarily came from base flow, which continuously moves through the canal during dry spells. A pit located at the base of the canal allowed stormwater to drain by gravity to a nearby wet well. From there, it was pumped through to a control valve pit where turbidity levels are monitored. Should the turbidity exceed 50 NTU, the stormwater is diverted to a return pit leading back to the canal; otherwise, it continues to the filtration plant at a flow rate of 0.7 L/s (2.5 kL/h)

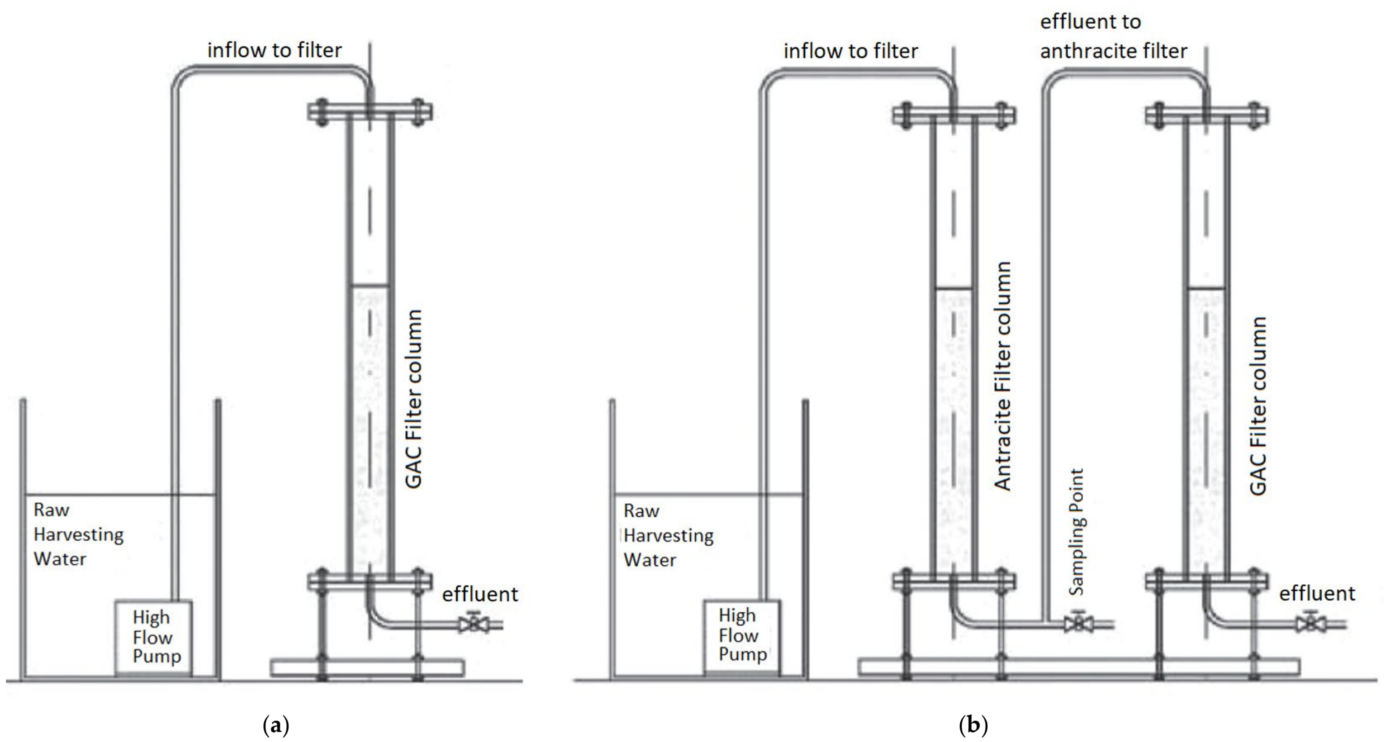

Figure 2. GAC media filter (**a**) without and (**b**) with prefilter packed with anthracite (filtration rate = 10 m/h, filter media height = 1 m, filter column height = 1.8 m, filter diameter = 0.1 m).

Raw water from the tank was pumped to the filter column which was operated in downflow mode. Two filter set-ups were used. In the first setup (Figure 2a) GAC media filter was operated alone. The characteristics of GAC are given in the Supporting Information Table S1. In the second (Figure 2b) a prefilter column packed with anthracite followed by a GAC filter was used. The columns had a medium height of 1 m and were operated at a flow rate of 10 m/h. Samples were taken at the outlet tap to each filter column. They were operated continuously for 4 h each day over a period of three days. At the conclusion of each operational day, the filter columns underwent a backwashing process lasting 60 s, which effectively kept the pressure across the columns below 1 bar.

Table 8 presents the influent stormwater and effluent concentrations of total organic carbon (TOC). The results are based on seven samples taken daily for a period of three days. The GAC filter column achieved a TOC removal rate ranging from a minimum of 86% (0.95 mg/l) to over 99.9%, effectively adsorbing most organic matter. Additionally, one other treatment configuration was evaluated. It consisted of first an anthracite filter column and then a GAC filter column. However, incorporating the anthracite filter did not enhance the overall TOC removal. The average reduction rate by the anthracite filter for TOC was recorded at 10.8% with the anthracite filter showing a 4.1 mg/l decline in concentration decline.

Table 9 presents the turbidity concentrations of influent stormwater. These findings are derived from seven samples collected daily over a period of three consecutive days. The granular activated carbon (GAC) filter alone achieved an average turbidity reduction of 84%. The average turbidity levels for the influent raw water and the effluent from the GAC filter were 29.2 NTU and 4.5 NTU, respectively. When an anthracite filter was incorporated into the treatment setup, the average turbidity removal became 71%, i.e., turbidity reduced from 28.9NTU to 8.5 NTU. The GAC filter then further reduced the turbidity to 4.2 NTU.

Table 9. Turbidity reduction values (modified from Kus et al. [54]).

Treatment Train	Influent (NTU)	Anthracite (NTU)	GAC (NTU)
GAC filter	14.0–48.5 (range) 29.2 (average)		3.0–6.0 (range) 4.5 (average)
Anthracite and GAC	14.0–48.5 (range) 28.9 (average)	5.0–12.0 (range) 8.5 (average)	3.0–6.0 (range) 4.2 (average)

Heavy Metals: Table 10 summarizes the concentrations of heavy metals found in the influent stormwater. Typically, the raw stormwater showed low levels of these metals. The granular activated carbon (GAC) filter performed well, achieving notable reductions in most heavy metals. Most of the heavy metals were removed through adsorption, with average removal rates of 85% for aluminum, 94% for iron, 80% for manganese, and 64% for zinc, as indicated in Table 10. Parameters for the batch equilibrium adsorption models fit experimental data for Cu, Pb, and Zn adsorption on GAC are given in Table S1.

Table 10. Removal of heavy metals using filtration/adsorption columns (modified from Kus et al. [54]).

Parameter	Raw Canal (mg/L)	Treatment	
		GAC Filter Alone (mg/L)	Anthracite Followed by GAC Filter (mg/L)
Aluminum	0.25	0.038	ND
Copper	0.025	NA	0.019
Iron	1.277	0.082	NA
Manganese	0.478	0.098	0.053
Lead	0.003	NA	0.002
Zinc	0.058	0.021	0.038

Organic Characterization: The dissolved organic carbon (DOC) concentration in the canal water was measured at 5.86 mg/L, comprising 66% hydrophobic and 34% hydrophilic components. Various organic fractions were analyzed using LC-OCD (liquid chromatography organic carbon detection). Within the hydrophilic fraction, humic substances represented 52%, building blocks (23%), biopolymers (8%), and lower molecular neutrals and acids (16%). For comparison, Table 11 provides data for raw rainwater. After GAC filtration, the DOC concentration in the stormwater decreased to 1.76 mg/L, indicating a removal efficiency of 70%. The GAC filter effectively trapped over 75% of hydrophobic materials. The composition of the hydrophilic fraction included biopolymers (15%), humic substances (52%), building blocks (27%), and lower molecular neutrals and acids (7%).

Table 11. Organic compound fractions measured by LC-OCD (modified from Kus et al. [54]).

Sample	Dissolved Organic Carbon (DOC) mg/L	Hydrophobic Organic Carbon (HOC) mg/L	Hydrophilic Organic Carbon (CDOC) mg/L	BIO-Polymers mg/L	Humic Substances (HS) mg/L	Building Blocks mg/L	Low Molecular Weight Substances mg/L
Stormwater (Raw)	5.86	3.87	1.99	0.17	1.04	0.46	0.32
GAC Filter	1.76	1.08	0.68	0.10	0.35	0.35	0.05
Raw rainwater (for comparison)	1.63	1.26	1.26	n.q.	0.2	0.2	0.06

Practical Implications: The filter demonstrated effective performance at a discharge of 10 m/h, consistently removing suspended solids, organic matter, and heavy metals, even with fluctuations in the concentrations of influent pollutants. To simulate conditions typical of a stormwater harvesting system, the performance was maintained over a continuous period of three days, totaling 5 h. Rainfall and the subsequent runoff events generated in urban areas usually last only a few hours. The treated effluent generated by the filtration process is appropriate for non-potable uses, including street washing, certain industrial applications, and irrigation of parks.

6. Conclusions

GSI is a promising concept that efficiently manages stormwater pollution while promoting greener technologies. Many researchers have documented the fate, impacts, and removal of pollutants in stormwater.

Vegetated biofiltration is a popular treatment approach in urban areas, requiring less land than constructed wetlands and making it particularly suitable for local stormwater harvesting solutions. Although both constructed wetlands and biofilters have demonstrated significant potential in reducing pathogen levels, they do not satisfy reuse standards. A number of filter media were successfully used in low-impact development (LID) systems, such as green roofs, bioretention systems, and swales to remove additional pollutants such as nutrients, heavy metals, poly aromatic hydrocarbons (PAHs), and other micropollutants in a consistent manner.

High-rate treatment systems offer an opportunity for sustainable urban development by minimizing the demand for municipal water, reducing stormwater pollution, and lowering stormwater discharges. High-rate treatment systems that can be used are media filtration packed with GAC and anthracite, fiber filtration, and membrane filtration. The GAC filter column demonstrated a strong capacity for reducing influent DOC concentrations. It removes most types of organic matter.

On its own, the GAC filter achieved an average turbidity reduction of 84%. The anthracite filter did contribute to lowering turbidity levels prior to water entering the GAC filter. Utilizing an anthracite medium filter before GAC filtration serves as a screening mechanism, capturing sediments and pollutants that could otherwise clog the GAC and shorten its lifespan.

Although the raw influent stormwater typically exhibited low levels of heavy metals, the GAC filter effectively removed a significant proportion of these metals. Both anthracite and GAC filters were back-washed after each storm event to remove the solids retained. Since the concentrations of heavy metals and organic content in the stormwater were typically low the GAC medium in the filter can be replaced on a biennial basis. This depends on the rainfall intensity. The management of emerging contaminants and microplastics is relatively less understood yet and deserves future attention.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15020590/s1. Characteristics of GAC used in Section 5. Table S1. Parameters for the models fits to experimental data for Cu, Pb, and Zn adsorption on GAC. Reference [55] is cited in the Supplementary Materials.

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