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Review

Impacts of Extreme Rainfalls on Sewer Overflows and WSUD-Based Mitigation Strategies: A Review

Nitin Muttil [1,2,*], Tasnim Nasrin [2] and Ashok K. Sharma [1,2]

[1] Institute for Sustainability and Innovation, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, Australia
[2] College of Engineering and Science, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, Australia
* Correspondence: nitin.muttil@vu.edu.au

Abstract: Extreme rainfall events cause an increase in the flow into aging sewer networks, which can lead to Sanitary Sewer Overflows (SSOs). This literature review presents a complete assessment of the application of Water Sensitive Urban Design (WSUD) approaches as mitigation strategies for reducing rainfall-induced SSOs. The review highlights the various WSUD techniques identified in past studies for reducing sewer overflows. In these studies, it was identified that permeable pavements, green roofs, raingardens/bio-retention cells and rainwater tanks were the most popular WSUD strategies that have been extensively used in the past for the mitigation of sewer overflows. WSUD or "green" approaches also have enormous environmental, social and economic benefits when compared to the conventional "gray" approaches for sewer overflow mitigation. However, there have been limited studies conducted in the past that highlight and quantify the benefits of WSUD approaches for sewer overflow mitigation, particularly when such strategies are applied at a large scale (e.g., city scale). This review has identified the modelling software, SWMM, to be the most widely applied tool that has been used in the literature for WSUD modelling. It was also identified that with climate change-induced extreme rainfall events on the increase, WSUD-based "green" strategies alone may not be enough for the mitigation of sewer overflows. A suitable sewer overflow mitigation strategy could be green or a hybrid green-gray strategy, which would need to be identified based on a detailed context specific analysis.

Keywords: sanitary sewer overflows; mitigation strategies; WSUD; LID; SUDS; extreme rainfalls; climate change; urbanization

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1. Introduction

Urban sewerage systems form critical components of any city's infrastructure. They are primarily designed to collect and convey stormwater and wastewater. These systems are becoming increasingly vulnerable to failure, partly due to a lack of consideration of the consequences of exceeding design specifications. Studies have noted that increased global warming would trigger severe and frequent high-intensity rainfall events [1–4]. Concurrently, rapid urbanization has also resulted in more impervious areas in cities, which has led to shorter response times in urban catchment areas. This, in turn, increases stormwater runoff volumes beyond the capacity of the existing urban drainage systems. When these systems become less efficient, issues such as urban flooding and sewage overflow hazards increase, thereby posing a major threat to human life, property and the urban water environment [1,5–11].

Conventional drainage systems are divided into combined and separate drainage systems. In a combined drainage system, a single pipe is used to collect and convey both stormwater runoff and sanitary wastewater. The system is designed in such a way that wastewater is transported to a sewage treatment plant and the resultant effluent is released into receiving water bodies [12]. During intense rainfall events, the increased stormwater runoff in urban areas increases the inflow into the combined drainage system. When the inflow volume exceeds the potential capacity of the system or the treatment plant, then the untreated sewage, along with excess stormwater, is released directly into the suburban creeks and waterways in order to reduce the pressure on the overall system. This discharge of diluted sewage is defined as combined sewer overflow (CSO).

In the separate drainage system, separate pipes are used to collect and convey stormwater runoff and sanitary wastewater. Sanitary sewer pipes are designed to convey only wastewater, whereas stormwater drainage pipes are designed to convey only stormwater runoff. In the separate drainage system, intense rainfall increases the inflow, not just into the stormwater drainage system, but also into the sanitary sewer network. This increased portion of inflow that occurs in the sewer network during and after a rainfall event is called Rainfall Derived Infiltration and Inflow (RDII) [13]. Sanitary sewers are designed to accommodate a certain volume of inflow and infiltration. Past studies have observed that during intense rainfall events, this designed inflow volume and infiltration is exceeded and, hence, it leads to sanitary sewer overflows (SSOs) [1,14–18]. The SSOs occur when the sewage overflows from the manholes to the surface level due to the sewers running under increased pressure. Manhole surcharge is another situation in which sewage rises in the manhole shaft but does not overflow, as in the case of SSOs. It is therefore necessary to have a better understanding of the sources of RDII when planning a sewer system and proposing mitigation strategies to reduce SSOs. As is indicative of its name, RDII consists of storm-water entering the sanitary sewer system through the inflow, as well as rainfall derived infiltration. Inflow is the stormwater entering the sewer pipes through direct connections through. roof downpipes which are illegally connected to the sanitary sewers, broken manhole covers and cross-connections between the stormwater and sewer pipes. On the other hand, infiltration refers to the runoff that is filtered through the soil and then enters the sewer network through cracked pipe sections, defective joints and damaged manhole walls. It can also occur due to a rise in the ground water table [13].

CSOs and SSOs are serious threats to public health and possess water quality concerns because these overflows increase the amount of transported nutrients, micro-organisms, particulates and metals in the receiving waters [9,19,20]. Thus, they affect the quality of the receiving waters and carry inherent risks to human health, as well as leading to environmental pollution. Many studies have been conducted in the past which note that these sewer overflows are prominent sources of water pollution in receiving water bodies [21–24]. Hence, the planning and implementation of suitable mitigation strategies is imperative for reducing the negative impacts of rainfall-induced sewer overflows and for protecting the health of aquatic ecosystems.

Several conventional approaches exist and are applied for eliminating the potential effects of sewer overflows. These strategies primarily propound structural actions, such as maximizing storage capacity, replacing sewer pipes, increasing pump stations and maximizing treatment facilities [25,26]. These structural strategies are often costly to build, and their implementation incurs intensive time and labor costs. Moreover, they also fail to cope with the consequences of the increasing intensities of extreme rainfall events and urbanization. Therefore, these strategies are becoming less attractive for enhancing the sustainability of the sewer network, particularly under future uncertainties.

Recent studies have demonstrated that Water Sensitive Urban Design (WSUD) strategies are sustainable, innovative and cost-effective for managing stormwater runoff in urban areas [27–31]. These strategies are also referred to using different terminologies, such as low impact development (LID), sustainable urban drainage system (SUDS), best management practices (BMPs) and, most recently, green infrastructure (GI) [32]. The purpose of implementing the WSUD strategies is to restore the city to its natural state, the main element of which is to restore the natural circulation of runoff. Studies have also exhibited that WSUD approaches can capture stormwater runoff entering the sewer network during intense rainfall events [33–39]. The WSUD strategies have benefits other than retarding stormwater runoff, such as reducing the pollutant load entering receiving waterways, replacing potable water with alternate sources for non-consumptive uses, mitigating urban heat and improving the general urban landscape. These benefits have led to various water utilities and local councils adopting the use of WSUD strategies as part of both existing and new developments. In spite of these benefits, limited studies quantifying the benefits of WSUD approaches exist in the available literature [27,33–35,40–45].

Recent studies have assessed the impacts of WSUD approaches for reducing rainfall-induced sewer overflow events, volumes and peak overflow rates. Therefore, this review provides a comprehensive assessment on the WSUD strategies that have been studied in the past for mitigating rainfall-induced CSOs and SSOs. This review paper is organized as follows. Section 2 describes in detail on how the database of the reviewed papers were assembled, including an overview of the research undertaken for the use of WSUD strategies for sewer overflow mitigation. Section 3 provides a descriptive overview of the WSUD-based sewer overflow mitigation strategies. A brief description of commonly applied traditional overflow mitigation strategies is also included in this section. Section 4 focuses on the selection of suitable WSUD modelling tools that are deemed essential for assessing the technical feasibility of the mitigation approaches. Section 5 provides further discussion towards developing a suitable sewer overflow mitigation strategy, including some directions for future research. Finally, the last section provides a summary and the conclusions drawn from this review.

2. Overview of Reviewed Studies

This study is based on a review of 66 articles that focus on the use of WSUD strategies for reducing rainfall-induced sewer overflows. The majority of the selected articles have been published in scientific, peer-reviewed international journals and a few were also from international conference proceedings, reports from government agencies, book chapters and dissertations. The review used the Scopus and Google Scholar search engines with a timeframe ranging between the years 1999 and 2022.

A set of search keywords were chosen, which included a combination of keywords related to sewer overflows (such as sewer overflow mitigation, CSO control and so on) and the type of mitigation strategy. The mitigation strategies included "WSUD", "LID", "SUDS", "BMP" and "GI" (in abbreviated as well as in full form), which were used one at a time in the search engine. The initial set of articles detected in the search were then subjected to a manual selection to identify the articles that would be within the scope of this review.

Table 1 provides a summary of the articles that have been included in this review. The table includes five different columns, namely: the author's names and year of publication; the study location; information about the sewer system; the type of WSUD strategies implemented; and, finally, the type of applications for which the WSUD strategies were implemented.

Table 1. A summary of articles reviewed in this study.

S. No.	Strategies Used	Type of Sewer System	Country of Application	Application Type	Authors, Year
1.	Permeable pavements	Combined Sewer Sanitary Sewer	United Kingdom, USA, Canada, Sweden, Belgium, Portugal, China, Switzerland	Reduce CSO and SSO volumes, events, stormwater runoff volume, peak runoff, CO_2 emissions, nutrients, pollutants.	Cahill, 2012 [36] Casal-Campos, et al., 2015 [23] Chen et al., 2019 [29] De Sousa et al., 2012 [46] Eulogi et al., 2022 [47] Foster et al., 2011 [48] Hansen, 2013 [25] Hou et al., 2021 [5] Joshi et al., 2021 [14] Keeley et al., 2013 [49] Kloss, 2008 [38]

Table 1. *Cont.*

S. No.	Strategies Used	Type of Sewer System	Country of Application	Application Type	Authors, Year
					Kloss and Calarusse 2006 [50] MMSD, 2011 [51] Montalto et al., 2007 [52] Myers et al., 2004 [53] Patwardhan et al., 2005 [54] Pickering et al., 2012 [55] Podolsky, 2008 [56] Ptomey, 2013 [57] Quigley and Brown, 2015 [58] Raucher and Clements, 2010 [59] Roseboro et al., 2021 [60] Sample et al., 2014 [61] Semadeni-Davies et al., 2008 [9] Smullen et al., 2008 [62] Spatari et al., 2011 [63] Stovin et al., 2013 [64] Struck et al., 2010 [65] Tackett and Mills, 2010 [66] Talebi and Pitt, 2018 [31] Wang et al., 2013 [67] Wise, 2008 [68]
2.	Green roofs	Combined Sewer Sanitary Sewer	USA, Canada, Denmark, Sweden, United Kingdom, Norway, Switzerland, Germany	Reduce stormwater runoff volume, peak runoff, CSO and SSO volumes, events, peak overflows, frequency, pollutants, direct energy consumption, urban heat island effect, improve air, water quality and urban aesthetics.	Banting et al., 2005 [69] Cahill, 2012 [36] Chen et al., 2019 [29] Foster et al., 2011 [48] Fryd et al., 2012 [70] Gao and Sage, 2015 [71] Hansen, 2013 [25] Hartman, 2008 [72] Hernes et al., 2020 [28] Joshi et al., 2021 [14] Keeley et al., 2013 [49] Kloss, 2008 [38] Li, 2008 [73] Lucas and Sample, 2015 [74] Montalto et al., 2007 [52] Patwardhan et al., 2005 [54] Pennino et al., 2016 [22] Perez et al., 2010 [37] Podolsky, 2008 [56] Quigley and Brown, 2015 [58] Raucher and Clements, 2010 [59] Riechel et al., 2020 [21] Sample et al., 2014 [61] Semadeni-Davies et al., 2008 [9] Smullen et al., 2008 [62] Stovin et al., 2013 [64] Tackett and Mills, 2010 [66] Talebi and Pitt, 2018 [31] Villarreal et al., 2004 [75] Wang et al., 2013 [67] Wise et al., 2010 [76]
3.	Raingardens	Combined Sewer Sanitary Sewer	USA, Canada, United Kingdom, Denmark, Sweden. Norway, China, Switzerland, Korea	Reduce stormwater runoff volume, peak runoff, CSO and SSO volumes, events, peak overflows, frequency, nutrients, pollutants, CO_2 emissions, improve water quality.	Abi Aad et al., 2009 [77] Autixier et al., 2014 [78] Casal-Campos, et al., 2015 [23] Cahill, 2012 [36] Chen et al., 2019 [29] Colwell and Tackett, 2015 [79] De Sousa et al., 2012 [46] Foster et al., 2011 [48] Fryd et al., 2012 [70] Hernes et al., 2020 [28] Hou et al., 2021 [5]

Table 1. *Cont.*

S. No.	Strategies Used	Type of Sewer System	Country of Application	Application Type	Authors, Year
					Joshi et al., 2021 [14] Keeley et al., 2013 [49] Kim et al., 2022 [1] Kloss, 2008 [38] Kloss and Calarusse, 2006 [50] MMSD, 2011 [51] Muhandes et al., 2022 [80] Pennino et al., 2016 [22] Pickering et al., 2012 [55] Podolsky, 2008 [56] Ptomey, 2013 [57] Semadeni-Davies et al., 2008 [9] Shamsi, 2012 [35] Shamsi 2015 [81] Struck et al., 2010 [65] Tackett and Mills, 2010 [66] Talebi and Pitt, 2018 [31] Wise, 2008 [68] Wise et al., 2010 [76]
4.	Rainwater tanks	Combined Sewer Sanitary Sewer	USA, Thailand, China, Australia, Canada, Belgium, Switzerland, France	Reduce stormwater runoff volume, peak runoff, CSO and SSO volumes, events, peak flows overflow hours, demand of potable water.	Abi Aad et al., 2009 [77] Boyd, 2011 [12] Chaosakul et al., 2013 [24] Chen et al., 2019 [29] De Sousa et al., 2012 [46] Foster et al., 2011 [48] Gao and Sage, 2015 [71] Ghodsi et al., 2021 [27] Hou et al., 2021 [5] Joshi et al., 2021 [14] Keeley et al., 2013 [49] Kloss, 2008 [38] Kloss and Calarusse, 2006 [50] Liao et al., 2015 [34] Myers et al., 2004 [53] Nasrin et al., 2016 [82] Patwardhan et al., 2005 [54] Petrucci et al., 2012 [83] Pitt and Voorhees, 2011 [84] Podolsky, 2008 [56] Ptomey, 2013 [57] Quigley and Brown, 2015 [58] Struck et al., 2010 [65] Tackett and Mills, 2010 [66] Talebi and Pitt, 2018 [31] Tavakol-Davani et al., 2016 [85] Vaes and Berlamont, 1999 [86] Wise, 2008 [68] Wise et al., 2010 [76]
5.	Swales	Combined Sewer	USA, Denmark, China	Reduce stormwater runoff volume, peak runoff, CSO volumes, events, nutrient, pollutants	Foster et al., 2011 [48] Fryd et al., 2012 [70] Hansen, 2013 [25] Hou et al., 2021 [5] Keeley et al., 2013 [49] Kloss, 2008 [38] Kloss and Calarusse, 2006 [50] Myers et al., 2004 [53] Pennino et al., 2016 [22] Ptomey, 2013 [57] Struck et al., 2010 [65] Wise, 2008 [68] Wise et al., 2010 [76]

Table 1. *Cont.*

S. No.	Strategies Used	Type of Sewer System	Country of Application	Application Type	Authors, Year
6.	Wetlands	Combined Sewer Sanitary Sewer	USA, United Kingdom, Germany, France, Italy	Reduce stormwater runoff volume, peak runoff, CSO and SSO volumes, events, peak overflows, nutrients, pollutants, improve water quality.	Foster et al., 2011 [48] Hansen, 2013 [25] Kloss, 2008 [38] Kloss and Calarusse, 2006 [50] Montalto et al., 2007 [52] Meyer et al., 2013 [87] Myers et al., 2004 [53] Ptomey, 2013 [57] Quaranta et al., 2022 [88] Quigley and Brown, 2015 [58] Tao et al., 2014 [89] Wise et al., 2010 [76]
7.	Urban trees	Combined Sewer	USA, Germany	Reduce stormwater runoff volume, peak runoff, CSO volumes, events, peak overflows, air pollutants, urban heat island effect, direct energy consumption.	Foster et al., 2011 [48] Hansen, 2013 [25] Keeley et al., 2013 [49] Pickering et al., 2012 [55] Raucher and Clements, 2010 [59] Riechel et al., 2020 [21] Spatari et al., 2011 [63] Tackett and Mills, 2010 [66] Tao et al., 2017 [90]
8.	Infiltration trenches	Combined Sewer	Denmark, China, USA	Reduce stormwater runoff volume, CSO volumes, peak overflows, pollutants,	Fryd et al., 2012 [70] Hou et al., 2021 [5] Liao et al., 2015 [34] Lucas and Sample, 2015 [74] Myers et al., 2004 [53] Ptomey, 2013 [57] Sample et al., 2014 [61] Tao et al., 2017 [90]
9.	Detention ponds	Combined Sewer	USA, Sweden, China	Reduce stormwater runoff volume, peak runoff, CSO volumes, events, peak overflows, nutrients, pollutants	Hou et al., 2021 [5] Pennino et al., 2016 [22] Ptomey, 2013 [57] Semadeni-Davies et al., 2008 [9] Villarreal et al., 2004 [75]
10.	Soakaway retrofits	Combined Sewer	Denmark, United Kingdom	Reduce stormwater runoff volume, CSO volumes, events.	Fryd et al., 2012 [70] Roldin et al., 2012 [44] Stovin et al., 2013 [64]

As mentioned earlier, different types of WSUD strategies have been proposed and implemented in past studies for sewer overflow mitigation. Figure 1 presents the most commonly used WSUD strategies and the number of articles corresponding to the stated approaches. This figure presents the top ten WSUD strategies that were studied in the reviewed articles. There were a few other strategies that were not commonly used for sewer overflow mitigation and, hence, are not presented in this figure; for example, stormwater harvesting and stormwater bump-outs were considered only in one study each, by Riechel et al., 2020 [21] and Tao et al., 2017 [90], respectively.

From Figure 1 it can be observed that four WSUD strategies are widely applied for mitigating sewer overflows in the reviewed studies, which are permeable pavements, green roofs, raingardens/bio-retention cells and rainwater tanks. These four WSUD strategies were observed to be the most popular, with around 30 studies each (out of the 66 studies reviewed) having recommended and analyzed these strategies. This is followed by swales and wetlands being analyzed in 13 and 12 studies, respectively. Urban trees (nine studies), infiltration trenches (eight studies), detention ponds (five studies) and soakaway retrofits (three studies) were the remaining WSUD strategies that were analyzed in the reviewed articles.

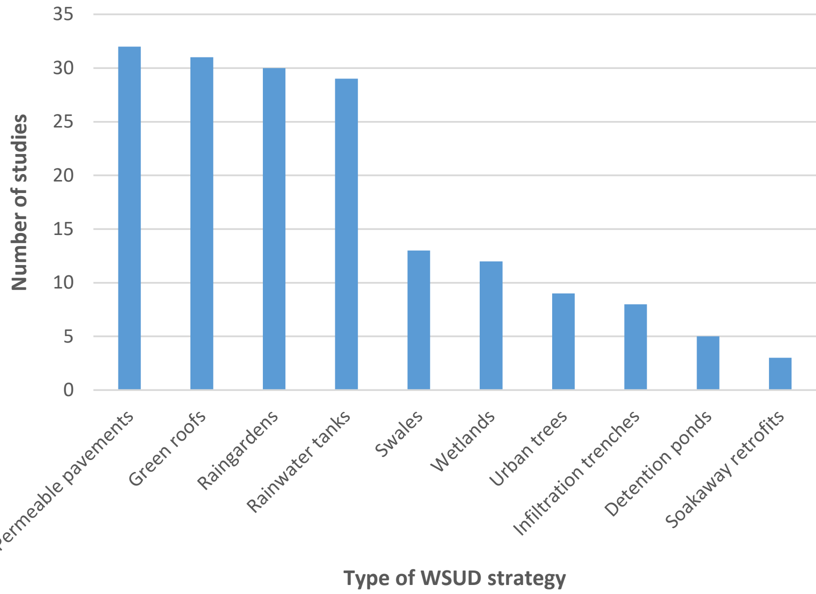

Figure 1. WSUD strategies which have been used in reviewed articles.

3. Sewer Overflow Mitigation Strategies

This paper reviews the mitigation strategies for reducing SSOs and CSOs and primarily focuses on WSUD-based strategies for mitigating the adverse impacts of sewer overflows due to the increase in extreme rainfall events and rapid urbanization. There also exist several conventional approaches which are commonly applied to eliminate the harmful impacts of sewer overflows. The following sub-sections briefly describe the commonly applied conventional sewer overflow mitigation strategies, followed by a discussion on the various WSUD strategies.

3.1. Conventional Strategies to Mitigate Sewer Overflows

As stated earlier, the majority of the conventional mitigation strategies seek to increase the storage or conveyance capacity within the sewer system and also include the maintenance and operational actions that are applied for the short-term management of sewer overflows. These conventional sewer overflow mitigation strategies, also called “gray infrastructure” approaches, are described in this sub-section.

Sewer rehabilitation is one of the most commonly used techniques to reduce sewer overflows and spills during heavy rainfall. Some of the sewer facilities were installed many years in the past and these ageing sewer networks cannot hold the capacity necessitated by the expansion of cities. The replacement of sewer pipes aims at introducing new volumes and structural capacities to cope with the increasing intensity of extreme rainfall, combined with increasing urbanization. Additionally, some old sewer networks have blockages, cracks and/or joint defects. A past study has noted that excess build up, poor installations and foreign objects (such as tree roots) in a sewer pipe may reduce its capacity, thereby necessitating sewer pipe replacement [46].

Maximizing the storage capacity is another traditional method of reducing sewer overflows [52]. In this method, more storage is built into the sewer system to reduce the effect of widespread urban flooding and sewage overflow hazards through tanks (such as end-of-pipe storage chambers), tunnels and basins. The objective and structural component of a storage facility is to store wastewater directly. The use of storage tanks is effective if enough space exists and is far from people in urban zones. A storage tunnel is an attractive option in urban areas as they are able to share the storage capacity between many CSO outfalls underneath dense urban lands. Storage basins are another storage technology that can provide attenuation in peak flows, as well as the removal of pathogens, solids, floatables, etc. Although it could be less costly than storage tanks and tunnels in terms of implementation, it might be very challenging to site storage basins in densely urbanized cities. However, it has previously been noted that the cost of a conventional storage facility is high and also has adverse aesthetic impacts [91].

Increasing the number of pumping stations is another technique that has traditionally been applied for a long time. Prior to the occurrence of an overflow, the pumps help to transfer the overflow to safer areas, thereby mitigating the flood risk. It has been stated that, due to the high operating pressure of the pumps, a smaller volume channel can be used to carry a higher capacity in comparison to areas that do not have the pumps [65]. People in low lying areas can install more pumps in the event of intense rainfall to reduce overflows. Pumping stations can also be increased in the areas where there is a higher risk of overflow to help in pumping out the excess stormwater.

These aforementioned traditional gray infrastructure strategies lack the sufficient flexibility to adapt to the negative impacts of urbanization and climate change. Additionally, these strategies are expensive to build and less effective in terms of cost, site selection, sustainability and human health benefits [52]. Therefore, the recent years have witnessed a decline in the use of such gray infrastructure approaches and there has been an increase in the implementation of sustainable, cost-effective WSUD approaches.

3.2. WSUD Strategies to Mitigate Sewer Overflows

Past studies have extensively researched the different types of sustainable WSUD strategies for sewer overflow mitigation, which include permeable pavements, green roofs, raingardens/bio-retention cells, rainwater tanks, swales, wetlands, urban trees, in-filtration trenches, detention ponds and soakaway retrofits.

These strategies, also called “green infrastructure” approaches, are said to have benefits from the perspectives of the environment, economy and society when compared to the conventional “gray infrastructure” approaches [33]. As indicated earlier, they not only capture the rain and prevent it from flowing into the drainage pipes, thus reducing flood and sewer overflow risks, but also effectively remove contaminants. The contaminants that could be removed range between conventional pollutants, such as biochemical oxygen demand (BOD); total suspended solids (TSS); ammonia; total Kjeldahl nitrogen (TKN); nitrate; total phosphorus (TP); and pathogens, and high priority pollutants, such as heavy metals. WSUD strategies are not only cheaper than the gray infrastructure approaches, they are also multipurpose strategies delivering several secondary benefits that include climate change adaptation, providing wildlife habitat, making cities more sustainable and being aesthetically pleasing. This makes the WSUD strategies an attractive option for mitigating sewer overflows and its harmful impacts [52,88,89].

The WSUD strategies that are commonly used for sewer overflow mitigation (and were previously presented in Table 1 and Figure 1) are described below:

3.2.1. Permeable Pavements

Permeable pavements are excavated areas where gravel is used to fill the area. A porous concrete layer or asphalt mix is used for paving the surface. Stormwater runoff can then pass through the permeable surface, filter through the soil layer and then enter the gravel storage zone beneath the pavement. Following this, the runoff can enter the natural soil or to a storm drain through an optional drainage system. It has been shown to be effective in reducing peak runoff and improving groundwater recharge [54]. It has also been noted to improve water quality by reducing sediments, nutrients and metals [61].

3.2.2. Green Roofs

These systems are also known as vegetated roof covers. Green roofs have a surface layer of living plants that grow on the top of a roof, a thin soil layer and a special drainage mat below the soil layer. It has been stated that green roofs can retain a significant amount of rainfall and roof runoff, which then filters through the soil layer and drains as excess percolated water off the roof [72]. They have a multitude of benefits other than retarding stormwater runoff and decreasing flows to sewer network during intense rainfall. Some of the potential benefits which have been observed include reducing direct energy uses and urban heat island effects via evaporative cooling, removing sound pollution and improving air quality and biodiversity [76]. They can also provide green spaces in dense urban zones, thereby improving the community's aesthetic.

3.2.3. Raingardens/Bio-Retention Cells

Raingardens/bio-retention cells are shallow depression storages which contain vegetation layers over an engineered soil mixture. A gravel bed resides beneath the layer of vegetation, thereby providing the storage, infiltration and evaporation of direct rainfall and surface runoff [35,92]. These vegetated depressions can provide a wide range of benefits to private properties and community communal entities. By design, the systems can retain, filter and treat stormwater runoff in urban areas. It has also been shown to improve water quality by removing suspended solids, as well as other pollutants, metals and organic compounds [78].

3.2.4. Rainwater Tanks

Rainwater tanks are amongst the most widely-used WSUD approaches for the non-potable reuse of water or for outdoor uses [43]. These are popular on-site stormwater and rainwater collection methods which store water during a storm event. Studies have exhibited that these storage tanks need to be placed beneath the roof downspouts, which in turn aids in the capturing of roof runoff water, thereby preventing stormwater inflow entering the sewer network [12,24,62,77].

3.2.5. Swales

Swales are depressed areas which act as channels for the routing of surface runoff. Past studies have used grass or vegetation as a cover for the sliding slopes of the depression areas [92]. Vegetative swales help in reducing the conveyance capacity of stormwater runoff and provide sufficient time for the stormwater to infiltrate into the natural soil.

3.2.6. Wetlands

Wetlands are the most efficient stormwater treatment areas. They help in the removal of stormwater pollutants, including dissolved contaminants, heavy metals, colloidal particles, suspended solids, ammonia and nutrients. Wetlands are primarily shallow, heavily vegetated artificial ponds consisting of a sedimentation zone. This sedimentation zone is used to remove coarse sediments, which is followed by a macrophyte zone that contains plants that remove the fine particulates and absorb soluble pollutants. The final layer consists of a high flow bypass channel that protects the plant zone. In addition to improving water quality, they have also been proven to reduce the stormwater runoff volume and peak flows which enter the sewer system during intense rainfall. Studies have noted that in various urban areas, they have also been used as recreational amenities and wildlife habitats [52,53,59].

3.2.7. Urban Trees

Trees are an important component of stormwater management in urban areas. They provide direct ground absorption via trunk flow and rainfall absorption using roots. Additionally, they decrease the dissolved nitrogen in rainwater and other pollutants in stormwater runoff. They are also efficient in improving air quality, consequently reducing urban heat island effects and energy consumption. They are usually noted to be located alongside urban streets, thus enhancing the landscape and improving the aesthetics of the community [51,59].

3.2.8. Infiltration Trenches

Infiltration trenches are narrow ditches that are filled with gravel to the ground level. They provide storage and capture stormwater runoff from impervious areas. The captured runoff then infiltrates into the natural soil [92]. They can significantly reduce the runoff volume that may enter the sewer system. They have been shown to improve the landscape and its aesthetic by providing green space [61].

3.2.9. Detention Ponds

Detention ponds are used to retain stormwater runoff from impervious areas during storm events; once the stormwater runoff is retained, they completely release the retained water through specific outlets within the span of a few hours. A past study stated that detention ponds can be used to store stormwater runoff temporarily, thereby reducing the runoff volume and peak flows [22]. They also have varying styles in terms of having manicured or naturally appearing vegetation.

3.2.10. Soakaway Retrofits

These are circular or square excavations which are then filled with rubble or lined with brickwork to create a perforated storage structure with a granular backfill or precast concrete. They act as underground seepage pits for filtering stormwater and are popularly used on private properties or on the side of streets in densely urban zones. It has been stated that soakaway retrofits provide stormwater attenuation and help in the recharge of the groundwater table and stormwater treatment [44,70].

3.3. Performance Evaluation of WSUD Strategies

Based on the reviewed literature, Table 2 presents a list of the selected articles which highlight the performance of various WSUD strategies. There were 42 studies which assessed and compared the performance of various WSUD strategies in terms of reduction in sewer overflow volume and frequency, reduction in peak flow and runoff volume and also the reduction in various pollutant loads.

Table 2. Summary of articles highlighting the performance of various WSUD strategies.

S. No.	WSUD Strategies Used	Overflow Volume Reduction	Overflow Frequency Reduction	Peak Flow Reduction	Runoff Volume Reduction	Pollutant Reduction	Authors, Year
1.	Rainwater tanks, Raingardens	-	-	-	38%	-	Abi Aad et al., 2009 [77]
2.	Raingardens	31%	15%	26%	19.4%	-	Autixier et al., 2014 [78]
3.	Green Roofs	18.8%	-	-	65%	-	Banting et al., 2005 [69]
4.	Rainwater tanks	-	-	-	33%	-	Boyd, 2011 [12]
5.	Rainwater tanks, Bio-retention cells	41%	-	-	-	40%	Chaosakul et al., 2013 [24]
6.	Permeable pavements, Raingardens, Green roofs, Rain barrels	0.2–23.5%	-	-	-	-	Chen et al., 2019 [29]
7.	Raingardens	6.3%	-	-	-	-	Colwell and Tackett, 2015 [79]
8.	Permeable pavements	11–45%	-	-	-	-	Eulogi et al., 2022 [47]
9.	Green roofs, Permeable pavements, Rainwater tanks, Raingardens, Swales, Urban trees, Wetlands	22–36%	6–15%	5–36%	50–60%	-	Foster et al., 2011 [48]

Table 2. *Cont.*

S. No.	WSUD Strategies Used	Overflow Volume Reduction	Overflow Frequency Reduction	Peak Flow Reduction	Runoff Volume Reduction	Pollutant Reduction	Authors, Year
10.	Raingardens, Swales, Infiltration trenches, Green roofs, Soakaway retrofits	20%	-	-	-	-	Fryd et al., 2012 [70]
11.	Rainwater tanks, Urban trees, Green roofs,	6.3%	-	-	-	-	Gao and Sage, 2015 [71]
12.	LID at source	35–49%	22%	-	-	-	Gong et al., 2019 [33]
13.	Green Roofs	31%	73%	-	-	-	Hartman, 2008 [72]
14.	Raingardens, Green roofs	100%	50%	-	-	-	Hernes et al., 2020 [28]
15.	Permeable pavements, Raingardens, Rainwater tanks, Swales, Infiltration trenches, Detention ponds	47.02%	-	-	-	-	Hou et al., 2021 [5]
16.	Permeable pavement s, Raingardens, Rainwater tanks, Green roofs	50–92.3%	-	-	-	-	Joshi et al., 2021 [14]
17.	Bio-retention cells	70%	-	-	-	-	Kim et al., 2022 [1]
18.	Green roofs, Raingardens, Swales, Rainwater tanks, Wetlands, Permeable pavement	12–38%	14.7%	5–36%	26%	-	Kloss and Calarusse, 2006 [50]
19.	Rainwater tanks, Bio-retention cells, Infiltration trenches	15.5%	-	16.2%	-	-	Liao et al., 2015 [34]
20.	Green Roofs	18.8%	2.3%	-	-	-	Li, 2008 [73]
21.	Bio-retention cells, Green roofs, Infiltration trenches, Permeable pavements	74%	-	53%	65.1%	-	Lucas and Sample, 2015 [74]
22.	Constructed wetlands					42%	Meyer et al., 2013 [87]
23.	Raingardens, Rainwater tanks, Permeable pavements	33%	29%	27%	50%	36%	MMSD, 2011 [51]
24.	Green roofs, Permeable pavements, Wetlands	-	-	40%	-	-	Montalto et al., 2007 [52]
25.	Raingardens	20.3%	-	-	-	-	Muhandes et al., 2022 [80]
26.	Rainwater tanks	33%	-	-	-	-	Nasrin et al., 2016 [82]
27.	Bio-retention cells, Permeable pavements, Green roofs	-	46%	-	37%	-	Patwardhan et al., 2005 [54]
28.	Porous pavements, Bio-retention cells, Urban trees	90.3%	-	-	-	84.8%	Pickering et al., 2012 [55]
29.	Raingardens, Rainwater tanks, Permeable pavements, Green roofs, Swales, Infiltration trenches, Wetlands, Detention ponds	54%	-	-	20%	-	Ptomey, 2013 [57]

Table 2. *Cont.*

S. No.	WSUD Strategies Used	Overflow Volume Reduction	Overflow Frequency Reduction	Peak Flow Reduction	Runoff Volume Reduction	Pollutant Reduction	Authors, Year
30.	Constructed wetlands	46.3%	-	-	-	-	Quaranta et al., 2022 [88]
31.	Green roofs, tree trenches, stormwater harvesting	45–58%	-	31–48%	28–39%	-	Riechel et al., 2020 [21]
32.	Soakaways Retrofits	55%	48%	-	-	-	Roldin et al., 2012 [44]
33.	Permeable pavements	2–31%	-	-	-	-	Roseboro et al., 2021 [60]
34.	Raingardens	85%	64%	49%	-	-	Shamsi, 2012 [35]
35.	Raingardens	3.5%	-	-	-	-	Shamsi, 2015 [81]
36.	Green Roofs, Permeable pavements	61%	-	-	50%	-	Smullen et al., 2008 [62]
37.	Green roofs, Soakaways Retrofits, Permeable pavements	54%	31%	-	-	-	Stovin et al., 2013 [64]
38.	Raingardens, Rainwater tanks, Permeable pavements, Green roofs, Urban trees	83%	-	-	-	-	Tackett and Mills, 2010 [66]
39.	Green Roofs, Permeable pavements, Rainwater tanks Bio-retention cells	-	50%	-	20–80%	-	Talebi and Pitt, 2018 [31]
40.	Infiltration trenches, tree trenches, Stormwater bumpout	95.85%	-	-	-	-	Tao et al., 2017 [90]
41.	Green roofs, Detention ponds	-	-	-	21%	-	Villarreal et al., 2004 [75]
42.	Rainwater tanks, Raingardens, Green roofs, Swales, Wetlands	-	-	-	50%	58%	Wise et al., 2010 [76]

As can be seen in Table 2, the impacts of different WSUD options on sewer overflow and runoff volume reduction, overflow frequency reduction, peak flow reduction and pollutant reduction vary between studies. This is because the volume of reduction is dependent on various factors, including the number of WSUD strategy elements implemented, the layout and sizing of the WSUD elements, the intensity and duration of rainfall events and so on.

In their study, Tao et al. (2017) [90] implemented three different strategies for both CSO and flooding control under different circumstances, which included large and small single events, as well as multiple events, over a one-year period. They concluded that SuDS were more effective in reducing the peak urban runoff and CSO volume for low intensity and short duration rainfall events, but not for high-intensity events. For a small event, they were able to achieve a volume reduction of 95.85%.

Some studies have reported that the combined application of the different WSUD strategies show a better performance than the application of a single WSUD strategy. Hernes et al. (2020) [28] found that the combined implementation of green roofs and raingardens reduced CSO events by 100%. Chen et al. (2019) [29] concluded that the adoption of WSUD practices on all possible area could potentially achieve the greatest runoff and pollutant load reductions, but would not be the most cost-effective option. They also noted that, based on the site characteristics, adding more GI practices would not necessarily mean that a substantial runoff volume and pollutant load reduction would be achieved. Pickering et al. (2012) [55] used different strategies to reduce CSOs and found that urban tree filters were able to reduce the CSO volumes by 90.3% and the stormwater treatment, in terms of phosphorus removal, was at 84.8%. Chaosakul et al. (2013) [24] also recommended multiple WSUD strategies, and their modelling indicated that a combination of rain barrels and bio-retention cells reduced the CSO volumes by 41% and the CSO pollutant load by 40%.

Even when a combination of WSUD practices were used, some studies (such as [14,19]) identified that the installed location and distribution of the WSUD strategies can affect the performance of the combination scheme. Fan et al. (2022) [19] recommended downstream installation locations for implementing the WSUD strategies. Joshi et al. (2021) [14] implemented four WSUD strategies to understand their overall effectiveness in reducing the CSO volume and frequency. They noted that different WSUD strategies, with their different dimensions, dissimilar working mechanisms and unique deployment requirements, exhibited contrasting efficiencies in CSO reduction. With a mere 2% spatial coverage of bio-retention cells, the CSO volume reduction exceeded 71%; when the spatial coverage was increased to 30%, the CSO volume reduction increased, logarithmically, to 99%. Joshi et al. (2021) [14] also noted that although green roofs were better able to reduce the CSO volume, rain barrels fared better in reducing the CSO frequency.

4. Application of WSUD Modelling Tools

Many modelling tools have been developed in recent years for facilitating the management and modelling of sewer overflows [93–95]. The current review also assessed the different modelling tools used at present as the selection of an optimum analytical software is essential for evaluating the performance of the system at hand. An overview of the modelling tools used to implement WSUD-based strategies for mitigating sewer overflows is presented in Table 3.

Table 3. Overview of modelling tools used for the mitigation of sewer overflows.

S. No.	Modelling Tools	WSUD Strategy	Authors, Year
1.	Stormwater Management Model (SWMM); PCSWMM (advanced modelling software for SWMM)	Permeable pavements, green roofs, Raingardens, Rainwater tanks, Swales, Wetlands, Urban trees, Infiltration trenches, Detention ponds, Soakaway retrofits	Abi Aad et al., 2009 [77] Autixier et al., 2014 [78] Cahill, 2012 [36] Casal-Campos et al., 2015 [23] Chaosakul et al., 2013 [24] Colwell and Tackett, 2015 [79] De Sousa et al., 2012 [46] Eulogi et al., 2022 [47] Gong et al., 2019 [33] Hartman, 2008 [72] Hou et al., 2021 [5] Joshi et al., 2021 [14] Kim et al., 2022 [1] Liao et al., 2015 [34] Lucas and Sample, 2015 [74] MMSD, 2011 [51] Montalto et al., 2007 [52] Myers et al., 2004 [53] Nasrin et al., 2016 [82] Petrucci et al., 2012 [83] Pitt and Voorhees, 2011 [84] Quigley and Brown, 2015 [58] Roseboro et al., 2021 [60] Shamsi, 2012 [35] Shamsi, 2015 [81] Smullen et al., 2008 [62] Stovin et al., 2013 [64] Struck et al., 2010 [65] Tao et al., 2017 [90] Tavakol-Davani et al., 2016 [85] Wang et al., 2013 [67]

Table 3. *Cont.*

S. No.	Modelling Tools	WSUD Strategy	Authors, Year
2.	Source Loading and Management Model for Windows (WinSLAMM)	Permeable pavements, Green roofs, Raingardens, Rainwater tanks, Swales	Cahill, 2012 [36] Pitt and Voorhees, 2011 [84] Struck et al., 2010 [65]
3.	MOUSE (Model of Urban Sewers)	Permeable pavements, Green roofs, Raingardens, Detention ponds, Soakaway retrofits	Roldin et al., 2012 [44] Semadeni-Davies et al., 2008 [9]
4.	Analytical probabilistic model, SUDS	Green roofs	Banting et al., 2005 [69] Li, 2008 [73]
5.	CityWatStorm	Raingardens	Muhandes et al., 2022 [80]
6.	InfoWorks	Green roofs	Hartman, 2008 [72]
7.	Hydrus 2D model	Wetlands	Meyer et al., 2013 [87]
8.	LIFE™ Model (physically-based hydrologic and water quality simulation tool)	Bio-retention cells, permeable pavements, green roofs	Patwardhan et al., 2005 [54]
9.	Low Impact Development Rapid Assessment (LIDRA 2.0)	Permeable pavements, Urban trees	Spatari et al., 2011 [63]
10.	L-THIA-LID 2.1	Permeable pavements, Green roofs, Raingardens, Rainwater tanks	Chen et al., 2019 [29]
11.	Mike Urban model	Green roofs, Raingardens	Hernes et al., 2020 [28]
12.	PondPack (Surface Stormwater Modelling Program)	Green roofs, Detention ponds	Villarreal et al., 2004 [75]
13.	System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model	Permeable pavements, Raingardens	MMSD, 2011 [51]
14.	SIMBA 6.0	Permeable pavements, Raingardens	Casal-Campos et al., 2015 [23]
15.	RAINMAN	Green roofs	Hartman, 2008 [72]
16.	MATLAB and USGS FORTRAN program LOADEST	Green roofs, Raingardens, Swales, Detention ponds	Pennino et al., 2016 [22]
17.	The Reservoir Modelling System	Rainwater tanks	Vaes and Berlamont, 1999 [86]
18.	Microsoft Excel simulation model	Rainwater tanks	Boyd, 2011 [12]

Among the 66 reviewed studies, 45 of them used numerical modelling to simulate the behavior and performance of various WSUD strategies. As can be seen in Table 3, different models have been used to simulate the hydraulic effects of various WSUD strategies, ranging between state-of-the-art hydrologic-hydraulic simulation models and simple MS Excel-based models.

It can also be seen from the table that 31 out of the 45 studies that used numerical modelling have used the Stormwater Management Model (SWMM) as the modelling software. SWMM, which was developed by the US Environmental Protection Agency (EPA), is a freely downloadable and widely used platform to simulate rainfall-runoff processes and the behavior of GI/LID features [92]. It can also be seen in Table 3 that the reviewed studies used SWMM to model all ten of the WSUD strategies. In a recent review, Jayasooriya and Ng (2014) [96] reviewed 20 tools for the modeling of stormwater management and the economics of GI practices and found that SWMM is one of the most popular runoff modelling tools used by water resource professionals and researchers to model stormwater quality, quantity and GI performance.

Few studies (for example, [5,74]) have also used PCSWMM, which is the commercial version of SWMM. PCSWMM uses the SWMM engine and provides a complete GIS-based interface for enhanced data pre-processing and model parameterization.

A model such as SWMM is configured in a semi-distributed fashion and a typical model is composed of a limited number of lumped subcatchments. Each subcatchment is further divided into pervious and impervious areas to represent different the land cover and land use types. Using the LID module, SWMM can be used to model numerous types of LID/WSUD strategies, such as rain barrels, raingardens, green roofs, permeable pavements, infiltration trenches and vegetative swales. These WSUD strategies need to be programmed into the SWMM algorithms and can later be accessed easily through simple dialog boxes [92].

It is also worth mentioning that SMWW is a one-dimensional (1D) dynamic rainfall-runoff routing model and it works fine for sewer modelling as the drainage networks are closed pipes or open channels. Under normal circumstances, a 1D is enough to model the flow in sewer pipes and overflows. However, with extreme storm events occurring quite frequently, large portions of the urban environment could become flooded. In such situations, an ID sewer model coupled with a 1D surface network model (1D/1D) or a 1D sewer model coupled with a two-dimensional (2D) surface flow model (1D/2D) can better predict the impacts of extreme rainfalls on sewer overflows. The coupling between 1D and 2D hydraulic models has recently become popular for flood, sewer overflow and dam break modelling [97–99].

Although the SWMM's LID module provides substantial flexibility, it also has practical drawbacks. Platz et al. (2020) [100] undertook a study to quantify how accurately SWMM simulates the hydrologic activity of various practices in the LID module. They found limitations, particularly in deep LIDs, such as infiltration trenches, wherein SWMM could not simulate lateral exfiltration of water out of the storage layers of the LID measure. Other limitations include the need to configure each GI/LID practice individually and the lack of a dedicated model output that indicates how much flow is intercepted by the GI/LID.

5. Further Discussion

This section provides further discussion, which could aid in the selection of a suitable sewer overflow mitigation strategy. Some future directions for further research are also presented in this section.

5.1. Hybrid Scenario of Green-Gray Strategies

Although the WSUD strategies have been modelled and implemented on a large scale, some studies note that relying solely on WSUD or green strategies to improve drainage capacity, and thus reduce sewer overflows, is not sufficient, particularly under intense rainfall conditions. Therefore, adopting a combination of green and grey approaches is essential and necessary in most situations [5,33].

Montalto et al. (2007) [52] compared the cost effectiveness of different green strategies to conventional grey approaches for reducing CSO events in an urban watershed located in New York City. They found that incorporating WSUD systems into the watershed was a more cost-effective strategy for reducing CSO than building large-sized CSO tanks. They suggested that grey strategies such as the construction of tanks should be considered only after all WSUD options have been exhausted and if additional reductions in CSO are required.

Some studies have compared the cost-effectiveness of the gray-only and green-gray combination of sewer overflow control methods and have concluded that the green-gray combined alternative is more cost-effective than the gray-only option [85]. On the other hand, Quaranta et al. (2022) [88] undertook a cost-benefit analysis of various sewer overflow management strategies and concluded that green strategies entail higher multipurpose benefits, including urban runoff and wastewater reduction, urban heat island mitigation, carbon removal and biodiversity improvement. Hence, green strategies exhibit a benefit to the cost ratio, which is generally one order of magnitude higher than the corresponding grey strategies. Therefore, green strategies can attract investments from various sectors and could contribute to different policy strategies. Furthermore, citizens are often willing to pay for the benefits entailed by green solutions.

5.2. Improving Sewer Overflow Mitigation with RTC Systems

Recent research has demonstrated that real time control (RTC) has potential to bring further improvements in sewer overflow reduction [47,88]. RTC systems are designed to achieve the real-time management of existing sewer networks through the continuous monitoring of process data (e.g., wastewater levels and flow) and the dynamic adjustment of flow conditions with flow control devices (FCDs) such as pumps, sluice gates, and moveable weirs.

Eulogi et al. (2022) [47] combined FCDs into a WSUD system by using genetic algorithms to optimally position the RTC actuators. They found that the FCD-WSUD configuration resulted in a reduction in CSO spill volumes ranging between 11% and 45% when compared to the baseline networks. Similar results were obtained by Quaranta et al. (2022) [88], wherein RTC was implemented in the existing infrastructure, which could bring, on average, a reduction in CSO volume of about 20%.

5.3. Lack of Modelling at Larger Scales

Various studies have demonstrated that WSUD strategies could significantly decrease sewer overflow volumes and pollutant loads [88,90]. However, there are only a few studies that have evaluated the effects of multiple WSUD practices on sewer overflow and pollutant load reduction at large spatial scales, for example, at a city scale [80]. This could be due to the difficulties in implementing sewer overflow mitigation strategies on large spatial scales because of the influence of complex factors and a lack of basic data. Hence, it is recommended that research related to strategies for sewer overflow mitigation at large scales or city-scales is undertaken in a systematic way.

5.4. Developing a Suitable Sewer Overflow Mitigation Strategy

It is observed that recent research has paid more attention to controlling sewer overflows with WSUD strategies. Despite the advantages of WSUD-based green strategies over gray strategies, they still face some obstacles. For example, the widespread implementation and management of WSUD practices may be challenging due to space availability, particularly in highly urbanized areas. The same can be said about the implementation of gray sewer overflow mitigation strategies because the construction of such gray facilities also possesses difficulties in terms of site selections, high costs, limited land availability and so on.

Hence, it can be said that there is no single strategy that can be called a fix-all solution for the problem of sewer overflow mitigation. It will require the consideration of multiple strategies (green or a hybrid green-gray strategy) that allow for the possibility of wider application and, therefore, an increase in the potential impact. The design of an appropriate sewer overflow management strategy will require the consideration of context-specific conditions. The successful selection of suitable strategies will typically require multiple levels and types of analysis (i.e., suitability of the strategies, site availability, cost, performance, maintenance, etc.). The application of state-of-the-art modelling software, aided by optimization tools for optimally locating the selected strategies, as well as for the optimal placement of the flow control devices for RTC systems, can enhance the performance of the sewer overflow mitigation strategy.

6. Summary and Conclusions

Short duration intense rainfall events, coupled with rapid pace of urbanization, have an adverse impact on the performance of the existing sewer networks by causing sewage overflow hazards. Conventional "gray" overflow mitigation strategies lack the sufficient flexibility to adapt to adverse events. WSUD "green" strategies, on the other hand, can manage stormwater runoff more sustainably and in cost effective ways, which the conventional strategies are unable to do.

This review highlights the increasing trend of implementing WSUD strategies over the past couple of decades for mitigating rainfall-induced sewer overflows. Furthermore, this review also identifies and elaborates upon commonly used WSUD strategies, based upon their extensive use in past studies. The identified WSUD strategies are permeable pavements, green roofs, raingardens/bio-retention cells and rainwater tanks, which have all been widely applied in the past and have been recommended in most of the reviewed articles.

WSUD strategies have enormous environmental, social and economic benefits for minimizing the negative impacts of sewer overflows. The environmental benefits include reducing the pollutant loads and improving the water quality of the receiving water, protecting the existing natural and ecological processes and maintaining the natural hydrologic cycle and aquatic ecosystems. The WSUD strategies also accord social benefits that include protecting public health, improving the landscape and aesthetics, providing green spaces and increasing biodiversity, as well as providing economic benefits by being cost-effective when compared to conventional strategies. Regardless of these benefits, there are only a handful of studies available in the literature that quantify the benefits of the various WSUD strategies for sewer overflow mitigation. Hence, this review has highlighted the existing gap of a lack of studies and systematic methods in the current practices where WSUD strategies can be implemented for sewer overflow mitigation. A lack of modelling studies at a large scale (e.g., at the city scale) was also identified and, hence, it was also recommended to undertake sewer overflow mitigation studies at large scales in a systematic way. This study also undertook a review of modelling tools, which had identified the SWMM to be the most widely applied modelling tool that has been recommended in the literature for hydraulic analysis, as well as for WSUD modelling.

Finally, this review has also concluded that WSUD strategies on their own may not be enough to mitigate sewer overflows, particularly with the increase in extreme rainfall events. The selection of suitable mitigation strategies (green or a hybrid green-gray strategy) will depend on the context-specific conditions and will require detailed analysis in terms of suitability, site availability, cost and so on. The development of a suitable sewer overflow mitigation strategy will also need to use the latest software, which can include optimization tools for optimally locating the selected strategies.

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