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Sustainable Stormwater Management Using Stormwater Quality Improvement Devices: A Review

Sesugh Yua[1], Ataur Rahman[2], Mohammad A. Alim[3] and Blake Allingham[4]

[1]Master of Philosophy student, School of Engineering, Design and Built Environment, Western Sydney University, Kingswood, Penrith, NSW, Australia
[2]Professor, School of Engineering, Design and Built Environment, Western Sydney University, Kingswood, Penrith, NSW, Australia
[3]Lecturer, School of Engineering, Design and Built Environment, Western Sydney University, Kingswood, Penrith, NSW, Australia
[4]Ocean Protect Pty Ltd, 60 Lyn Parade, Prestons, NSW, Australia

Corresponding author's E-mail: 22169972@student.westernsydney.edu.au

Abstract

The rise in urbanisation has led to increased stormwater runoff due to the proliferation of impervious surfaces, vegetation loss, and decreased drainage efficiency. To manage urban stormwater, water sensitive urban design (WSUD) has been proposed in Australia, which reduces urban flooding and protects our natural waterways. Stormwater quality improvement devices (SQIDs) are elements of WSUD that can remove pollutants from urban stormwater. This paper reviews key SQIDs, which are widely adopted globally. A bibliometric analysis is conducted based on relevant publications from 2000 to 2024, which reveals that the USA, China, and Australia are the leading countries in sustainable stormwater management research. A significant international collaboration between USA and Australia is found. Also, research on bioretention and other nature-based solutions has been increasing in recent years, highlighting the need for sustainable urban stormwater management. It is expected that WSUD will be up-taken by developing countries following its success in developed countries. This paper also presents learning aspects of stormwater engineering by the first author.

Keywords: *Urban hydrology, floods, water quality, eutrophication, sustainability, runoff*

1. INTRODUCTION

In recent decades, urbanisation has rapidly increased due to economic and population growth, escalating the risk of urban flooding and soil erosion (Azad et al., 2024). Urbanisation has caused large areas of natural lands to be replaced by impervious surfaces, leading to decreased infiltration and evapotranspiration, consequently elevating stormwater runoff (Meng et al., 2022). Stormwater in urban or developed regions refers to precipitation flowing off impermeable surfaces like roofs, driveways, and roads, which is then conveyed through a network of pipes known as the stormwater drainage system to reach natural water bodies such as creeks, rivers, seas, or, in certain locations, directly into the groundwater (Australia, 2021). Stormwater produced from urban areas contains numerous pollutants (Aryal et al., 2010), and if a proper stormwater management system is not implemented, public health and the environment's quality can be adversely affected (Barbosa et al., 2012). The nature and amount of stormwater pollutants are determined largely by human activities and land use (Aryal et al., 2010; Rupak, et al., 2010). Stormwater carries both organic and inorganic pollutants. Pollutants often present in stormwater runoff include heavy metals, biochemical oxygen demand (BOD), bacteria, and nutrient concentrations (Barbosa et al., 2012).

Pollutants of particular concern and key interest for urban stormwater management are total nitrogen (TN), total phosphorous (TP), and total suspended solids (TSS). An overabundance of nutrients, specifically in the form of TP and TN in receiving waters, has the potential to induce eutrophication and foster the proliferation of algae. The presence of TSS in receiving waters poses a threat to ecology and concurrently diminishes hydraulic efficiency through continuous sediment accumulation (Shahzad et al., 2022). Suspended solids in water diminish light penetration, which reduces photosynthesis and subsequently decreases energy production and dissolved oxygen levels, threatening aquatic ecosystems (Azad et al., 2024).

To address the adverse effects of urbanisation, a variety of sustainable stormwater management strategies have been implemented, which aim to preserve natural hydrologic processes in developed landscapes (Kuruppu et al., 2019). In recent decades, water sensitive urban design (WSUD) has emerged as a pivotal approach for sustainable water cycle management in numerous developed nations. This methodology has been adopted and refined by professionals across various regions globally, to enhance its effectiveness in the removal of pollutants from stormwater runoff (Pipil et al., 2022). These approaches are referred to by various terms across different regions globally, including 'Sustainable Drainage Systems' (SUD) in the United Kingdom, 'Low Impact Development' (LID) techniques in the United States, 'Water Sensitive Urban Design' (WSUD) in Australia, and 'sponge city' strategies in China (Narasimhan et al., 2023). WSUD integrates various low-cost and natural strategies to manage stormwater quality and mitigate urban flooding. Key techniques employed within this framework include filtration, sedimentation, adsorption, rainwater harvesting, low-volume attenuation, biodegradation, and plant uptake. Additionally, the water sensitive design incorporates elements of detention and retention to optimise water management outcomes (Pipil et al., 2022).

Treating stormwaterwater is essential for effective water management, particularly within the WSUD framework. Various treatment systems, including gross pollutant traps (GPT), constructed wetlands, rain gardens, and vegetated swales, play a significant role in this approach by facilitating the removal of physical and chemical pollutants from stormwater runoff. These treatment units are designed to address a range of pollutants commonly found in urban stormwater. They effectively remove suspended and floating debris, organic loads such as BOD, nutrients including nitrogen and phosphorus, heavy metals, hydrocarbons, and pathogens, such as coliform bacteria. By integrating these systems into urban planning, WSUD aims to enhance water quality and promotes sustainable water management practices, thereby mitigating the adverse impacts of urbanisation on the natural water cycle (Pipil et al., 2022).

The Australian regulatory pollution reduction objectives recommended by ANZECC for TSS, TP, and TN are 80%, 60% and 45%, respectively (Lucke et al., 2017). The aim of this paper is to conduct a literature review on five of the major stormwater quality improvement devices (SQIDS) and investigate their performance in removing TSS, TN & TP from stormwater.

2. DIFFERENT TYPES OF SQIDS

2.1. Permeable Pavement

Permeable pavements (PPs) are porous surfaces made from materials such as asphalt, concrete, or open-pore pavers, designed to enhance water infiltration and temporarily store rainwater (Narasimhan et al., 2023; Coogan, 2022). Atypical, a storage reservoir or tank is installed beneath these pavements to hold water and direct it into the stormwater management system. Permeable pavements present several challenges, including the initial cost of installation and the necessity for ongoing maintenance. One significant concern is their susceptibility to clogging; if not properly drained and maintained, these pavements can become inefficient in facilitating water infiltration after a certain time (Coogan, 2022).

A report by Kuruppu et al. (2019) shows that PPs have low efficiencies in the removal of TN. Research findings by Niu et al. (2016) showed that the maximum total nitrogen removal rate for a PP system is 35.6%. According to Xie et al. (2021), the commonly used PPs include pervious concrete. This study investigated modified versions of pervious concrete comprising a mixture of cement, aggregates, fly ash, blast furnace slag, and biochar. It showed that depending on the percentage of the mixtures into the pervious concrete, the TN and TP removal efficiency can vary between 66.7-89.4% for TN and 55.6-82% for TP. The results further showed that biochar plays an instrumental role in removing TN and TP as biochar has the characteristics of absorbing pollutants and improving the performance of concrete. Research by Azad et al. (2024) shows that TSS removal efficiency by permeable pavements can range between 22.1% to 96.4%. The varying TSS removal is dependent on the material mixture used, and the porosity and permeability of the PP. The PP investigated in the report is made up of different percentages of ordinary portland cement, fly ash, and silica fume in the mixture.

2.2. Constructed Wetland

Constructed wetlands mimic natural wetlands by providing shallow, vegetated basins with slow-flowing or stagnant water. These systems utilise sedimentation, filtration, and biological uptake to remove contaminants from stormwater. Constructed wetlands are particularly effective in removing nutrients, pathogens, and organic matter. Constructed wetlands are highly effective at removing nutrients such as nitrogen and phosphorus. They also enhance biodiversity by supporting a wide range of wildlife. With proper maintenance, constructed wetlands can have a long lifespan, lasting for decades. Furthermore, these wetlands serve multiple purposes, providing habitat for wildlife, recreational opportunities, and aesthetic benefits to the surrounding area (Moshiri, 2020).

Constructed wetlands require a significant land area, which may not be readily available in urban settings. The initial costs associated with land acquisition and construction can also be high. Additionally, these basins necessitate ongoing maintenance to manage vegetation and ensure proper water flow. Their performance can vary based on local climatic conditions, particularly during extreme weather events (O'Sullivan et al., 2015).

Constructed wetlands are highly effective in removing nutrients, such as nitrogen and phosphorus, achieving 70-90% removal efficiencies for both nutrients. These systems also excel in reducing BOD and TSS (Moshiri, 2020). Another research on constructed wetlands demonstrated the system to have a high TSS removal efficiency, averaging 85% to 90%, a total nitrogen removal efficiency between 40% to 55% (Vymazal, 2007) and a phosphorus removal efficiency between 60% to 70% (Mitsch & Gosselink, 2015).

2.3. Vegetation Swale

Vegetated swales serve as an effective alternative to traditional drainage systems, facilitating the conveyance of stormwater while providing a buffer between impervious surfaces and receiving water bodies. These shallow, vegetated channels utilise overland flow and gentle slopes to transport and gradually distribute stormwater evenly downstream. The design of swales promotes sediment capture and enhances water quality through natural filtration processes. A critical consideration in the design of vegetated swales is their longitudinal slope, which is optimally maintained between 2% and 4%. Slopes that are too mild may lead to waterlogging and stagnant ponding; however, this issue can be mitigated by incorporating underdrains. Conversely, swales with slopes exceeding 4% may experience high flow velocities, which can be managed by installing check dams to slow down the water flow (Water, 2005; Coogan, 2022). Vegetation plays a vital role in the functionality of swales, as it not only provides aesthetic benefits but also enhances the filtration of stormwater runoff. When selecting vegetation for swale implementation, it is essential to choose species that can withstand the anticipated design flow and exhibit sufficient density. For optimal treatment performance, the height of the vegetation should exceed the water levels of the treatment flow, ensuring effective pollutant removal and minimising the risk of flooding (Water, 2005).

Vegetated swales enhance urban aesthetics, increase green cover in an area, and contribute to lower urban temperatures. They are effective in removing total suspended solids (TSS) and total phosphorus (TP) from stormwater. However, vegetated swales often struggle to remove total nitrogen (TN). The establishment of these systems typically requires about five years, during this time, the maintenance costs may be higher. Additionally, these systems may experience vegetation wilting during dry seasons due to limited stormwater supply (Pipil et al., 2022).

Research by Wu and Allan (2018) shows that swales can achieve pollutant removal efficiencies of 77%, 67%, and 33% for TSS, TN, and TP, respectively. A report by Stagge et al. (2012) shows that swales removal efficiency for TSS can range between 48-98%, while for TP it ranges between 12-60%. However, the report highlighted that testing the effect of swales on TN is challenging due to the need for comprehensive measurements and difficulties in nitrate analysis. However, the trend suggests that swales moderately reduce TN in most storm events.

2.4. Bioretention System

Bioretention systems offer high pollutant removal efficiency, effectively eliminating a wide range of pollutants, including heavy metals and nutrients. Their flexible design allows them to be tailored to fit various urban landscapes and space constraints. Additionally, these basins enhance urban aesthetics by adding greenery to the environment. Furthermore, they are cost-effective, featuring relatively low construction and maintenance costs compared to other stormwater management systems (Flynn & Traver, 2013). Their performance may be limited in cold climates or during heavy rainfall events. Additionally, the efficiency of these basins can vary based on factors such as soil type, vegetation, and maintenance practices (Vijayaraghavan et al., 2021).

Bioretention systems are effective at removing pollutants such as heavy metals, nutrients, and suspended solids. Studies by Lucas and Greenway (2008) have shown that vegetated bioretention mesocosms can remove 90% of total phosphorus TP and 80% of total nitrogen TN. Studies by Fahui et al. (2013) showed that bioretention media removed 95% of TSS and 82-96% of phosphorus. The results by Wang et al. (2017) from their case study showed a bioretention can remove TN, TP, and TSS by 25%, 46%, and 53% respectively. However, the report pointed out that the low removal efficiency was due to high overflow and lack of storage capacity during high rainfall events.

2.5. Gross Pollutant Trap

Gross Pollutant Traps (GPTs) are a key component of WSUD strategies, designed to remove floating impurities, suspended solids, and anthropogenic litter from stormwater runoff. These devices sutilise physical processes such as screening and gravity settling to capture floating debris, including plastics, leaves, branches, and other litter, as well as suspended particles like sand and silt with a diameter greater than 5.0 mm. By intercepting and retaining these pollutants, GPTs prevent the entry of litter into waterways at the initial stage of the stormwater treatment process. As such, they serve as effective pre-treatment units for downstream treatment systems, such as constructed wetlands, ensuring that the water entering these secondary treatment devices is relatively free of coarse pollutants.

There are numerous types of GPTs available, each employing distinct mechanisms for the removal of impurities from stormwater runoff. These GPTs come in a variety of styles and configurations, including trash racks, litter control devices, baffled walls, circular screens, hydrodynamic deflective separation (HDS) devices, and catchpit grates. Some GPTs rely on the principle of sedimentation to remove suspended impurities through gravitational force. These systems slow down the water flow, allowing heavier particles to settle out. Other GPTs utilise physical screening separation, where stormwater passes through a series of screens or filters that trap larger debris and pollutants. HDS devices, on the other hand, employ centrifugal force to remove physical impurities. These systems direct the flow of stormwater into a circular motion, causing heavier particles to be pushed to the outer edges of the chamber, where they can be captured and retained (Pipil et al., 2022). Field testing results conducted by Nichols and Lucke (2016) on gross pollutant traps showed the systems can remove 49.2%, 26.6% and 40.6% of TSS, TN, and TP, respectively.

3. BIBLIOMETRIC ANALYSIS

Bibliometric analysis is an effective method for understanding research trends and developments across various fields. It organises large amounts of data into concise knowledge, evaluates research performance, identifies key contributions from authors, institutions, and countries, and creates visual maps of scientific evolution (Su et al., 2024). The scientific output data used in the bibliometric study, presented here, were obtained from Scopus. For achieving reliable results, an advanced search was performed using selected words from the title, abstract, keywords, and keywords-plus of each article on the topic: ("bioretention" OR "gross pollutant trap" OR "vegetation swale" OR "constructed wetland" OR "permeable pavement") AND ("low impact development" OR "water sensitive urban design" OR "best management practice" OR "sponge city" OR "green infrastructure" OR "nature-based solution" OR "stormwater quality improvement device") Document types were limited to 'article' and 'review', and searches were limited to 2000-2024, which resulted in 1320 publications. An advanced bibliometric tool, namely “VOSviewer” was used to facilitate an in-depth analysis of these 1320 publications pertaining to stormwater quality improvement devices.

As seen in Figure 1, the analysis shows a significant number of publications with the keywords LID and Sponge City, both of which are sustainable water management methodologies developed for the United States of America (USA) and China. It also reveals that a great deal of research has been done on WSUD, which is Australia’s sustainable water management methodology. The analysis reveals that numerous research studies have been carried out on bioretention. It can be seen that a high volume of research into nature-based solutions for the treatment of stormwater runoff has been conducted in the last few years, between 2022 and 2024. It shows that of the SQIDs researched, biorientation has the most related publication, while PPs are the second most researched SQID within the years 2000 and 2024. Constructed wetlands appear to be the third most researched SQID. All three SQIDs research studies have occurred mainly between 2016 and 2021.

Geographically, as seen in Figure 2, the top three countries with the highest publications and citations involved in stormwater management and SQUIDS are the USA, China, and Australia. With a total recorded number of countries with publications in the aforementioned fields is 86. The analysis finds significant country cooperation/collaboration between the USA, China, and Australia. A significant international collaboration between USA and Ausralia is noted.

4. ENGINEERING EDUCATION ASPECTS

Learning of stormwater science and engineering is not an easy task for the begginers as little is taught in undergraduate degree on stromwater. Moreover, learning of hydrologic modelling is an art that can be mastered well when working with a real project under the supervision of an expert. In this study, the first author has been learning the stormwater engineering based on the principle of ‘project based learning’ from the other authors who are recognized experts in this field. The stages of learing by the first author include (i) Regular meetings with the supervisory panel where key concepts of stormwater engineering is learnt along with the important keywords and works by key researchers in this field; (ii) Visiting the study site at Western Sydney University (WSU) Kingswood campus; (iii) Conducting a literature review via scoping review and bibliometric analysis methods on stormwater management; (iv) Attending a webinar on stromwater management run by Ocean Protect Australia, an important player in stromwater industry; (v) Watching relevant YouTube contents on stormwater management; and (vi)

Presenting research ideas on stormwater in the postgraduate forum, organized by the water engineering team at WSU. Further learning is being made by the first author via a laboratory risk assessment, extensive literature review and writing this conference paper and a review journal article. Furthermore, sample collection and testing will be undertaken by the first author to evaluate the efficiency of few SQIDs at WSU project site.

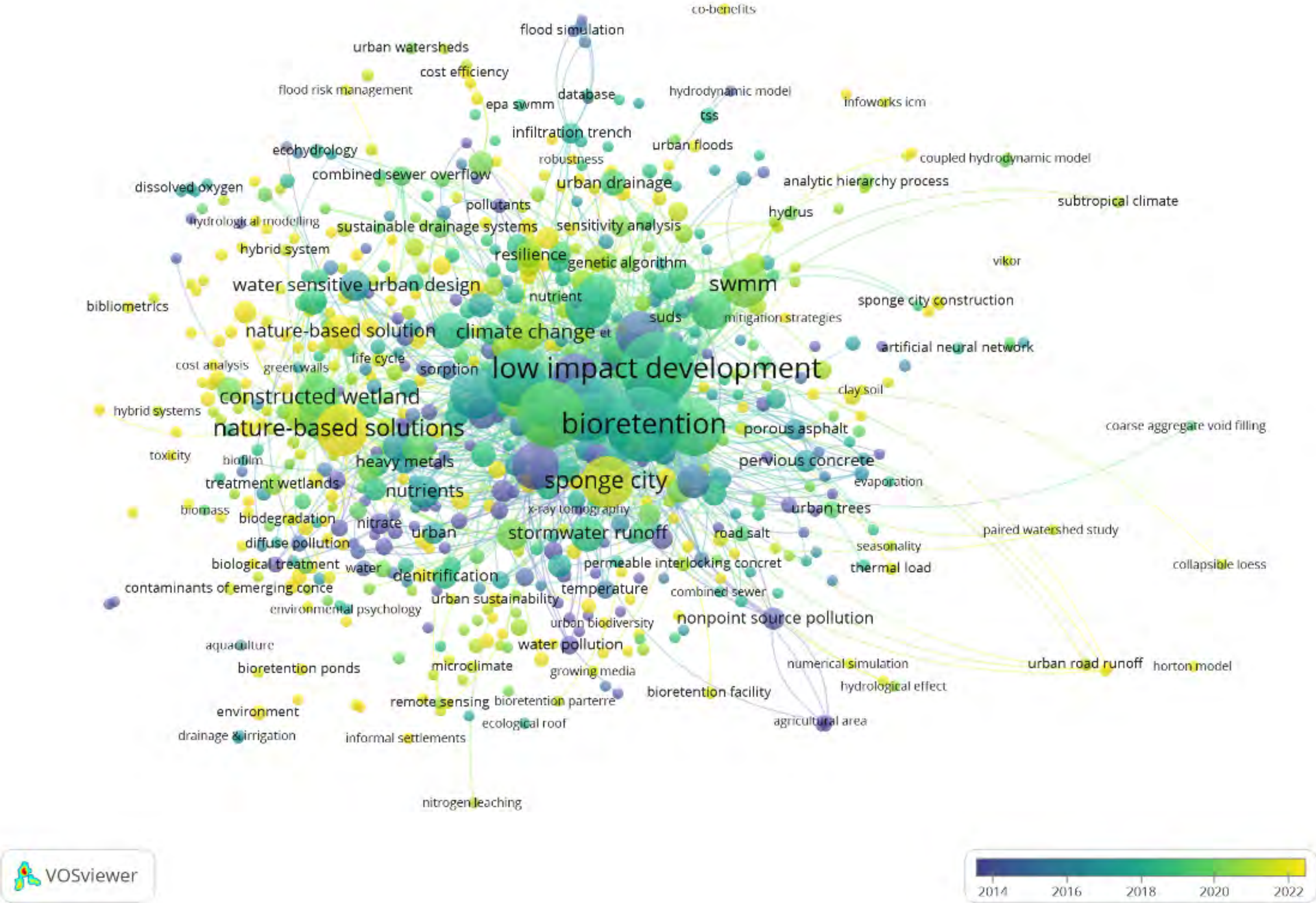

Figure 1: Authors publication key words from 2000 - 2024

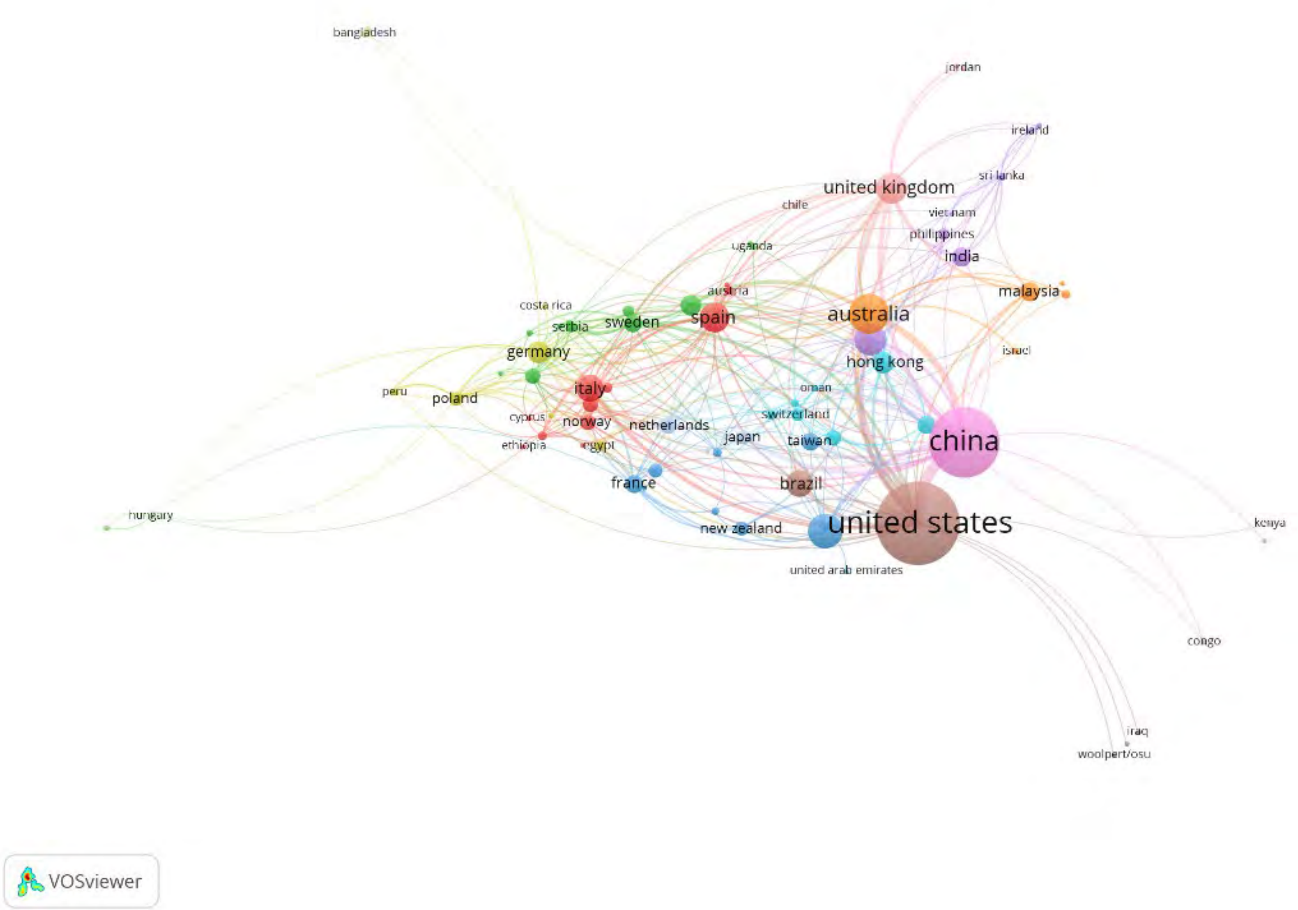

Figure 2: Number of research publications and citations on stormwater quality management by country from 2000 – 2024.

5. CONCLUSION

In recent decades, surbanisation has intensified, leading to increased impervious surfaces that exacerbate stormwater runoff, contributing to urban flooding and water pollution. This issue has necessitated the development of sustainable stormwater management strategies, such as WSUD, LID, and other nature-based solutions. These approaches aim to mimic natural hydrological processes, thereby improving stormwater quality and mitigating the adverse impacts of urbanisation.

The literature review highlights various SQIDs, including PPs, constructed wetlands, vegetated swales, bioretention systems, and GPTs. Each of these systems shows varying degrees of effectiveness in removing pollutants like TSS, TN and TP from stormwater. For instance, bioretention systems demonstrate high pollutant removal efficiencies, while PPs and vegetated swales show moderate effectiveness, particularly in nitrogen removal.

The bibliometric analysis of research output from 2000 to 2024 reveals that the USA, China, and Australia lead in publications and citations related to stormwater management. There has been significant international collaboration, especially between Australia and the United Kingdom. The analysis also shows a growing focus on bioretention and other nature-based solutions in recent years, indicating an evolving research landscape that increasingly sprioritises sustainable urban water management. This review underscores the importance of continued research and collaboration in developing effective stormwater management practices to address the environmental challenges posed by urbanisation.

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