Evaluation of permeable pavement systems (PPS) as best management practices for stormwater runoff control: A review

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Abstract

A comprehensive study was conducted to provide research clarifications and evaluations of measures aimed at controlling stormwater runoff from roads and highways. The study specifically focuses on sustainable strategies, particularly permeable pavement systems (PPS), as a solution for stormwater management within the framework of sustainable drainage systems (SuDS). This research paper offers insight into PPS effectiveness in addressing aspects such as hydrological features, environmental impact, and overall functionality. Comparing with traditional methods of stormwater management with modern PPS, this review highlights the benefits of PPS and how it has demonstrated positive impacts, influencing the stormwater pollutant removal efficacies, reduction in runoff volumetric flowrates and benefits of increased groundwater recharge. The literature examined highlights the characteristics of PPS, its permeability and stormwater retention capacities. The findings from this research study, emphasizes how PPS as a SuDS contributes to effective stormwater management from roads. Furthermore, the study explores how PPS mitigates urban heat island (UHI) impacts by minimizing heat absorption, promoting cooling effects, while simultaneously filtering pollutants, in reducing heat-related urban pollution with specific focus on interlocking permeable pavements. The research indicates that PPS continues to play a crucial role in managing stormwater runoff, providing solutions to flooding challenges reducing runoff and improving stormwater quality through pollutant retention and removal. The benefits of PPS contribute significantly towards creating more eco-friendly environments and green urban ecosystems, yielding practical, environmental and financial benefits.

Keywords: Permeable Pavement Systems (PPS); Sustainable Drainage Systems (SuDS); interlocking pavement blocks; pollutant removal; stormwater runoff; water quality; volumetric control

1. INTRODUCTION

1.1 Background and Context

According to a 2019 United Nations report, 55% of the world's population lives in cities, and by 2050, two-thirds of all people on earth are expected to do so (Chen and Gaspari, 2023). With the increase in urban population, there is an impact on runoff surfaces due to the increase in impervious surfaces. This increasing impervious surfaces from roads, highways, and parking lots has made urban stormwater runoff a major source of water contamination which is one of the major challenges (Müller et al., 2020; Revitt et al., 2014). Unmanaged planning of settlement and infrastructure has led to a narrowing down of the road space that could accommodate retrofitting of the drainage system.

According to the previous research (Yunianta et al., 2020; Turer and Maynard, 2002; Buckler and Granato, 1999), "Roads and highways are a recurring source of environmental toxicity" that can be deposited via runoff. Globally, it has been demonstrated that road and highway runoff have major contribution in polluting the aquatic environment having significant impact on both surface and groundwater quality (Coffin, 2007; Doamekpor et al., 2015). The runoff from the road platforms carries substantial range of chemical pollutants originating from automobiles, road surfaces, infrastructures, maintenance work such as de-icing, tunnel cleaning and vegetation control (Meland, 2010) making its way to nearby water bodies and ecosystem (EPA, 2015) that have detrimental immediate and long-term effects on the physical, chemical, and biological aspects of both the land and water environments (Angermeier et al., 2004; Wheeler et al., 2005). The chemical pollutant in such runoff consists of heavy metals like zinc, cadmium, lead, mercury and other components like oil, grease, sediments, and nutrients to name a few (Meland, 2016; Nagajyoti and Sreekanth, 2010; Pamuru et al., 2022). These stress the need for a sustainable, socioeconomic, and environmentally sustainable road and highway runoff control.

The necessity for sustainable practices in relation to energy and water resources is highlighted by the fact that climate change and global warming are urgent worldwide issues. The adoption of permeable pavement systems (PPS) is one method for resolving these issues (Monrose and Tota-Maharaj, 2018). Due to structural loading restrictions and geotechnical design factors, historically it has been used in locations with light-duty pavement requirements (Spicer et al., 2006; Scholz and Grabowiecki, 2007). In addition to controlling stormwater runoff through infiltration, storage, and dispersion mechanisms, these systems provide a simple yet effective method for building structurally solid pavements suitable for automotive and pedestrian traffic (Tota-Maharaj and Scholz 2010; Kuruppu et al., 2019). PPS are essential to sustainable stormwater management because they encourage groundwater recharge, lessen surface runoff, enable stormwater reuse, and guard against runoff pollution in a variety of situations, including commercial, residential, and industrial locations. Stormwater management in urban areas, parking lots, walkways, open markets, and on highway shoulders is crucial and closely related to the planning and installation of permeable pavement systems (Srishantha and Rathnayake, 2017). These porous pavements are an excellent choice for stormwater management because they excel at collecting water on their surfaces and promoting its infiltration into the subgrade layer and groundwater. Contrarily, traditional impermeable road pavements tend to collect a lot of storm runoff that is full of contaminants from traffic and related activities (Ferguson, 2005; U.S. Environmental Protection Agency, 2005; Zhang and Chui, 2020). The volume of sidewalk runoff and the contaminants it transports can both be decreased using permeable pavement systems, which is a better option for the environment (Barrett and Shaw, 2007; Chopra et al., 2010; Dreelin et al., 2006; Collins et al., 2008).

Modern stormwater management techniques place a strong emphasis on the sustainable control of urban stormwater runoff, which is frequently accomplished through Sustainable Urban Drainage Systems (SuDS) like PPS. The collection, storage, treatment, and reuse of stormwater runoff are all included in this strategy. With a primary focus on light-duty and frequent usage, PPS emerge as a flexible solution for regulating stormwater runoff in various urban, commercial, and industrial environments. These systems do, however, exhibit adaptability, allowing for a larger range of significance (Grabowiecki and Scholz, 2006; Charlesworth et al., 2003). Although Ground Source Heat Pumps (GSHP) and permeable pavement system can be purchased commercially, relatively little study has been done in this field (Nnadi et al., 2009; Scholz and Grabowiecki, 2009). The utilization of geothermal energy systems, which lower greenhouse gas emissions and offer a renewable energy source, has grown over the past few decades. When combined with the right technology and geothermal heat pumps, the sub-base of permeable pavement systems offers a promising geothermal resource. Through heat exchange networks that are normally filled with water, such systems enable the extraction or injection of heat into the subsurface at relatively low temperatures. This geothermal and permeable pavement systems combination offers a compelling path towards environmentally and economically responsible urban development. The increase in impermeable surfaces, such as roads and highways, brought by the fast urbanization of places has led to decreased groundwater infiltration and increased runoff volumes (Finkenbine et al., 2000; Nie et al., 2011; Minnig et al., 2018). According to Chai et al. (2012) and the USEPA (1996), urban runoff, which frequently contains pollutants from numerous urban sources, is responsible for 46% of all contamination in surface waters. Urban road dust contains trace metals such as copper, lead, zinc, and platinum group elements (PGEs) that mainly originated from vehicle emissions. These are transported by stormwater runoff into nearby waterbodies, and they cause serious water quality issues threatening aquatic organisms and ecosystem health (Hwang et al., 2016). Effective management of urban runoff has become crucial in this situation, both in terms of quantity and quality.

The use of PPS as a sustainable Low Impact Development (LID) strategy is one cutting-edge method to reduce the negative effects of urban runoff. PPS have the potential to improve water quality and lower runoff quantities, which would lower the cost of runoff treatment (Sansalone and Teng, 2005; Andersen et al., 1999). There is a significant gap in the literature regarding the hydraulic performance of sidewalk PPS when subjected to clogging phenomena, even though the infiltration rates of PPS have been studied in various settings, particularly sidewalks, using techniques such as double ring infiltrometer tests (Example: Qin et al., 2013; Valinski and Chandler, 2015). The ability of PPS to improve water quality has been the subject of numerous research, with a particular emphasis on the removal of Total Suspended Solids (TSS) from runoff. Heavy metals found in TSS are frequently harmful to aquatic environments (Brown et al., 2009; Rossi et al., 2006; Sekabira et al., 2010). These studies have shown encouraging findings, showing that PPS can significantly reduce TSS, turbidity, and total phosphorus, frequently by more than 50% (Pitt et al., 2005). In addition, high removal efficiency for TSS, N-NH4, and P-PO4 has been noted in runoff (Tota-Maharaj and Scholz, 2010). However, the design and upkeep of PPS continue to be significant determinants of how well they function. The build-up of sediments within the pavement structure, which causes clogging problems, is one of the main problems with PPS (Bean et al., 2007). The widespread use of PPS for stormwater management is significantly hampered by clogging (Bean et al., 2007; Drake et al., 2013; Sanicola et al., 2018). There is an urgent need to explore PPS under plausible scenarios that mimic real sediment loads and precipitation patterns, even though substantial research has extensively replicated blockage under controlled laboratory circumstances. To protect water quality, it is strictly banned in many parts of the world for stormwater runoff from urban roads and highways to enter natural water bodies. Therefore, "best management practices" (BMPs) aimed at gathering and treating road runoff before its release into the environment are required of municipalities and transportation agencies. However, because of the lack of readily available right-of-way property, the actual application of widely accessible BMPs on urban roadways presents significant obstacles. Even when there isn't a space issue, it can be extremely expensive to manage large amounts of the toxic runoff that impermeable urban roadways produce. As a result, it is becoming more and more accepted that current conventional stormwater runoff management solutions in metropolitan settings are unworkable and unsustainable. Furthermore, many urban communities may find themselves pushed or motivated to switch from traditional impermeable paved surfaces to more ecologically friendly urban surfaces in anticipation of future environmental rules that will be even stricter. Weiss et al. (2017) stated that permeable pavement surfaces should be widely used to facilitate this transition. As opposed to traditional impermeable pavement, full-depth permeable pavement offers a variety of sustainability benefits, including improvements to the environment, society, and human health. Table 1. depicts the comparison of various parameters that are related to the full-depth permeable pavement (FDPP) and conventional pavement.

Table 1. Comparison of various parameters related to the full-depth permeable pavement (FDPP) and conventional pavement (Source: Kayhanian et al., 2019)

Parameter	Impacting factor	Full-depth permeable pavement (FDPP)	Conventional pavement
Construction	Structural capacity	Low	High
Hydrologic	Vertical permeability	High	Very low
	Water storage	High	Very low
	Surface overflow	Low	High
Environmental	Pollution type	Point and non-point source	Point and non-point source
	Pollution level	Low	High
	Noise level	Low	High
Energy	Heat island effect	Medium	High
Economic	Initial cost	Medium/high	Low

This thorough examination of PPS as BMPs for regulating road and highway runoff fills up this important gap in the literature. This literature review focuses on their performance to better understand PPS as sustainable drainage systems, particularly in terms of clogging behavior and water flow patterns. The aim is to optimize the performance of PPS within the broader context of urban runoff control by synthesizing existing research findings to inform the development of effective maintenance techniques.

1.2 Overarching of Research Aim, Objectives, and Research Question

The overarching aim, this research conducts a comprehensive literature to evaluate the use of PPS as a viable long-term method, for managing runoff from roads and highways. The study aims to analyze the performance and effectiveness of PPS in controlling runoff with particular emphasis on its structural capacity and hydrologic attributes. By amalgamating findings from studies, the intention is to provide insights into optimizing PPS as a sustainable solution, within the broader framework of urban drainage systems.

1.2.1 Research Objectives

RO1. Asses Long-Term Runoff Control with PPS

To conduct a comprehensive literature review to evaluate PPS's structural performance and hydrological properties in managing and highway runoff throughout time.

RO2. Evaluate PPS's effects on Urban Runoff Control

To review PPS's effectiveness in managing runoff and its effects on water quality, runoff volume and flood risk management based on past research.

RO3. Optimize PPS for Sustainable Urban Drainage

To identify techniques to maximize PPS's sustainability in urban drainage systems, using historical studies to guide future practices.

1.2.2 Research Question Formulation

The research is guided by a collection of precise research questions and formulations that help to accomplish the study goal. These study topics are created to explore important facets of the performance of PPS as a sustainable urban drainage system (SuDS).

RQ1. How does permeable pavement system (PPS) stack up structurally against traditional pavement, and what does this mean for its application to runoff control on roads and highways?

RQ2. How do PPS's hydrological properties, particularly its vertical permeability and water storage capacity, help to lessen surface runoff and encourage groundwater recharge?

RQ3. How does PPS affect the urban heat island effect and what environmental advantages does it provide in terms of pollution reduction?

RQ4. In terms of cost-effectiveness, how do the economic aspects of using PPS as a sustainable urban drainage system compared to those of conventional pavement solutions?

1.3 Research Significance

Regarding the management of water resources and the sustainability of urban environments, the evaluation of BMPs for road and highway runoff control is of utmost importance. The significance of PPS as a sustainable drainage method is highlighted in this systematic literature evaluation across several parameters.

1.3.1 Environmental Sustainability

The need to address climate change and its effects, particularly rising incidences of floods owing to changing precipitation patterns, is one of the most serious global concerns now. Urbanization considerably increases surface runoff and reduces groundwater recharge, especially because impermeable surfaces like roads and highways are so prevalent. Evaluating the effectiveness of PPS, this research can encourage environmentally sustainable practices. Additionally evaluating the efficiency of PPS in reducing these adverse effects, this research has the potential to support environmentally friendly practices. By eliminating contaminants from runoff, PPS has the potential to lower surface runoff, boost groundwater recharge, and enhance water quality. For urban areas attempting to embrace sustainable stormwater management strategies, understanding its performance is essential.

1.3.2 Urban Infrastructure Improvements

The research on urban infrastructure improvements holds practical relevance for urban planners, engineers, and decision-makers involved in infrastructure development. Conventional impermeable pavements often face higher maintenance costs due to frequent floods. In contrast, the utilization of PPS has the potential to reduce surface runoff, leading to significant cost savings. Furthermore, the study highlights the importance of PPS's structural strength in ensuring the longevity and durability of roads and highways. By emphasizing the structural capability of PPS, the study contributes to the design and implementation of more resilient urban infrastructure.

1.3.3 Water Resource Management

Efficient utilization of water resources is a crucial aspect of sustainable urban development. Water resource managers and authorities responsible for safeguarding water quality and quantity can greatly benefit from the findings of this comprehensive literature evaluation. The implementation of PPS plays a significant role in minimizing the transmission of contaminants in urban runoff, thereby improving water quality in receiving bodies such as rivers and lakes. Additionally, PPS can contribute to addressing issues related to water scarcity and dwindling water tables by promoting groundwater recharge.

1.4 Overview of Research Structure

The research structure can be observed in Figure 1. The flow diagram illustrates the sequential progression of the study. Initially, the problem at hand, which pertains to the influence of stormwater on roads and highways, is identified. Subsequently, a comprehensive literature review is conducted, followed by the collection of pertinent data regarding runoff control. The obtained data are then subjected to analysis based on various parameters. The findings are further deliberated upon to derive a suitable conclusion that aligns with the research aims and objectives, thereby addressing the research questions.

Figure 1. Research flow diagram, Source: Author

2. METHODOLOGY: SYSTEMATIC LITERATURE REVIEW

This chapter provides an overview of the technique used to perform a thorough analysis of the research articles related to stormwater runoff and permeable pavement systems that were retrieved from majorly from the database of "Google Scholar." The technique selected enables an organized and methodical analysis of the research environment, including historical trends, subject areas, and global contributions. To examine the junction of stormwater runoff and permeable pavement systems research, this chapter serves as a guide to the procedures followed in the data collection, filtering, and analysis phases.

The highlights to different stormwater strategies adopted around the world with the key objectives are represented in Table 2.

Table 2. Stormwater Management Strategies, Source: modified from Fletcher et al.,(2015).

Stormwater Management Strategies	References	Terminology Used Regions/ Countries	Objectives/ Function

Low Impact Development (LID) and Low Impact Urban Design and Development (LIUDD)	(Barlow et al., 1977); (Department of Environmental Resources, 1999)	North America and New Zealand	water quality protection by reduction of polluted runoff through the design of smart sites that avoid environmental impacts from the beginning, minimize stormwater runoff impact through small-scale and decentralized practices, maintain pre-development hydrology via infiltration and evapotranspiration and focuses on sustainability goals and ecosystem health
Sustainable Drainage System (SuDS)	(CIRIA, 2000); (DEFRA, 2011)	UK	control flooding, improve water quality along with habitat and amenity benefits, replicate natural drainage patterns by an integrated approach sustainably manage urban stormwater
Water Sensitive Urban Design (WSUD)	(Mouritz, 1992); (Whelans et al., 1994); (Wong, 2007)	Australia and New Zealand	protect and enhance natural water systems by integrating stormwater treatment into landscape design, reduce runoff volumes and peak flows, protect water quality by reducing polluted runoff, promote water conservation including reuse, and taking an integrated approach to urban water management by guiding sustainable planning design of cities
Best Management Practices (BMPs)	(Schueler, 1987); (United States of America, 1990)	United States and Canada	prevent and reduce stormwater pollution, control and treat stormwater at the source that complies with stormwater quality

			regulations, address stormwater quality and quantity issues by linking the structural and non-structural techniques
Integrated Urban Water Management (IUWM)	(Geldof, 1995); (Harremoes, 1997); (Niemczynowicz, 1996)	Europe, Australia, Melbourne, Copenhagen, New Yor, Berlin, Toronto, Paris, Hamburg, Tokyo	a closely linked system to WSUD and water-sensitive cities that manages the entire urban water cycle encompassing water supply, wastewater, stormwater, and groundwater balancing environmental, social, and economic needs including perspective of all stakeholders
Stormwater Control Measures (SCMs)	(National Research Council, 2008); (Choat et al., 2023); (Blecken et al., 2017)	United States	manage stormwater quantity and quality by structural and non-structural stormwater control, treat stormwater at the source, control runoff and pollution that enables selection for site conditions
Alternative Techniques (Ats) or Compensatory Techniques (CTs)	STU (1981), (1982) and (Baptista et al., 2005)	France, Brazil, and other European countries	provide an alternative to traditional piped drainage that maintains pre-development flow rates by reducing runoff volume and peak flows, reducing the vulnerability of urban areas to flooding, protecting the quality of receiving environments that improves amenity and landscapes utilizing multifunctional corridors and limits drainage infrastructure costs

Source Control	(MetroVancouver, 2012); (Ontario Ministry of Natural Resources, 1987)	Canada	manage stormwater at or near the source, maintain pre-development hydrology, minimize downstream impacts, prevent pollution through site design, treat stormwater via near-source structures, control pollutant sources and contaminations, and mitigate runoff impacts on receiving waters
Green Infrastructure (GI)	(Walmsley, 1995); (Benedict and MacMahon, 2006); (Kim, 2018)	USA	integrate natural processes into built areas that capture and infiltrate rainfall to reduce runoff, use vegetation and soil to sustainably manage rain, provide ecosystem services beyond stormwater by enhancing amenity, health, and equity
Stormwater Quality Improvement Devices (SQIDs)	(SQIDS monitoring report, 1998)	Australia	superseded by WSUD, a structural device that improves the stormwater quality although the system doesn't address stormwater quantity by focusing on removing pollutants
Sponge-City	(MOHURD, 2014); (Yin et al., 2021); (Li et al., 2016)	China	a system inspired by other stormwater management strategies such as LID, SUDS, and WSUD to name a few with an objective to improve water quality with its security, developing healthy ecosystems and water utilization efficiency

2.1 Search Strategy

Search strategy helps in planning the layout of conducting organized research that focuses on the selected topic. It is the first and very crucial step as it aids in developing a comprehensive research search strategy while conducting a systematic literature review. This research aims to capture the peer-reviewed articles, case studies, conference proceedings, and reports that are related to the permeable pavement systems in the urban context that precisely delves into road and highway runoff. The search was designed with the following strategies to filter the search; below are the listed criteria:

2.1.1 Database Selection Criteria

For the authentication of data, it is very important to use a reliable database to review any literature for the research. In this dissertation, multiple databases were used to conduct the search that majorly focused on data of "Google Scholar" and other database like "Scopus" and "Taylor & Fransis." It is also very important to ensure the comprehensiveness of the search, therefore, additional grey literature sources including relevant conference proceedings and institutional repositories were explored.

2.1.2 Keyword Selection Criteria

The search terms used keywords that were coherent with the topic and relevant to the abstract and key terms of the paper. The key search terms for this research include "permeable pavements", "permeable pavement systems", "stormwater runoff", "flood risk management", "water quality improvement" and "runoff volume reduction". Use of Boolean Operators such as "AND" and "OR" were used to combine search terms and obtain more precise academic literature. The precise keywords used can be seen in section 2.3.3.

2.1.3 Inclusion and Exclusion Criteria

The Inclusion and Exclusion Criteria in a Systematic Literature Review help in narrowing down the search and focus on the relevant topic. The systematic review in this research followed a set of inclusion and exclusion criteria to concise the study that aligned with the objectives of the research. The inclusion criteria accommodated (1) literature published in peer-reviewed journals, case studies, and reports with open access, (2) literature that focused on permeable pavement systems in the urban context, (3) literature reports on flood risk management, water quality improvement, or runoff volume reduction as a result, (4) literature published in English and (5) literature that were conducted in urban or peri-urban locations.

The exclusion criteria accommodated (1) literature that was not peer-reviewed and didn’t have open access although peer-reviewed (2) literature that was not relevant to the topic i.e., permeable pavement, (3) literature that didn’t give a clear report on flood risk management, water quality, or runoff volume reduction, (4) literature that was Non-English or any other foreign language, and (5) literature that was conducted other than urban and peri-urban locations.

2.2 Data Source and Extraction Processes

The literature data sources for this research were extracted from the final academic journal electronic databases, institutional repositories, grey literature sources, and conference proceedings. These chosen sources determined the competency that allowed a comprehensive and diverse pool of study for analysis. Similarly, the data extraction process also has a systematic process of gathering all the key information and findings from each selected study. In this research, a predefined data extraction format was used to collect the information that included (1) study citation details: title, authors, publication year, and source, (2) study design and methodology, (3) characteristics of permeable pavement systems such as design, materials, and maintenance practices, (4) results related to flood risk management, water quality improvement, and runoff volume reduction, (5) findings and results and lastly (6) limitations and challenges reported in the literature.

Hereby, the standardize data extraction process not only ensures the competency and consistency of capturing relevant data from each study but also facilitates subsequent analysis and synthesis of the data.

2.3 Result Summary

2.3.1 Types of Research

The research conducted for this study can be categorized into two distinct types: exploratory research and descriptive research. Each type of research serves a specific purpose in the investigation. The main objective of descriptive research is to elucidate the characteristics of a specific event or subject, thereby establishing a solid foundation for a comprehensive comprehension of the subject matter. This study relied heavily on descriptive research to give a thorough overview of the field of study around permeable pavement systems and stormwater flow. This study aimed to produce useful insights into the field's evolution, growth trends, and emphasis points across time by evaluating and synthesizing data from a wide range of sources. Data analysis, which is a form of descriptive research, made it possible to extract statistics from the selected articles as well as identify new trends and recurrent patterns. To negotiate the complicated interdisciplinary nature of stormwater runoff and permeable pavement systems investigations, exploratory research was also used in this dissertation. When a topic or issue is new or not fully understood, exploratory study becomes crucial. The exploration in this context entailed plunging into the unexplored realms of research on stormwater runoff and PPS to uncover the various facets, identify key subject areas, and investigate keywords that define PPS' function in efficient stormwater management.

2.3.2 Data Collections

In the database of "Google Scholar", a search for the terms "stormwater" AND "runoff" produced a sizable result of 10124 research papers. With records going back to 1970 and ongoing research up until the present, this search illustrates the extensive and ongoing study of the subject over the years. The trendline (Linear (Document)) in Figure 2. indicates that research in this field has advanced steadily. A significant 630 research articles were published in 2021, according to the data, which also shows that year had the most research activity. This increase in research production over the past few years reflects society's growing concern for effective stormwater management in the face of urbanization and climate change, indicating the growing significance of stormwater runoff as a crucial issue of exploration. The results demonstrate not only the relevance of this subject but also the increased scholarly interest in and dedication to solving the problems posed by stormwater runoff in modern urban settings.

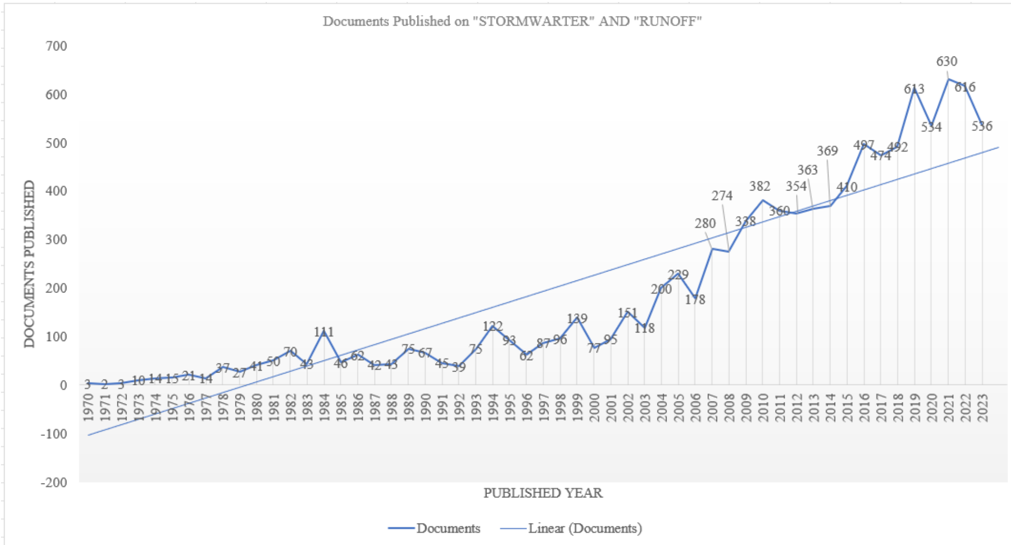

Figure 2. Documents Published on “Stormwater” and “Runoff”, Source: Scopus/ Google Scholar

2.3.3 Focused Research Collections

The distribution of research across different fields of study is depicted in Figure 3., with a specific focus on the sectors that have made noteworthy contributions to the exploration of "stormwater" and "runoff." It is worth noting that the majority of research, approximately 65% of the overall output, is concentrated in the domains of "Environmental Science" and "Engineering." This observation underscores the interdisciplinary nature of stormwater and runoff studies, which places considerable research emphasis on the intersection of these two fields. These subject areas are extensively referenced in the research publications analyzed, highlighting their crucial role in advancing our understanding of stormwater management, water quality, pollution control, and related subjects. To conduct a more focused analysis, the search was refined using specific keywords, enabling the identification of studies on "permeable pavement systems" in relation to "stormwater" and "runoff." The search employed filters to narrow down the studies that pertain to the fields of "Environmental Science" and "Engineering."

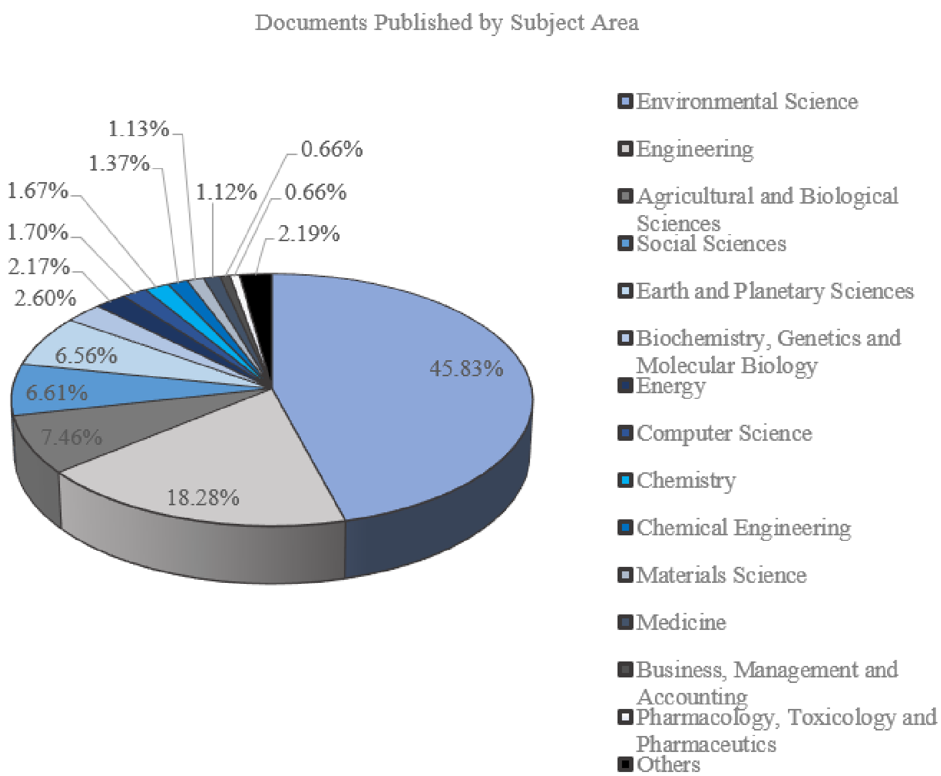

Figure ~~2~~3. Pie-chart of Documents Published by Subject Area, Source: Scopus/ Google Scholar

The investigation examined a collection of 454 documents published with the same database, focusing on papers using the specified keywords "permeable pavement systems.” Furthermore, a set of keywords including "water quality," "water pollution," "pollutant control," "pollutant removal," "peak flow," "runoff reduction," "flood control," "flooding," "volume reduction," and "climate change" were used to navigate the precise research. The time horizon was restricted to the recent ten years i.e., “2012-2023”.

A more focused search yielded a compilation of 286 research publications that specifically investigated the correlations between permeable pavement systems and the diverse and crucial aspects of stormwater management. The selection of specific keywords and accompanying research papers underscores the significance of permeable pavement systems as a sustainable solution to a multitude of challenges faced by industry. These challenges include enhancing water quality, reducing pollution, preventing flooding, and lessening the effects of climate change. The large number of papers found in this focused search demonstrates the depth and scope of scholarly research in these fields. Academic and research communities are actively exploring the potential of permeable pavement systems as a versatile solution for stormwater and runoff management.

In addition to advancing our knowledge of the theoretical elements of permeable pavement systems, these studies aim to address engineering difficulties and environmental issues by offering practical solutions. Furthermore, the interdisciplinary approach necessary to properly handle stormwater and runoff concerns is emphasized by the concentration on "Environmental Science" and "Engineering" as dominating subject areas. Environmental scientists and engineers collaborate to develop innovative, long-term strategies for managing urban stormwater, enhancing water quality, reducing pollution, and mitigating the negative consequences of stormwater runoff.

2.3.4 Geographical Distribution

On tracing the research history on “permeable pavement systems” as a remedy for “stormwater runoff” control/ management it can be observed that the concept began in 1989 which is more than two decades after the introduction of the broader concept of “stormwater management.” This targeted search, limited to studies written in English-language, yielded a collection of 282 relevant peer-reviewed documents. The dataset further delved into the geographical distribution of these research contributions which highlighted the global significance and emphasis on the topic. Among the countries and territories analysed for research output, the United States emerged as a leader in exploring permeable pavement as an option for managing stormwater runoff, with a notable publication count of 131 documents. challenges, such as stormwater runoff, through research and development of permeable pavement systems has positioned it as a leader in this field. The significant number of documents published by the United States in relation to permeable pavement systems as a stormwater runoff management option highlights its commitment to finding sustainable solutions. However, it is important to note that following the United States several other countries, including China, Canada, Australia, and the United Kingdom, have also made substantial contributions to this area of study. This international collaboration has expanded the body of knowledge surrounding permeable pavement systems and their role in stormwater management.

The global interest and collaboration in adopting permeable pavement systems to address problems related to stormwater runoff illustrated by the distribution of documents by country/ territory, as depicted in Figure 4. This distribution highlights the active involvement of researchers, professionals, and policymakers from various countries in advancing the understanding and application of permeable pavement systems as sustainable solutions. It also emphasizes the global relevance of the problem and the extensive efforts made by researchers, professionals, and policymakers from multiple countries to enhance the understanding and adoption of permeable pavement systems as effective and sustainable methods for stormwater management. The dominance of research output from the United States can be attributed to the country's ongoing commitment to addressing environmental and infrastructure challenges. American academics have assumed a leadership role in investigating the effectiveness of permeable pavement systems in mitigating the adverse effects of stormwater runoff, with a particular focus on sustainable urban development and improved stormwater management. China's significant presence in the research community reflects the country's recognition of the importance of cutting-edge stormwater management strategies amidst urbanization and environmental concerns. Similarly, the contributions from Canada, Australia, and the United Kingdom demonstrate their dedication to finding sustainable solutions for the issues posed by urban stormwater runoff. These countries' active involvement in research and development indicates their commitment to addressing the challenges associated with stormwater management and their recognition of the need for sustainable approaches.

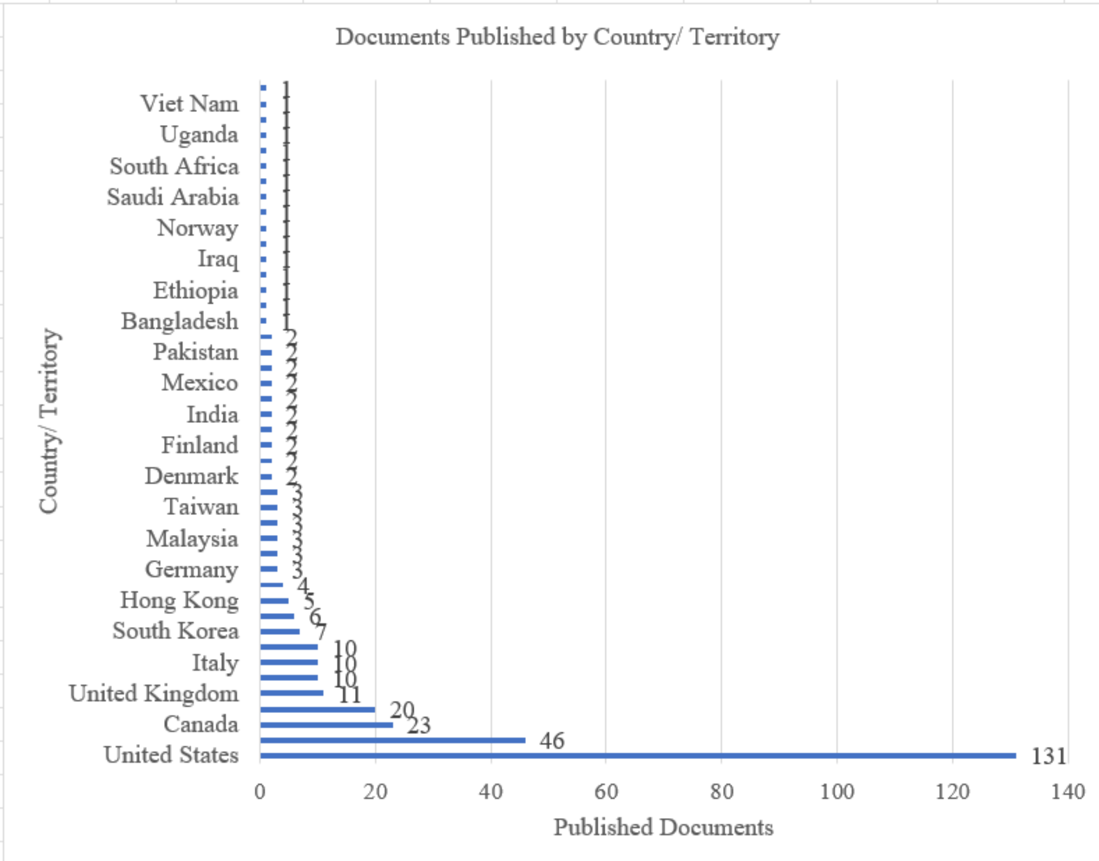

Figure ~~3~~4. Bar Graph documents published by country/ territory, Source: Scopus/ Google Scholar

After employing the research selection criteria, a comprehensive set of 63 documents were procured from the initial pool of 286 documents that fulfilled the specified topic of interest. A meticulous examination was carried out, employing an equitable evaluation procedure guided by various significant factors that played a pivotal role in ascertaining the scope and profundity of the research. Consequently, only nine articles were deemed suitable for the purpose of discussing the reflective aspects within this dissertation. During the process of selection, the criteria prioritized relevance and quality of the data. Each of the nine articles that were selected stood out for its high-caliber material and connection to the main idea of the dissertation. This approach ensured that the articles chosen contributed to understanding stormwater runoff and the crucial role played by permeable pavement systems in stormwater management and runoff control. In addition, the articles were chosen to create a representative sample.

The selection of publications for the thesis encompassed a diverse range of topics and areas within the academic landscape. These publications employed various research methodologies and covered a wide array of subject areas, thereby presenting a multitude of significant discoveries. This inclusive approach ensured that the thesis offered a comprehensive and well-rounded perspective, avoiding a narrow and limited portrayal of the subject matter.

The issue of space constraints posed a significant challenge in the composition of the master's dissertation. To address this challenge, a limited number of articles were deliberately chosen to facilitate a thorough investigation of each one while adhering to the space limitations. This strategic approach, centered around the selected articles, struck a harmonious balance between practicality and in-depth study. The decision to include only nine articles was further influenced by the time and resource limitations associated with the master's thesis. By limiting the scope of research to these nine publications, the strain on resources was minimized, and a specific timeline was established.

Furthermore, it was imperative that the chosen articles exhibited an interdisciplinary nature. These articles transcended the boundaries of "Environmental Science" and "Engineering," thereby highlighting the necessity of an interdisciplinary strategy in addressing complex and pressing issues related to stormwater management. Moreover, the inclusion of these articles added depth to the understanding of how permeable pavement systems play a pivotal role in resolving these issues.

3. LITERATURE REVIEW

In this chapter, the significance of urban water management is overviewed, with a particular focus on the need for creative solutions in light of the growing metropolitan population. Also, the chapter delves into introducing Permeable Interlocking Concrete Pavement (PICP) as a possible stormwater control solution in the literature review.

3.1 Novel Application: Permeable Pavement Systems (PPS)

PPS are a type of pavement system that allows water to flow through it, preventing stormwater from collecting on the surface. This not only prevents structural damage caused by stormwater but also contributes to sustainable drainage systems (SuDS) for various applications such as driveways, walkways, parking lots, and low-traffic roadways. PPS have traditionally been used for stormwater management and flood control (Yu et al., 2021; Imran et al., 2013). Figure 5. shows the principal sketch of PPS (Muttuvelu et al., 2022). The design of PPS considers both structural and hydrological performance to ensure it can withstand traffic loads and effectively manage stormwater. However, in modern context, the innovative applications of PPS are emerging in various field such as Urban Heat Island Mitigation (UHI), Renewable Energy Generation, Air Quality Improvement, Wastewater Treatment, Agriculture and Landscaping, Recreational and Sports Surfaces, Erosion Control, Wildlife Conservation, and Historic Preservation to name a few. PPS in recent years have been well-known as adaptable and eco-friendly systems that provide creative answers to problems with stormwater management, urban development, and environmental sustainability. This change is the result of growing awareness that PPS is a multidimensional technology that can solve a range of environmental and urban problems, not only a stormwater management tool. These articles examine several cutting-edge applications that use PPS to tackle these problems in novel and inventive ways.

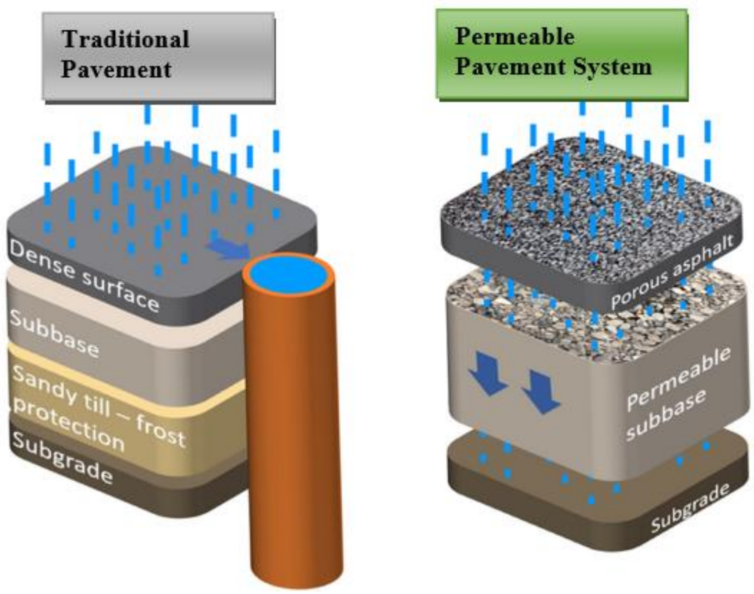

Figure 45. Principle sketch of Permeable Pavement System (PPS), Source: (Muttuvelu et al., 2022)

The article titled “Stormwater Management in Urban and Rural Areas” discusses the stormwater management principles in urban and rural settings. Generally, these systems used to primarily entail rapidly moving water to ditches or sewage systems, which had a number of negative consequences. Due to this method, a significant amount of water and contaminants were transported to rivers and streams, disturbing the hydrological cycle and contributing to the depletion of groundwater. Ecosystems were also harmed by changed water flow patterns. However, changing patterns of urbanisation, changes in agricultural activities, and changes in the climate have highlighted the necessity of a paradigm shift in stormwater management approaches (Kazak et al., 2022). On the other hand, a 22-year bibliometric analysis (2000–2021) was conducted by Singer et al. (2022) revealed some important findings: minor adjustments to PPS layers or creative filters can improve the efficiency of removing contaminants; impermeable soils and PPS pore size greatly affect permeability and infiltration rates; clogging in the upper PPS layers can be effectively maintained; partial replacement of PPS mix design with recycled aggregates improves permeability, although at a slight compromise to compressive strength; and ongoing research focuses on improving water quality through creative methods. The significance of continuous research and innovation in enhancing PPS performance for sustainable stormwater management is highlighted by these findings.

"Feasibility of Low-Carbon Permeable Pavement Systems for Stormwater Management," the article (Tota-Maharaj et al., 2021), looked at the influence of low-carbon materials on mechanical performance and their application in PPS. It addressed the rising carbon emissions from the construction industry, particularly from the transportation, pavement, and road sectors, and investigated the possibility of combining low-carbon materials with PPS. The study investigated four different low carbon designed materials: recycled rubber, recycled glass, recycled grit, and regular pavement materials. These components are incorporated into the permeable paver concrete mixtures and embedded into several PPS layers and subsections. According to pertinent criteria, the study assesses PPS's mechanical, absorption, and infiltration capabilities. While absorption tests determine which concrete mix has the lowest water-holding capacity, compression testing determines the highest permitted compressive force. Effluent infiltration rate and volume are used in infiltration testing to determine the best-performing pavement material. The outcomes of the laboratory experiments showed that the mechanical and hydrological performance of PPS is improved by using recycled materials. This fits with sustainable building methods and gives PPS an additional ecologically favorable component. The study also highlighted how important it is to consider hydrological and structural performance when developing PPS. Hydrological performance is the pavement's ability to effectively infiltrate, store, and release water for sustainable stormwater management. Structural performance is the pavement's ability to support the weight of cars and pedestrians. According to the article, PPS may experience clogging as a problem that could compromise their long-term functionality. It is emphasized that proper design and upkeep are essential to guarantee PPS's continuous quality and operation. The study paper presented the idea of Life Cycle Assessment (LCA) as a useful system to assess and improve the environmental performance of PPS throughout their life cycle to obtain a thorough understanding of the environmental impact of PPS. The researcher stated that a well-designed and constructed PPS has the potential to last for 20-40 years with minimal maintenance. Additionally, environmental effects must be considered at every stage of manufacture, usage, and, eventually, disposal or recycling. This demonstrated the research's dedication to ecologically friendly methods and sustainable urban development.

In Tota-Maharaj (2010), new uses for PPS are examined, with an emphasis on integrating geothermal heat pumps with renewable energy sources. It explores PPS's diverse potential in resolving issues with stormwater management, urban runoff, and renewable energy efficiency. The study investigated how well PPS works to clean up urban runoff and enhance water quality. It looks at how well different pollutants are removed, such as microbiological pathogens and physiochemical factors, and offers insightful information on how these systems may be used for long-term, sustainable stormwater management. This work is the first to integrate PPS with geothermal heat pumps. This creative combination makes it possible to use the energy reserve found in pavements, which turns them into a practical source for building heating and cooling. The study evaluates these integrated systems' temperature and energy performance and shows how well they might work for renewable energy applications. The integration of geothermal heat pumps into permeable pavement systems enhanced their capacity to use renewable energy. The report addresses the systems' coefficients of performance (COP) and energy efficiency ratios (EER), offering insights into their ability to save energy and lessen dependency on conventional energy sources. The study investigated the application of artificial neural networks (ANNs) to the simulation of integrated earth energy and permeable pavement systems for stormwater treatment. Decision-makers can benefit from this innovative method's ability to analyze and optimize PPS, which promotes sustainable stormwater management techniques. Innovative applications of PPS are presented in this article, with a focus on the integration of ANNs for system simulation, renewable energy efficiency, and geothermal heat pump integration. These developments open the door for more effective stormwater management techniques and aid in the creation of sustainable urban drainage systems.

The emphasis in “Technological Review of Permeable Pavement Systems for Applications in Small Island Developing States” (Monrose and Tota-Maharaj, 2018) is shifted to the special use of PPS in Small Island Developing States (SIDS). These areas confront a unique combination of difficulties, such as restricted availability of potable water and increased susceptibility to the effects of climate change. The authors of this paper stress how critical it is to identify cost-effective and long-lasting solutions to these problems. The article recognized the wide range of political, social, cultural, physical, and economic traits that exist within SIDS. It serves as a reminder that the complex problems these regions face cannot be solved with a one-size-fits-all strategy. Nonetheless, a lot of SIDSs have similar issues with water resources, like inconsistent and limited access to clean water. These problems are made worse by climate change, which affects groundwater, causes seawater intrusion, salinification of coastal groundwater, and reduces the amount of freshwater available in some SIDS coastal zones. Systems of permeable pavement are offered as a possible remedy for these problems associated with SIDS's water resources. By allowing rainwater to permeate the pavement, these systems lessen runoff and encourage the recharging of groundwater. According to the article, PPS can lessen the negative effects of climate change on SIDS's water supplies. It draws attention to the necessity of specialized solutions that consider the limitations and circumstances of these areas, including traffic volumes, the choice of construction aggregate, the depth of the water table, the possibility of groundwater contamination, and the local climate. Crucially, the study urged additional investigation to evaluate PPS's efficacy in other SIDS scenarios. It emphasized how important it is to collect extensive data and conduct long-term monitoring to assess the overall effectiveness and impact of PPS in these areas. It further stressed the significance of community involvement and education in PPS implementation, since local collaboration and knowledge are essential to the effective use of these systems.

The idea of incorporating ground source heat pumps (GSHP) into PPS for stormwater treatment and improving water quality is introduced in "Sustainable Approaches for Stormwater Quality Improvements with Experimental Geothermal Paving Systems" by Kiran Tota-Maharaj and Parneet Paul (Tota-Maharaj and Paul, 2015). The research, which is being done in Edinburgh, UK, shows how these integrated systems might lessen ecological concerns related to stormwater discharges and enhance the quality of the water. The planning and building of experimental geothermal PPS are described in detail in the paper. GSHPs, which are installed in these pavements, draw heat from the earth to provide neighboring buildings with heating and cooling. Because the integrated systems lower pollutant loads, stormwater quality is shown to be greatly improved. The capacity of these systems to eliminate prevalent stormwater pollutants, including suspended particles, heavy metals, and hydrocarbons, is assessed in this study. This study analyses the environmental and economic aspects of integrated systems, focusing on their advantages and cost-effectiveness throughout their life cycle. It specifically explores the potential for cost savings and reduced environmental impact. The research emphasizes the importance of reducing pollutant loads in stormwater runoff to protect nearby water bodies and ecosystems, highlighting the significance of this strategy in environmental protection. The research highlights the significance of mitigating pollutant loads in stormwater runoff as a means of safeguarding nearby water bodies and ecosystems. The integrated geothermal PPS helps achieve this objective by offering a cutting-edge approach to stormwater management. This paper demonstrated how permeable pavements and geothermal heat pumps can work together to improve stormwater quality and lower ecological concerns. It drew attention to the advantages these integrated systems have for the economy and environment, supporting more environmentally friendly methods of urban development.

The investigation conducted by Tota-Maharaj et al. (2012) aimed to assess the efficacy of PPS integrated with geotextiles in managing stormwater pollution in the UK. The researchers employed environmental monitoring techniques that analyzed various water parameters namely, nutrients, BOD, chemical oxygen demand (COD), and suspended solids. The outcomes of the study demonstrated that the contaminants were effectively captured within the pavement structure, with the inclusion of geotextile membranes significantly enhancing the removal efficiencies for nutrients, phosphates, and organic matter in urban runoff. Geotextiles function as a filtration system, collecting and eliminating contaminants before they reach nearby water bodies or groundwater. The research primarily focused on treating concentrated stormwater from various sources, such as transportation hubs and industrial sites. It demonstrates the effectiveness of geotextile-integrated PPS in eliminating a wide range of pollutants, particularly the phosphate-based herbicide glyphosate. The integration of these systems has resulted in improved ecological conditions and enhanced water quality by efficiently removing pollutants from stormwater. These findings hold significant implications for the design, construction, and maintenance of PPS, providing valuable insights for the development of sustainable urban drainage systems. Consequently, both human health and local ecosystems stand to benefit from these advancements elucidating innovative methodologies for assessing the efficacy of geotextile-integrated PPS, encompassing field-scale testing and laboratory investigations.

Similarly, an innovative approach to simulating temperature and energy balances in geothermal pavement systems is presented in Tota-Maharaj et al. (2011) research. This research offered a novel solution that processes urban runoff and uses renewable energy for heating and cooling by combining ground source heat pumps with permeable pavements. In the research, two experimental systems, case studies, were analyzed, and a numerical approach was developed to simulate heat flux and energy balance where the use of energy and temperature balance models for geothermal paving systems were explored. These case studies models were statically tested and proven effective with a strong correlation between modelled and measured temperatures offering useful information about the layout, functionality, and performance of these systems. In addition to effectively managing stormwater, these systems provide neighboring buildings with renewable energy. While the article emphasizes the importance of monitoring microbiological contamination and considering health and safety, the researcher also focused on mentioning that the model has potential applications in optimizing and designing a geothermal paving system that particularly helps in evaluating and controlling temperatures in PPS. Thus, one of the ways to promote sustainable urban development is by combining PPS with geothermal heat pumps which lessens the dependency on conventional energy sources addressing problems with stormwater runoff and may result in financial savings.

PPS have been designed to increase durability, permeability, and effectively remove contaminants; hence, technological advancements have been incorporated into the process. Research indicates that minor adjustments to the PPS layers or the addition of novel filters can improve pollutant removal effectiveness (Singer et al., 2022). One way to slow down water infiltration and lessen surface runoff is to employ base layers of open-graded aggregates (Oktariza and Gofar, 2023). Researchers have also created new designs of permeable concrete pavements that are more clog-resistant and porous (Kia, 2022). Enhancing performance and longevity has been investigated through the creation of novel permeable pavement types featuring a consistent low tortuosity pore structure (Kia, 2023).

A study titled “Permeable pavement systems with low carbon and recycled materials for Caribbean Small Island Developing States” was conducted by John Monroose in 2020. This study also studied the effect of PPS and climate change. By lowering the total carbon footprint during pavement construction, PPS can help mitigate the effects of climate change. Carbon emissions related to the extraction and processing of natural resources can be decreased by employing recycled materials in PPS, which will also lower the amount of natural materials needed in the construction industry. Furthermore, by enhancing the quality of stormwater runoff and lowering the danger of flooding in urban areas, PPS can assist in lessening the effects of climate change. By allowing rainwater to seep into the earth, they lessen the load on conventional stormwater drainage systems and stop contaminants from entering water bodies. The integration of experimental and modelling methodologies in PPS research enables a numerical evaluation of their efficacy in reducing flood hazards and enhancing the quality of stormwater runoff, offering significant perspectives for the development of climate change adaptation plans in the Caribbean's Small Island Developing States (SIDS).

Looking into the track records of research carried out, PPS was traditionally used for stormwater management and flood control, but presently the diversity has expanded into various fields. For example, adding low-carbon materials can improve their environmental impact, and geothermal paving systems can manage stormwater by improving water quality and providing renewable energy. The studies conducted by various researchers have shown that PPS effectively captures contaminants, with geotextile membranes enhancing removal efficiencies for nutrients, phosphates, and organic matter in urban runoff showcasing the novelty of the application of PPS.

3.2 Review of Different Authors

The authors of the paper “Permeable Interlocking Concrete Pavement: A Review”, Vinit Sawant, Karan Shukla, Yash Sawant, Suraj Shah, and Prof. Kiran Thombre (Sawant et al., 2022) provide a thorough analysis of the use of Permeable Interlocking Concrete Pavement (PICP) as a green infrastructure technology to address stormwater and waterlogging issues in urban areas, with a focus on its implementation in advanced Indian cities like Mumbai, Kolkata, Delhi, and Bhubaneshwar. While there have been many measures used to reduce stormwater throughout the years, the authors contend that traditional methods have shown to be ineffective. In contrast, the paper argues that using PICP provides a better stormwater management option. All the aspects that must be carefully considered to create PICP are painstakingly reviewed in this work. Parking lots, lawns, parks, pathways, road shoulders, and residential streets are just a few of the places where these permeable pavements might be used. With the help of an efficient filtration system, the design enables temporary storage of surface runoff water within the pavement layers, making it ideal for non-potable uses including irrigation, car cleaning, and toilet flushing.

The relevance of concrete paver blocks, which function as a wearing surface and a way to lower subgrade pressures, is highlighted by the authors when they delve into the technicalities of PICP construction. They emphasize the value of interconnecting blocks and suggest arrangements for setting them out. The use of permeable crushed stone is emphasized when discussing joint filling materials, and the study clarified the function of open-graded bedding courses, base reservoirs, and subbase reservoirs in withstanding and storing water. For separation and soil prevention, an optional geotextile layer is taken into consideration, and underdrains are suggested for low-infiltration soil sites to make it easier to remove water. Given that the PICP system's capacity to infiltrate water into the soil subgrade degrades with time due to clogging by suspended particles and pollutants, maintenance is acknowledged as a crucial component of the system's long-term performance. To increase infiltration rates, the authors advised maintenance practices such as pressure washing and hand or vacuum sweeping. The need for routine upkeep, as advised by past studies, is highlighted by the possibility that these permeable pavements system' capabilities will be compromised by improper maintenance.

Faisal Ahammed (Ahammed, 2017) offered a thorough examination of water-sensitive urban design (WSUD) techniques and technology, emphasizing their critical contribution to the long-term sustainability of urban water cycle management as shown in Figure 6. WSUD's main goal is to reduce the hydrological effects of urban growth on the area because stormwater is a valuable resource that can be used for a variety of things. The study focused on the real-world usage of WSUD technologies, which provide answers to typical problems in small-scale stormwater management, like flood control, pollutant reduction, and stormwater harvesting. Infiltration systems, PPS, bioretention systems, vegetated swales, and rainwater harvesting systems are just a few of the WSUD technologies covered in the review. These technologies are studied considering their adaptations and constraints, revealing potential limitations and solutions for them. The study also described future research priorities in the area, offering a road map for developing sustainable stormwater management further as mentioned in Table 3.

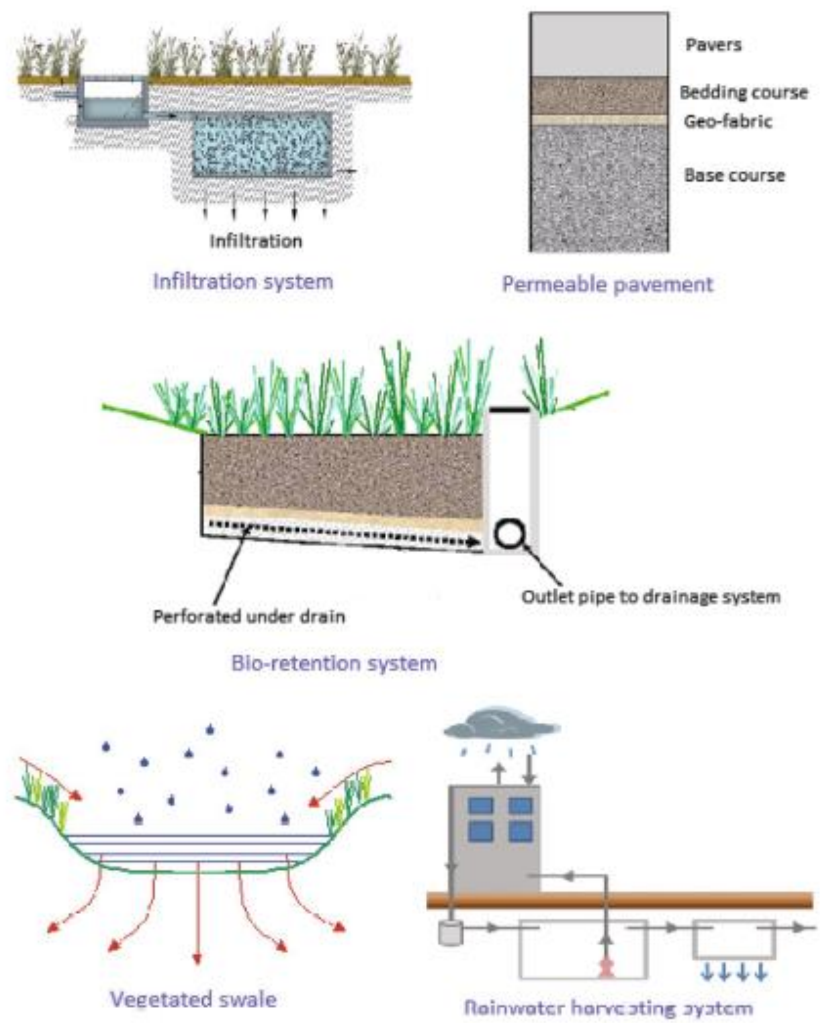

Figure ~~5~~6. WSUD technologies, Source: modified from Gold Coast City Council, 2005

Table ~~1~~3. Water-Sensitive Urban Design (WSUD) Technologies and Their Role in Water Quality Improvement and Flood Risk Management Strategy, Source: (Gold Coast City Council, 2005; Department of Planning and Local Government, 2009; Chowdhury, 2011; Kim et al., 2012)

WSUD Technology	**Main Features**	**Significance in Strategy**	**Potential Limitations and Solutions**

Infiltration Systems	Reduces stormwater quantity effects of urban growth	Significant in controlling stormwater quantity	Clogging problems needs to be addressed
	Efficient removal of Total Suspended Solids (TSS) in sandy and sandy clay soils	Effectively removes TSS in specific soil types	Consideration of groundwater table and catchment slope
	-	Cost-effective compared to some alternatives	-
Permeable Pavement Systems	Efficient in managing runoff during intense rainfall events	Effective for managing runoff even in extreme conditions	-
	Large pollutant removal capacities, including TSS, TN, TP, BOD, E. coli	Highly effective in removing various pollutants	The addition of nanoparticles to improve durability
Bioretention Systems	A component of WSUD technology, contributes to pollutant reduction	Vital for reducing pollutants in stormwater	Maintenance and vegetation quality may affect efficiency
	Promotes stormwater infiltration, reducing runoff and flood risks	Contributes to flood risk management	-
Rainwater Harvesting Systems	Collects and stores rainwater for various uses	Reduces dependency on mains water	Requires suitable infrastructure for storage and distribution
	Helps in flood risk management by	Contributes to flood risk management	-

	reducing stormwater runoff		
Vegetated Swales	Promotes natural filtration of stormwater runoff	Contributes to water quality improvement	Regular maintenance to ensure vegetation health
	Helps in reducing flood risk by storing and slowing stormwater	Contributes to flood risk management	-

A thorough overview of green pavement technology as a cutting-edge method for sustainable stormwater management in urban settings is provided by N. Bateni, S. H. Lai, R. Ahmad Bustami, M. A. Mannan, and D. Y. S. Mah. The primary aim of the review was to assess the hydrological performance and effectiveness of permeable pavement systems. The article encompassed various aspects of permeable pavement system technology, emphasizing its significance, benefits for stormwater management, and distinct hydrological characteristics and designs. For stakeholders looking for insights into the study and development of green pavement solutions, this information is a helpful resource (Bateni et al., 2021). The StormPav, a permeable pavement system with subsurface detention, which is presented as a promising invention, was one of the primary topics covered in the article. The study of hydrological design changes focuses on how they could improve stormwater management as mentioned in Figure 7 and Table 4. The study provides a further alternative for green pavement infrastructure that can be used in roadworks, leading to more efficient urban stormwater management, by highlighting the advantages of these adjustments.

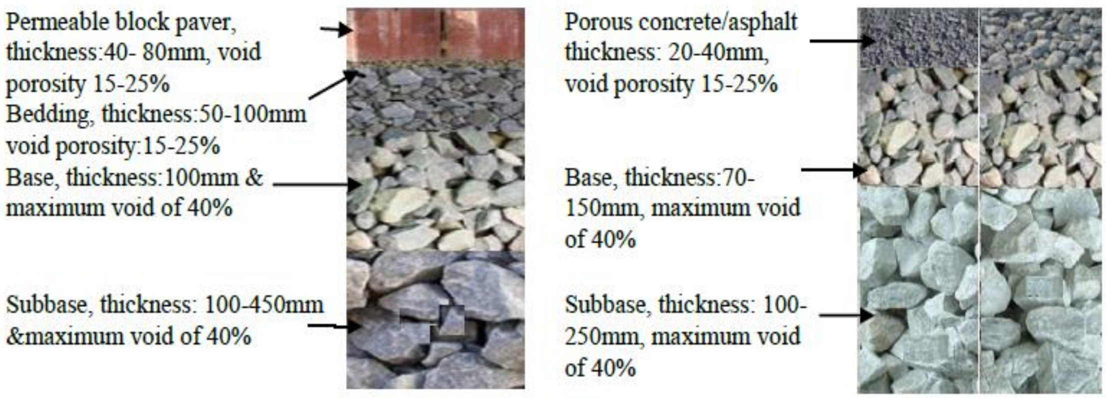

Figure ~~6~~7. Permeable Pavement Systems (PPS) types and properties, Source: (Bateni et al., 2021)

Table ~~2~~4. Green Pavement Technology for Water Quality Improvement and Flood Risk Management, Source: (Bateni et al., 2021)

Key Strategies	Highlight the significance of green pavement technology in optimizing rainfall-runoff responses and reducing flood risks, contributing to water quality improvement.
Highlighted Innovation	Introduce StormPav, a permeable pavement system with subsurface detention, as a promising invention for enhanced stormwater management.
Hydrological Design Changes	Emphasize how design changes in permeable pavement systems technology can lead to more efficient urban stormwater management, addressing flood risk.
Economic Benefits	Economic models use green infrastructure, such as permeable pavement systems, over traditional gray infrastructure, aligning with sustainable water quality improvement strategies.
Permeable Pavement System Features	Describe the benefits of permeable pavement system, such as reducing runoff, replenishing groundwater, mitigating heat islands, and removing contaminants, all contributing to improved water quality.

Historical Development	Trace the evolution of permeable pavement systems technology from basic concrete grass blocks to more complex patterns, reflecting progress in flood risk management strategies.
Recent Advancements	Recent advancements focus on sustainability, economic factors, and low-impact development strategies to optimize the benefits of stormwater management for water quality improvement and flood risk reduction.
Clogging Mitigation	Discuss strategies to address clogging issues in permeable pavement systems, including the use of subsurface detention storage to enhance system efficiency and prolong functionality.
Impact on Water Quality	Green pavement significantly optimizes rainfall-runoff responses and has the potential to improve water quality by reducing contaminants in stormwater runoff.
Role in Flood Risk Management	Permeable pavement systems contribute to lowering the risk of floods, reducing financial losses, and enhancing flood risk management strategies.
Urban Stormwater Management	Permeable pavement systems offer an alternative for urban stormwater management, aligning with the goal of improving water quality and mitigating flood risks in urban settings.
Pervious Surface Materials	Different types of permeable pavement systems, including pervious concrete, porous asphalt, and permeable interlocking concrete pavers, are explored as practical options for water quality improvement.

A recent study conducted by Yang Wang, Hao Yin, Zhiruo Liu, and Xinyu Wang (Wang et al., 2022) revealed that by implementing various Stormwater Control Measures (SCMs), Vacant Urban Lands (VULs) can play a crucial role in improving urban water quality. This groundbreaking research highlights the potential of VULs to contribute to effective stormwater management strategies, providing a sustainable solution for urban areas. This topic has gained a touch of attention and is discussed in Tables 5 and 6. The primary objective of the project was to equip urban planners with valuable insights into the remediation of unoccupied land by means of urban runoff pollutant removal techniques. The authors aimed to ascertain pragmatic approaches for mitigating the impact of urban runoff pollutants on vacant lands and to determine the types of unoccupied lands that are most susceptible to such pollution by conducting a comprehensive analysis of pertinent scholarly literature and case studies. The findings showed that abandoned and formerly constructed property in urban areas, including parking lots and residential areas, as well as commercial and industrial regions, are frequently contaminated places. SCMs offer eco-friendly, cost-efficient, nature-based treatment methods, and redevelopment strategies that are successful in reducing nonpoint source pollution in stormwater runoff.

Table ~~3~~5. Summary of the proposed SCM cost estimates for the "Opti-Tool", Source: (Mateleska and EPA Region I, 2016)

SCM type	Cost (USD/ft^3)	Cost (USD/ft^3)-2016 Dollars
Bioretention (includes rain garden)	13.37	15.46
Dry pond or detention basin	5.88	6.8
Enhanced bioretention (biofiltration practice)	13.5	15.61
Infiltration basin (or other surface infiltration practice)	5.4	6.24
Infiltration trench	10.8	12.49
Porous pavement-Porous asphalt payment	4.6	5.32
Porous pavement-Pervious concrete	15.63	18.07
Sand filter	15.51	17.94
Gravel wetland system (subsurface gravel wetland)	7.59	8.78
Wet pond or wet detention basin	5.88	6.8
Subsurface infiltration/Detention system (infiltration chamber)	54.54	67.85

Table ~~4~~6. Utilizing Vacant Urban Lands and Stormwater Control Measures for Enhanced Water Quality Improvement and Flood Risk Management in Urban Environments, Source: (Wang et al., 2022)

Findings	Impact on Strategy
Urban areas frequently have contaminated vacant lands, including parking lots, residential, commercial, and industrial areas.	Emphasizes the need for runoff management strategies in urban areas.

Stormwater Control Measures (SCMs) offer cost-efficient, nature-based treatment and redevelopment strategies.	Suggests using SCMs as a sustainable strategy to runoff management.
Bioretention systems are effective at removing nutrients (nitrogen, phosphate) and heavy metals (zinc, lead).	Bioretention systems can be a key component in water quality improvement.
Filter media selection significantly affects bioretention systems' pollutant removal effectiveness.	Highlights the importance of selecting filter media.
Four-medium biofiltration system mix improves heavy metal removal.	Recommends specific media mix for advanced heavy metal removal.
Different plant species and deeper filter media enhance nitrate nitrogen (NO_3-N) removal.	Encourages using diverse plant species and deep filter media for nitrate nitrogen removal.
High hydraulic conductivity medium improves phosphorus (P) removal.	Advocates for high hydraulic conductivity media for effective phosphorus removal.
Wet ponds are effective for removing polycyclic aromatic hydrocarbons (PAHs).	Wet ponds can contribute to pollutant removal and improved water quality.
Research on Perfluoroalkyl Acid (PFAA) contaminants removal by SCMs in metropolitan environments is lacking.	Indicates the need for further research on PFAA contaminants.
VUL size, shape, and connectivity greatly impact pollutant removal and stormwater runoff reduction.	Highlights the influence of VUL characteristics on runoff management.
Landscape architects and urban planners can make informed decisions to improve stormwater flow from VULs.	Provides actionable insights for landscape architects and planners in adopting runoff for water quality improvement and flood risk management.

The adoption of Analytical Probabilistic Models (APMs) within the planning and design of urban runoff control systems is explored in-depth in this thorough review by Ali Aldrees and Salisu Dan'azumi, (Aldrees and Dan’azumi., 2023) addressing a variety of challenges associated with urban stormwater management, from flooding to water quality degradation. A systematic way to comprehend the long-term performance of runoff control systems is provided by APMs, which are mathematical expressions generated from the probability distribution of input variables as mentioned in Figure 8. They offer a useful tool for tackling the problems with urban stormwater quantity and quality, and their value also extends to maximizing the advantages gained from these systems. The review stresses both the significance of BMPs in runoff management as well as the detrimental effects of urbanization on runoff quantity and quality. In addition to highlighting the detrimental effects of urbanization on runoff quantity and quality, the review also emphasizes the significance of BMPs in reducing these effects. Examining three different design strategies for urban stormwater control systems gives a thorough understanding of the methods typically used mentioned in Table 7.

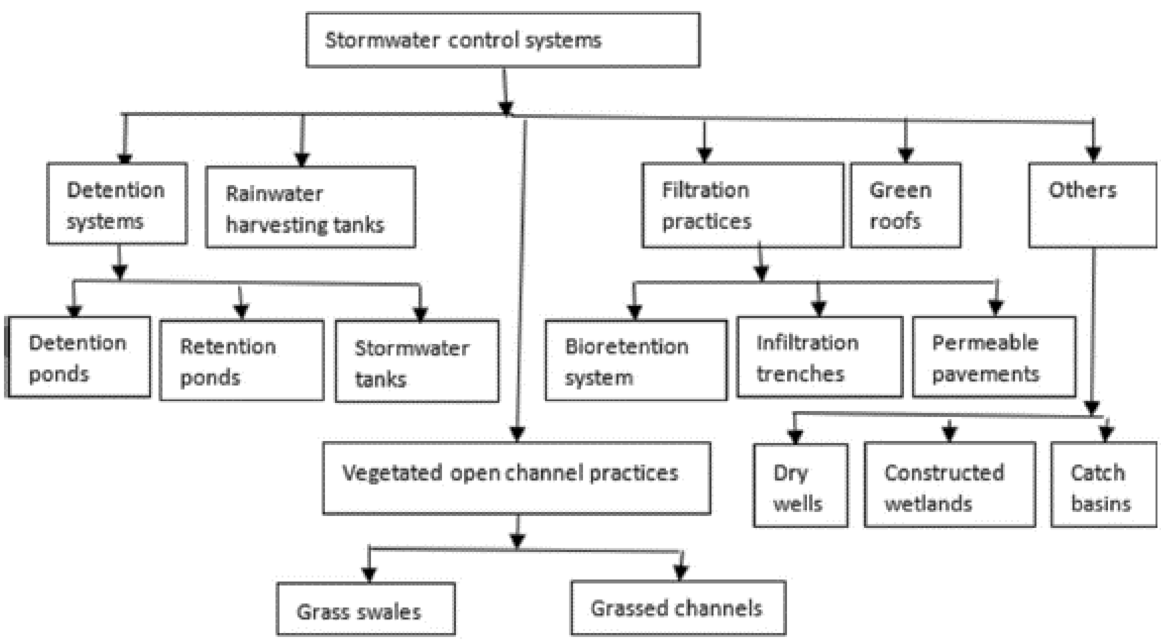

Figure 8. Stormwater Control Systems, Source: (Aldrees and Dan’azumi, 2023)

Table ~~5~~7. Comprehensive Overview of Strategies for Runoff Management, Water Quality Improvement, and Flood Risk Mitigation in Urban Environments, Source: (Aldrees and Dan'azumi, 2023)

Aspect	Key Findings
Pervious Pavements	Infiltration rates vary from new projects (up to 1000 mm/h) to a decrease of 10% over the pavement's lifetime.
Runoff Capture Efficiency and Modeling	Analytical expressions for runoff capture efficiency were developed and validated using SWMM simulations.
	Stochastic differential equations simulate dynamic water balance in permeable pavement systems.
	Analytical expressions for long-term effectiveness were created using Probability Density Functions (PDFs).
Cost-Effectiveness Evaluation	Bioretention cells have the greatest capacity to reduce runoff.
	PPS become financially viable, especially in high-land cost metropolitan regions.
	Other Stormwater BMPs, including manmade wetlands, dry wells, marshes, and separators, were recognized.
	Infiltration-based BMPs effectively lower the Soil Conservation Service (SCS) curve number for basins.
	The ideal number and placement of infiltration based BMPs are influenced by various factors like flow travel time, catchment network connection, land use, contributing area, and distance to the channel.
Systematic Analysis with APMs	Analytical expressions generated from probability distributions of input variables provide a systematic approach for understanding the long-term performance of runoff control systems.
Urbanization Impact	Urbanization has detrimental effects on runoff quantity and quality.
Role of BMPs	BMPs play a crucial role in mitigating the adverse effects of urbanization on runoff quantity and quality.

Design Strategies	The study examines three design strategies for urban stormwater control systems to offer a comprehensive understanding of commonly used methods.

Metropolitan areas worldwide have encountered significant challenges in water management due to the intricate interactions between climate change and rising urbanization. In response to these concerns, China initiated the "Sponge City" project, recognizing the need to address water-related issues in urban planning and development. This endeavor, guided by the principles of Low-Impact Development (LID), intends to enhance urban water management, mitigate the impacts of climate change, and promote sustainable development through nature-based strategies. Three crucial nature-based technologies, namely rain gardens, green roofs, and permeable pavement systems, have emerged as integral components of the Sponge City initiative. In addition to being used for sidewalks and roads, PPS have garnered praise for their ability to reduce runoff, eliminate waterlogging, and mitigate urban heat island effects. These solutions play a vital role in managing urban flooding, water scarcity, and water quality degradation. The article by Chen Song (Song, 2022) provides historical background on the evolution of Best Management Practices (BMPs) in urban drainage, with a specific focus on non-structural measures and wastewater treatment procedures as mentioned in Figure 9. The concept of BMPs expanded with the establishment of the National Pollutant Discharge Elimination System (NPDES) regulations in the United States, stressing technologies, activities, or structures that minimize contaminants in stormwater. The Water Sensitive Urban Design (WSUD) and "water-sensitive cities" concepts, popularized in Australia, have greatly influenced Sponge City projects. WSUD, a subset of stormwater management, aims to reduce the hydrological impact of urban growth and prioritizes flood prevention, water quality improvement, and rainwater collection. China's Sponge City initiatives encompass a comprehensive strategy that incorporates various LID strategies, including permeable pavement systems, green roofs, and more. The underlying idea behind these initiatives is to manage urban runoff and include natural water bodies as discussed in Table 8. The study underlines how crucial it is to comprehend these technologies' adaptability since doing so can help plan and operate Sponge City in a way that is more practical and efficient.

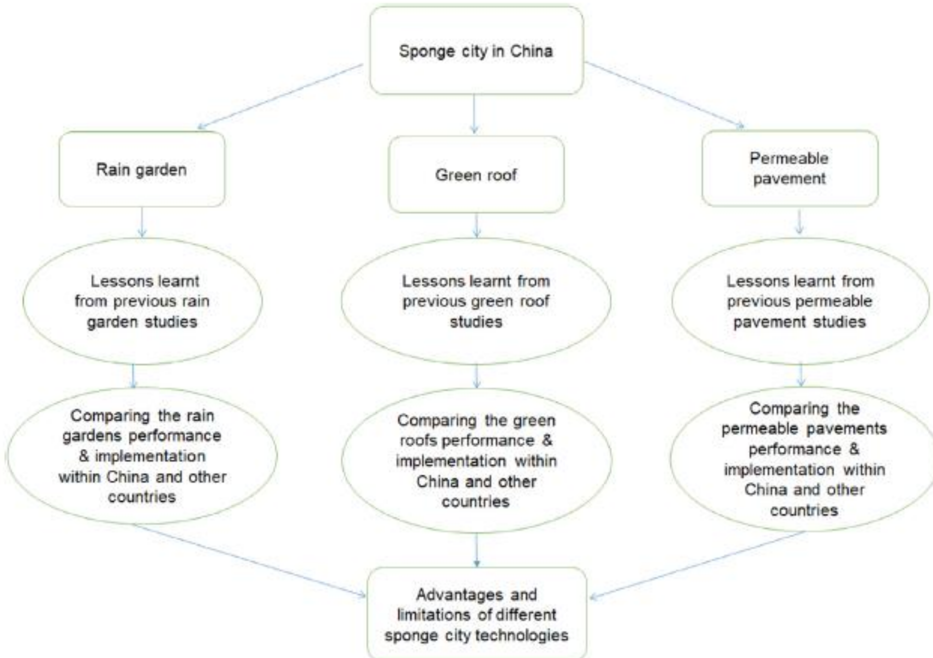

Figure ~~7~~9. Flow diagram for describing the relationship of perspectives, Source: (Song, 2022)

Table ~~6~~8. Key Findings by Cheng Song on China's Sponge City, Source: (Song, 2022)

Aspect	**Key Findings**
Sponge City Projects	Benefit from WSUD and "water sensitive cities" concepts
	Manage urban runoff and include natural water bodies
	Utilize Low Impact Development (LID) strategies (e.g., permeable pavement systems, green roofs)
	Enhance flood prevention, water quality, and rainfall collection
Key Takeaways	Understand adaptability of technologies for practical and efficient Sponge City planning and operation
Key Concepts	Best Management Practices (BMPs)
	NPDES Regulations (USA)

With a major focus on their design, use, and potential for performance improvement, all within the context of harmonizing with the ground-breaking "sponge city" concept, this in-depth research by Mingjing, Xiao, Jianjun, Zhouying, and Yiming (Fang et al., 2022), explored the world of eco-permeable pavement materials (Eco-PPMs) as mentioned in Table 9. Whether they are made of asphalt or cement, Eco-PPMs are carefully designed with three main factors in mind: air void, aggregate gradation, and mix proportion. These criteria are essential for creating materials that meet ecological requirements while still offering structural stability. Permeable asphalt pavement (PAP), permeable concrete pavement (PCP), and permeable brick pavement (PBP) are the three main manifestations of these permeable pavement materials as shown in Figure 10. PAP and PCP stand out among them for their superior ability to lessen noise pollution, improve water quality by serving as a natural filter, and aid in the reduction of the urban heat island effect.

Table 91. Permeable Pavement Systems: Types, Benefits, Challenges, and Ongoing Innovations, Source: (Fang et al., 2022)

Forms of Permeable Pavement Systems	Unique Benefits	Distinctive Challenges
PAP	High level of permeability	Mechanical properties and lifespan around 50% less desirable compared to traditional materials
	Eco-friendly and ecological	Ongoing efforts to improve mechanical characteristics and robustness with a target of at least 20% improvement
PCP	Eco-friendly and permeable	Focus on improving road performance, adopting construction technology, and developing maintenance procedures
	-	Challenges in achieving desired mechanical characteristics and longevity
PBP	Use of various raw materials	Complex manufacturing process and significant cost implications
	Promotes flexibility	Problems with permeability and load-bearing capability
	Abundance of resources	Decreased permeability over time due to factors like traffic and motor vehicle dust

	-	Economic considerations limit widespread use, demanding further research and innovation for simplification
	The ideal number and placement of infiltration based BMPs are influenced by various factors like flow travel time, catchment network connection, land use, contributing area, and distance to the channel.	-
Systematic Analysis with APMs	Analytical expressions generated from probability distributions of input variables provide a systematic way for understanding the long-term performance of runoff control systems.	-
Urbanization Impact	Urbanization has detrimental effects on runoff quantity and quality.	-
Role of BMPs	BMPs play a crucial role in mitigating the adverse effects of urbanization on runoff quantity and quality.	-
Design Strategies	The study examines three design strategies for urban stormwater control systems to offer a comprehensive understanding of commonly used methods.	-

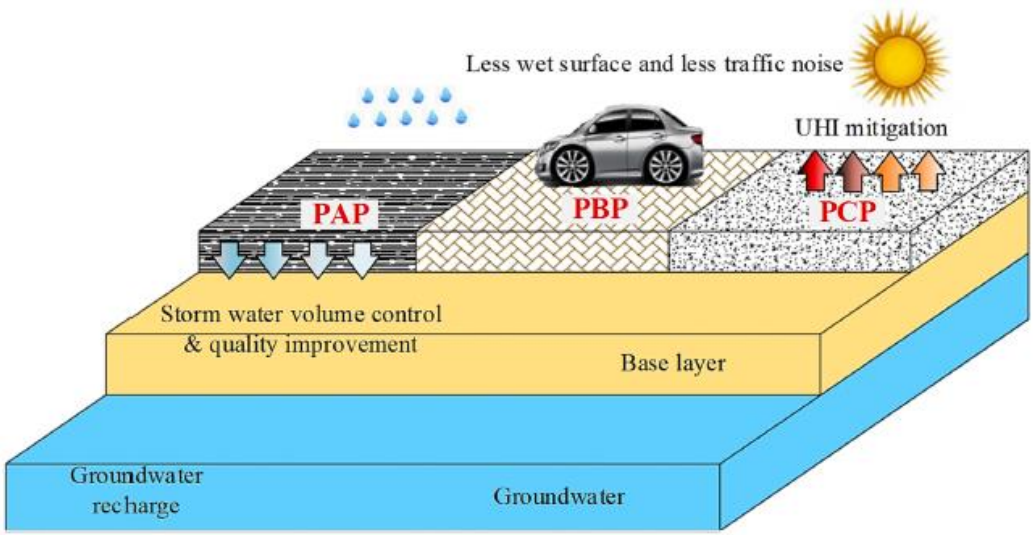

Figure ~~8~~10. Comprehensive demonstration of Eco-PPMs, Source: (Fang et al., 2022)

Urban floods are a major global problem that is made worse by unchecked urban growth that encroaches on natural drainage systems. The increased hydrological response has proven to be too much for conventional drainage networks to handle. In response, numerous adaptive management strategies for surface runoff are being researched and implemented globally (Arya and Kumar, 2023). Saumya Arya and Arun Kumar reviewed and examined recent developments in the fields of stormwater management, green infrastructure (GI), stormwater modelling, vulnerability assessment, and flood risk assessment. It highlights the possibilities for ecological restoration using floodwater while summarizing several methods to combating urban floods (as shown in Figure 11). The paper discusses the challenges that prevent stormwater management solutions from being implemented, but it also provides suggestions for how to overcome them. An Indian city named Gurugram is used as a case study to illustrate these ideas. Due to its role as a financial and technical centre, this region is expanding quickly and seeing an increase in population, but it also struggles every year with urban flooding during the monsoon season. Urban flooding has substantial root causes, according to a professional study with 39 participants from a range of disciplines, including water resources, hydrology, remote sensing, and urban planning. Unplanned urbanization, encroachment on floodplains, and poor drainage network management are three of the main ones. Even though a state water resources body was set up to address these problems, operational difficulties still exist. To reduce the risk of flooding, natural solutions like eco-corridors and green belts have been put in place. The state government launched GuruJal in 2019 as one program to combat flooding and declining groundwater levels. It focuses on rehabilitating ponds and revitalizing 250 of them using decentralized water treatment technologies (St-Hilaire et al., 2015). Urban stormwater management has been studied in Gurugram from a variety of perspectives, including comparing the effects of GI practices like infiltration trenches and retention ponds on the drainage system, designing urban drainage systems with SWMM software, and highlighting the value of remote sensing and GIS techniques in data-scarce areas. Despite these initiatives, urban flooding continues to be a serious problem in Gurugram, demanding continuing research and coordinated efforts to successfully reduce the danger.

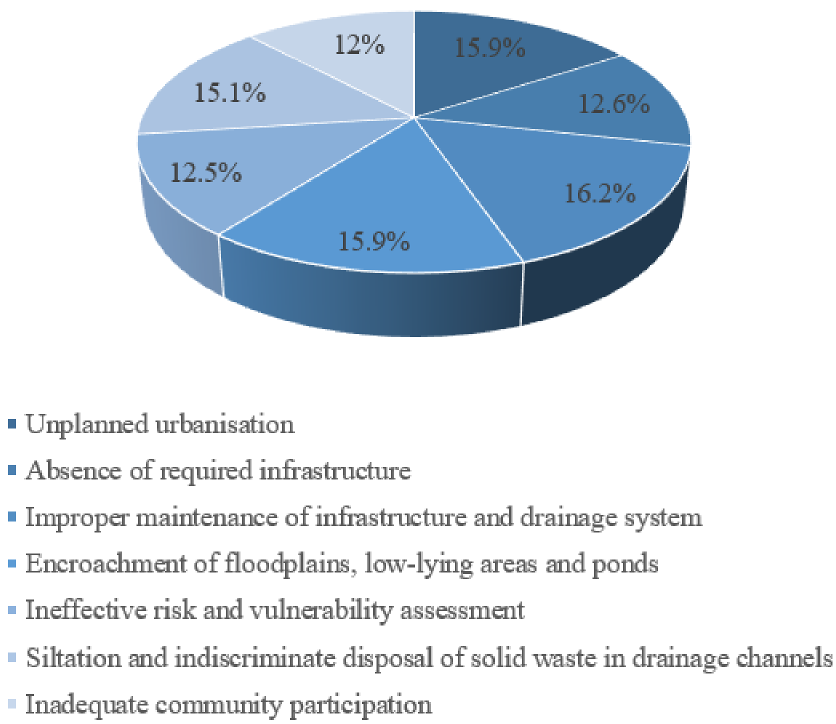

Figure ~~9~~11. Major causes of urban flooding in Gurugram, India, Source: (Arya and Kumar, 2023)

3.3 Interconnected Themes and Arguments

Urban water management is a complex problem since cities must deal with things like stormwater management, flood prevention, and water quality protection. The use of Permeable Interlocking Concrete Pavement (PICP) has emerged as a potential approach in this field. In the context of urban water management, and with an emphasis on the integration of PICP, this discussion examines how a network of nine different pieces engages in an intellectual conversation where each item contributes to, complements, or challenges the others. We may construct a narrative that demonstrates how these publications together shape our understanding of urban water management by looking at them through the perspective of argumentation and counter-argumentation.

Article-1: Stormwater Management Using PPS, the work of Sawant, Shukla, Sawant, Shah, and Thombre forms the basis of our analysis. They lay the groundwork for the next talks with their examination of PICP in the context of urban Indian cities. The claim made here is unmistakable: PICP provides a better stormwater management solution than conventional methods. It highlights the failure of conventional methods to address the urban water concerns brought on by growing urbanization and severe weather. While this article highlights the positive aspects of the implementation of PICP, it also leaves room for more research.

Article-2: First Flush Stormwater Runoff in Urban Catchments, the previous piece continues where Marla Maniquiz-Redillas and her crew leave off. The initial phase of stormwater runoff, which frequently carries the largest pollution loads, is referred to as the "first flush" in this context. Maniquiz-Redillas and colleagues examine this occurrence in detail. Here, a nuanced rebuttal is made. The paper argues that while PICP may be a useful tool in stormwater management, it is important to understand that the initial flush's properties can vary greatly. This adds a layer of complexity and suggests that adopting PICP may not be as simple as using a one-size-fits-all strategy. It emphasizes how important it is to consider elements like geography, pollutants, and climate when incorporating PICP into urban water management methods.

Article-3: Green Infrastructure and Water-Sensitive Urban Design, the discourse is widened by Faisal Ahammed's studies on green infrastructure (GI) and water-sensitive urban design. Although it covers a variety of GI techniques, the integration of these techniques into small-scale stormwater management is the focus. Ahammed (2017) emphasizes the usefulness of solutions like PICP by doing this. This section complements the claim made in Article 1 that PICP can successfully address problems with urban water management. It strengthens the argument for GI as a strategy that can simultaneously address problems including floods, pollutant reduction, and stormwater harvesting, with PICP serving as a key component.

Article 4: Urban Runoff Control Using Analytical Probabilistic Models, Analytical Probabilistic Models (APMs) are introduced by Aldrees and Dan'azumi. This research deepens our understanding of stormwater control by exploring the mathematical models used to comprehend urban runoff. This argument goes beyond PICP as the only remedy, but it is consistent with Articles 1 and 3 in underlining the importance of cutting-edge models for stormwater management. APMs can serve as a base for validating and improving PICP performance models, which will strengthen the framework for urban water management.

Article 5: Eco-Permeable Pavement Materials and Sponge Cities, Bateni, Lai, Bustami, Mannan, and Mah introduce the idea of "Sponge Cities." The article provides information about eco-permeable materials, particularly those used in PICP, even if it covers a wider framework. While PICP is a valuable component, this essay reframes the conversation by arguing that it should be seen in the context of comprehensive urban water management. It promotes the use of eco-permeable materials to address problems like urban flooding and the urban heat island effect, and it places PICP at the center of this strategy.

Article-6: Urban Water Management on Vacant Urban Lands, an original viewpoint is offered by Wang, Yin, Liu, and Xinyu Wang, who concentrate on the stormwater management remediation of abandoned urban sites. While it doesn't specifically mention PICP, this provides a realistic implementation of stormwater control methods and positions PICP as a useful tool for redeveloping unused urban space. The claim made here is that PICP may significantly improve the utility of unused areas, assisting in efficient urban water management.

Article-7: Eco-Permeable Pavement Materials in Urban Areas, in their technical analysis of eco-permeable pavement materials, Mingjing, Xiao, Jianjun, Zhouying, and Yiming address factors including air void, aggregate gradation, and mix proportion. The specifications of these materials are covered in this article, which places PICP in a subclass. It emphasizes the value of durable and environmentally friendly materials, which are necessary for the successful use of solutions like PICP.

Article-8: Environmentally friendly permeable pavement materials, Further exploration of the composition and layout of environmentally friendly permeable pavement materials is provided by Gao, Zhai, Song, and Chen. It states that the quality of the materials is crucial to the success of solutions like PICP, they provide a case for improving the mechanical properties of these materials. To strengthen their function in urban water management, the PICP materials are the main emphasis of this argument, which calls for enhancements to their mechanical qualities.

Article 9: Using Adaptive Strategies to Manage Urban Floods, Arya concludes the conversation by highlighting the importance of adaptive management techniques for preventing urban flooding. Although not unique to PICP, this piece emphasizes the continued difficulties in managing urban flooding. It implies the urgent concerns about urbanization's impact on water quality and quantity in cities and the need for study, innovation, and useful solutions like PICP.

There is an active and developing dialogue on urban water management because of the way these arguments and refutations are woven together as shown in Table 10. Together, the articles present evidence for the usefulness of PICP as a tool while also emphasizing the necessity for flexibility and specificity in its usage. The setting, materials, and models employed are essential components in the success of PICP, which shows promise as a flexible method for managing urban water resources. The goal of sustainable urban water management is pursued through a constant process of improvement and adaptation, which is the essence of scientific investigation.

Table ~~8~~10. Literature Interventions

Article Title and Authors	**Focus**	**Key Findings/Aspects Addressed**	**Potential Complementarity with Other Articles**
Stormwater Management with Permeable Pavements and Materials (Authors: Vinit Sawant, Karan Shukla, Yash Sawant, Suraj Shah, Prof. Kiran Thombre)	PICP in urban areas, especially Indian cities	PICP's effectiveness in managing stormwater and improving water quality.	Bridging PICP's design and performance with research on first flush, eco-permeable materials, and urban water management.
First Flush Stormwater Runoff in Urban Catchments (Authors: Marla Maniquiz-Redillas, Miguel Enrico Robles, Gil	First flush phenomena in stormwater runoff	Variability of the first flush, impacting factors, and importance in urban catchments.	Providing insights into how specific pavement materials (e.g., PICP) influence first flush and urban water quality.

Cruz, Nash Jett Reyes, Lee-Hyung Kim)			
Green Infrastructure and Water-Sensitive Urban Design (Authors: Faisal Ahammed)	Role of Green Infrastructure in urban water management	Various Green Infrastructure practices and their contribution to water-sensitive urban design.	Demonstrating practical examples and case studies where PICP fits within broader water-sensitive urban design.
Analytical Probabilistic Models in Urban Runoff Control (Authors: Ali Aldrees, Salisu Dan'azumi)	APMs in runoff control	Utilization of Analytical Probabilistic Models to manage urban runoff and reduce flooding.	Grounding APMs with its practical use and potentially providing data for model validation using insights from articles on specific materials like PICP.
Sponge Cities and Eco-Permeable Pavement Materials (Authors: N. Bateni, S. H. Lai, R. Ahmad Bustami, M. A. Mannan, D. Y. S. Mah)	Sponge Cities and eco-permeable pavement materials	Concept of "Sponge Cities," eco-permeable materials, and their benefits in urban water management.	Providing technical details, examples, and data on specific permeable pavement materials (e.g., PICP), reinforcing the ecological and economic benefits.
Urban Water Management on Vacant Urban Lands (Authors: Yang Wang, Hao Yin,	Utilizing vacant urban lands for	Potential for vacant urban lands in stormwater management, focusing on	Integration of permeable pavements like PICP as viable SCMs for vacant land

Zhiruo Liu, Xinyu Wang)	stormwater management	Stormwater Control Measures (SCMs).	redevelopment, offering practical solutions.

4. FINDINGS AND DISCUSSION

4.1 Permeable Pavement Systems (PPS) Stacks Up Structurally Against Traditional Pavement

Case Study-1 (Sawant et al., 2022) Permeable pavement systems in Portland, Oregon, PPS were first used as a stormwater control strategy in Portland, Oregon. A project to construct PPS on city streets was started by the city's Bureau of Environmental Services as a novel solution to lessen stormwater runoff and the difficulties it causes.

Comparing the two structures: In this instance, permeable asphalt surfaces took the place of conventional, impervious asphalt ones. Concrete pavers with interlocking joints that are permeable were used for the surface. A sub-base reservoir, a base reservoir, and an open-graded bedding course were just a few of the layers under the pavers that were made to help with drainage and filtering. Rainwater was able to seep into the ground through these layers.

Runoff control implications:

a) Runoff reduction: Portland considerably reduced surface runoff on the city streets where PPS were constructed. Less localized flooding and erosion during periods of heavy precipitation were the result of this.
b) Pollutant Removal: PPS successfully filtered out pollutants from stormwater, including oil, heavy metals, and silt. The filtration procedure increased water quality and decreased pollution in nearby bodies of water.
c) Groundwater Recharge: Rainwater penetration through PPS helped recharge groundwater, maintaining a healthy water table in the area.

Maintenance Considerations: Although PPS were efficient at reducing runoff, ongoing care was necessary to guarantee their continued effectiveness. The permeable surface required regular vacuum sweeping and pressure cleaning to keep it unclogged.

Case Study 2 (Ahammed, 2017): Old-School Pavement in Los Angeles, California, California's Los Angeles is renowned for its large system of conventional pavements. However, because of impermeable surfaces and increased urbanization, the city experienced significant problems with urban flooding and water pollution.

Comparing the two structures: Large portions of Los Angeles are covered on conventional asphalt pavements. Because of their impermeability, these pavements let water drain into storm drains. Road and highway runoff frequently caused flash flooding and overtaxed the city's drainage systems.

Runoff control repercussions:

a) Increased Runoff: Surface runoff concerns were made worse by conventional pavements. They made runoff control more difficult while contributing to flooding and erosion during storms.
b) Pollution Concerns: Water flowing over impermeable surfaces picks up pollutants like oil, chemicals, and debris, contaminating nearby water bodies and causing problems with water quality.
c) Limited Groundwater Recharge: Traditional pavements were not able to recharge groundwater with little infiltration, which caused water tables to drop.

Environmental Consequences: Los Angeles saw the drawbacks of depending mostly on conventional pavements, including damage from flooding, problems with pollution, and the urban heat island effect brought on by the heat retention of impermeable surfaces.

Conclusions and Comparative Evaluation

In terms of runoff control on roads and highways, the case studies offer helpful insights into the structural and practical distinctions between permeable pavement systems and conventional pavements.

- Effective Runoff Control: PPS efficiently minimize runoff, as demonstrated in the Portland case study, preventing localized flooding, and eroding during heavy precipitation events.
- Pollutant Removal: PPS effectively remove pollutants, improving the quality of the water. On the other side, conventional pavements exacerbate pollution problems.
- Groundwater Recharge: PPS encourage groundwater recharge, keeping water levels in good shape. This important natural process is restricted by conventional pavements.
- Maintenance: Both permeable and conventional pavement systems need upkeep. Traditional pavement systems require stormwater management through intricate and expensive drainage systems, whereas PPS require maintenance to avoid clogging.

Cost Considerations: Although PPS may cost more to install initially, they can save money over time by eliminating the need for costly drainage systems, flood damage restoration, and water quality improvement measures.

4.2 PPS’s Hydrological Properties

PPS are an innovative method to stormwater management that differs from conventional impermeable surfaces like asphalt or concrete in terms of their unique hydrological characteristics. The ability to store water and its vertical permeability are two of PPS's primary hydrological characteristics. We may learn more about these hydrological characteristics and how important they are for stormwater management by reading recent research publications that have investigated this issue as mentioned in Table 11.

Table 11. The PPS's Hydrological Properties

Source	Key Findings
(Sawant et al., 2021)	• PICP design enables temporary storage of surface runoff water within pavement layers. - Ideal for non-potable uses like irrigation and car cleaning.
(Ahammed, 2017)	• PPS, as part of WSUD, reduces hydrological effects of urban growth. • Promote stormwater infiltration, encouraging groundwater recharge.
(Bateni et al., 2021)	• PPS, like StormPav, manage runoff during intense rainfall events. • Focus on improving stormwater management. • Encouraging infiltration to reduce runoff.
(Wang et al., 2022)	• SCMs, including PPS, offer cost-effective and eco-friendly methods to manage urban runoff and reduce nonpoint source pollution. • Mitigate urban flooding and improve water quality. Encourage groundwater recharge.

(Aldrees and Dan'azumi, 2023)	• Analytical Probabilistic Models (APMs) help understand the long-term performance of runoff control systems. • BMPs, including PPS, mitigate adverse effects of urbanization, indirectly contributing to groundwater recharge.
(Song, 2022)	• PPS in the "Sponge City" concept reduces runoff, waterlogging, and improve water quality. • Nature-based solutions like PPS encourage groundwater recharge.
(Fang et al., 2022)	• Eco-Permeable Pavement Materials (Eco-PPMs) reduce noise pollution, improve water quality, and mitigate the urban heat island effect. • Benefits reduce surface runoff and encourage groundwater recharge.
(Arya and Kumar, 2023)	• Nature-based solutions, including PPS, help combat urban flooding, reduce runoff, and improve water quality, which indirectly encourages groundwater recharge.

4.2.1 Vertical Permeability

PPS are distinguished by their vertical permeability. It speaks to the pavements' capacity to permit water to permeate them vertically, penetrating the surface and seeping into the deeper layers. To manage stormwater effectively, this attribute is essential. The layered pavement design used in Sawant et al. (2021)'s discussion of the PICP system allows for vertical permeability. Water can enter through the surface layer of permeable pavers, and vertical permeability is made possible by the open-graded bedding courses, base reservoirs, and subbase reservoirs. The layers make routes for water to travel vertically as precipitation or extra surface water infiltrates. According to Faisal Ahammed's study, vertical permeability is crucial to water-sensitive urban design (WSUD) technology. Vertical permeability is significant because of the emphasis on minimizing the hydrological effects of urban expansion and encouraging infiltration. Key elements of WSUD strategies are permeable pavement systems, which enable water to permeate the surface and seep into the layers beneath.

4.2.2 Water Storage Capacity

Due to their critical function in stormwater management, PPS have received a lot of attention in recent years for their hydrological characteristics, particularly about their water storage capacity. These ground-breaking pavements are made to temporarily store stormwater within their layers, reducing the negative consequences of uncontrolled surface runoff while also improving water quality and encouraging sustainable urban growth as mentioned in Table 12.

Table ~~9~~12. Water Storage Capacity

Aspect	Key Information
Introduction	PPS are crucial in stormwater management for their ability to store and manage stormwater effectively. They are designed to reduce the negative consequences of surface runoff, enhance water quality, and encourage sustainable urban growth.
PPS Structure	A typical PPS consists of various layers, starting with a surface layer made of porous materials like concrete, asphalt, or pavers, designed to facilitate water infiltration. Open-graded bedding courses, base reservoirs, and subbase reservoirs are located beneath the surface layer.
Water Movement and Filtration	Water infiltrates through the surface layer during precipitation events and moves vertically into the base and subbase reservoirs. Open-graded bedding courses with void spaces aid in this vertical water movement. Stormwater is temporarily held within these layers, allowing for natural filtration as it passes through the pavement structure.
Key Functions of Stormwater Storage	1. **Reducing Flood Risk**: PPS significantly lowers the volume and speed of surface runoff, reducing the risk of floods and erosion.
	2. **Enhancement of Water Quality**: Stormwater storage within PPS employs a natural filtration system, removing pollutants and sediments, raising water quality.

	3. **Groundwater Recharge**: PPS promotes groundwater recharge by slowly releasing stored water into the ground.
	4. **Sustainable Urban Development**: PPS align with low-impact development (LID) and green infrastructure principles, addressing issues like urban heat islands and pollution.
Supporting Research	- The study by Sawant et al. (2021) emphasized the importance of effective filtering systems within PICP for water storage and quality enhancement.
	- Faisal Ahammed's research highlighted PPS's ability to remove pollutants and enhance water quality in urban contexts.
	- Bateni et al. (2021) focused on the financial advantages and optimization of rainfall-runoff responses.
Significance in Stormwater Management	The studies collectively underscore the significance of PPS's water storage capacity in addressing various urban stormwater concerns. PPS, with their ability to temporarily store and naturally filter runoff, are a key component of contemporary stormwater management, addressing flood risk, water quality improvement, groundwater recharge, and sustainable urban growth.

Additional information on the significance of water storage capacity within PPS for efficient stormwater management can be found in recent research papers. For instance, the study on PICP by Sawant et al. (2021) highlighted the importance of effective filtering systems within PICP for water storage and quality enhancement. An in-depth analysis of water-sensitive urban design (WSUD) technologies by Faisal Ahammed brought to light PPS's ability to remove pollutants and their function in enhancing water quality in urban contexts. The performance of PPS as a stormwater management solution was greatly influenced by their capacity to store stormwater. The hydrological performance and efficiency of permeable pavements were examined by Bateni et al. (2021), who focused on their financial advantages and the ability to optimize rainfall-runoff responses. A key element in lowering surface runoff and fostering sustainable urban stormwater management is water storage capacity.

Together, these studies highlight the significance of the ability of PPS to store water as a holistic response to urban stormwater concerns. With its capacity to temporarily store and naturally filter runoff, PPS are a crucial part of contemporary stormwater management techniques, whether they are used to reduce flood risk, improve water quality, replenish groundwater, or promote sustainable urban growth.

4.3 PPS Effect on the Urban Heat Island effect in Terms of Pollution Reduction

4.3.1 Urban Heat Island Effect Mitigation

Urban regions frequently experience the UHI effect, which is characterised by higher temperatures brought on by crowded infrastructure and human activity. The selected studies under evaluation address the critical role PPS play in reducing this issue. Traditional impermeable pavements tend to absorb and hold heat, which raises temperatures. PPS, in comparison, have poorer heat-absorbing qualities, particularly those made of porous materials. They enable rainwater infiltration, which cools the ground and lessens heat retention in populated areas. Articles like the study by Bateni et al. (2021) demonstrate this ability to avoid heat buildup. In addition, as these papers emphasize, the presence of flora within PPS considerably aids in cooling urban microclimates. A cooling effect is produced by trees and grass, which both provide shade and lower air temperatures through transpiration. In particular, the study by Faisal Ahammed highlights the cooling effect of green infrastructure components in PPS. Additional benefits of PPS include enhancing pedestrian thermal comfort and decreasing the need for air conditioning in neighbouring buildings. Studies like Saumya Arya and Arun Kumar show that cooler outdoor conditions produced by PPS are more attractive and conducive to outdoor activities. This decrease in energy usage for cooling reasons is consistent with more general sustainability objectives.

4.3.2 Environmental Benefits of Pollution Reduction

According to the studies under consideration, PPS have numerous benefits for the environment in terms of reducing pollutants.

a) Runoff Filtration: Stormwater runoff is naturally filtered by PPS. They filter pollutants like heavy metals, oil, grease, and silt from runoff as they permeate the pavement layers thanks to their vertical permeability. According to Ahammed (2017) study and Arya and Kumar (2023) research, this filtration procedure considerably improves water quality.

b) Nutrient Retention: PPS effectively catch and retain nutrients from runoff, such as nitrogen and phosphorus. Through this retention, as Wang et al. (2022) methodical investigation examined, nutrient-rich runoff is kept out of aquatic bodies, lowering the possibility of ecological harm and water contamination. PPS serve as nutrient sinks, promoting the well-being of aquatic environments.

c) Reduction in Heat-Related Pollution: Air pollution issues are frequently made worse by urban heat islands. The development and concentration of heat-related pollutants, such as ground-level ozone, are made easier by high temperatures. As shown in the publications under evaluation, PPS indirectly minimize the generation and concentration of harmful pollutants by cooling the urban environment.

d) Reactive Surface Materials: Mingjing, Xiao, Jianjun, Zhouying, and Yiming's research emphasizes the importance of choosing reactive surface materials for PPS as a means of reducing pollution. These substances may neutralize and absorb pollutants, which enhances the ability of PPS to reduce pollution. The effectiveness of PPS in reducing pollution is increased by choosing suitable materials that interact with pollutants in an efficient manner.

e) Promotion of Low-Impact Development (LID): A key component of LID plans is the use of PPS. They are ideal for LID because of their capability to control stormwater on-site, lessen runoff, and enhance water quality. Sustainable practices are promoted by incorporating PPS into urban planning, giving pollution reduction and environmental protection priority.

The use of PPS in various urban environments, as illustrated in the publications under evaluation, offers verifiable proof of their efficacy in reducing pollution and mitigating UHI. By regulating surface temperatures, enhancing water quality, and promoting ecosystem health, these cutting-edge stormwater management strategies provide a route to healthier, more sustainable urban landscapes as mentioned in Table 13.

Table 13. PPS effect on the Urban Heat Island (UHI) effect in terms of pollution reduction

Source	**Key Findings**
(Sawant et al., 2021)	• PPS's design can mitigate the UHI effect by allowing water infiltration, which cools the pavement and the surrounding area.
	• The design enables temporary storage of surface runoff water within the pavement layers, providing opportunities for evaporative cooling.

	• PPS acts as a natural filter and removes pollutants, improving water quality and reducing pollution.
(Ahammed, 2017)	• PPS, as part of WSUD, help reduce the UHI effect by allowing water infiltration and vegetation growth, providing shade and cooling effects.
	• They contribute to pollution reduction by capturing and treating stormwater, reducing the pollutant load in runoff.
(Bateni et al., 2021)	• PPS, such as StormPav, mitigate the UHI effect by promoting green infrastructure and encouraging vegetation.
	• They reduce runoff, which can carry heat-absorbing pollutants, thereby reducing heat island formation.
(Wang et al., 2022)	• SCMs, including PPS, help combat the UHI effect by promoting natural stormwater management, reducing the heat-absorbing characteristics of traditional pavements.
	• They contribute to pollution reduction by capturing and treating stormwater pollutants.
(Aldrees and Dan'azumi, 2023)	• The review emphasizes the importance of BMPs, including PPS, in addressing the UHI effect by promoting green infrastructure and nature-based solutions.
	• They play a crucial role in pollution reduction by capturing and filtering stormwater.
(Song, 2022)	• PPS in the "Sponge City" concept has a cooling effect, reducing the UHI effect in urban areas.
	• They improve water quality by acting as a natural filter and capturing pollutants, reducing pollution in urban runoff.

4.4 In terms of cost-effectiveness, how do the economic aspects of using PPS as a suitable drainage system compared to those of conventional pavement solutions.

The authors of Articles 5 and 6, Mingjing, Xiao, Jianjun, Zhouying, Yiming, and Yang Wang, Saumya Arya and Arun Kumar explore the financial benefits of using PPS as a long-term drainage system (refer to Table 14). These papers provide insightful information about the financial effects of PPS and its cost-effectiveness, further supporting its position as an economically sound method of managing urban stormwater.

Table ~~10~~2. Study Summary

Aspect	**Authors**	**Summary**
Cost-Effectiveness	Vinit Sawant, Karan Shukla, Yash Sawant, Suraj Shah, Prof. Kiran Thombre (Article 1)	• PICP is a cost-effective solution, eliminating the need for additional drainage systems and reducing infrastructure expenses.
		• PICP offers multifunctionality, serving as both a durable pavement and an efficient stormwater management system, reducing the expenses of separate solutions.
		• Maintenance, including pressure washing and sweeping, is essential for long-term cost-effectiveness.
		• PICP reduces the need for centralized stormwater management infrastructure and replenishes groundwater, making it advantageous in land-scarce urban areas with high land prices.
Cost-Effectiveness	Faisal Ahammed (Article 2)	• PPS is cost-effective for urban stormwater management.
		• PPS stands out as an economically sensible choice among various WSUD techniques.
		• PPS are ideal for urban areas with rising land prices, as they are decentralized and do not require significant land use.
		• PPS's pollution removal capabilities reduce water treatment and pollution control expenses, and its

		installation and upkeep are less expensive than conventional solutions.
Economic Benefits	N. Bateni, S. H. Lai, R. Ahmad Bustami, M. A. Mannan, D. Y. S. Mah (Article 3)	• PPS, as part of green infrastructure, offer economic advantages in managing urban stormwater, cost-effectively preventing flooding and its financial consequences.
		• Green infrastructures, like PPS, are more cost-effective than traditional gray infrastructure in managing stormwater.
		• Cost-effective PPS contribute to urban flood management.
Economic Implications	Saumya Arya and Arun Kumar (Article 4)	• Urban flooding management is a significant financial concern, which can be mitigated by effective surface runoff management techniques.
		• Adaptive measures, including PPS, contribute to managing urban water effectively and reducing financial losses.
		• Sustainable urban water management must consider the financial implications of implementing runoff management technologies.
		• Unplanned urbanization and inadequate drainage management have significant economic consequences related to urban flooding.
Financial benefits	Mingjing Fang, Xiao Wang, Jianjun Liu, Zhouying Xu, and Yiming Chen (Article 5)	• Eco-Permeable Pavement Materials (Eco-PPMs) provide cooling effects by reducing the heat island effect.
		• They improve water quality by acting as a natural filter and reducing pollutant runoff, contributing to pollution reduction.

Urban stormwater management's economic implications	Saumya Arya and Arun Kumar (Article 6)	• Nature-based solutions, including PPS, help combat the UHI effect by promoting vegetation and natural stormwater management. • They play a crucial role in pollution reduction by capturing and treating stormwater pollutants.

Permeable asphalt pavement (PAP), permeable concrete pavement (PCP), and permeable brick pavement (PBP) are only a few examples of eco-permeable pavement materials (Eco-PPMs) that are further explored in Article 5. When using them, the cost aspect is an important factor. While eco-PPMs excel in environmentally friendly areas, they may have mechanical characteristics and a lifespan that are about 50% less desired than those of conventional paving materials. Due to the potential for larger upfront costs, this presents an economic hurdle. According to the research, however, ongoing attempts are being undertaken to strengthen these properties' economic viability and achieve at least a 20% improvement. Eco-PPMs' economic viability is based on several factors, including their environmental advantages, long-term performance, and the requirement for continual research and innovation to make them more cost competitive.

Urban stormwater management's economic implications and difficulties are covered in Article 6. The economic effects of adoption of surface runoff control techniques and the efficacy of using green infrastructure solutions, such as permeable pavement systems, are the main topics of this study. When addressing the enormous issues presented by urban flooding and nonpoint source pollution in metropolitan regions, the economic dimension becomes especially important. The study emphasizes the financial costs of urban floods and the financial advantages of effectively managing stormwater in urban settings. PPS are a part of sustainable urban water management, which is portrayed as a cost-effective strategy for lowering financial losses brought on by urban flooding incidents.

Together, Articles 5 and 6 highlight several significant financial benefits of utilizing PPS as a sustainable drainage system:

1. Long-Term Cost reductions: Although some PPS materials may have greater upfront prices than conventional substitutes, there are significant long-term cost reductions. These

savings are frequently attained through lowering maintenance requirements, extending product life, and using less expensive water treatment methods.

2. Environmental Benefits: PPS materials are sustainable and the reuse of floodwater aid in ecological restoration. This ecological strategy may result in lower expenditures for pollution control and mitigation, which would be advantageous economically.
3. Urban Flooding Mitigation: PPS assist in reducing financial losses linked to urban flooding occurrences by efficiently handling stormwater and lowering the danger of flooding. Their economic worth is furthered by their capacity to reduce expensive flood damage.
4. Resource Efficiency: The production of PPS using raw materials, particularly PBP, can help to increase resource efficiency. PBP's resource-efficient nature might have economic advantages in terms of material costs despite its initial complexity.

Articles 7 and 8, respectively written by Saumya Arya with Arun Kumar and Ali Aldrees with Salisu Dan'azumi, provide insight into the financial implications of using PPS as a long-term drainage method. These articles illustrate the economic benefits of PPS and offer insightful information about how cost-effective it is at managing urban stormwater.

Article 7 by Saumya Arya with Arun Kumar explore the financial costs associated with using surface runoff adaptive management options in the context of urban flooding. Effective and affordable solutions are essential due to the limits of conventional drainage networks and the encroachment of urban expansion on natural drainage systems. The article discusses various strategies for preventing urban flooding, with a focus on ecological restoration and long-term urban water management. The following are the study's main economic benefits:

1. Lower Costs for Flood Management: Managing and mitigating urban flooding may be done for less money with effective urban water management, which frequently involves PPS and green infrastructure. The economic advantage comes from avoiding expensive flood damages and the related costs of cleanup and recovery.

2. Resource Efficiency: Green infrastructure, such as PPS, is used to encourage resource efficiency. PPS aids in lowering the number of resources needed for water treatment and pollution control by promoting the reuse of floodwater and utilizing nature-based solutions. Savings on the economy are the result.

3. Economic Viability of Adaptive Measures: In the context of climate change and urbanization, the study emphasizes the economic viability of adaptive measures like PPS. Such techniques

demonstrate how to reduce the financial impacts of flooding and provide sustainable water management.

The economic implications of employing Analytical Probabilistic Models (APMs) in the planning and construction of urban runoff management systems are examined in Article 8 by Ali Aldrees and Salisu Dan'azumi. APMs are mathematical expressions that are created from probability distributions of input data and offer a systematic way to understand how runoff control systems operate over the long term. The advantages of BMPs in reducing runoff and enhancing water quality in urban environments are the main topic of this essay. The following are the main economic benefits highlighted in the study:

1. Cost-Effective BMPs: The paper emphasizes how different BMPs, such as permeable pavement systems, offer affordable alternatives for managing urban stormwater. These BMPs lessen the financial burden involved with managing runoff quantity and quality.
2. Lifespan Cost Evaluation: Article 8 uses lifespan cost analyses to examine the cost-effectiveness of different runoff control technologies, such as green roofs, permeable pavements, and bioretention cells. This analysis provides insights into the financial benefits of these solutions by accounting for reducing efficiencies, and operating, and maintenance expenses.
3. Optimization using APMs: The study shows how optimization tactics can improve the financial viability of BMPs by including APMs in the design and planning of urban runoff management systems. With this modification, costs are reduced, and runoff reduction capability is increased.
4. Infiltration-based BMPs' Economic Benefits: The article highlights the BMPs' economic benefits, such as permeable pavement systems. Significant economic gains can be attained by lowering the Soil Conservation Service (SCS) curve number for basins and utilizing a variety of infiltration based BMPs.

Article 9 explores the financial aspects of eco-permeable pavement materials (Eco-PPMs) and their function in sustainable urban water management. It was written by Mingjing, Xiao, Jianjun, Zhouying, and Yiming. This article offers a distinctive viewpoint on the relationship between the use of specialty materials created for ecological and economic efficiency and the economic considerations of PPS.

The key economic lessons from Article 9 are as follows:

1. Eco-friendly pavement materials that are affordable: The cost-effectiveness of Eco-PPMs is highlighted in the article, highlighting the fact that these materials were created with both ecological and financial efficiency in mind. These materials' air void, aggregate gradation, and mix proportions were carefully chosen so that they would both satisfy structural needs and adhere to ecological standards. They are therefore affordable options for managing urban water resources.

2. Superior Advantages of Permeable Concrete Pavement and Permeable Asphalt Pavement: PAP and PCP are two popular types of Eco-PPMs that are the subject of Article 9. These materials have clear economic benefits such noise reduction, improved water quality, and a decrease in the urban heat island effect. By eliminating the need for separate noise-reduction equipment and water treatment costs, these advantages lead to financial savings.

3. Resource Efficiency and Green Infrastructure: The study identifies Eco-PPMs as resource efficiency. These materials are green infrastructure as they lower the urban heat island effect, enhancing water quality through natural filtration, and facilitating groundwater recharge. Conserving resources and lowering the need for expensive traditional infrastructure is advantageous economically.

4. Long-Term Sustainability: Article 9 emphasizes the benefits of long-term sustainability on the economy. Due to their meticulous design and attention to the environment, eco-PPMs eventually require less maintenance. Municipalities and urban planners gain financially from the increased lifespan and reduced maintenance requirements.

5. Economic Efficiency in Noise Reduction: Because PPS like PAP and PCP are excellent at reducing noise, no extra noise-reduction infrastructure is required. This not only results in financial savings but also raises the standard of living in metropolitan areas.

6. Advantages of Urban Heat Island Mitigation: Eco-PPMs contribute significantly to minimizing the urban heat island effect, which can have economic repercussions by lowering cooling and energy costs in metropolitan areas.

4.5 Environmental Impact and Ecological Implications of PPS

Sambito et al. (2021) carried out a study titled "A Systematic Review of the Hydrological, Environmental and Durability Performance of Permeable Pavement Systems" which reviewed the environmental performance of PPS. This study reveals that PPS positively impacts the environment by decreasing runoff volume and increasing evapotranspiration and water penetration. PPS facilitate water penetration into the ground, reducing urbanisation's negative effects, such as increased discharges and decreased infiltration. According to studies, PPS can efficiently remove traditional pollutants from stormwater, enhancing water quality and lessening the strain on aquatic bodies downstream. PPS are beneficial in lowering the levels of contaminants in stormwater runoff, including fertilisers, suspended particles, and heavy metals.

A study was carried out by Fotaneda et al. (2018) to assess PPS's long-term performance, primarily focusing on the end-of-life concept. It was found that over time, PPS may see a decline in infiltration rates, impairing the effectiveness of stormwater management. Sediment and debris buildup in the pavement voids can cause clogging, which lowers the system's permeability and may result in localised floods. PPS may need routine maintenance, which can be expensive and time-consuming, to avoid blockage and guarantee optimal operation. There may be particular concerns about contaminants being released into the environment due to the usage of certain materials in PPS, such as recycled tyres.

Santhanam and Majumdar (2020) studied using PPS as a nature-based solution (NbS) to manage urban lake ecosystems. This study discusses how PPS can promote biodiversity in urban areas. PPS has the potential to improve and conserve biodiversity in urban settings. They serve as habitat for many plant and animal species, including insects, birds, and small mammals. Green water collection and storage can be increased through PPS design and implementation, supporting vegetation development and fostering an environment. In urban lakes, PPS can also aid in preserving nearly natural flow patterns, promoting aquatic biodiversity. PPS can indirectly support biodiversity conservation by maintaining the habitats and biological roles of urban aquatic ecosystems by strengthening the resilience of lake systems.

4.6 Exploring Challenges, Limitations, and Maintenance Considerations in PPS

The challenges and limitations associated with PPS are also discussed in the study conducted by Sambito et al. (2021). This study has shown that the efficacy of PPS in eliminating traditional pollutants varies. While some studies have indicated that PPS can efficiently remove contaminants such as hydrocarbons, heavy metals, and suspended particles, others have discovered that the removal effectiveness is only somewhat achieved. To guarantee optimal performance, PPS need to undergo routine maintenance. Debris, sediment, and organic matter buildup can lower the pavement surface's permeability, resulting in a drop in infiltration rates and possible clogging. To avoid these problems, regular maintenance and cleaning are required.

Santhanam and Majumdar (2020) highlight that a well-designed PPS is essential to its effective deployment. Factors such as soil type, slope, and rainfall patterns must be considered to guarantee optimum performance. Due to their susceptibility to being overloaded by the amount of water, PPS may not be able to handle severe rainstorm events effectively. In these situations, further stormwater management strategies could be needed. Compared to conventional pavement systems, PPS installation may initially cost more. However, long-term advantages and financial savings in the form of less infrastructure needed for stormwater management and better water quality can outweigh these expenses.

Regular maintenance is necessary to guarantee that PPS remain effective over time. One of the most essential aspects of maintenance is to keep the system from clogging by routinely clearing the subbase and top layers of residue, leaves, and silt. Maintaining permeability and preventing obstructions requires surface vacuuming or sweeping, and checking the penetration rates regularly aids in tracking the system's performance over time. Controlling weeds is vital to stop them from growing within the pavement matrix, and surface repairs are necessary to fix any wear or damage to the surface and keep it functional. Resealing joints between blocks or pavers guarantees correct couplings and reduces the possibility of problems with water intrusion. The lifetime and efficacy of PPS in controlling stormwater runoff and advancing sustainable urban drainage depend on these maintenance measures (Fotaneda et al., 2018).

5. CONCLUSION & OUTLOOK

PPS adoption has drawn a lot of interest recently because of rising urbanization, climate change, and the urgent need for sustainable environmental solutions. The key concepts covered in this in-depth assessment are summarized in the paper title, "Permeable Pavement Systems for Flood Risk Management, Water Quality Improvement, and Volume Reduction." The numerous benefits of PPS in preventing flooding, improving water quality, and lowering runoff quantities have emerged during the analysis of nine academic studies. The findings underscore the significant role played by PPS in addressing contemporary challenges related to water management and indicate its potential applications in the domains of urban and environmental planning.

5.1 Managing Flood Risk to Prevent Urban Disasters

Urban flooding is now more likely to occur because of the growth of impermeable surfaces, which has increased surface runoff. Recent studies suggest that PPS appears to be a viable option for managing flood risk. The case studies included in the review show how effective PPS is at lowering peak stormwater runoff flow rates in the real-world scenario. These findings highlight the potential of PPS in effectively managing heavy rainfall to prevent urban tragedies. Through its infiltration ability and integrated architecture, PPS can greatly reduce the risk of flooding, especially in regions susceptible to intense precipitation and flash floods. This feature of PPS emphasizes how crucial it is to use sustainable drainage systems in modern urban development to protect the security and well-being of urban residents.

5.2 Enhancing Water Quality: Using Nature as a Filter to Remove Pollutants

The ability of PPS to act as a natural filter and improve water quality by lowering the levels of contaminants in stormwater runoff is one of its most alluring features. Collectively, the publications under evaluation highlight PPS's amazing ability to remove pollutants, particularly when it comes to total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), and other contaminants. This environmentally friendly service offered by PPS emphasizes the necessity of integrated water management strategies that include green infrastructure. The ability of PPS to remove contaminants before they are introduced into water bodies can contribute to the well-being of ecosystems, safeguard aquatic organisms, and enhance the quality of urban water resources. The land holds considerable environmental advantages as clean water resources are crucial for ecological sustainability and the promotion of public health.

5.3 Volume Reduction: Reducing the Impact of Urban Hydrological

The impermeable nature of traditional pavements exacerbates surface runoff, resulting in a range of hydrological consequences such as flooding, streambank erosion, and reduced groundwater recharge. Numerous studies have demonstrated that PPS possess the ability to significantly reduce runoff volumes, making them a crucial component of sustainable urban development and flood risk management. Case studies have highlighted the potential for volume reduction, particularly during heavy rainfall events, which enhances the resilience of urban areas to changing precipitation patterns. Additionally, PPS promotes the sustainable use of urban water resources, particularly in water-scarce regions, by increasing infiltration rates and facilitating groundwater recharge.

5.4 Systematic Approach to Sustainable Urban Drainage

Throughout the review, the concept of SuDS emerges as a recurring subject. PPS plays a crucial role in SuDS and embodies the sustainable practices of managing urban water. PPS encompasses a holistic approach that addresses various interconnected issues related to floods, water quality degradation, and volume control, making it an essential component of modern urban development. The studies illustrate how PPS can effectively collaborate with other elements of green infrastructure, such as wetlands, bioretention systems, and green roofs, to create resilient and durable urban landscapes. This comprehensive integration not only offers opportunities for enhancing urban liveability but also mitigates the negative impacts of urbanization on the environment.

5.5 Climate Resilience through Green Infrastructure

The review papers concur that PPS plays a significant role in bolstering climate resilience. Given the escalating impacts of climate change, including increased precipitation, more frequent storms, and heat waves, adaptive urban planning becomes imperative. PPS emerges as a resilient green infrastructure solution due to its capacity to mitigate flood risks, improve water quality, and sustain groundwater supplies. Moreover, PPS's effectiveness in mitigating the effects of urban heat islands underscores its crucial role in climate adaptation. Cities grappling with rising temperatures can derive advantages from cooler urban areas, as they enhance the well-being of residents and require less energy for cooling purposes.

5.6 Economic Factors: Juggling Benefits and Costs

It is important to consider the economic benefits of PPS adoption in urban planning. The financial effects of utilizing PPS are crucial to consider even though the ecological advantages are obvious. The analysis proves that PPS can, in the long run, be a cost-effective solution. It lessens the need for pricey infrastructure for flood control, pollutant removal systems, and upkeep. PPS's multifunctionality, which concurrently handles flooding, water quality, and volume control, also contributes to its increased economic viability. PPS provides urban planners with a complete and economically appealing package by helping to reduce noise, save energy, and minimize maintenance costs.

5.7 Research Needs and Knowledge Gaps

Despite the many benefits of PPS that have been discussed throughout the research, it is important to emphasize the literature gaps that remain in the course. Further research is required to improve design criteria because the effectiveness of PPS can vary depending on regional variables such as climate, soil type, and land use. Furthermore, to guarantee that these systems continue to live up to their promise, it is essential to comprehend the long-term performance and maintenance requirements of PPS. This includes investigating factors such as clogging mechanisms, material degradation, and the effectiveness of maintenance practices. Thorough investigation is needed regarding the integration of PPS with other elements of green infrastructure as well as its applicability at the regional and national levels. Filling in these research voids will help PPS become more advanced and optimised as long-term urban stormwater management systems.

5.8 Conclusion: The Hopeful Road Ahead

A compelling narrative of the potential of PPS in modern urban water management can be found in the evaluation of publications that explore the multidimensional role of PPS in flood risk management, water quality improvement, and volume reduction. PPS adheres to sustainability principles and provides comprehensive solutions to the urgent problems of urbanization and climate change. It offers a chance to improve water quality, lessen runoff, and lessen the destructive effects of flooding while simultaneously boosting economic efficiency and climate resilience. The use of PPS emerges as a possible solution as cities struggle with the changing dynamics of urbanization and environmental change. PPS have demonstrated their versatility and adaptability in addressing a range of urban and environmental challenges through their inventive implementations. The collective body of research showcases the evolution of PPS from conventional stormwater management tools to holistic solutions that promote environmental consciousness and sustainable practices in urban planning. These innovative applications underscore the multifaceted nature of PPS, which extends beyond traditional stormwater management approaches. Notably, these advancements encompass the utilization of geotextiles for controlling pollutant sources, integration of renewable energy technologies, incorporation of low-carbon materials, and customization of PPS to cater to the unique needs of Small Island Developing States.

Given how future cities and environments will be shaped by urbanization and climate change, PPS's revolutionary potential seems especially intriguing. PPS are now crucial in lowering environmental impact, making cities cleaner, and opening the door for more environmentally friendly and sustainable urban development. They are a key component of sustainable urban development and an essential instrument for tackling the social, economic, and environmental elements of contemporary cities due to their versatility in the face of a variety of issues.

In the future, it is imperative to continue exploring and implementing innovative PPS applications. The potential for more resilient and sustainable urban development is presented by these developments. PPS's performance can be improved and optimized with more research, and its applications can be tailored to address area difficulties. By lowering the carbon footprint of building projects, the use of low-carbon materials can promote environmentally friendly and sustainable development. Furthermore, integrating renewable energy technologies like geothermal heat pumps offers building owners the possibility of money savings in addition to environmental advantages.

With the difficulties that SIDS encounter, the use of PPS in these areas has great potential. PPS can be very helpful in improving the standard of living in SIDS by tackling issues like water scarcity, the need for sustainable development, and vulnerability to climate change. Customized solutions that take into account regional variables and limitations are necessary, and community involvement is crucial to the accomplishment of such initiatives. The diverse uses of permeable pavement systems are a monument to human creativity and ingenuity at a time when the world is still struggling with the effects of urbanization and climate change. These adaptable technologies offer a comprehensive response to the various issues that our urban settings encounter rather than merely a fix for a specific issue. We can anticipate more resilient and sustainable cities in the future generations by keeping up the innovative development, adaptation, and application of PPS.

5.9 Recommendations for urban planners and environmental policymakers

Promote the adoption of PPS: As a component of stormwater management plans, promote the broad implementation of PPS in metropolitan areas. Provide regulations and financial incentives to encourage property owners, developers, and governments to include PPS in newly constructed and redeveloped areas.

Invest in Research and Development: Provide funds for projects aiming at enhancing the longevity, performance, and design of PPSs. To close information gaps, improve comprehension of regional variations, improve maintenance methods, and support interdisciplinary research collaborations.

Encourage Green Infrastructure Investments: Provide grants, cash incentives, and refunds to defray the upfront costs of putting PPS and other green infrastructure solutions into place. To support PPS initiatives and prioritise investments in areas with the most need, investigate cutting-edge financing options like green bonds or stormwater utility fees.

Monitor and Evaluate Performance: To determine the efficacy and long-term performance of PPS in accomplishing flood risk reduction, improving water quality, and controlling volume, establish monitoring and evaluation techniques. Refine policies, rank investments, and modify tactics in response to changing community demands and environmental conditions by using data-driven decision-making procedures.

In addition, the stakeholders' roles in implementing PPS are highly important in reaching sustainable goals for future. This includes policy makers, consultants, contractors and also the end users of the holistic system. Therefore, involving all stakeholders in developing and implementing PPS and the related strategies are highly essential.

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