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The trajectory of water sensitive urban design: integrating water management with urban planning and design

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ABSTRACT
Since the late 1990s, the development of Water Sensitive Urban Design (WSUD) has evolved to include broader concepts such as water-sensitive cities, offering a complementary alternative to conventional urban water management. While widely accepted in principle, WSUD continues to face critical shortcomings in practice. Through the bibliometric analysis of 688 publications and an in-depth content analysis of the 30 most highly cited articles, this study identifies persistent discrepancies between WSUD's stated objectives and its real-world outcomes. Key gaps are evident in areas such as long-term performance monitoring, socio-economic impacts, climate resilience, policy integration, and community engagement. The findings also point to recurring social, institutional, technological, and economic limitations that hinder implementation and diffusion. These insights call for a re-evaluation of existing WSUD approaches and underline the importance of interdisciplinary collaboration. Future directions in urban planning and design should place greater emphasis on the socio-economic dimensions, climate adaptability, governance structures, and technological innovation necessary to advance WSUD as a core component of sustainable and resilient urban development.

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Water sensitive urban design (WSUD); systematic review; HistCite; bibliometric analysis; urban planning and design; sustainable urban water management

1. Introduction

Over the past decades, cities worldwide are undergoing significant changes in urban water management in response to the challenges posed by climate change (Hooimeijer and van der Toorn Vrijthoff 2008; Newman 2001; Wong, Rogers, and Brown 2020). Among these challenges, the management of water resources has emerged as a critical concern, becoming increasingly crucial for urban areas. These challenges are exacerbated by rapid population growth, decreasing household density ratios, ageing infrastructure, compromised water supply and distribution systems, conflicts in water governance, and limited commitment to environmental management (Newman 2001; Rashetnia et al. 2022).

In line with the broader discourse of urban sustainability, there has been a growing emphasis on the importance of water system services management to enhance resilience against climate change and urbanisation pressures (Tasnia and Growe 2025; Zhang & Chui, 2018) . This emphasis has led to the adaptation of water-sensitive approaches in cities, integrating sustainable water management strategies, such as blue–green infrastructure and nature-based solutions, into urban planning (Almaaitah et al. 2021; Bichai and Cabrera Flamini 2018). These approaches consider water systems as an integral part of the urban landscape and promote the active engagement of citizens as stakeholders in water resource management (Wong and Brown 2009; Kuller et al., 2018).

Water Sensitive Urban Design (WSUD) is an integrated approach to urban water management that aims to enhance sustainability, resilience, and ecological integrity. The concept was first introduced by Mike Mouritz in the context of sustainable urban water systems, with an emphasis on the policy and professional practice (Fletcher et al. 2015). The first formal guidance on WSUD was provided by Whelans and Halpern Glick Maunsell (1994) in their report 'Planning and Management Guidelines for Water Sensitive Urban (Residential) Design', prepared for the Department of Planning and Urban Development of Western Australia (Whelans Consultants et al. 1994). These foundational contributions laid the groundwork for WSUD principles, which promote the integration of water cycle management into urban planning and design.

Since the late 1990s, WSUD has emerged as a complementary approach to conventional water management, incorporating principles of sustainability and integration with urban planning (Fletcher et al. 2015; Wong and Brown 2009). In recent years, WSUD has evolved to address broader challenges, including

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climate resilience, urban flood risk reduction, and the impacts of rapid urbanisation (Khalaji, Zhang, and Sharma 2025; Kuller, Bach, Ramirez-Lovering, & Deletic, 2018). Studies have demonstrated that integrating WSUD with green infrastructure and decentralised water systems enhances adaptive capacity and mitigates urban heat island effects (Coutts et al. 2013; Stojković, Mijić, Dobson, Marjanović, & Majkić-Dursun 2024). Unlike traditional linear water management systems, focused on collection, storage, treatment, and discharge, WSUD offers a more integrated and multifunctional strategy aimed at aligning water cycle management with urban design.

WSUD aligns with a range of water-sensitive strategies developed globally, such as Low-Impact Development (LID) in North America (Ahiablame, Engel, and Chaubey 2012; Khalaji, Zhang, and Sharma 2025), Sustainable Urban Drainage Systems (SUDS) in the UK (Kuller, Bach, et al. 2018; Lerer, Arnbjerg-Nielsen, and Mikkelsen 2015), Green Infrastructure (GI) in the US and UK, Decentralised Urban Design (DUD), and Low Impact Urban Design and Development (LIUDD) in New Zealand, each shaped by distinct regional priorities, regulatory contexts, and terminologies (Ahammed 2017; Ashley et al. 2013; Barton and Argue 2007; Booth and Jackson 1997; Coutts et al. 2013; Donofrio et al. 2017; Kazemi, Beecham, and Gibbs 2009, 2011; Lim and Lu 2016; Lloyd, Wong, and Porter 2002; Razzaghmanesh, Beecham, and Kazemi 2014; Roldin et al. 2012; Roy et al. 2008; Sharma et al. 2012; Walsh, Fletcher, and Ladson 2005; Wong 2006). WSUD has been chosen as the focus of this study due to its holistic and integrative approach to water management within urban planning, particularly in the Australian context where it has been extensively conceptualised and applied. It offers a flexible yet comprehensive framework that is responsive to local hydrological and climatic conditions, making it a valuable approach through which to examine the evolution of water-sensitive urban design practices.

Despite these advancements, the long-term performance of WSUD remains underexplored, particularly with regard to its socio-economic impacts and governance dimensions (Ahammed 2017; Khalaji, Zhang, and Sharma 2025; Lerer, Arnbjerg-Nielsen, and Mikkelsen 2015; Morison and Brown 2011). In addition, further research is needed to optimise the spatial allocation of WSUD interventions and to strengthen their integration within broader urban planning frameworks (Tasnia and Growe 2025; Zhang & Chui, 2018). Few studies have undertaken a systematic review of WSUD. Notably, while Bichai and Cabrera Flamini (2018) identified WSUD as a novel and evolving approach, its broader implications and long-term impacts remain insufficiently explored. Similarly, Ashley et al. (2013) offered valuable insights into the socio-political drivers shaping the water-city relationship, but gave limited attention to the economic and social dimensions of WSUD implementation, highlighting a critical gap in the existing literature. While Ashley et al. (2013) highlighted the limited socio-economic research on WSUD at the time, more recent studies have expanded this perspective. For example, Whiteoak (2019) offers a comprehensive account of the economic dimensions of WSUD. This evolving body of research reflects a growing recognition of socio-economic factors influencing WSUD implementation. Furthermore, Koop and van Leeuwen (2017) categorised the evolution of WSUD, further illustrating the shift towards more integrated and systemic approaches. However, persistent gaps remain, particularly in areas related to climate change resilience, social and economic integration, alignment with other urban systems, and long-term performance monitoring. Rashetnia et al. (2022) emphasised the need for further research on the sustained impacts of WSUD, underscoring a limited understanding of its long-term effectiveness. While the article acknowledged WSUD's strengths and limitations, a more comprehensive examination of these aspects is crucial for developing sustainable design, budgeting, and maintenance urban water systems.

This research aims to examine the historical evolution and development trajectory of WSUD and how it has transitioned from a technical water management approach to a broader urban planning and design framework. By analysing bibliometric trends, citation networks, and key knowledge gaps, this study uncovers the intellectual foundations and critical turning points that have shaped WSUD's adoption in the planning discourse. Understanding how WSUD has been conceptualised and applied in highly cited works allows for an assessment of its incorporation into contemporary planning practices, the identification of limitations, and the recognition of emerging directions for sustainable urban water management. To achieve this, the paper analyses patterns in the published literature, covering aspects such as temporal evolution, key journals, authorship, institutional affiliations, and geographical distribution. It employs knowledge mapping and development trajectory techniques through citation network analysis to identify current gaps and future trajectories in WSUD research and practice. This research contributes to a better understanding of how WSUD can coexist and complement existing urban infrastructure. Additionally, addressing key challenges, such as the complexities of climate change resilience, the absence of standardised guidelines, and persistent regulatory barriers, is critical. Overcoming these obstacles will be instrumental in advancing the implementation of WSUD as a sustainable and resilient approach to urban water management. Finally, this study concludes with WSUD's implications for urban planning and design fields to integrate with water management.

2. Methodology

To conduct a systematic review based on the PRISMA model, which provides a structured, evidence-based checklist to ensure transparency and completeness in review reporting (Cassarino, Shahab, and Biscaya 2021; Page et al. 2021),an extensive search was initially performed in the Web of Science database using the keyword 'water sensitive urban design', including variations and derivatives of the term in the title, abstract, and keywords of scientific documents (Figure 1). This search identified 701 scientific sources produced from 1997 to 2022 in seven languages across 66 countries. During the screening phase, sources with unrelated backgrounds were excluded, resulting in a final dataset of 688 relevant publications, including journal articles, conference papers and proceedings, and books and book chapters.

This study employed bibliometric analysis to examine the geographical distribution of WSUD research, as well as key contributing institutions, journals, and relevant keywords, based on a database of 688 articles. Bibliometric analysis, which involves using bibliographic information such as titles, authors, publication dates, institutional affiliations, and reference lists to quantify and explore trends within a specific research field, was supported in this study by HistCite,a software tool designed to facilitate the visualisation and interpretation of bibliometric networks (Garfield 2009). The analysis also identifies key authors, their affiliated institutions, and the most influential publications within the WSUD literature.

In the content analysis phase, the top 30 sources with the greatest impact on the WSUD knowledge network were identified using HistCite for further qualitative analysis. A content analysis approach was employed to examine these influential articles in order to develop a comprehensive understanding of WSUD, its related concepts and approaches, and the evolution of its theoretical foundations and practical applications.

3. Results and discussion

3.1. Bibliometric analysis of the 688 sources of the research network

Preliminary findings indicate that a substantial body of WSUD research has been conducted across various countries and cities, predominantly published in the English language. The total number of published documents (including the term WSUD in scientific publications) shows a rapid increase since 2005, with the highest number of papers published in 2020 (Figure 2).

Based on HistCite software, this study examines two research indexes including the local citation scores (LCS) and global citation scores (GCS) of scientific sources. The LCS refers to the number of citations to a source within the collection of 688 scientific sources, while the GCS measures the total number of citations to a source in the Web of Science Collection (Garfield 2009).

3.1.1. Analysis of citation scores over time

The analysis reveals interesting trends in citation scores over time. From 1997 to 2005, both LCS and GCS showed a gradual increase, with a significant surge in 2005. However, in subsequent years, there were fluctuations in both scores, with some years experiencing higher citation rates than others especially in LCS (Figure 3). Notably, 2015 recorded the highest LCS and GCS, indicating global recognition of articles published that year.

3.1.2. Comparative analysis of countries

This study further explores the citation scores in the realm of scientific research related to WSUD across 58 countries, ranging from highly developed nations to emerging economies. Australia leads the field with an LCS of 860 and a GCS of 8411, followed by the United States with an LCS of 200 and a GCS of 3729. Additionally, countries like China and the United

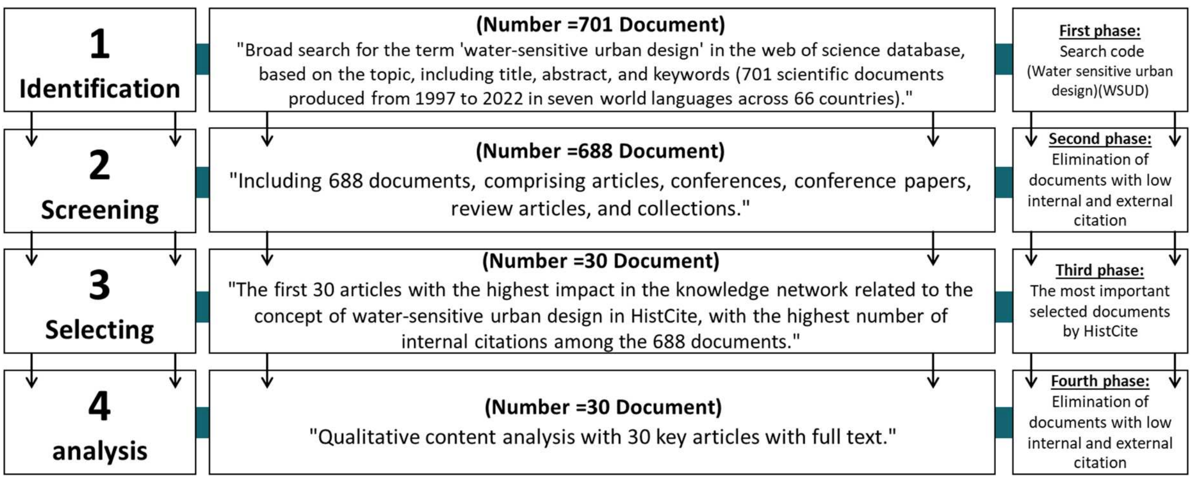

Figure 1. The process of selecting papers based on the PRISMA checklist.

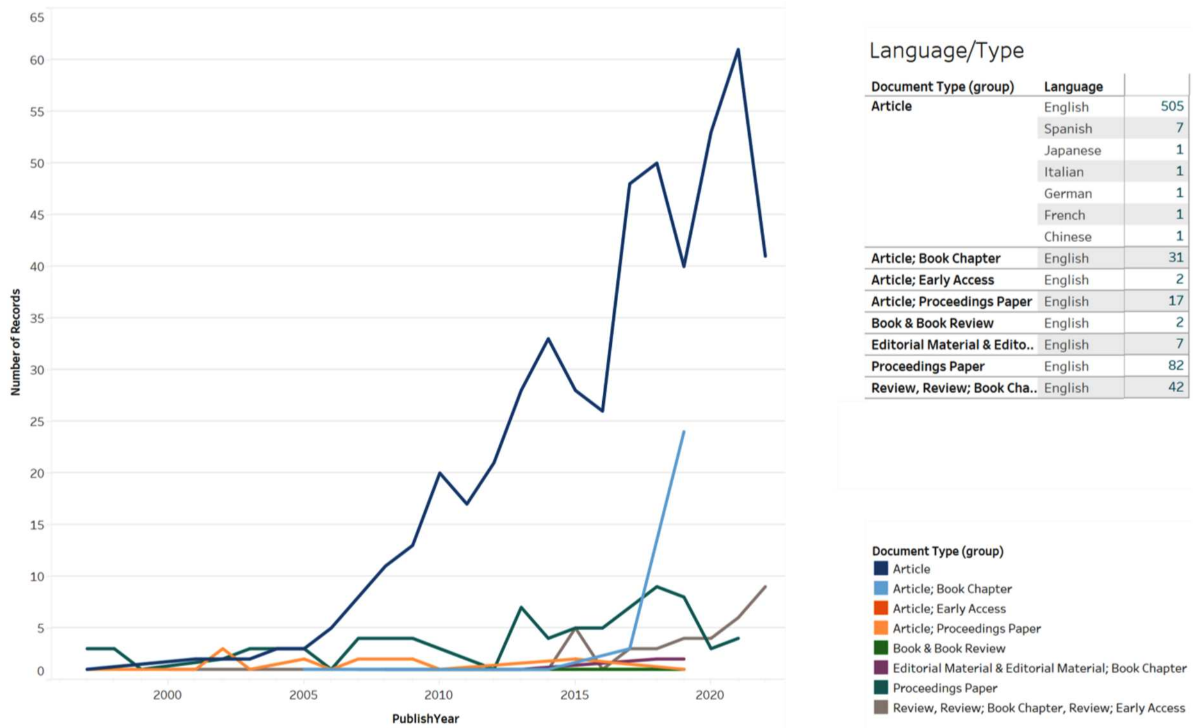

Figure 2. Scientific resources published on the subject of WSUD by document type and language from 1997 to 2022.

Kingdom demonstrate strong performance, reflecting their significant contributions to global scientific knowledge. Interestingly, smaller countries such as New Zealand and the Netherlands also showcase commendable performance relative to their size (Figure 4).

3.1.3. Prominent institutions in WSUD research

To shed light on influential institutions in the field of WSUD, we conducted an analysis of LCS and GCS scores of various organisations. Notable performers include Monash University with an LCS of 80 and a GCS of 409, as well as the University of Melbourne with an LCS of 30 and a GCS of 148. Other institutions like the University of South Australia, Griffith University, and the University of Western Australia also demonstrate significant contributions to WSUD research and innovation (Figure 5).

3.1.4. Major journals

WSUD has gained significant attention in recent years due to its potential to mitigate the adverse impacts of urbanisation on water resources especially in urban design and planning journals. Several scientific journals have contributed to the advancement of WSUD research and its application in urban planning and management. Notable publications in this field include ‘Urban Climate’ with a GCS of 102 and ‘Journal of the American Water Resources Association’ with a GCS of 786. These journals provide valuable insights into the design, ecological health, urban greening, economics, policies, and community perceptions associated with WSUD. Furthermore, journals such as ‘Water Research’ and ‘Journal of Hydrology’ have demonstrated their commitment to this field by consistently publishing high-quality research, reflected in their respective GCS scores of 895 and 596.

3.2. Content analysis of the top 30 sources of the research network

Through conducting a content analysis of the top 30 sources (Table 1), we delve deeper into related concepts and approaches, goals of WSUD, as well as an analysis of the citation network, existing knowledge gaps and the future directions of WSUD.

3.2.1. WSUD definitions: the WSUD can be approached as follows

- **Urban Design oriented definitions:** WSUD is a multifaceted urban planning and design approach that integrates strategies to mitigate and minimise the hydrological impacts of urban development (Ahammed 2017; Roldin et al. 2012). It’s a process for integrating urban design with the various disciplines with the aim of aquatic environment protection (Ashley et al. 2013). It is also defined as the integration of water management practices into urban design (Booth and Jackson 1997; Wong 2006; Wong and Brown 2009). It uses various techniques and practices to integrate water management into urban planning and design (Roldin et al. 2012).

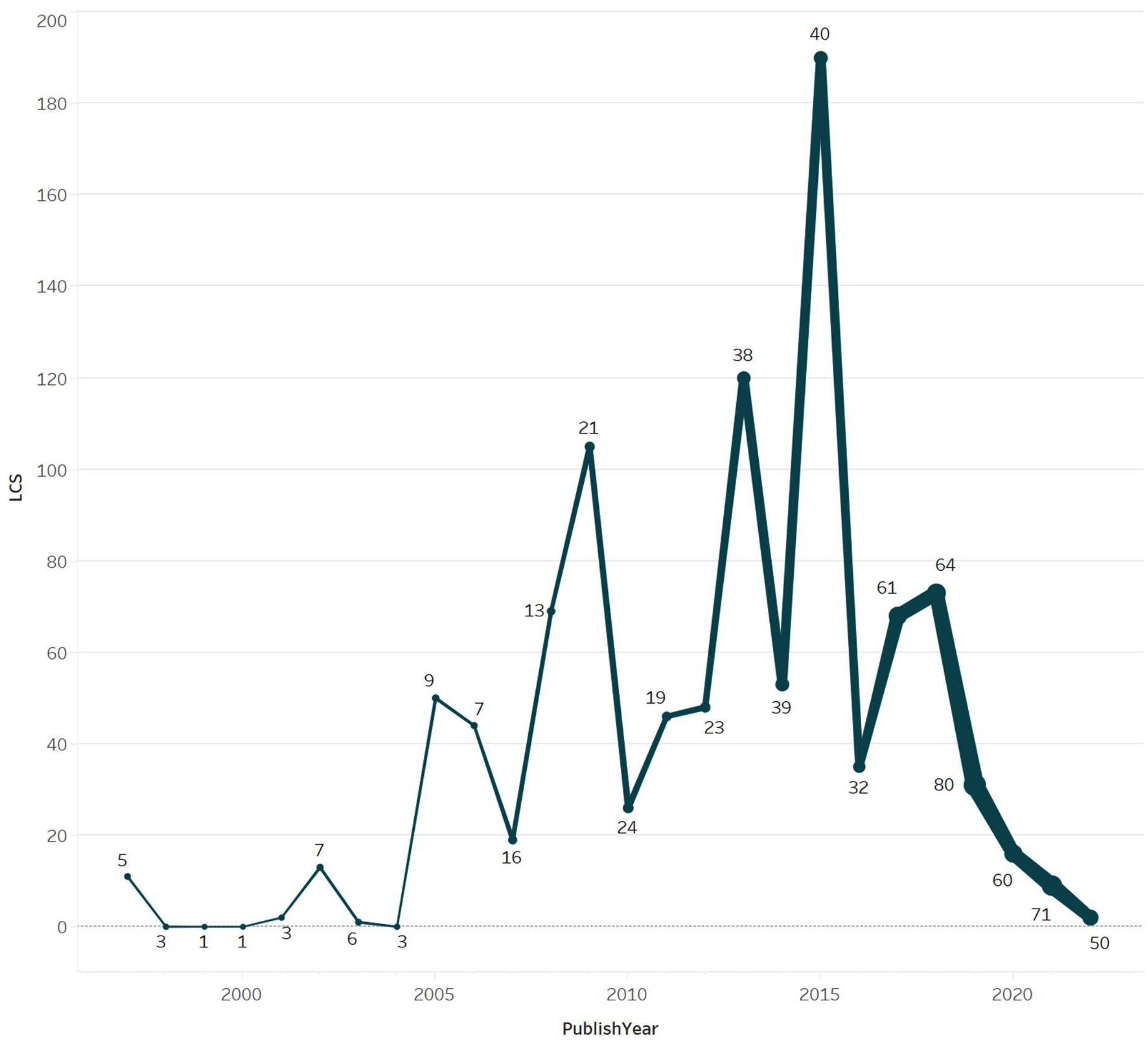

Figure 3. The variations of Local Citation Scores (LCS) of scientific sources published on the topic of WSUD from 1997 to 2022-The numerals adjacent to each data point represent the number of publications produced in that year.

- **Sustainable water-cycle management definitions**: WSUD blends sustainable water-cycle management with urban planning and development (Coutts et al. 2013; Donofrio et al. 2017; Kuller et al. 2017; Lloyd, Wong, and Porter 2002)., offering an alternative paradigm for the planning and implementation of urban water systems (Bach, Deletic, et al. 2013; Bach, McCarthy, et al. 2013; Ferguson, Frantzeskaki, and Brown 2013; Barton and Argue 2007; Sharma et al. 2012).
- **Hydrological restoration definitions:** Some interpretations of WSUD emphasise its role in environmental conservation and restoration, viewing it as a means to restore natural hydrological and geomorphic processes (Lim and Lu 2016). Moreover, it entails a systematic and strategic allocation of practices within urban areas, such as low impact development (LID), best management practices (BMP), and green infrastructure (GI), to effectively address hydro-environmental and socio-economic considerations (Morison and Brown 2011; Zhang & Chui, 2018).
- **Stormwater management definitions:** In certain contexts, WSUD serves as a vital stormwater management strategy and sustainable approach for conserving and reusing water resources (Kazemi, Beecham, and Gibbs 2009, 2011; Kuller, Bach, et al. 2018; Kuller, Farrelly, Deletic, & Bach 2018; Lerer, Arnbjerg-Nielsen, and Mikkelsen 2015; Mitchell et al. 2008; Razzaghmanesh, Beecham, and Kazemi 2014; Roy et al. 2008; Walsh, Fletcher, and Ladson 2005). It also plays a crucial role in treating urban runoff, demonstrating its versatility in addressing contemporary urban water challenges (Bach, McCarthy, et al. 2013; Fletcher et al. 2015).

3.2.2. Goals of WSUD

Table 2 presents an overview of the goals and objectives derived from content analysis related to WSUD. Key goals include the sustainable management of the urban water cycle, sustainable stormwater management, protection of aquatic and natural resources, water security, flood mitigation, human

Figure 4. Geographical distribution of scientific publications on WSUD from 1997 to 2022. The size of each circle is proportional to the total number of publications for each country, and the numerals adjacent to the circles represent the exact publication counts.

health and safety, aesthetic values, and landscape amenity. Additionally, a multi-disciplinary approach, community involvement, and education are recognised as essential components of WSUD, contributing to governance and community capital. These objectives collectively align with the broader goals of WSUD provided by the Cooperative Research Centre for Water Sensitive Cities (CRCWSC) (Rogers et al. 2020), such as promoting ecological health, resource efficiency, equity of essential services, and the creation of high-quality urban spaces (Table 2).

3.2.3. Analysis of the network diagram of the most cited articles (Analysis of the citation network)

Analysis of the network diagram (Figure 6) shows that the article by Fletcher et al. (2015) [source number: 275] with an LCS of 115, has the highest frequency among 688 articles. This article discusses 'The evolution and application of terminology surrounding urban drainage' and references terms such as SUD, LID, BMP, WSUD, geographical origin, and principles. Following that, the article by Wong and

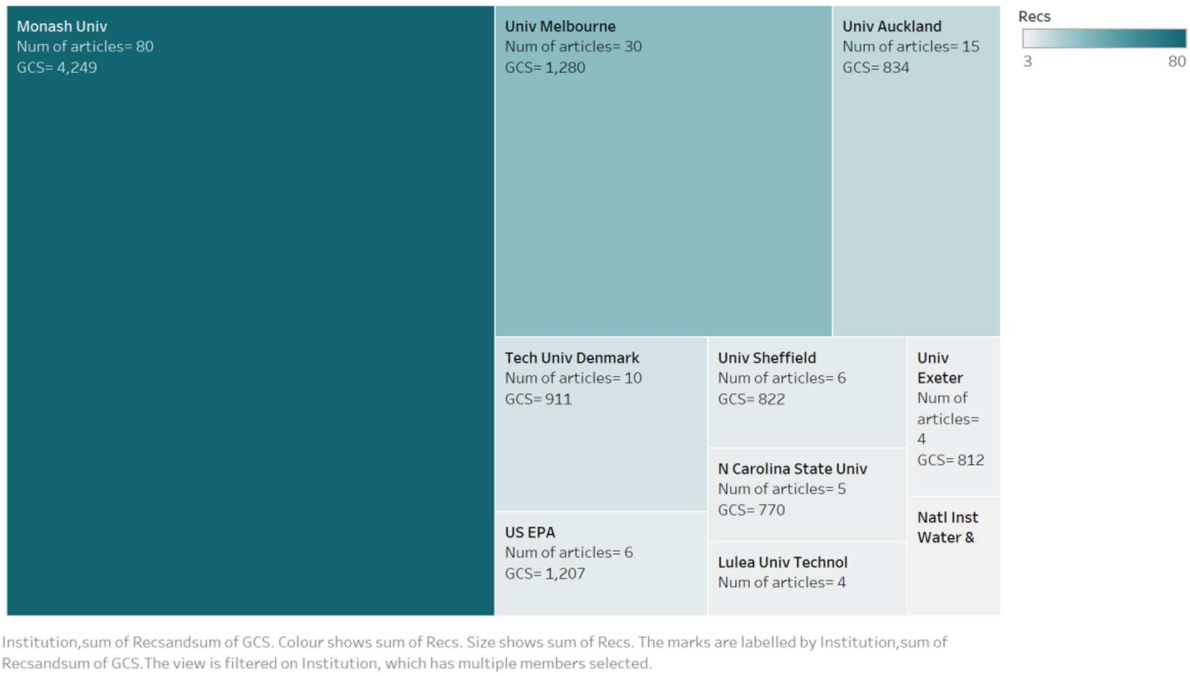

Figure 5. List of the top 10 universities and research institutions with the highest number of scientific publications and global citation scores(GCS) on WSUD from 1997 to 2022.

Table 1. A list of the top 30 sources with the highest local citation scores (LCS) among 688 sources on WSUD from 1997 to 2022 in the Web of Science database.

No.	LCS	GCS	Source number in the list of 688 sources	Publication Year	Author(s)
1	115	685	275	2015	Fletcher TD
2	62	292	84	2009	Wong T
3	49	1892	41	2005	Walsh CJ
4	42	375	75	2008	Roy AH
5	38	132	42	2006	Wong T
6	26	69	368	2017	Kuller M
7	25	215	180	2013	Coutts AM
8	23	68	187	2013	Ashley R
9	21	77	131	2011	Morison PJ
10	19	41	255	2015	Lerer SM
11	17	41	146	2012	Sharma AK
12	14	99	193	2013	Ferguson BC
13	13	27	91	2009	Donofrio J
14	12	33	414	2018	Kuller M
15	11	73	303	2016	Lim HS
16	11	637	8	1997	Booth DB
17	10	27	366	2017	Ahammed F
18	10	29	157	2012	Roldin M
19	10	34	177	2013	Bach PM
20	10	52	21	2002	Lloyd SD
21	10	72	133	2011	Kazemi F
22	9	58	219	2014	Razzaghmanesh M
23	9	84	76	2008	Fletcher TD
24	9	124	56	2007	Henderson C
25	8	15	49	2007	Barton AB
26	8	21	432	2018	Kuller M
27	8	29	196	2013	Bach PM
28	8	98	404	2018	Zhang K
29	7	44	94	2009	Kazemi F
30	7	80	74	2008	Mitchell VG

Note: The source numbers correspond to those used in the network diagram (Figure 6) to facilitate cross-referencing.

Brown (2009) [source number: 84] on 'Water-sensitive cities' with a significant gap (LCS = 62) emphasises moving away from conventional approaches toward new practices, focusing on three principles: 1-Access to a diversity of water sources, 2- Provision of ecosystem services for the built and natural environment, and 3-Socio-political capital for water-sensitive behaviours.

After these two articles, three more articles with substantial gaps and LCS ranging from 49 to 38 had the most internal references: Walsh [source number: 41] discusses 'Stream restoration through redesigning stormwater systems' in collaboration with researchers from Monash University, Australia (Walsh, Fletcher, and Ladson 2005). Roy et al. [source number: 75] explores experiences from Australia and the United States regarding 'Sustainable Urban Stormwater Management' (Roy et al. 2008) and Wong [source number: 42] provides an overview of the current state of adoption of 'WSUD' in Australia, describing future trends (Wong 2006). It concludes that there are barriers in the construction and management sectors for achieving WSUD, and socio-institutional aspects remain underdeveloped.

The first article among the top 30 articles with the highest LCS, published by Booth [source number: 8] in 1997 in the 'American Water Resources Association' journal, focuses on the 'Urbanisation of aquatic systems' and its impact on downstream aquatic systems in form and function. It concludes that a better understanding of the critical processes leading to degradation is needed to prevent future damage to downstream aquatic systems (Booth and Jackson 1997).

One of the latest articles among the top 30 articles with the highest citations are from 2018: Kuller et al. [source number: 432] emphasises the strong relationship between the distribution of existing WSUD infrastructure in Australia (Melbourne) and its connection to the urban context, including biophysical, socio-economic, and urban form. Moreover, Kuller et al. addresses the implementation gap and concerning water sensitive urban design and planning (Kuller, Farrelly, et al. 2018). Also, Zhang & Chui (2018) [source number: 404] reviews and examines strategies and optimisation tools for the spatial allocation of stormwater (LID-BMP-GI) practices that benefit practitioners.

In general, it can be concluded that WSUD, as a knowledge domain, has been evolving since 1997. Initially, the focus was on the consequences of urbanisation and the need for alternative principles in urban drainage. Then, from 2005 to 2009, the WSUD approach and related experiences in Australia and the United States gained prominence and grew. By 2015, it reached its peak, spreading with various terminologies worldwide, and becoming an active research domain. With the implementation of WSUD practices in different countries, research in this field continued, focusing on various aspects, including factors influencing project distribution, feasibility gaps, strategies, and spatial distribution tools, up until 2018.

3.2.4. Knowledge gaps

Despite progress in understanding and implementing WSUD, notable knowledge gaps remain. First, there is a need for more extensive research into the long-term performance and monitoring of WSUD interventions and practices in urban design and planning (Sharma et al. 2012). Understanding how these designs function over extended periods and under various conditions is critical for their continued success. (Lerer, Arnbjerg-Nielsen, and Mikkelsen 2015; Wong 2006) highlight a paucity of practical experience in implementing WSUD, especially compared to traditional piped systems. Furthermore, a lack of rigorous consideration of the urban context, encompassing biophysical, socio-economic, and urban form factors, remains a substantial knowledge gap (Kuller et al. 2017; Wong 2006). Also, there is a need for systematic research into WSUD's practical use and outcomes to evaluate and improve its performance (Hemati, Irandoost, and Alizadeh 2025).

Moreover, an interdisciplinary approach to WSUD is needed incorporating related disciplines especially urban planning and design and other fields such as

Table 2. Goals of WSUD.

Goals of WSUD based on the content analysis	Codes (derived from the content analysis)	Sources	Goals of WSUD (CRCWSC)
Sustainable management of the urban water cycle	Sustainable management of the urban water cycle/ Sustainable water management/Conserve water use	(Ahammed 2017; Ashley et al. 2013; Barton and Argue 2007; Booth and Jackson 1997; Coutts et al. 2013; Donofrio et al. 2017; Lloyd, Wong, and Porter 2002; Razzaghmanesh, Beecham, and Kazemi 2014; Sharma et al. 2012; Wong 2006; Wong and Brown 2009; Zhang & Chui, 2018)	G3: equity of essential services and G5: ecological health
Sustainable stormwater management	Achieving sustainable and environmentally friendly stormwater management /Integrating stormwater management systems into urban landscapes/Stormwater quality /Stormwater harvesting and use/Stormwater drainage/ Reduce the impact of stormwater runoff on existing sewer systems/ Rain and Stormwater reuse or improvement/ Greywater or blackwater reuse	(Barton and Argue 2007; Booth and Jackson 1997; Coutts et al. 2013; Donofrio et al. 2017; Fletcher et al. 2015; Fletcher et al. 2008; Henderson, Greenway, and Phillips 2007; Kazemi, Beecham, and Gibbs 2009, 2011; Kuller, Farrelly, et al. 2018; Lerer, Arnbjerg-Nielsen, and Mikkelsen 2015; Lim and Lu 2016; Lloyd, Wong, and Porter 2002; Mitchell et al. 2008; Morison and Brown 2011; Razzaghmanesh, Beecham, and Kazemi 2014; Roldin et al. 2012; Roy et al. 2008; Sharma et al. 2012; Walsh, Fletcher, and Ladson 2005; Wong 2006; Zhang & Chui, 2018)	G5: ecological health
Protection of aquatic and natural resources and processes	Protect aquatic and natural resources/Conserve biodiversity/Ecological habitat/Protect stream ecosystems/Minimise disruption to natural processes/ Restore the pre-development flow regime/Restore natural waterways/Reduce stress on conventional water systems	(Bach, Deletic, et al. 2013; Barton and Argue 2007; Coutts et al. 2013; Kuller, Farrelly, et al. 2018; Lim and Lu 2016; Roy et al. 2008; Sharma et al. 2012; Walsh, Fletcher, and Ladson 2005; Wong 2006; Wong and Brown 2009)	G5: ecological health and G4: resource efficiency
Water security and quality (health)	Water security/ Address water shortages/ Supplementing water supplies/ Waterway health/Enhance water quality	(Fletcher et al. 2008; Fletcher et al. 2015; Kuller et al. 2017; Morison and Brown 2011; Roy et al. 2008; Wong and Brown 2009)	G5: ecological health
Flood mitigation	Flood protection/Flood mitigation/Decrease flood risk	(Booth and Jackson 1997; Kuller, Bach, et al. 2018; Kuller, Farrelly, et al. 2018; Lerer, Arnbjerg-Nielsen, and Mikkelsen 2015)	G5: ecological health
Human health and safety	Improve outdoor human thermal comfort in urban areas /Public health/Mitigating urban heat island effects	Coutts et al. 2013; Fletcher et al. 2008; Fletcher) et al. 2015; Roy et al. 2008; Wong and Brown 2009)	G3: equity of essential services and G5: ecological health
Providing aesthetic values	Aesthetics/ Aesthetic value of neighbourhoods/ Providing recreational space	(Bach, Deletic, et al. 2013; Kuller, Farrelly, et al. 2018; Lloyd, Wong, and Porter 2002; Morison and Brown 2011; Wong and Brown 2009)	G6: quality urban space
Landscape amenity	Landscape amenity/Enhancing amenities	(Bach, Deletic, et al. 2013; Bach, McCarthy, et al. 2013; Kuller et al. 2017, 2018; Lloyd, Wong, and Porter 2002; Razzaghmanesh, Beecham, and Kazemi 2014)	G6: quality urban space
A multi-disciplinary approach	Considering a multi-disciplinary approach to integrating urban planning, design, and water-cycle management	(Bach, McCarthy, et al. 2013; Booth and Jackson 1997; Donofrio et al. 2017; Roldin et al. 2012)	G1: governance
Community involvement and education	Educating communities about urban sustainability/ Incorporation of community values and aspirations in design decisions/Role of communities in defining urban water issues and developing strategies	(Booth and Jackson 1997; Sharma et al. 2012; Wong 2006; Wong and Brown 2009)	G2: community capital

engineering, social sciences, landscape architecture, ecology, and environmental economics. Furthermore, the integration of WSUD with other urban systems remains an understudied area. Additionally, in-depth research is needed on the policy and governance frameworks that either support or hinder the implementation of WSUD, particularly within urban planning systems. Addressing regulatory barriers and aligning urban policies with WSUD objectives can play a crucial role in promoting its broader adoption and success. A strong commitment at the local policy level is essential, linking WSUD to broader public concerns and fostering support through a range of public policy measures and interventions (Morison and Brown 2011).

As the terminology associated with WSUD is rapidly changing, it becomes essential for local regions to embrace and customise terminology according to their specific social, institutional, and political circumstances. The localised formulation of terminology plays a crucial role in progressing the concept in urban planning. However, research efforts in urban planning and design should focus on enhancing communication across disciplines and global regions by ensuring clarity and precision in the use of these terms. In conclusion, addressing these knowledge gaps will not only deepen our understanding of WSUD, but also support the development of more effective and sustainable strategies for urban water management within the field of urban planning.

3.2.5. Limitations of WSUD

Several limitations hinder the full realisation of WSUD which can be categorised in five major issues including:

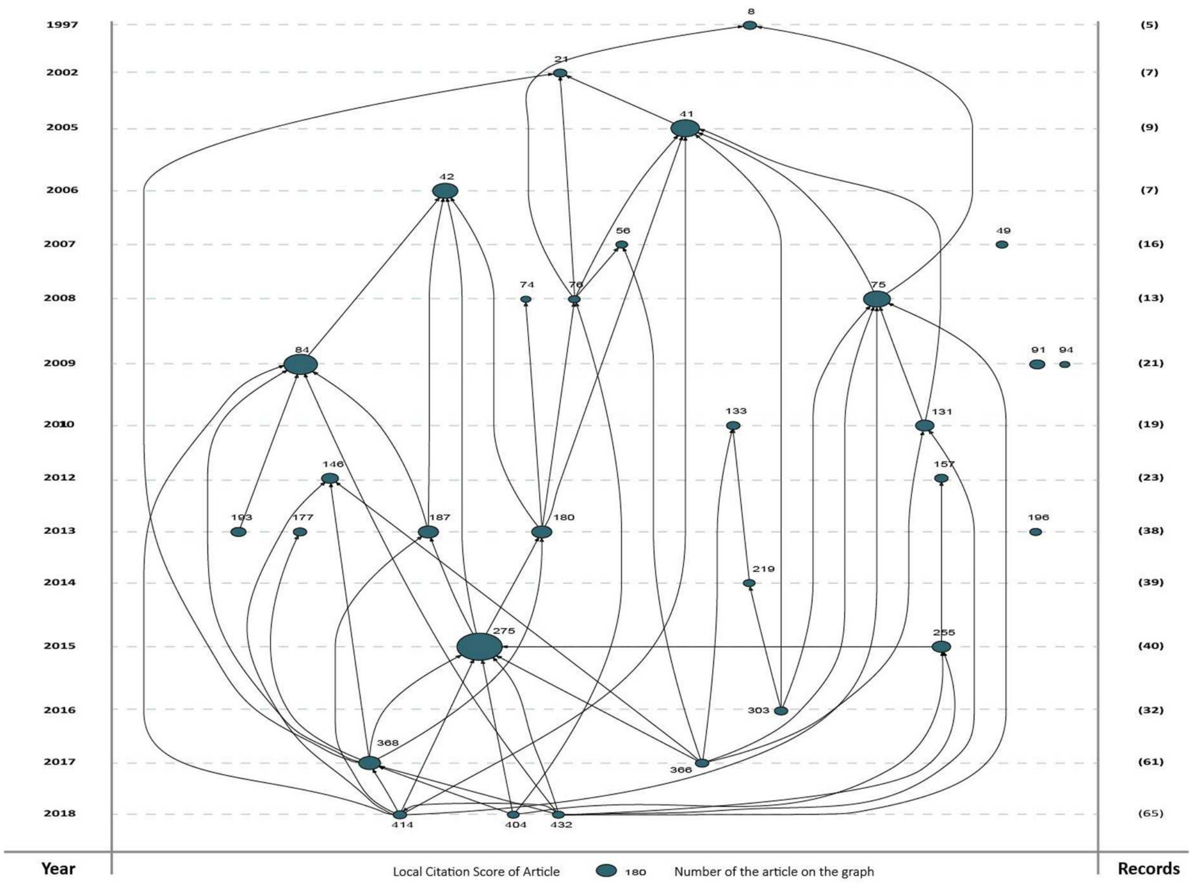

Figure 6. The top 30 sources with the highest local citation scores (LCS) among 688 sources on WSUD from 1997 to 2022 in the Web of Science database mentioned in Table 1 (the numbers above the circles represent the source number in the list of 688 sources). Notably, only six of these publications were produced in the five years leading up to 2022, underscoring the time-dependent nature of citation accumulation and a limitation of this type of analysis

Table 3. Summary of the most important Limitations in WSUD identified by several studies.

Main limitation	Issues	Source
Social issues	Community acceptance and social impacts	Sharma et al. 2012
	Community resistance to change	Roy et al. 2008
Institutional and political issues	Governance, regulations, and guidelines issues /Insufficient regulatory framework /Lack of governance structure	Sharma et al, 2018 Ahammed 2017 Ashley et al. 2013
	Lack of local policy commitment	Morison and Brown 2011
	Fragmented responsibilities/ Lack of institutional capacities/ Lack of legislative mandate	Roy et al. 2008
Technological, design and evaluation issues	System operation and maintenance	Sharma et al. 2012
	Insufficient engineering standards and guidelines/ Lack of design experience	Roy et al. 2008 Ahammed 2017
	Lack of appropriate modelling tools	Ahammed 2017
	Fragmented adoption of planning tools	Kuller et al. 2017
	Challenges in system evaluation, performance, and monitoring	Sharma et al. 2012 Kuller et al. 2017
	Lack of skills and knowledge (i.e. lack of awareness among urban planners)	Sharma et al. 2012 Kuller et al., 2017
	Challenges in data availability and quality, and user-friendliness of planning tools	Kuller et al. 2017, Kuller, Bach, et al. 2018; Mitchell et al. 2008
	Limited collaboration at catchment scales	Kuller, Bach, et al. 2018
	Ad-hoc decision-making prevalent, with no strategic and integrated planning	Kuller, Farrelly, et al. 2018
Implementation, economic and management issues	Operation and management uncertainty Uncertainty in performance	Ahammed 2017 Roy et al. 2008
	Insufficient data management	Ahammed 2017
	Lack of appropriate tools for addressing the full spectrum of WSUD's aspects in decision support system (policy makers)	Lerer, Arnbjerg-Nielsen, and Mikkelsen 2015
	Uncertainty in cost/ lack of funding and effective market incentives and marketing mechanisms	Roy et al. 2008 Ahammed 2017 Sharma et al. 2012
Public health and sustainability issues	Public health issues	Sharma et al. 2012
	Sustainability and broader system impacts	Sharma et al. 2012

1 – Social issues and community acceptance, 2 – Institutional and political issues addressing governance, regulations, and guidelines issues and lack of regulatory frameworks, 3 – Technological, design and evaluation issues emphasising insufficient engineering standards and guidelines, lack of design experience and user-friendliness tools and data availability, 4 – Implementation, economic and management issues focusing on operation and management uncertainty and lack of funding and effective marketing mechanisms and incentives, and 5 – public health and sustainability issues. Table 3 represents the most important limitations in WSUD identified by several studies.

Collectively, these limitations underscore the complexity of WSUD studies and practices, and emphasise the urgent need for collaborative, strategic, and systematic approaches to fully capitalise on their potential in urban water management.

3.2.6. Future directions of WSUD

The future of WSUD research and practices, as envisioned by various research articles, entails several directions to overcome challenges in sustainable urban water management regarding urban planning system and practices. We summarise these directions as follows:

1. Institutional integration: The urban planning system should consider urban development and its integration with sustainable urban water management. Therefore, it can play a coordinating role in all the actions of the institutions responsible for sustainable urban water management. Collaboration at catchment scales and within organisations is emphasised, with Planning Support Systems (PSS) serving as platforms for stakeholder communication and idea exchange (Kuller, Bach, et al. 2018). Lloyd et al. propose continued research into stakeholder engagement, and policy advocacy for WSUD integration (Lloyd, Wong, and Porter 2002).
2. Context-sensitive approach: Future research should seek to apply WSUD in developing countries as the socio-economic and environmental challenges of these countries along with their planning systems are different from developed countries with various practices and experiences of WSUD implementation. Moreover, (Lim and Lu 2016) highlight research into innovative designs for land-scarce areas and locally relevant guidelines for WSUD practices, especially in tropical climates.
3. Socio-economic aspect: The social and economic aspects of WSUD implementation require further exploration (Ahammed 2017). While WSUD aims to improve water management in urban areas, its impact on communities and the economic viability of its practices are essential considerations that deserve more in-depth study.
4. Climate change and resiliency: As urban areas face shifting weather patterns and increasingly frequent extreme events, understanding how WSUD can contribute to climate change resilience is crucial. This includes both the adaptation of existing WSUD infrastructure in response to evolving climate conditions and the design of future systems that anticipate and accommodate projected changes, rather than just current conditions. Hence, more research is needed to support cost/benefit analysis of different WSUD implementation approaches, particularly against other available approaches for mitigating excess urban heating (Coutts et al. 2013).
5. Implementation and managerial aspects: Future research should focus on the management and implementation aspect of WSUD integrating technological, social, economic, and marketing issues of WSUD practices (Ahammed 2017; Roy et al. 2008) at various spatial scales with appropriate applications and tools (Ashley et al. 2013).
6. Technological and technical development and methods: The development of user-friendly tools tailored to planning practice is also recommended (Kuller, Farrelly, et al. 2018). Mitchell et al. call for further development of WSUD models, improved parameterisation, and advanced microclimate modelling (Mitchell et al. 2008).

3.3. Implications for urban planning and design

Given the focus of WSUD on integrating water management with urban planning and design, it is crucial to explore the implications of findings for these fields. This systematic review highlights several key areas where WSUD can significantly impact urban planning and design practices:

3.3.1. Integration with urban infrastructure

WSUD ostensibly promotes the integration of water management systems with urban infrastructure, yet the real challenge lies in its implementation. Features like green roofs, permeable pavements, and bio-retention systems are frequently discussed in academic circles, but their adoption is inconsistent and often superficial. The supposed holistic approach to improve urban resilience to climate change and reduce the urban heat island effect remains largely aspirational. Moreover, a more comprehensive understanding of how WSUD can be harmoniously integrated with transportation, energy, and green space planning is necessary for achieving holistic urban development.

3.3.2. Sustainable urban development

While WSUD principles theoretically support sustainable urban development, their practical application is fraught with challenges. Urban planners are urged to design cities that minimise water consumption and enhance water recycling, but such strategies are rarely prioritised in actual urban development projects. The alignment with broader sustainability goals is often more rhetorical than real, with little tangible impact on creating truly livable, green cities.(Booth and Jackson 1997; Kazemi, Beecham, and Gibbs 2011; Kuller, Farrelly, et al. 2018; Sharma et al. 2012).

3.3.3. Policy and governance

The implementation of WSUD is critically dependent on supportive integrated policy frameworks and governance structures, which are typically lacking. The need for collaboration between urban planners and policymakers to revise building codes, zoning laws, and land use policies is well-recognised but seldom realised. Without substantive regulatory changes and incentives, WSUD practices remain underutilised and ineffective (Kuller et al. 2017; Morison and Brown 2011; Sharma et al. 2012).

3.3.4. Community engagement and education

The success of WSUD initiatives hinges on engaging communities, yet this engagement is often superficial. Urban planners and designers are encouraged to involve local communities, but there is a persistent gap between policy intentions and actual community involvement. Educating the public about the benefits of WSUD and securing their participation remains an uphill battle, with long-term sustainability of projects frequently in doubt(Morison and Brown 2011; Wong 2006; Wong and Brown 2009).

3.3.5. Design innovation

WSUD encourages innovative design solutions, but the pace of innovation is slow and uneven. Designers are urged to experiment with new materials and techniques, but practical constraints and limited incentives hinder significant advancements. The aspiration to improve the overall quality of urban spaces through WSUD remains largely unmet, with existing designs falling short of addressing critical water management issues (Ahammed 2017; Bach, Deletic, et al. 2013; Kuller et al. 2017; Kuller, Farrelly, et al. 2018; Lerer, Arnbjerg-Nielsen, and Mikkelsen 2015; Zhang & Chui, 2018).

3.3.6. Climate resilience

Urban areas' vulnerability to climate change underscores the potential of WSUD, but actual implementation lags behind. While WSUD provides a framework for enhancing urban resilience, adaptive water management strategies are often inadequately integrated into urban design. Planners struggle to design systems that can cope with changing climate conditions, leading to persistent risks of flooding and water scarcity. By effectively integrating WSUD principles, planners can develop more resilient urban environments that are better equipped to adapt to the impacts of climate change (Ashley et al. 2013; Bach, McCarthy, et al. 2013; Booth and Jackson 1997; Donofrio et al. 2017; Kuller et al. 2017; Lim and Lu 2016).

3.3.7. Monitoring WSUD interventions

While there is an evaluation process for many urban plans and interventions, by integrating WSUD with urban development processes, it is essential to evaluate and monitor the Long-term performance and monitoring of WSUD interventions (Fletcher et al. 2015; Sharma et al. 2012).

3.3.8. Interdisciplinary approach to WSUD

Interdisciplinary collaboration is essential to bridge the gap between WSUD research and urban development practice for instance, in the UK provides a platform for sharing best practices in Sustainable Drainage Systems (SuDS) or state-based initiatives in Australia. Furthermore, the evolution of WSUD terminology highlights the dynamic and interdisciplinary nature of discourse within the field. Prioritising ongoing research, fostering stakeholder engagement, and promoting interdisciplinary collaboration can advance the integration of WSUD principles into urban planning and design practices for more resilient and sustainable urban futures globally (Bach, McCarthy, et al. 2013).

3.3.9. Promoting WSUD in urban planning studies

Concentration of highly cited articles in specialised journals suggests a need for broader integration of WSUD into urban planning and design discourses. Urban planning researchers and planning journals have been less inclined to this approach than water journals and urban hydrology specialists. Therefore, while in practice this approach should be integrated with urban development processes, in the field of knowledge and research WSUD should also be seriously considered by urban planning researchers and relevant journals.

4. Conclusion

This study has examined the historical evolution and development trajectory of WSUD, shedding light on its transformation from a predominantly technical and engineering-based approach to one increasingly situated within broader urban planning and design frameworks. Through a systematic review of 688 scholarly publications and a content analysis of the 30 most influential articles, the research has mapped the intellectual foundations of WSUD, identified critical turning points in its development, and traced the diffusion of the concept across geographical and disciplinary boundaries. By combining bibliometric techniques with qualitative content analysis, the study has provided a comprehensive overview of the scholarly landscape, highlighting the major contributors, institutions, and journals shaping WSUD discourse over the past three decades.

The findings suggest that WSUD has become a prominent framework in urban water management, particularly in the Australian context, where it has been supported by institutional mechanisms, policy initiatives, and research investment. Yet the concept remains unevenly integrated into urban planning discourse globally, with much of the highly cited literature still concentrated in water and environmental science journals. This disciplinary clustering underscores the need for greater interdisciplinary engagement between water engineers, urban planners, designers, social scientists, and policymakers. The study also reveals persistent knowledge gaps in the literature, particularly concerning the socio-economic dimensions of WSUD, its long-term performance and monitoring, and its integration into existing urban governance structures.

Several implications emerge from this analysis. First, there is a clear need to strengthen the institutional and regulatory frameworks that support WSUD implementation, particularly in contexts where fragmented governance and lack of coordination across sectors act as barriers. Second, more robust mechanisms for performance evaluation and adaptive management are required to ensure that WSUD initiatives deliver measurable outcomes in terms of water quality, urban livability, and climate resilience. Third, there is an urgent need to mainstream WSUD into planning education and professional practice so that it is not treated as an environmental add-on, but as a core component of sustainable urban development. Finally, researchers and practitioners should actively engage with underrepresented contexts, particularly in the Global South, where locally tailored WSUD approaches may offer valuable insights but remain absent from global citation networks.

Theoretically, this study contributes to the growing body of literature on integrated urban infrastructure by clarifying how WSUD has evolved conceptually and where it sits in relation to complementary approaches such as Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), Green Infrastructure (GI), and Nature-Based Solutions (NBS). Practically, it highlights the importance of knowledge transfer between research and policy, and between global frameworks and local practices. It also identifies the value of bibliometric and citation network analysis in making visible the dynamics of scholarly attention and influence, while acknowledging the limitations of such methods, particularly their tendency to overlook innovative, practice-based work that lacks citation visibility.

In conclusion, this research contributes to a more nuanced understanding of WSUD's intellectual development and practical relevance. It underscores the importance of interdisciplinary collaboration, locally informed strategies, and long-term commitment to institutional learning in achieving water-sensitive urban futures. By identifying key gaps, limitations, and emerging directions in WSUD research, this study lays the groundwork for more adaptive, inclusive, and context-sensitive planning practices that integrate water management into the heart of urban development.

Disclosure statement

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