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Review

Bioswales as Engineering Functions of Nature-Based Solutions to Increase Urban Resilience: A Review

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ABSTRACT

The increasing challenges posed by climate change are having a more pronounced impact on urban areas than ever before. To ensure the well-being of urban residents, it is imperative to allocate resources for both theoretical knowledge and practical implementation of urban green infrastructure in adaptation and mitigation measures.

Nature-based solutions offer a multifaceted approach to addressing these complex challenges. Among these innovative strategies, bioswales emerge as a fundamental and widely adapted element in urban areas, designed to manage stormwater runoff effectively. The successful implementation of bioswales relies on factors such as the choice of materials, orientation, and location within the urban landscape.

A systematic literature review was conducted to establish a comprehensive framework for the use of bioswales concerning ecosystem services and their impact on the quality of urban residents' lives. This review aimed to scrutinize case studies that examined the selection and engineering aspects of bioswales based on site-specific and climatic conditions, available resources, performance, maintenance, and design decisions. The resulting framework promotes the use of bioswales in the aspect of technological, natural, and socio-economic systems for the sustainable resilience of the cities.

The research findings suggest that by optimizing the integration of bioswales with urban elements and improving maintenance practices, there is the potential for a significant and lasting improvement in the quality of urban life. Given the complex landscape of governmental policies and the limited body of research addressing the accessibility and engineering system of nature-based solutions, there is a need for future investigations that involve real-life implementations and additional case studies.

Keywords: Bioswales, ecosystem services, green infrastructure, nature-based solutions, urban resilience

Introduction

Climate change is the difference between the temperature degrees and weather conditions at certain extended periods that impact the world and its resources. These effects need urgent precaution to minimize the impairment of the natural environment (Byrne et al., 2015). There are measures to take, such as adaptation and mitigation strategies, that enhance the ability to prevent and adapt to specific circumstances of the consequences of climate change, such as disastrous events (Emmanuel & Loconsole, 2015; Rojas-Downing et al., 2017). These events arise from alterations in the natural cycle, resulting in the loss of natural resources. Additionally, they can induce problems including reduced quality of living, human health, well-being, and property value (Gill et al., 2007; Matthews et al., 2015; Venkataramanan et al., 2019).

Hydraulic events, primarily due to deterioration in the hydrologic cycle of the world, are affected by increased temperatures, changing sea levels, water depth, floods, landslides, and river scour and deposition (Trajkovic et al., 2016).

Due to the further expected implications on the urban collecting networks, while regaining stormwater, the contamination and toxicity linked with urban stormwater runoff are the emerging and exceedingly critical challenges of climate change (Behbahani et al., 2022). Stormwater may be absorbed, transferred, treated, and infiltrated through bioswales, which are longitudinal, planted trenches. They may be utilized to develop stormwater networks that are more eco-friendly while simultaneously contributing native vegetation to the area (Spahr et al., 2020).

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The purpose of this paper is to comprehend the applications of urban green infrastructure (UGI), with a focus on bioswales, and to examine various sustainable urban resilience techniques through a systematic literature review of related case studies. This review also includes research results that indicate how bioswales lessen volumes of airborne metals, hydrocarbons, and particles (Anderson et al., 2016). Bioswales, as nature-based solutions, address sustainable treatment methodologies for enhancing urban resilience from various perspectives. Some of the beneficial impacts of bioswales, according to the American Society of Landscape Architects (ASLA, n.d.), are as follows:

- Lower runoff: In a normal street, a 4-meter (13-foot) swale may reduce runoff by around 25%.
- Lowered contamination: Bioswales lower pollution by filtering stormwater runoff using organic topsoil and plants.
- Charged-up groundwater: Stormwater could be treated and perhaps restored to local rainwater rather than being discharged into the sewage network.
- Increased energy performance: Ecological methods ease the burden on current infrastructure and lower the budget of operation in integrated stormwater treatment networks (ASLA, n.d.).

To address multiple hydrologic scenarios such as floods, fast population rise, and environmental degradation, urban stormwater control must adopt a variety of distinct approaches as cities face climate change and flooding risks worldwide (Xu et al., 2023).

In urban ecosystems, which are composed of natural (vegetation, wildlife, and many varieties of life forms) and physical (soil, water, air, weather, and landscape) modules, the natural compound also incorporates inhabitants, their demographic characteristics, their economic establishments, and the cultural-financial instruments they utilize as well (Mugume, 2015).

The physical complexity, which refers to gray infrastructure, consists of buildings, nodes of transit, altered terrain (such as car parks, rooftops, and vegetation), and environmental changes. Also, that physical complexity contains various processes that are effective on energy consumption, import–export transits, and materials along with contamination, waste, and heating (Dong et al., 2017). Therefore, to implement the composition of UGIs in line with gray infrastructure is inevitable. Studies on the benefits and drawbacks of gray infrastructure, such as building drainage networks, underground tubes, pipeline systems, and other urban artificial constructions, are also vital (Chen et.al., 2021). Hybrid strategies of urban green–gray infrastructure, which should be advanced to solve the mentioned problems, require both local and national planning and strategy to implement and maintain. Therefore, relevant institutions and governmental authorities should post organizational-level improvements and collaborative participant involvement (USEPA, 2010; Mark et. al., 2006). Those strategies are directly related to the European sustainability goals of 11 (sustainable cities and communities), 13 (Climate action), 14 (Life below water), and 15 (Life on land). Participation involvement of the authorities is also related to goals 16 (Justice and strong institutions) and 17 (Partnership for the goals).

To perform this, regional control organizations and the municipal authority must establish industry skills and education initiatives to encourage participants in their operations, increase experimental facilities, and limit harmful ecological consequences such as insufficient runoff and application of chemicals (Duman & Şat, 2022).

Material and Methods

This paper follows a qualitative methodology that focuses on the literature review results of previous papers that are related to the subject of the manuscript (MS). A table is composed of the findings of the literature review. The table includes some categories depending on the results of keyword screening.

Three keywords have been chosen, which are directly related to the subject of the MS. These are namely C1: green infrastructure; C2: nature-based solutions; and C3: ecosystem services. While C1, as GI, is the main subject of the MS, since the problem statement is directly related to UGIs, C2 and C3 keywords are the sub-subjects of the MS. Nature-based solutions and ecosystem services are the keywords that determine and specify the scope of UGIs (Akbari, 2001; Church, 2015; Farrugia et.al., 2013).

The C2 keyword, nature-based solutions, is selected since it comprises various applications, tools, and strategies to tackle community concerns, including climate change successfully and efficaciously, public wellness, agriculture, resource protection, and hazard-preventative risk measures. The relevant research results should be addressed well since such activities may also enhance both people's health and biodiversity (Cameron et al., 2012).

The C3 keyword is selected ecosystem services, where the ecosystem is solely identified as "a set of interacting species and their local, nonbiological environment functioning together to sustain life" (Moll & Petit, 1994). For this reason, ecosystem services are linked with urban resilience. Costanza et al. (1997) identify ecosystem services as "the advantages human populations obtain, directly or indirectly, from ecological functioning" and outline 17 main types of ecosystem services. Several such ecological services are vital to preserving ecosystems but are not explicitly used by people. The categorization of those secondary services, which also include vegetation fertilization and biogeochemical cycles, is ambiguous (Bolund & Hunhammar, 1999).

This study reviews findings that include a selection of ecosystem services delivered by urban ecosystems and evaluates the potential significance of urban living quality. The focus is on recognizing these services and, if they are feasible, estimating their value, with examples from diverse locations offering the most relevant scenarios.

By the chosen keywords, three combinations of C1, C2, and C3 are performed and searched through the research database of Web of Science (WoS) as follows:

- X: C1 and C2 – Green infrastructure and nature-based solutions.
- Y: C2 and C3 – Nature-based solutions and ecosystem services.
- Z: C1 and C3 – Green infrastructure and ecosystem services.

While screening for the keywords, a refining keyword of "Bioswale" is also used, which is one of the major applications in nature-based solutions to increase urban resilience and decrease flood risk (Everett et al., 2018).

All research findings from WoS are recorded into a spreadsheet for further examination using the PRISMA Flow Chart, which has methodological steps of identifying, screening, eliminating, and including (Figure 1). The research was conducted in the year 2022 without considering a specific period.

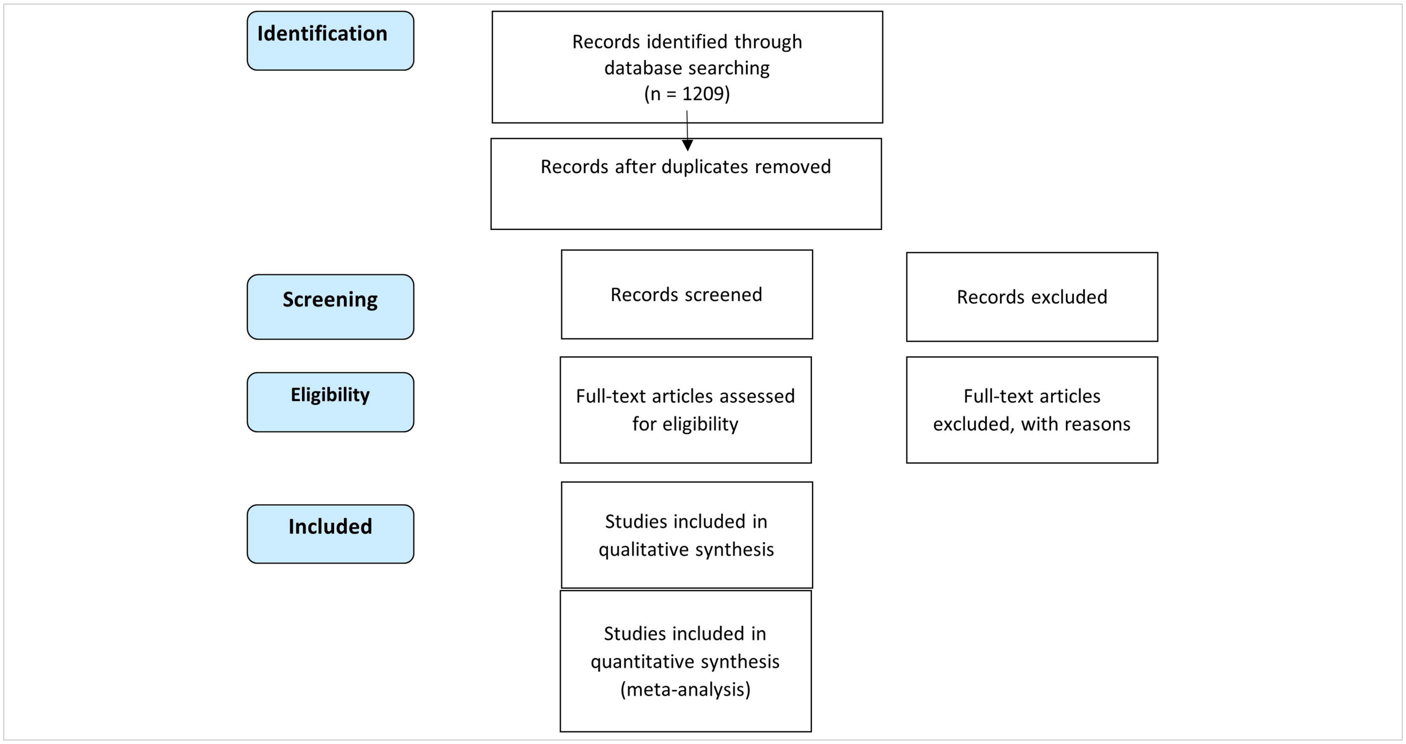

Figure 1.
PRISMA Flow Diagram (Adapted from Moher et al., 2009).

A 4-step criterion is determined for the PRISMA Flow Chart, which starts with the first manual screening of identification. During the first step, the duplicates from three keyword combinations are removed from the spreadsheet.

After the removal of duplicates, it was initially decided that the identification criteria for the data could be used to spot the specific keywords' high relation by scanning through the ordered titles. To decide if the results are sufficient for admission, the abstract contents have first been skim-read.

The research titles and their abstracts containing the precise keywords have all been chosen and passed to the second screening step. Screening involved these individual records, and it was done by identification from specific resources (Journals, articles, etc.) and the accessibility of the full manuscripts.

The elimination step has been completed by the field of the research area, abstract, and skim-read evaluation of results-discussion or conclusion. Also, the research type and methodologies are one of the determinants of removing irrelevant data and theoretical knowledge.

Accordingly, all the findings are composed as a systematic table with relevant categorization. The categories below are selected to evaluate the stages of the applications. The success of the applications in the name of economic benefits, human well-being impacts (mental/physical), and urban resilience for flood risks.

- Site location (country) and the climatic conditions (features of the area).
- Vacant capital levels (size of the application area and cost-feasibility).
- Performance and maintenance ability (sustainability, period)
- Decisions based on design stages (application process)
- Data collection method—qualitative/quantitate/both

Results and Discussion

As mentioned in the "Material and Methods" section, five issues are considered in applicational research papers. Those were: 1—location and climatic conditions, 2—size of the application area and cost feasibility, 3—sustainability aspect, 4—application processes, and 5—data collection methodology. In the evaluation stage, three categories were used for eliminating the papers, namely: 1—economic benefits, 2—human well-being, which is directly related to ecosystem services as one of the keywords, and 3—urban resilience for flood risks. The evaluation stage requires careful reading of the papers and qualitative classification of the content. So, the table occurred after all those readings. Fourteen papers were investigated after all the eliminations and took place in the categorized table. According to the recorded findings in Table 1, the majority of trials and investigations on green stormwater management have been conducted at the parcel level. If we expand this parcel level, we should mention urban stormwater management. Three levels of urban stormwater management are the micro level as parcel level, the meso level as community and neighborhood level, and the macro level as regional or city level (Xu et al., 2023). Despite the results indicating limited construction of green stormwater infrastructures, enhancements to the provision, moderation, sociocultural, and maintenance of ecosystem services are evident. To finalize the assessment of the green stormwater treatment effectiveness in the provincial consequences, further study of the drainage is necessary.

The studies addressed application challenges and provided concepts or methods for implementing green flood control. Models were created for various cities and areas to facilitate decision-making and the

Table 1.
PRISMA Flow Records According to Selected Categories

Author Full Names (Paper Reference Numbers)	Article Title	Source Title	Publication Year	Keywords	The Site Location (Country)	Design Stage	Data Collection Method
Scherer, B and Sehuttrumpf, H (37)	Nature-based solutions in coastal research— A new challenge for coastal engineers?	10th International Conference on Asian and Pacific Coasts (APAC)	2020	Nature-based solutions Ecosystem services green infrastructure ecosystem engineering	Gray coastal city level	Research	Qualitative
Frantzeskaki, N (20)	Seven lessons for planning nature-based solutions in cities	Environmental Science & Policy	2019	Nature-based solutions, Cities, Climate adaptation, Urban resilience	Neighborhood and city levels	Research, Renovation	Qualitative
Acosta, F and Haroon, S (1)	Memorial parking trees: Resilient modular design with nature-based solutions in vulnerable urban areas	Land	2021	Nature-based solutions; Environmental justice; Geographic information systems; Urban resilience; Green infrastructure; Sustainable urban design; Urban vulnerability	Regional city level	Renovation	Quantitative
White, C; Collier, MJ and Stout, JC (42)	Using ecosystem services to measure the degree to which a solution is nature-based	Ecosystem services	2021	Nature-based solutions ecosystem services; Ecosystem management method; Sustainability	The metropolitan scale	Research, Implementation	Quantitative, Qualitative
Pan, HZ; Page, J; (...); Kalantari, Z (32)	How ecosystems services drive urban growth: Integrating nature-based solutions	Anthropocene	2021	Nature-based solutions; Land use/cover change; Ecosystem services; Ecosystem service supply and demand; Social-ecological system	Land-based, 30 × 30 m grid	Research	Quantitative
Xuezhu, Z; Lange, E (43)	Using social media To explore perceptions of ecosystem services by nature-based solution projects	Landscape architecture frontiers	2020	Nature-based solutions; Wetland park; Ecosystem services	Regional city wetland parks	Research	Qualitative
Prudencio, L and Null, SE (34)	Stormwater management and ecosystem services: A review	Environmental research letters	2018	Green infrastructure; Managed aquifer recharge; Low impact development; Stormwater harvesting	Worldwide	Research	Qualitative
Liao, KH; Deng, SN and Tan, PY (23)	Blue-green infrastructure: New frontier for sustainable urban stormwater management	Greening cities: Forms and functions	2017	Blue-green infrastructure; Sustainable stormwater management; Ecosystem-based solutions; Ecosystem services; Low-impact development; Urban drainage	Regional city level	Research, Renovation	Qualitative
Elderbrock, E; Enright, C; (...); Rempel, AR (16)	A guide to public green space planning for urban ecosystem services	Land	2020	Green infrastructure; Urban planning; LiDAR/NDVI; Stakeholders; Delphi analysis	Neighborhood level	Research, Implementation	Quantitative
Papuga, SA; Seifert, E; (...); Hwang, K (33)	Ecohydrology of green stormwater infrastructure in shrinking cities: A two-year case study of a retrofitted bioswale in Detroit, MI	Water	2022	Urban green, Water use efficiency; Soil moisture; Combined sewer systems; Green infrastructure; Ecosystem services	Campus level—308 m^2 Bioswale	Implementation	Quantitative, Qualitative
Hoover, FA; Price, JI and Hopton, ME (22)	Examining the effects of green infrastructure on residential sales prices in Omaha, Nebraska	Urban Forestry & Urban Greening	2020	Green infrastructure; Ecosystem services; Greenspace amenity; Residential property sales; Hedonic analysis	Urban public parks	Research, Renovation	Quantitative, Qualitative

(*Continued*)

Table 1.
PRISMA Flow Records According to Selected Categories (Continued)

Author Full Names (Paper Reference Numbers)	Article Title	Source Title	Publication Year	Keywords	The Site Location (Country)	Design Stage	Data Collection Method
Battisti, L; Pille, L; (...); Saumel, I (5)	Residential greenery: State of the art and health-related ecosystem services and disservices in the city of Berlin	Sustainability	2019	Allergenic potential; Ecosystem services; Green gentrification; Wellbeing; Multifunctional living environments; Urban horticulture	Neighborhood level	Research, Implementation	Quantitative, Qualitative
Rainey, W; McHale, M and Arabi, M (35)	Characterization of co-benefits of green stormwater infrastructure across ecohydrologic regions in the United States	Urban Forestry & Urban Greening	2022	Green infrastructure systems; Rain gardens; Permeable pavement; Bioswales	Regional city level	Research, Implementation	Quantitative, Qualitative
Matsler, AM (26)	Making "green" fit in a "gray" accounting system: The institutional knowledge system challenges of valuing urban nature as infrastructural assets	Environmental Science & Policy	2019	Green infrastructure; Asset management; SETS; Knowledge systems; GASB; SASB; Standardization	Regional city level	Research	Quantitative, Qualitative

regional flood-planning process. Based on the results of the literature research, city and regional-level implementations (cty and regional-level case paper reference numbers; 1, 22, 23, 26, 35, 37, 42, 43) of the UGIs come first, rather than the neighborhood level (neighborhood-level case paper reference numbers; 5, 16, 20, 33). However, bioswale applications, as one of the most effective nature-based solutions, can be applied in medians on streets and avenues in terms of scale and are compatible with the neighborhood level (Li et al., 2005).

Based on literature reviews and case reports, researchers designed models, focusing their methodologies on the use of green flood control facilities. The aim was to compensate for ecological systems displaced by urban growth, adapt to climate change, and integrate various ecosystem services into flood control. Various reports outlined broad connections between green flood infrastructure and ecological processes or correlations that were expected to be present. More frequently, regulatory functions are measured using a variety of indicators, such as carbon buildup and phosphate deposition, that are directly related to ecosystem services (Bhomia et al., 2015; Merriman et al., 2017).

Existing studies assess the utilization of bioswales as nature-based solutions to enhance urban resilience. The findings demonstrate that bioswales play a crucial role in stormwater management, reducing flood risks, and enhancing urban green spaces. Their increased incorporation into urban planning and engineering practices, coupled with the development of guidelines for authorities, could significantly contribute to urban areas becoming more resilient to environmental changes. This also suggests the potential for further research in this field.
In conclusion, this literature review highlights that bioswales may offer an important nature-based solution to increase urban resilience. With functions such as rainwater management, flood risk reduction, and increasing urban green areas, bioswales can contribute to urban areas becoming better prepared against environmental threats. It is also clear that more research needs to be done on this topic, as there is potential for the applicability and effectiveness of this solution in urban areas. Therefore, it is predicted that bioswales may play a greater role in urban sustainability and resilience in the future.

Another evaluation is that there were no notable regional tendencies in the findings on ecological services and efficient flood control. Lastly, it is necessary to integrate technological, economic, and ecological factors to determine the optimum suitable and efficient flood facilities and to assess cross-disciplinary linkages for comprehensive runoff decision-making and administration.

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