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Systematic Review

Advancing Urban Flood Resilience: A Systematic Review of Urban Flood Risk Mitigation Model, Research Trends, and Future Directions

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Abstract: Climate change has increased the frequency of extreme weather events, challenging traditional flood risk assessments. New methods, like InVEST's urban flood risk mitigation model (UFRM), are crucial for assessing flood-prone areas, especially those vulnerable to pluvial flooding. This systematic review examines the utilization and limitations of the UFRM model for identifying flood-prone areas and designing adaptation plans in response to climate change, based on research articles published between 2019 and 2024. The articles were identified through Scinapse and Google Scholar using predefined criteria, including relevance to UFRM applications and publication within the specified timeframe. An analysis of the 21 selected papers using bibliometric techniques reveals geographic concentrations of the case studies that utilized the UFRM model primarily in Italy, Turkey, China, and the United States, with notable research gaps in Central Europe. The journal publication trends highlight the prominence of certain journals, such as the Journal of Land. A network analysis using VOSviewer identifies thematic clusters aligned with the UFRM research areas, including Urban Planning and Nature-Based Solutions (NBSs), Urbanization and Sustainable Development, the Economic and Social Effects of Flood Mitigation, Adaptation and Risk Management, and Resilience and Vulnerability. This review contributes to gaining a deeper understanding of the research landscape regarding the utilization of the UFRM model and provides recommendations for advancing sustainable and resilient urban development practices. The review was not preregistered in a formal registry. The finding reveals that integrating automation and optimization tools to suggest different solutions for problematic nodes in urban areas is crucial for addressing multiple issues simultaneously and optimizing adaptation plans effectively.

Keywords: urban flood risk; flood resiliency; inclusive urban planning; ecosystem services

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1. Introduction

Climate change is a phenomenon that has profoundly challenged life on Earth in numerous ways [1,2]. It entails long-term shifts in temperatures and weather patterns, primarily driven by human activities such as burning fossil fuels, which elevates the heat-trapping greenhouse gas levels in the Earth's atmosphere [3,4]. These changes manifest in a wide array of observed undesired effects, including rising global temperatures, rising sea levels, ice melting, extreme weather events, and alterations in vegetation cover [5–7]. Moreover, climate change can significantly modify ecosystem services in various ways [8–10]. Ecosystem Services (ESs) are defined as the benefits people derive from natural environments and ecosystems [11–13]. ESs form the link between human well-being, natural systems, and ecological and economic development, serving as a bridge between nature and society [14,15]. ESs can be categorized into three main types of provisioning, regulation and maintenance, and cultural [16].

Urbanization has intensified environmental challenges, including flooding, pollution, and habitat loss. To mitigate these issues, strategies such as nature-based solutions (NBSs), which refer to the actions that harness natural processes to address societal challenges, and green infrastructure (GI), a network of natural and semi-natural features delivering ecosystem services, have gained prominence [17,18].

Unfortunately, climate change significantly affects ESs, impacting their quality and quantity over time. Its influence is extensive and diverse, disrupting supporting services like biomass production, nutrient cycling, and soil formation, as well as provisioning services such as food, water, and resources [19]. Additionally, regulating services like air quality, flood control, and microclimate regulation are also affected. Furthermore, cultural services like tourism, recreation, and aesthetic values are at risk of decline due to climate change impacts [20–23]. Naturally, taking into account their importance and the inevitable changes due to climate change, efforts have been put into understanding the way ESs function and how they are affected by climate change, so adaptation and mitigation measures can be implemented to preserve them for future use by humans and also for environmental sustainability [24,25]. However, measuring and mapping ESs to support decision-making in urban planning is complex, time-consuming, and requires a lot of knowledge [26–28]. In fact, mapping is only a fraction of the process that drives the so-called "adaptive planning" [29,30] because the interpretation of results and their practical utilization requires interdisciplinary collaboration between experts to understand the ecological, economic, social, and cultural aspects [31]. Moreover, ESs operate at various spatial and temporal scales [32–34], necessitating a comprehensive data collection and analysis to capture their full impact and variability. These challenges underscore the importance of effectively measuring and studying ESs to inform decision-making and conservation strategies [35–37]. In recent years, various tools have been created to map them. These include i-Tree, ARIES (Artificial Intelligence for ES), Costing Nature, and SolVES (Social Values for ES). However, these tools just represent a way to spatialize ecosystems in a space. But the site-specificity, the interpretation, the reliability, and the use of maps are typically a context-based action that depends on the planning target. However, maps provide tangible support for urban decision-making since the spatial knowledge of the ESs' delivering capacity can be used to identify the vulnerable areas and then enact local climate adaptation strategies, zoning regulations, biodiversity conservation, or flood control [9,38–40].

Among these tools, InVEST (Integrated Valuation of ES and Trade-offs) can be used as it covers a wide array of scopes [41]. It is a suite of free, open-source software models, which maps and values nature's goods and services which are vital for human sustenance. With multiple models for mapping and valuing ESs, along with supporting tools for data preparation and visualization, InVEST aids with decisions on natural resource management on various scales, helping to understand how the ecosystem changes affect the benefits to people. The software can be employed for quantifying natural capital, evaluating trade-offs, and integrating conservation with human development.

Recently, a lot of attention on modeling has been dedicated to the issue of temporary flooding [42–45]. Due to a higher frequency in urban areas, flooding has boomed as one of the main targets of city adaptation. In fact, one of the consequences of climate change affecting flood protection is how extreme weather events are becoming more and more frequent, thus flood-prone areas largely extend over the traditional riverine protection areas [45–47]. While fluvial flooding is caused by riverbanks overflowing due to excessive rainfall or snowmelt, pluvial flooding occurs when intense rainfall overwhelms drainage systems, leading to surface runoff and water accumulation in urban areas [47]. The latter is particularly problematic in cities, as urbanization has increased the number of impervious surfaces, reducing water absorption and leading to greater surface runoff [17]. This issue calls for new methods for identifying flood-prone areas, especially in dense urban catchments where pluvial flooding can be more frequent and dangerous than fluvial flooding [44,48]. At the same time, being geometrically precise in locating vulnerable areas

is key to calibrating and designing adaptation plans. InVEST's urban flood risk mitigation (UFRM) model is a helpful tool in this regard. The urban flood risk mitigation (UFRM) model is a recent (2019) product of InVEST.

As noted earlier, the UFRM model is specifically designed to address pluvial flooding. Firstly, the model assesses the supply, which represents water retention during storm events, determining how much water infiltrates rather than contributing to the direct runoff, thereby potentially increasing the flood risk. Secondly, it calculates the service, which denotes the reduction of the floodwater volume in susceptible areas, including transpiration and evapotranspiration in the equation [49].

Lastly, it quantifies the economic value, calculated as the prevented flood damage. To compute the supply, UFRM implements the Soil Conservation Service (SCS) curve number method, which essentially calculates the direct runoff based on a soil hydraulic conductibility classification [50,51]. The accuracy of this method heavily relies on factors such as land use, land cover, soil type, and antecedent moisture conditions. Essentially, the model employs this method to calculate the runoff for each pixel by subtracting the storm value from the infiltration rate. The model inputs encompass the climate (design storm depth in millimeters), soils (hydrologic soil group), land use/land cover (LULC, curve numbers per hydrologic soil group), watersheds (areas draining into flood-prone regions), flood-prone areas, and optionally, buildings for assessing damage costs. Ultimately, the model produces outputs in both the shapefile and raster formats. This process is illustrated in Figure 1.

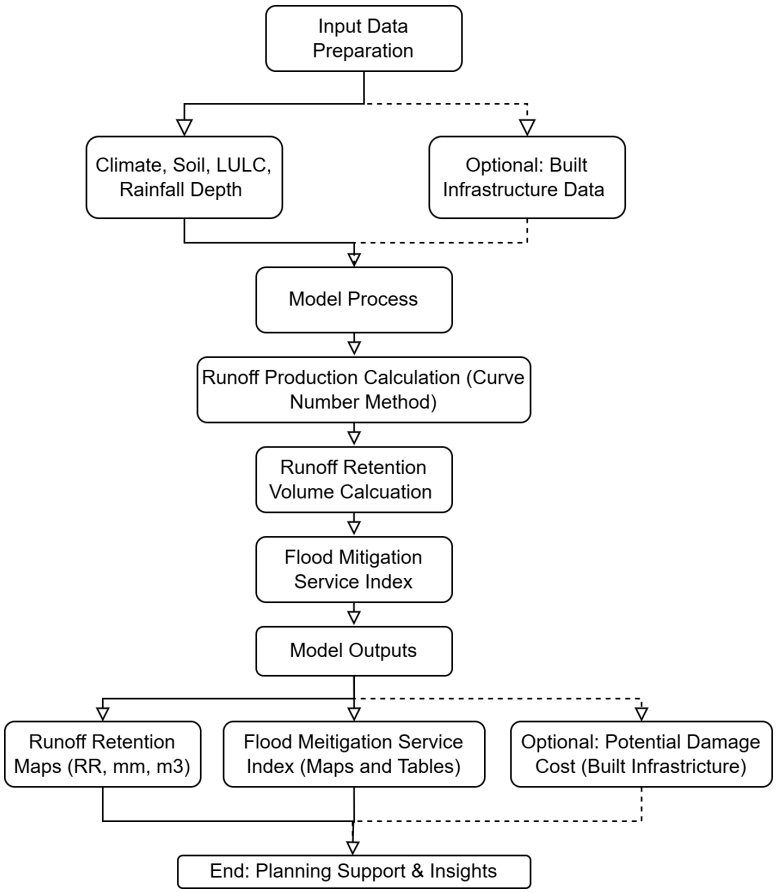


Figure 1. Workflow of the UFRM Model in InVEST.

In this study, a systematic and quantitative literature review on the topic of UFRM has been performed. The aim is to identify the relevant research papers published between 2019 and 2024 that address the integration of ES assessments and trade-offs within the context of urban flood risk management. The article aims to evaluate and analyze the selected

papers using bibliometric analysis techniques, including a keyword co-occurrence analysis, to uncover recurring themes, methodologies, and trends in the literature. Additionally, the goal is to visually represent the bibliometric analysis results using VOSviewer software, providing insights into the relationships among the variables and the significance of the attributes within the literature. Through this comprehensive analysis, the article seeks to contribute to a deeper understanding of the research landscape surrounding UFRM by finding the limitations and constraints of the model and suggesting possible solutions and future research directions.

2. Materials and Methods

2.1. Article Exploration Approach

This article undertook a systematic and quantitative literature review of research papers published in scientific journals. The PRISMA 2020 Checklist [52] has been used as a guide for the review process. No formal review protocol was prepared for this systematic review and the review has not been registered in a formal registry. The review followed the established guidelines, including the PRISMA 2020 checklist, to ensure methodological rigor and transparency. The search for relevant articles was conducted in February 2024 using two online platforms: Scinapse and Google Scholar. On Scinapse, three advanced filters were applied. Initially, the papers matching the keywords "Integrated Evaluation of Ecosystem Services and Trade-offs" were included. Subsequently, the papers containing any of the keywords "flood", "flooding", or "floods" were incorporated. Finally, since the UFRM, which is the focus of this review, was introduced in 2019, an additional filter was applied, limiting the results to the papers published between 2019 and 2024, resulting in 36 matches. In Google Scholar, the phrases "Integrated Valuation of Ecosystem Services and Trade-offs" AND "Urban Flood Risk Mitigation model" were searched, with results bounded to the years 2019 to 2024, resulting in 38 documents.

2.2. Evaluation and Eligibility

After screening all the identified documents and eliminating the duplicate entries using EndNote, a total of 63 articles remained for further inspection. The review process was conducted by two independent reviewers. Each reviewer screened the titles, abstracts, and keywords independently to minimize bias. Discrepancies were resolved through discussion or by involving a third reviewer.

During the data extraction phase, any missing or incomplete information (e.g., missing publication years, incomplete citation data) was addressed by cross-referencing with additional sources such as Scopus or the original publications. Where summary statistics were unavailable, efforts were made to derive or estimate these values based on other reported data, or the study was excluded from the quantitative synthesis. The risk of bias due to missing results was assessed qualitatively by ensuring diverse data sources and examining the consistency in outcome reporting across the studies.

Many of the excluded articles were deemed irrelevant because they were either review articles or utilized models other than UFRM, focusing instead on different ecosystem issues, such as water pollution or biodiversity, rather than the primary focus of the present review paper. The final count of papers deemed eligible for inclusion in the review was 21.

2.3. Bibliometric Analysis

The initial citation data, encompassing details such as the title, authors, source title, publication year, and total citations, were sourced from Google Scholar. The findings, including the publication years, funding agencies, affiliations, source titles, and countries/regions, were analyzed using Excel, with the results presented in the final section in the form of several charts.

Bibliometric methodologies were employed to extract several insights, utilizing techniques such as keyword co-occurrence. These methods allowed for the identification of highly cited publications, recurring keywords, and the clusters of indicative document

similarities. Since the UFRM model has gained widespread adoption across scientific fields, including urban planning, environmental sciences, and social sciences, utilizing VOSviewer proves advantageous for organizing the study's aspects, streamlining the analysis, and identifying trends. The network theory involves studying the relationships between interconnected elements using mathematical and computational tools [53,54]. In the case of the present review, VOSviewer employs this theory to cluster the keywords from the papers reviewed by the authors, facilitating an easier analysis. The keywords served as channels for unveiling the research themes, methodologies, and trends [55,56] in regard to the topics followed by this research. The bibliometric analysis was visually represented using VOSviewer, a Java-based software capable of generating network visualizations [19]. After setting a minimum threshold of two occurrences, relationships among the variables (in our case, index keywords) were established, whether through co-occurrence or co-citation. The significance of the attributes was determined by the strength and frequency of the connections, reflected in the size of the nodes within the visualization [57]. The data inputs utilized in VOSviewer were bibliometric export files obtained in CSV format from the Scopus platform. This format enabled their processing and visualization within the mentioned software.

3. Results

3.1. General Statistics of Publications

The Methodology Section outlined the process for identifying the relevant papers using the specified keywords, resulting in a pool of 21 papers for analysis in this study. The general characteristics of the analyzed papers, including their publication year, journals, affiliations, citations, funding organizers, and authors, are presented in Table 1. The limited number of papers associated with these keywords can be attributed to the recent introduction of the UFRM model in 2019. An examination of the publication and citation counts, depicted in Figure 2, reveals a consistent upward trend reaching its peak for both the publications and citations in 2023. A comprehensive analysis of all selected papers and their outcomes is provided in Appendix A.

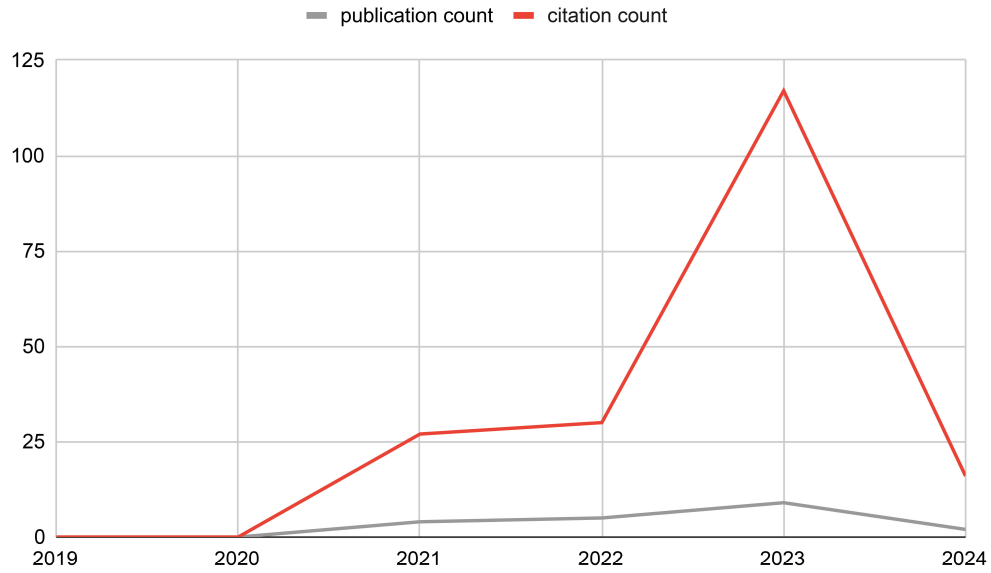


Figure 2. Publication and citation count of analyzed papers, source: authors.

Table 1. Details regarding the analyzed scientific papers (alphabetically ordered by authors' names).

Authors	Title	Reference Number	Year	Source Title	Cited by	Affiliations	Funding Organizations
AlRuheili, 2022	A tale of Shaheen's cyclone consequences in Al Khaboura City	[58]	2022	Water (Switzerland)	8	Sultan Qaboos University	-
Biasin et al., 2023	Nature-based solutions modeling and cost-benefit analysis to face climate change risks in an urban area: the case of Turin (Italy)	[17]	2023	Land	8	University of Padova	-
Costadone et al., 2024	Co-creating urban ecosystem accounting: physical and monetary accounts of runoff retention service provided by urban green spaces	[59]	2024	ES	0	Finnish Environment Institute	-
Da silva, Campos & Paz, 2023	Spatiotemporal land-use and land-cover changes and associated runoff impact in Itaperuna, Brazil	[60]	2023	Sustainability (Switzerland)	0	Instituto Militar de Engenharia	Coordination of Superior Level Staff Improvement (CAPES Foundation)
Egegård et al., 2024	Climate proofing cities by navigating nature-based solutions in a multi-scale, social–ecological urban planning context: a case study of flood protection in the city of Gothenburg, Sweden	[61]	2024	Land	0	University of Gävle; Royal Swedish Academy of Sciences; Chalmers University of Technology	Mistra and Formas via the national research program on climate; University of Gävle; Beijer Institute of Ecological Economics; Formas; Chalmers University of Technology

Table 1. *Cont.*

Authors	Title	Reference Number	Year	Source Title	Cited by	Affiliations	Funding Organizations
Hamel et al., 2021	Mapping the benefits of nature in cities with the InVEST software	[62]	2021	Npj (Nature Partner Journals) Urban Sustainability	76	Stanford University; University of Washington; University of Minnesota; Chinese Academy of Sciences; Stockholm University; Paris-Saclay University; nature conservancy; Leiden University; spring research innovation network; University of Montpellier; Agro Paris Tech; Nanyang Technological University	Marianne and Marcus Wallenberg Foundation; FORMAS; LuEsther T. Mertz Charitable Trust; Nanyang Technological University; US Golf Association; Chinese Academy of Sciences; Ministry of Ecological Transition; ADEME; AgroParisTech; Nanyang Technological University
Li et al., 2023	Proactive intervention of green infrastructure on flood regulation and mitigation service based on landscape pattern	[63]	2023	Journal of Cleaner Production	3	Jiangsu University; Zhejiang University; Nanjing University	-
Li & Kim, 2022	Analysis of effects of sponge city projects applying the geo-design framework	[64]	2022	Land	2	University of Seoul	National Research Foundation of Korea (NRF)
Ma et al., 2022	A nature-based solution in forest management to improve ecosystem services and mitigate their trade-offs	[65]	2022	Journal of Cleaner Production	25	Nanjing Forestry University; Zheijiang academy of forestry	-
Marino et al., 2023	Linking flood risk mitigation and food security: an analysis of land-use change in the metropolitan area of Rome	[66]	2023	Land	11	University of Molise; Italian Institute for Environmental Protection and Research	Metropolitan City of Rome Capital
Ogawa et al., 2023	Capacity assessment of urban green space for mitigating combined sewer overflows in the Tokyo metropolitan area	[67]	2023	Land	0	Tokyo Institute of Technology	-

Table 1. *Cont.*

Authors	Title	Reference Number	Year	Source Title	Cited by	Affiliations	Funding Organizations
Quagliolo et al., 2023	Experimental flash floods assessment through urban flood risk mitigation (UFRM) model: the case study of Ligurian coastal cities	[68]	2021	Frontiers in Water	4	Politecnico di Torino; Università degli Studi di Torino	-
Quagliolo et al., 2021	Pluvial flood adaptation using nature-based solutions: an integrated biophysical–economic assessment	[69]	2023	Science of the Total Environment	0	Politecnico di Torino; Università degli Studi di Torino; University of Aveiro	-
Salata & Arsalan, 2022	Designing with ecosystem modelling: the sponge district application in İzmir, Turkey	[47]	2023	Land	0	Politecnico di Milano	-
Salata et al., 2021	Performance-based planning to reduce flooding vulnerability insights from the case of Turin (North-West Italy)	[70]	2022	Sustainability (Switzerland)	11	Izmir Institute of Technology	-
Salata et al., 2022	Adapting cities to pluvial flooding: the case of Izmir (Türkiye)	[71]	2021	Sustainability (Switzerland)	17	Izmir Institute of Technology; Politechnico di Milano; Politechnico di Torino	-
Salata, 2023	Filling the gaps in biophysical knowledge of urban ecosystems: flooding mitigation and stormwater retention	[49]	2022	Sustainability (Switzerland)	2	Izmir Institute of Technology; Politechnico di Milano	-
Sebastiani & Fares, 2023	Spatial prioritization of ecosystem services for land conservation: the case study of Central Italy	[72]	2023	Forests	5	Research Centre for Forestry and Wood; National Research Council of Italy	Ministry of University and Research of Italy
Wang et al., 2023	Multi-scale characteristics and drivers of the bundles of ecosystem service budgets in the Su-Xi-Chang region, China	[73]	2022	International Journal of Environmental Research and Public Health	1	Soochow University	National Natural Science Foundation of China; Jiangsu Social Science Foundation; State Key Laboratory of Urban and Regional Ecology

Table 1. *Cont.*

Authors	Title	Reference Number	Year	Source Title	Cited by	Affiliations	Funding Organizations
Watson et al., 2021	Does agricultural intensification cause tipping points in ecosystem services?	[74]	2021	Landscape Ecology	21	Bournemouth University; UK Centre for Ecology and Hydrology; University of Plymouth	-
Zhao et al., 2023	Investigating urban flooding and nutrient export under different urban development scenarios in the Rouge River Watershed in Michigan	[75]	2023	Land	0	University of Michigan; Cornell University; NYU; Stern University of Business	-

Figure 3 and Table 2 demonstrate that most case studies are concentrated in Italy, Turkey, and China, with the United States occupying the fourth position. An analysis of the geographical distribution of these case studies highlights a notable research gap in certain regions, for instance, in Central Europe. In other areas of the world, at least one country has implemented UFRM in an article (China in East Asia, Turkey in the Middle East, Italy in Western Europe, Brazil in Latin America). Regarding the affiliations in the papers, as demonstrated by Figure 4, they are mostly situated in the geographical location of the case studies, except the University of Seoul. This result can be related to the fact that modeling UFRM requires a significant amount of site-specific inputs that can only be found locally. Since the trend of publication in this field is exponentially growing, the expectation that in the future the implementation of UFRM will probably be extended to a broad geographical setting will enrich the case study representation, also accounting for different climatic and urban environments.

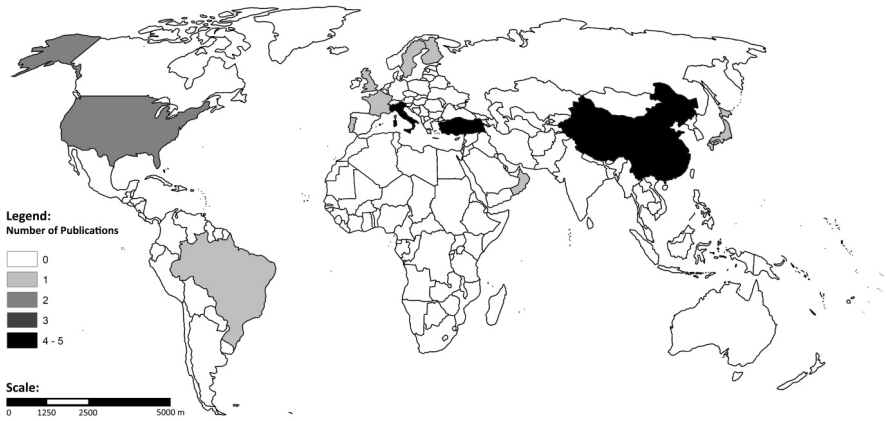


Figure 3. Geographical distributions of case studies, source: authors.

Table 2. Number of publications per case study, source: authors.

Case Study	Italy	China	Turkey	USA	Oman	Finland	Brazil	Sweden	France	Japan	Portugal	England
Number of publications	5	5	3	2	1	1	1	1	1	1	1	1

Considering Figure 5, which displays the publication count of different journals contributing to the subject of UFRM, it is worth noting that the Journal of Land leads the ranking with seven published papers, closely followed by the Journal of Sustainability with four, and then the Journal of Cleaner Production with two publications. The rest of the presented journals have all published one paper in this regard. Now, upon observing Figure 6 and Table 3 which displays a line chart of two variables, the publication count and citation count for the journals, it is noticeable that the highest number of citations belongs to "npj Urban Sustainability", which has only published one paper regarding UFRM. This observation showcases the importance of this single article, which has gained the highest number of citations compared to the other analyzed articles. In the second position, there is the Journal of Cleaner Production, with twenty-eight citations, and in the third position, there are the journals of Land and Landscape Ecology, both having twenty-one citations each and sharing the third spot. In the last spot, there are the journals of ES and Science of the Total Environment with no citations at all currently, which can be attributed to the fact that their articles were published very recently, in 2023 and 2024, respectively.

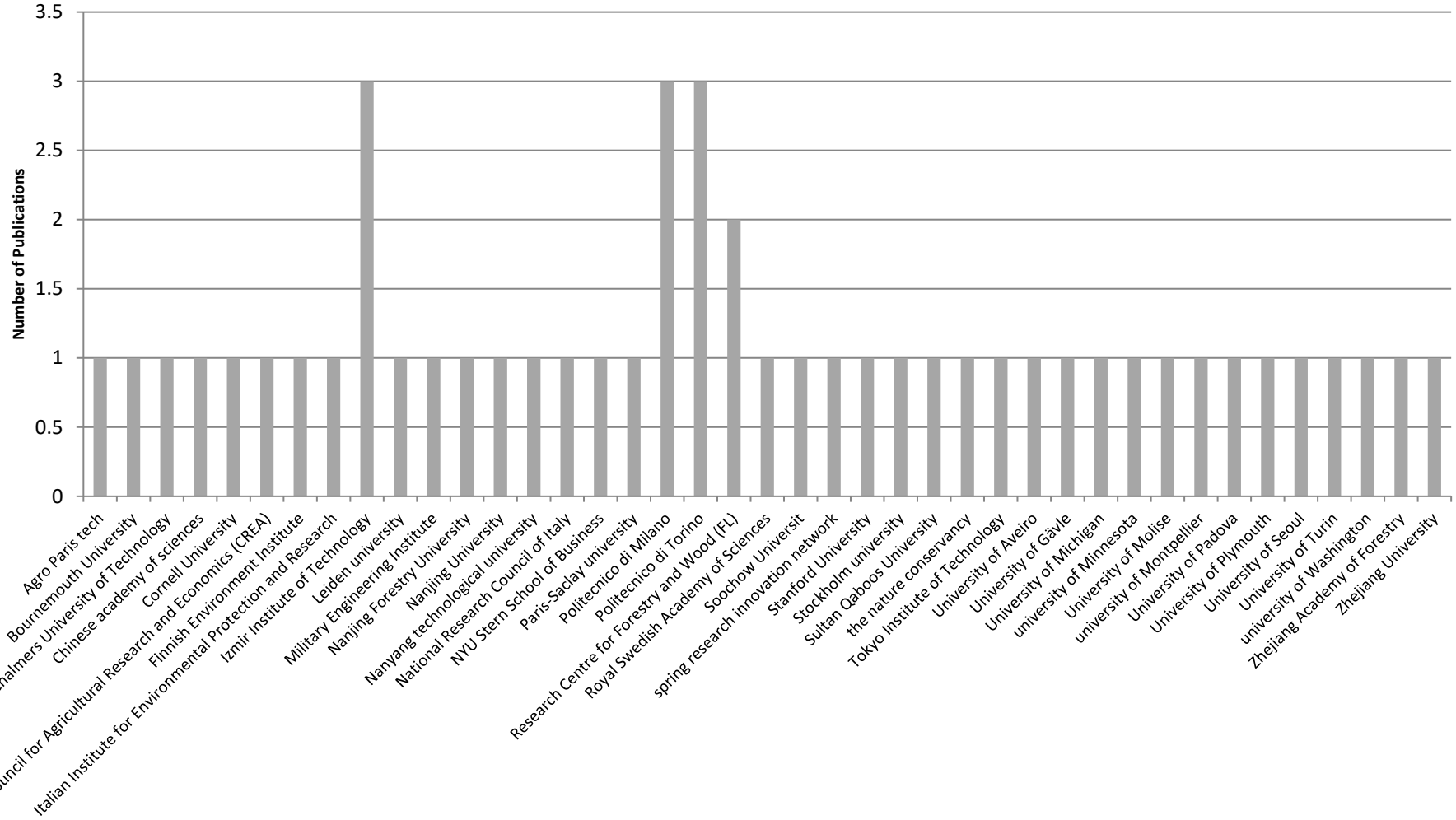


Figure 4. Number of publications for affiliations, source: authors.

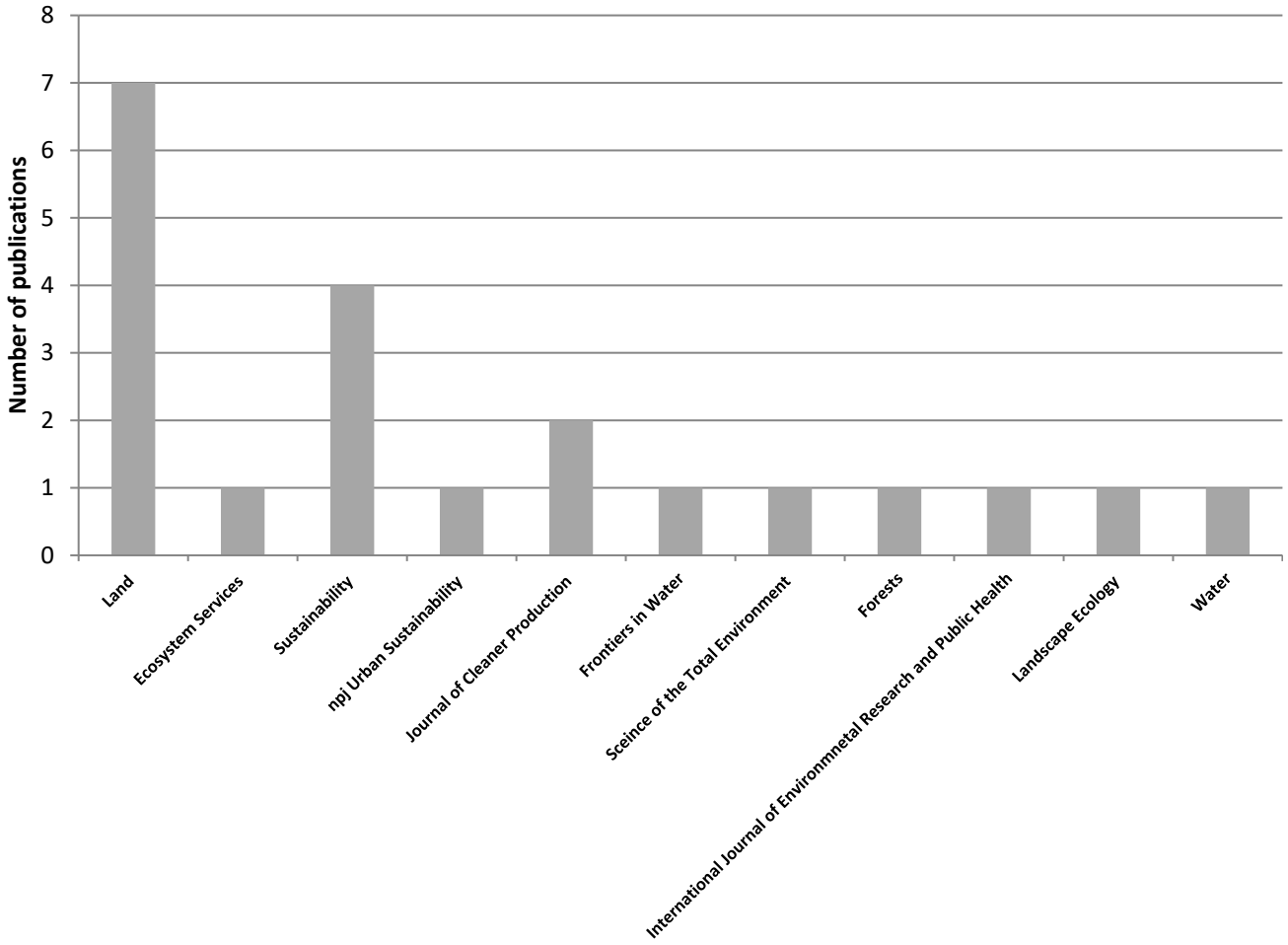


Figure 5. Number of publications for journals, source: authors.

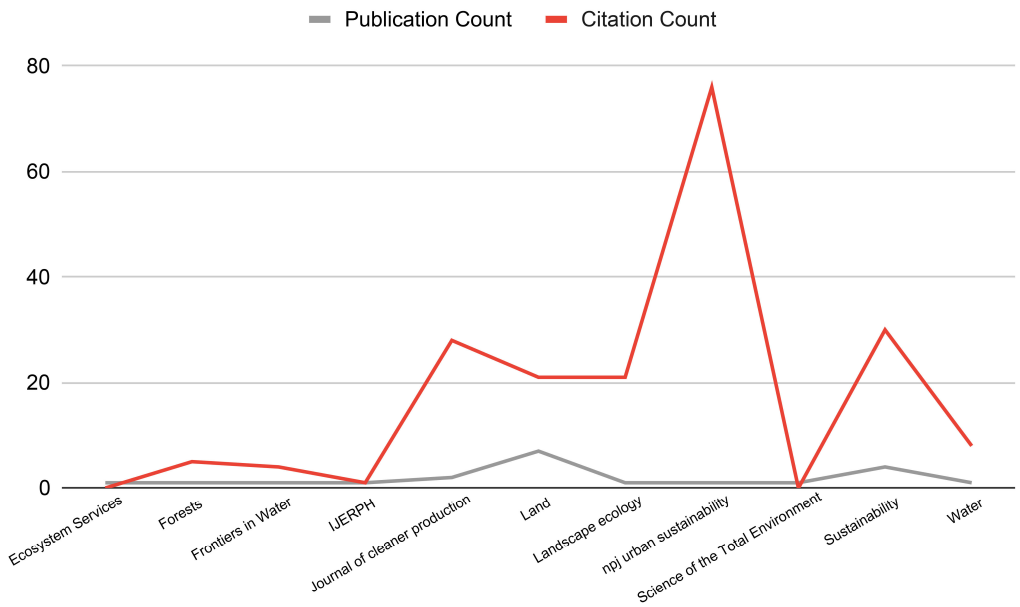


Figure 6. Number of publications and citations for each journal, source: authors.

Table 3. Number of publications and citations per journal, source: authors.

Journals	ES	Forests	Frontiers in Water	IJERPH	Journal of Cleaner Production	Land	Landscape Ecology	Npj Urban Sustainability	Science of the Total Environment	Sustainability	Water
Publication Count	1	1	1	1	2	7	1	1	1	4	1
Citation Count	0	5	4	1	28	21	21	76	0	30	8

3.2. Network Analysis of Publications

All the keywords from the analyzed papers, including the authors and indexes, were extracted from the Scopus database and imported into VOSviewer, reaching 223 keywords. Subsequently, in the software, the maximum number of occurrences for each keyword was set to two, resulting in 39 keywords. Then, two keywords, "Italy" and "article", were deselected, reducing the count to 37 keywords, as shown in Figure 7, which displays the network graph of the keywords. The occurrence frequency of the individual keywords and the co-occurrence patterns of the pairs of keywords were used to indicate the main fields of publications. The strength of the connections reflects how often two keywords appeared together, while the size of each sphere (labels and nodes) shows the frequency of occurrence, and the colors denote the distinct clusters. As observed in Figure 7, there are five clusters. Cluster 1 consists of keywords such as climate change, ES, food security, GIS, investment model, land management, nature-based solutions, urban design, urban green space, and urban planning (29.7%). Cluster 2 includes keywords like biodiversity, flood control, flooding, LULC (land use and land cover), sustainable development, urban area, urban flooding, urbanization, and watershed (24.3%). Cluster 3 includes the keywords related to the economic and social effects, ecosystems, flood mitigation, floods, natural hazards, risk mitigation, and runoff (18.9%). Subsequently, cluster 4 contains keywords such as adaptation, ecosystem, mitigation, nature-based solutions (NBSs), and risk management (13.5%). Finally, cluster 5 encompasses keywords including adaptive management, pluvial flooding, resilience, and vulnerability (10.8%). Out of all the keywords, studies in the realm of UFRM show strong connections to ES (links: 29, total link strength: 52, occurrences: 10), runoff (links: 30, total link strength: 46, occurrences: 6), climate change (links: 28, total link strength: 48, occurrences: 5), and ecosystems (links: 23, total link strength: 40, occurrences: 5).

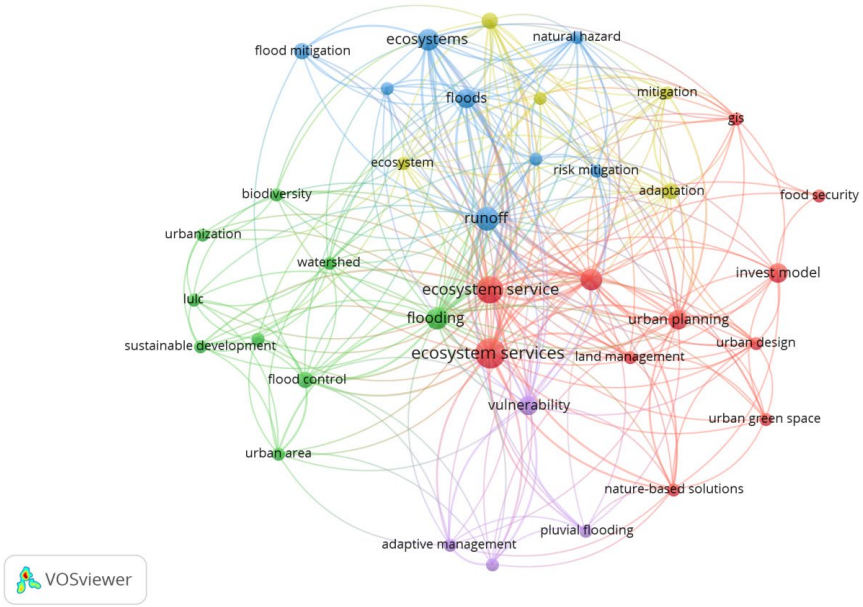


Figure 7. Network map of papers implementing UFRM created by VOSviewer using co-occurrence of keywords.

4. Discussion

4.1. Clustering the Papers

The analysis of the selected studies revealed five thematic clusters, reflecting the varied applications and research directions of the UFRM model. These clusters—Urban Planning and NBSs, Urbanization and Sustainable Development, Economic and Social Effects of Flood Mitigation, Adaptation and Risk Management, and Resilience and Vulnerability—highlight the distinct, yet interconnected, aspects of flood risk mitigation research. Below, we synthesize the findings across these themes, emphasizing the commonalities, differences, and research gaps.

4.1.1. Cluster 1: Urban Planning and NBSs

This cluster underscores the role of NBSs in urban flood mitigation. Studies such as Biasin et al. [17] and AlRuheili [58] highlight the potential of green infrastructure and landscape design to reduce flood risks effectively. For instance, Biasin et al. [17] found that forested green areas in Turin significantly reduced runoff, while Li et al. [63] demonstrated how specific green infrastructure patterns could enhance flood regulation in Nanjing. Similarly, AlRuheili [58] emphasized the usability of the UFRM model for urban planning in Oman, providing actionable insights for decision-making.

While these studies collectively affirm the effectiveness of NBSs, variations emerge based on geographic and urban contexts. For example, while the Mediterranean context of Biasin et al. [17] emphasizes forested areas, Li et al.'s [63] study in East Asia focuses more on landscape patterns. This suggests that the effectiveness of NBS interventions may be region-specific, requiring localized adaptation. However, a notable gap in this cluster is the limited exploration of the trade-offs between NBSs and other urban interventions, which future research should address.

4.1.2. Cluster 2: Urbanization and Sustainable Development

The studies in this cluster focus on the impacts of urbanization on ecosystem services and sustainable urban development. For example, Da Silva et al. [60] examined how land-use changes in Brazil amplified surface runoff, while Egegård et al. [61] demonstrated how urban development in Sweden reduced water retention capacity. Both studies highlight the need for integrated planning approaches to balance urban growth and flood risk mitigation.

However, the findings diverge in their recommendations. While Da Silva et al. [60] advocate for site-specific natural water retention measures, Egegård et al. [61] emphasize broader NBS-oriented adaptation strategies on multiple scales. This difference reflects the variability in urbanization patterns and climate conditions across regions. A recurring challenge in this cluster is the lack of tools to model the socio-economic dimensions of urbanization alongside flood risk, a critical gap for sustainable planning.

4.1.3. Cluster 3: Economic and Social Effects of Flood Mitigation

This cluster explores the broader implications of flood mitigation strategies, particularly on *economic valuations* and social equity. Hamel et al. [62] used the UFRM model to map and value the *benefits of* NBSs, demonstrating how these interventions could reduce economic losses in urban areas. Similarly, Wang et al. [73] examined the economic drivers of ecosystem service budgets in the Su-Xi-Chang region of China.

Despite the progress in valuing flood mitigation services, a key limitation across these studies is the narrow focus on economic metrics, often overlooking the social dimensions such as equity and accessibility. For instance, while Hamel et al. [62] integrated equity metrics in their Paris case study, most other studies fail to address distributive justice concerns. Future research should explore how the economic and social benefits of flood mitigation can be integrated to create more inclusive urban planning strategies.

4.1.4. Cluster 4: Adaptation and Risk Management

Studies in this cluster *focus on adaptive strategies and risk management approaches*. For example, Salata et al. [71] assessed the runoff vulnerabilities in Izmir, proposing NBS-based adaptation strategies, while Li and Kim [64] demonstrated how sponge city projects in Nanjing improved flood resilience. These studies emphasize the importance of proactive planning to mitigate the impacts of extreme weather events.

A significant limitation in this cluster is the oversimplification of the temporal dynamics in flood risk modeling. For example, Egegård et al. [61] criticized the UFRM model for its lack of temporal considerations in rainfall events, which can significantly influence runoff patterns. Addressing this gap requires advancing modeling techniques to incorporate dynamic and climate-responsive variables.

4.1.5. Cluster 5: Resilience and Vulnerability

This cluster focuses on enhancing the resilience of urban systems to flood risks. For instance, Sebastiani and Fares [72] prioritized ecosystem services to identify the areas with a high flood mitigation potential in central Italy, while Salata et al. [70] evaluated the vulnerability indices in Turin to guide resilience-building strategies. These studies underscore the importance of integrating biophysical, social, and economic factors into resilience planning. However, the studies in this cluster tend to focus on regional case studies, limiting their generalizability. Additionally, while vulnerability assessments are crucial, there is a lack of integration with long-term monitoring and evaluation frameworks. Future research should explore how resilience metrics can be standardized and scaled across diverse urban contexts.

4.1.6. Synthesis Across Clusters

While each cluster addresses specific aspects of flood risk mitigation, several cross-cutting themes emerge. First, the importance of localized and context-specific interventions is a recurring theme, as highlighted in the clusters on urbanization, NBSs, and resilience. Second, there is a growing recognition of the need to integrate the economic, social, and environmental dimensions, particularly in the clusters focusing on economic valuation and adaptation. Lastly, significant methodological gaps remain, particularly in capturing the temporal dynamics, the socio-economic trade-offs, and the long-term impacts.

4.1.7. Sensitivity Analysis

No formal sensitivity analysis was conducted in this study. However, future research could assess the robustness of the results by testing the effects of variations in the data inclusion criteria, keyword co-occurrence thresholds, and bibliometric analysis parameters. For instance, the influence of outlier studies with disproportionately high citation counts could be evaluated to determine their impact on the observed trends.

4.2. UFRM's Limitations in Their Practical Utilization for Urban Planning

The constraints and limitations regarding UFRM can be broken down into two major sections. Firstly, it is essential to discuss the technical shortcomings of the InVEST suite in general. These include the requirement for accurate input data, particularly regarding meteorological events and ES assessments, which may be challenging to obtain, as noted by Marino et al. [66] and Ma et al. [70]. Additionally, the model's focus on specific ESs may lead to the overlooking of others, and its spatial and temporal resolutions may introduce uncertainties, as observed by several authors [62,64]. Moreover, InVEST lacks comprehensive tools for urban planning, such as capturing built infrastructure and the temporal aspects of rainfall events [47,71]. Concerns also arise regarding the model's simplifications and limitations in representing real-world situations accurately, particularly in dense urban catchments and extreme climate change scenarios [72]. Furthermore, the model's reliance on assumptions and approximations for adaptation simulations and its sensitivity to changes in the input parameters pose significant challenges [73]. Despite its utility, these limitations underscore the importance of a cautious interpretation and application of the InVEST outputs in ES assessments and urban planning contexts.

As for the UFRM itself, several flaws have been pointed out in the literature. Marino et al. [66] highlighted the necessity for detailed hydrological soil group information to achieve accurate results. Li and Kim [64] stressed the need to balance environmental concerns with social and economic indicators and suggested incorporating additional factors like a stormwater runoff analysis and water recycling rates. However, the model's watershed scale operation, as noted by Li and Kim [64], results in outcomes encompassing larger areas than the study's focus, potentially reducing the precision of smaller case studies. Hamel et al. [62] pointed out the model's focus on natural rather than built urban infrastructure and its lack of fine-scale design tools for urban planning. Egegård et al. [61] criticized the model's absence of temporal aspects regarding rainfall events and topographical characteristics, while Da Silva, Campos, and Paz [60] highlighted its oversight of socio-economic factors.

Moreover, Costadone et al. [59] emphasized the absence of elevation data and the dynamics of rainfall intensity and duration within the model. AlRuheili [58] cautioned about the limitations of the curve number method in complex environments. Wang et al. [73] identified shortcomings in the differentiation between the actual and potential supply and the inability to define the range of the influence of ESs precisely. Sebastiani [72] criticized the InVEST models for oversimplifying water cycles. Salata [47] highlighted discrepancies between the models and real-world scenarios and their limited ability to quantify biophysical system performance or evaluate the benefits of nature-based solutions (NBSs). Furthermore, Salata et al. [70,71] and Quagliolo et al. [69] underscored the various limitations of the UFRM and InVEST models regarding runoff estimation, spatial distribution, flood damage costs, and the consideration of specific NBS features. Lastly, Zhao et al. [75] discussed the inherent limitations to a macro-level water ecological analysis using the UFRM models. These findings collectively reveal a spectrum of challenges that need to be addressed to enhance the effectiveness and applicability of UFRM in flood risk mitigation efforts.

4.3. Moving Forward: Facilitating the Creation of Adaptation Plans with Greater Ease, Speed, and Precision

Future urban ESs research should explore various critical areas. Marino et al. [66] suggest studying how urbanization impacts ESs and understanding the relationship between

land-use changes and flood risks. Ma et al. [70] propose investigating the long-term effects of bamboo forest expansion and assessing the benefits of agroforestry intercropping. Li et al. [63] call for examining the effectiveness of different Green Infrastructure (GI) strategies on flood management. Hamel et al. [62] recommend exploring the climate change impacts on urban ESs and improving tools like InVEST for practical use. Egegård et al. [61] stress the importance of advanced modeling in understanding urban growth's impact on ESs. Da Silva, Campos, and Paz [60] advocate for better hydrological modeling to predict water flow and assess the socio-economic effects of land-use changes on water quality. Costadone et al. [59] emphasize the need for accurate modeling tools for urban floods and standardized approaches for ecosystem accounting. Biasin et al. [66] highlight the need to research a more comprehensive range of nature-based solutions (NBSs) and understand the stakeholder needs for prioritizing NBS development. AlRuheili [58] suggests evaluating the hydrological aspects of urban vulnerability and exploring adaptive strategies for coastal and inland planning.

Additionally, Watson et al. [74], Wang et al. [73], Sebastiani et al. [72], Salata et al. [47,71], Quagliolo et al. [69], Ogawa et al. [67], and Zhao et al. [75] propose directions such as analyzing the temporal dynamics of ESs and developing sustainable strategies for urban flooding and water contamination. These research directions aim to provide practical solutions to the challenges posed by urbanization and climate change.

In urban planning, the need for spatial tools capable of providing comprehensive assessments to determine the current and future ecosystem delivering capacity is evident [76–78]. Technological advancements, particularly in geographic information systems, enable the identification of the hotspots of compound issues in urban areas and accelerate the analysis process through visual outputs [79,80]. For instance, tools like UFRM and the models of InVEST showcase these advancements by enabling urban planners to pinpoint the areas vulnerable to pluvial flooding and initiate solution development within the adaptation plans. However, a crucial aspect that remains unaddressed is how the automation of the recognition and analysis stages in urban planning can extend to a solution design. While each urban hotspot requires tailored attention, the development of quantitative tools capable of evaluating diverse solutions within specific urban regulations can guide planners in devising more effective and optimized solutions, potentially eliminating the inefficient preliminary options. One significant research gap can be found in the absence of comprehensive tools tailored to urban areas based on specific criteria. The existing tools often offer generalized approaches that may not sufficiently address the unique challenges and requirements of individual urban contexts, such as the socio-economic characteristics, environmental conditions, and infrastructure limitations. Moreover, they may not fully integrate diverse stakeholder perspectives or account for the dynamic nature of urban systems. Addressing these gaps requires the development of more flexible, customizable, and context-specific decision support tools that empower urban planners, policymakers, and stakeholders to co-create holistic solutions that meet the diverse needs of urban communities.

Another aspect earning attention in future research pertains to equity and environmental justice (EJ) considerations, which have garnered significant attention in recent years [81,82]. Spatial justice, in particular, can be integrated into mainstream discourse by harnessing the potential of geospatial analyses, exemplified in the article by Hamel et al., in 2021 [62], which was analyzed in this review. In their Paris case study, they employed various InVEST models, including the UFRM, to assess the impact of land-use changes on ESs. By quantifying the natural and semi-natural areas in both 1982 and 2017, they ran ES models for each land-use map. Consequently, they were able to simulate the areas where increasing urban greenery would most effectively reduce spatial inequality by combining criteria such as access to a green space and household income as indicators of well-being. Utilizing ES modeling proves to be a potent tool in identifying the areas of concern regarding environmental and distributive justice (DJ), as demonstrated by Hamel et al., (2021) [62]. Integrating elements of EJ and DJ with the automation of solution design

appears to be a significant step towards facilitating inclusive urban planning and achieving its objectives in a more efficient, speedy, and precise manner.

5. Conclusions

This study systematically reviewed the use of the UFRM model within the InVEST suite, highlighting its growing role in urban flood risk mitigation. Key research directions emerged, emphasizing the need for methodological improvements, the integration of equity considerations, and regional adaptability.

Enhancing UFRM accuracy is a critical priority as it addresses challenges such as limited hydrological and socio-economic data, spatial and temporal resolution gaps, and the oversimplification of dynamic processes. Advances in modeling tools to incorporate real-time climate data and urban growth scenarios will support more precise applications.

There is also a pressing need to integrate the social and economic dimensions into flood risk assessments. Future research should prioritize balancing economic efficiency with distributive justice, ensuring that the NBSs benefit all urban communities equitably.

Regional variability in the effectiveness of NBSs highlights the importance of context-specific solutions. Comparative studies across diverse urban environments are essential to develop guidelines that accommodate geographic and climatic differences.

Finally, automating and optimizing urban planning tools will advance the field by streamlining the evaluation of adaptation scenarios. Developing customizable, stakeholder-inclusive tools can enable planners to design tailored, holistic solutions for complex urban challenges. These research directions aim to overcome the current limitations and support the development of sustainable, resilient, and inclusive urban systems in the face of climate change.

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Appendix A

Reference	Reference Number	Case Study	Goal	Research Design	Main Results	Novel InVEST Contribution
AlRuheili, 2022,	[58]	Oman, Al Khaboura	Map and visualize runoff and retention in the study area, and evaluate the usability of the InVEST model for urban planning.	Utilized DSAS (digital shoreline analysis system) to quantify shoreline erosion due to Shaheen's storm and employed the InVEST model to estimate runoff from extreme rainfall events. Calculated shoreline erosion rate and inland area damage, providing insights for urban planning to manage flash flood events.	The model revealed the relationship between the Al Khaboura shoreline and UGSne erosion at a rate of 16.33 m per year. Research emphasizes integrating science for informed urban planning decisions.	Combining UFRM with DSAS to quantify shoreline erosion in a coastal case study.
Biasin et al., 2023	[17]	Italy, Turin	Test NBS potential in mitigating UHI effect and urban floods and economic viability of investments in them.	Identify NBSs for climate risks, test combinations, analyze costs and benefits, and draw conclusions for policymaking.	Flood risk mitigation NBSs, such as forested green areas, have a significant impact. NBSs in public areas are more effective at retaining runoff. Benefits outweigh costs for flood risk protection in all scenarios.	Analyzing the supply of ESs for different NBS-based scenarios by UFRM.
Costadone et al., 2024	[59]	Finland, Tampere	Creating co-developed urban ecosystem accounts in Tampere.	Ecosystem extent accounts were compiled for 2012 and 2018 to track changes in ecosystem types. Runoff retention service was measured using the UFRM for the same years, assessing physical and monetary values based on rainstorm scenarios and avoided damage costs.	Green spaces in Tampere increased runoff mitigation service by 7–40%. Importance of collaborative approach in urban ecosystem accounting.	Integrated UFRM's outputs into SEEA-EA framework through collaborative urban planning.

Reference	Reference Number	Case Study	Goal	Research Design	Main Results	Novel InVEST Contribution
Da silva, Campos & Paz, 2023	[60]	Brazil, Itapertuna	Document land-use and land-cover changes and their effects on water resources.	Utilized CBERS4 satellite images from 2015 and 2020 for analysis, applying SVM algorithm to classify six distinct land-use and land-cover (LULC) classes. Analyzed runoff impact due to urbanization across 17 urban sub-basins, investigating LULC changes and urban development using GIS and remote sensing.	Urban growth has directly amplified surface runoff in specific sub-basins, thereby impacting water resource management and flood prevention.	Identifying site-specific NWRM for flash flood vulnerabilities.
Egegard et al., 2024	[61]	Sweden, Gothenburg	Propose NBS-oriented flooding adaptation strategies on multiple biophysical scales.	Develop a methodology for modeling ESs and validate findings through user-friendly and cost-efficient approaches.	Modeling indicates urban development reduces water retention capacity. Runoff mitigation via green spaces aids in climate-proofing Gothenburg. Even small changes in rain event intensity cause notable shifts in runoff volume.	Quantifying the runoff mitigation service for different climate change scenarios by UFRM.
Hamel et al., 2021	[62]	China, Shenzhen USA, Minneapolis-St. Paul France, Paris	Quantifying and mapping the benefits of natural infrastructure in cities.	Quantify and map natural infrastructure benefits in urban areas using InVEST for economic valuation and land-use prioritization. Address the limitations, propose research directions for urban management tools, and integrate climate change into future urban scenario modeling.	Conversion of golf courses to parks increases ES supply.	- Assessing economic benefits with InVEST and empirical data. - Prioritizing land-use change. - Regional planning integrating equity metrics using InVEST.

Reference	Reference Number	Case Study	Goal	Research Design	Main Results	Novel InVEST Contribution
Li & Kim, 2022	[63]	China, Nanjing	Verify the effects of sponge city projects on water pollutants and urban flood control.	Defined study areas from Chinese sponge city projects and analyzed their impacts on water pollutants and flood control. Proposed and simulated three LULC scenarios, evaluating the effects using the geo-design framework and comparing improvements in water pollutant reduction and stormwater management.	Sponge projects improve water pollutant control by 11–18% and stormwater by 0.4–6.3%. Introducing a green infrastructure network can boost pollutant control by 9–15%. Geo-design framework bridges planning gaps and integrates scientific evaluation.	Using InVEST to assess the ESs of different LULC scenarios based on geo-design framework.
Li et al., 2023	[64]	Nanjing, China	Identify landscape patterns affecting ES supply and demand.	Quantified ESs' supply and assessed demand using landscape patterns. Identified landscape metric sensitivity to spatial scale. Formulated green infrastructure (GI) strategies for flood regulation. Conducted a regression analysis on landscape structure across districts.	There is a mismatch between ES supply and demand in Nanjing, where landscape pattern significantly affects this balance.	Conducting landscape pattern analysis to obtain ES supply/demand.
Ma et al., 2022	[65]	Anji County, China	Improving ES and mitigating trade-offs.	Used the InVEST model to quantify various ESs. Compared ES outcomes in different forest management scenarios.	Bamboo forest expansion increased product provision but decreased other ESs. Intercropped bamboo forest eliminated ES trade-offs, while agroforestry management improved ESs and reduced trade-offs.	Investigating the effect of monoculture plantations, specifically bamboo forests, on flood protection.

Reference	Reference Number	Case Study	Goal	Research Design	Main Results	Novel InVEST Contribution
Marino et al., 2023	[66]	Italy, Rome	Detecting the synergistic variations in the supply of flood mitigation and agricultural production ESs.	Analysis of LULCC, transition categories, variations in ESs' flood mitigation supply and synergies and the trade-offs between flood mitigation and agriculture.	Urbanization leads to a negative change in ESs. The reduction in agricultural land adversely affects flood mitigation and agricultural production. An innovative methodology is proposed, linking land-use and land-cover change (LULCC) to hydraulic safety and food security.	Combining GIS with UFRM to study LULCCs, hydraulic safety, and food security.
Ogawa et al., 2023	[67]	Japan, Tokyo	Developing a novel method for estimating the relationship between a UGS (urban green space) area and CSO (combined sewer overflow) in the Tokyo metropolitan area, covering 10 sewersheds.	Developed a method combining surface runoff modeling and sewer network analysis. Classified land use as UGS or impervious surface. Focused on Tokyo metropolitan area with 10 sewersheds. Estimated CSO flux using a semi-process-based model.	Increasing UGS proportion reduces CSO, from 5% to 10%. CSO increases exponentially with rainfall intensity. UGS significantly reduces CSO under low rainfall conditions.	Integrating surface runoff modeling, sewer network analysis, and response analysis to study the relation of the area of UGS (urban green space) to CSO (combined sewer overflow).
Quagliolo et al., 2023	[68]	Aveiro, Portugal	Assessing the benefits and costs of green roofs and bioswales for flood adaptation.	Assess green roofs and bioswales under current and future climates, calculate total annual NBS implementation costs, identify biophysical assessment limitations, present expected flood damage per neighborhood, and compare annual benefits and costs of green roofs and bioswales.	- Green roofs save 32% of flood damages, while bioswales save 0.1% and provide larger benefits in future climate scenarios. - NBS water retention benefits increase under more extreme climate scenarios.	Using InVEST, benefit transfer, and GIS for assessing flood risk mitigation impacts, costs, and the benefits of various NBS within a spatial biophysical–economic framework.

Reference	Reference Number	Case Study	Goal	Research Design	Main Results	Novel InVEST Contribution
Quagliolo, Comino & Pezzoli, 2021	[69]	Italy, Liguria region	Assessing runoff due to extreme rainfall events in the Liguria Region.	Analyzed InVEST model output for estimated runoff distribution. Integrated spatial runoff evaluation with flash flood resilience classes. Identified site-specific NWRM for flash flood vulnerabilities. Conducted sensitivity test on the model with a rain input parameter.	High runoff volume linked to urban areas and impervious surfaces.	Combining GIS and InVEST for an example of coastal cities and suggesting NWRM per land-use type.
Salata & Arsalan, 2022	[47]	Turkey, Izmir	Determining Izmir's cloudburst vulnerability level.	Analyzed land-use change data in Izmir due to rapid urbanization and demonstrated digital ecosystem modeling for sponge district design and performance measurement.	- Nature-based solutions in sponge district master plan reduced flood vulnerability significantly and increased the runoff retention index from 0.38 to 0.60 in sponge districts. - Master plan design emphasized nature-based solutions to reduce flood risk.	Applying sponge district method and designing performance-based ES solutions.
Salata et al., 2021	[70]	Italy, Turin	Implement performance-based planning to enhance resilience against climate change impacts.	Developed a Flooding Risk Mitigation model for Turin using InVEST, evaluated runoff retention index, incorporated land-use and soil data, and calculated urban discharge volume.	Turin's urban area is vulnerable to flooding due to high impermeable surfaces.	Evaluating the outcomes of UFRM to understand potential land-use adaptation strategies.

Reference	Reference Number	Case Study	Goal	Research Design	Main Results	Novel InVEST Contribution
Salata et al., 2022	[71]	Turkey, Izmir	Analyze runoff, model vulnerability, and suggest NBS.	Analyzed urban sub-watersheds for runoff intervention areas, identified stream routes, and proposed flooding adaptation strategies in Izmir. Verified modeled runoff quantity against sub-basin water discharge capacity and evaluated the impact of urbanization on runoff volume and discharge.	Results show that 10% of Izmir's urban areas are extremely vulnerable to cloudbursts, which means that 40% of the urban population is exposed to this phenomenon.	Determining potential areas for implementing NBS based on UFRM model in the context of the sponge district concept.
Salata, 2023	[49]	Turkey, Izmir	To understand the biophysical complexity of Izmir's Metropolitan City.	Integrate two spatial ecosystem models for urban flooding understanding and analyze and compare the results from the two modeling sessions.	Site-specific knowledge crucial for ecosystem performance and adaptation processes.	Designed by land-change model USRM (Urban Stormwater retention model).
Sebastiani & Fares, 2023	[72]	Lazio, Abruzzo, and Molise administrative regions, Italy	Enhance the network of protected areas by prioritizing ESs.	Identified high ecological value areas for ES assessment and used InVEST models to evaluate carbon storage, water yield, and flood risk. Proposed four new protected areas based on ESs findings.	Proposed four new protected areas spanning 888 km^2 in central Italy. Identified areas with high carbon storage, water yield, and flood risk mitigation. Current network covers 31.5% of priority areas; proposed areas could increase to 64.5%.	Using overlay analysis, found the areas with highest ES delivery, it is important they be protected.
Wang et al., 2023	[73]	China, Su-Xi-Chang region	Reveal the multi-scale patterns of supply, demand, and budgets in urban ESs in the Su-Xi-Chang region, and identify the spatial heterogeneity and scale dependence of ES budget bundles and their drivers.	Quantified six ESs' supply, demand, and budgets across scales. Investigated natural and socio-economic factors' influence on ES budget bundles, analyzing the drivers with a K-means cluster analysis.	ES budget bundles revealed a supply–demand mismatch across different scales. Factors such as population density and impervious surfaces influenced ES budget formation. ES budget bundles varied in area and location based on scale.	Economical study.

Reference	Reference Number	Case Study	Goal	Research Design	Main Results	Novel InVEST Contribution
Watson et al., 2021	[74]	England, County of Dorset	To understand the impact of agricultural intensification on ESs.	Quantify long-term spatial dynamics of ESs using InVEST models and historical land-cover maps. Determine thresholds or tipping points in ES provision and examine non-linear responses to agricultural intensification.	Agricultural intensification might trigger non-linear thresholds in ESs. Positive feedback mechanisms could signal tipping points in agricultural systems.	Used InVEST to study agriculture intensification.
Zhao et al., 2023	[75]	USA, Michigan	Investigate urban flooding and nutrient export in Rouge River Watershed.	Utilized land change modeler to design urban development scenarios and InVEST to evaluate them. Analyzed nutrient export and urban flooding in Rouge River Watershed, proposing green infrastructure for sustainable urban development.	Various urban development scenarios affect nutrient export and urban flooding.	Evaluating the results of different development scenarios designed by land change modeler (LCM) by UFRM.

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