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Review

Stormwater Management in Urban Coastal Areas—A Review

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Abstract: Stormwater management in coastal urban cities, where drainage networks are influenced by marine dynamics and specific soil and altimetry conditions, has specific challenges that need to be addressed to ensure adequate management in such areas, which are also heavily affected by floods. Their location downstream of drainage basins and the interaction of network outfalls with current and tidal variability increases the vulnerability of populations and should therefore be the target of specific studies. This article presents a literature review, where publications that focus on stormwater management in coastal urban areas were identified and analyzed. The main objective was to present the key issues related to drainage in coastal areas, the most relevant challenges, the solutions and strategies that reveal the greater potential for application and the challenges for modeling this type of case. It is intended to provide a grounded basis for new ways of optimizing stormwater drainage in coastal areas and promote a sustainable urban water cycle. This review reveals the necessity to implement a multidisciplinary approach to minimize three main issues: urban flooding, stormwater pollution and groundwater salinization, including the adaptation of existing infrastructures, complementing them with control solutions at source, correct urban planning and the involvement of populations. For an effective management of urban stormwater drainage in coastal areas, this approach must be carried out on a watershed scale, duly supported by reliable decision support tools and monitoring systems.

Keywords: stormwater management; coastal areas; decision support tools

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1. Introduction

Proper stormwater (SW) management in urban areas is essential for the regular functioning of cities, for their development and for safeguarding people and property. In the coming decades, several European cities will experience an increase in the frequency and severity of extreme weather events, which have already been responsible for numerous economic and social losses [1]. It is therefore important to implement measures to adapt to extreme events in order to ensure the resilience of cities since the forecasts of the European Environmental Agency (EEA) indicate that a large part of the European population (around 80%) will live in urban areas by 2050 [1]. According to this trend, it is expected that there will be an increase in soil sealing due to the growth of urban areas.

Several European cities have flooded in recent decades due to intense rainfall episodes and to the inefficiency of drainage systems that were unable to handle the water that flowed in. Many of these situations revealed the improper functioning of the SW drainage networks, which became undersized due to isolated network expansions that were made over time. As a consequence, the damage costs are increasing, mainly due to the rising population and consequent land use change and human activities in hazard-prone areas, and also to economic wealth and better reporting [2]. Besides the damages caused by these events, citizens had to deal with additional consequences such as the contamination of drinking water networks for weeks. Taking into account that more than 3/4 of European citizens live in urban areas, it is essential to carefully manage water in the cities to prevent the consequences of this kind of event. The European Environmental Agency [3] recommends different approaches to prevent urban water crises, especially when facing extreme events aggravated by climate change. They can go from reducing consumption to finding new ways of collecting and using water, pointing also to a better integration of water management in urban planning, considering the characteristics of the local environment.

In the scientific community, SW management has been a topic with increasing development in recent years. There are already several articles published on SW management where issues such as modeling, infrastructure improvement, nature-based solutions (NbS) and integrated management (IM) are focused on, and the benefits are properly presented and substantiated. The existing literature regarding the effects of land cover and climate change on runoff has considered different regions of the world, but specific research on the coastal–urban environments has been scarce. Therefore, further investigation is necessary to address the vulnerabilities of these areas, which frequently accommodate significant population centers and economic hubs [4].

SW management in coastal cities, where drainage networks are influenced by marine dynamics and specific soil and altimetry conditions, has additional challenges that need to be studied to ensure correct surface water management in such areas, which are also heavily affected by floods. Their location, downstream of drainage basins, and the interaction of network outfalls with current and tidal variability, increases the vulnerability of populations and should therefore be the target of specific studies.

To fill this gap, a detailed literature review was carried out, where publications that focus on SW management in coastal urban areas were identified and analyzed. The main objective of this review is to present the results of the bibliographic analysis which, in turn, sought to identify the most prominent issues presented by researchers on urban drainage in coastal areas (rather than coastal areas/waters that receive urban SW), which are the most relevant challenges, which solutions and strategies reveal greater potential for application and what are the challenges for the modeling of such cases. This study is important to provide the basis for new developments related to the management of SW in coastal urban areas that are threatened not only by flooding situations but also by water scarcity and the pollution of water resources. It is intended to drive new and appropriate ways to optimize SW drainage in coastal areas and thus promote a more sustainable urban water cycle.

2. Materials and Methods

As referred, this study intends to promote reflection about the current state of the art related to SW management in coastal urban areas. For that purpose, a search for articles concerning this topic was carried out in two databases, resulting in a selection of papers aligned with the intended scope. Then, a bibliometric analysis was carried out to identify the relevance of the selected portfolio, considering the spatial distribution and the tendency of the number of publications per year. Finally, a systemic analysis was made based on the content of each selected article using thematic axes that sustain the organization and the perception of the information that results from this review.

The first and second stages of this process are detailed in the following subsections, and the last one, the systematic analysis, is presented in Section 3.

2.1. Literature Review

The literature review was initiated by searching the keywords "stormwater management" and "coastal" in the title, keywords and abstract (advanced search) in the *Science Direct* database. A similar procedure was used in the *Web of Science* database. In total, 25 articles result from Science Direct without any kind of restriction: 1 review article, 23 research articles and 1 mini review. From Web of Science, 4 articles were collected.

The following step was the removal of the duplicates (from the two used databases) followed by the analysis of titles and abstracts to identify the ones that were out of scope in order to remove them from the resulting bibliographic portfolio. One article was dismissed because it was not available for download.

Articles that were considered out of scope (not related to SW management in coastal areas) were, for example, the ones focused only on specific subjects that were not relevant to this study, like SW quality, surveys related to detention ponds, agriculture, aquatic ecosystems, economic and fiscal benefits in the watershed and coastal administration.

The sequential steps presented in Figure 1 represent the described process. At the end, a set of 16 articles were selected and read in order to make the intended systematic review.

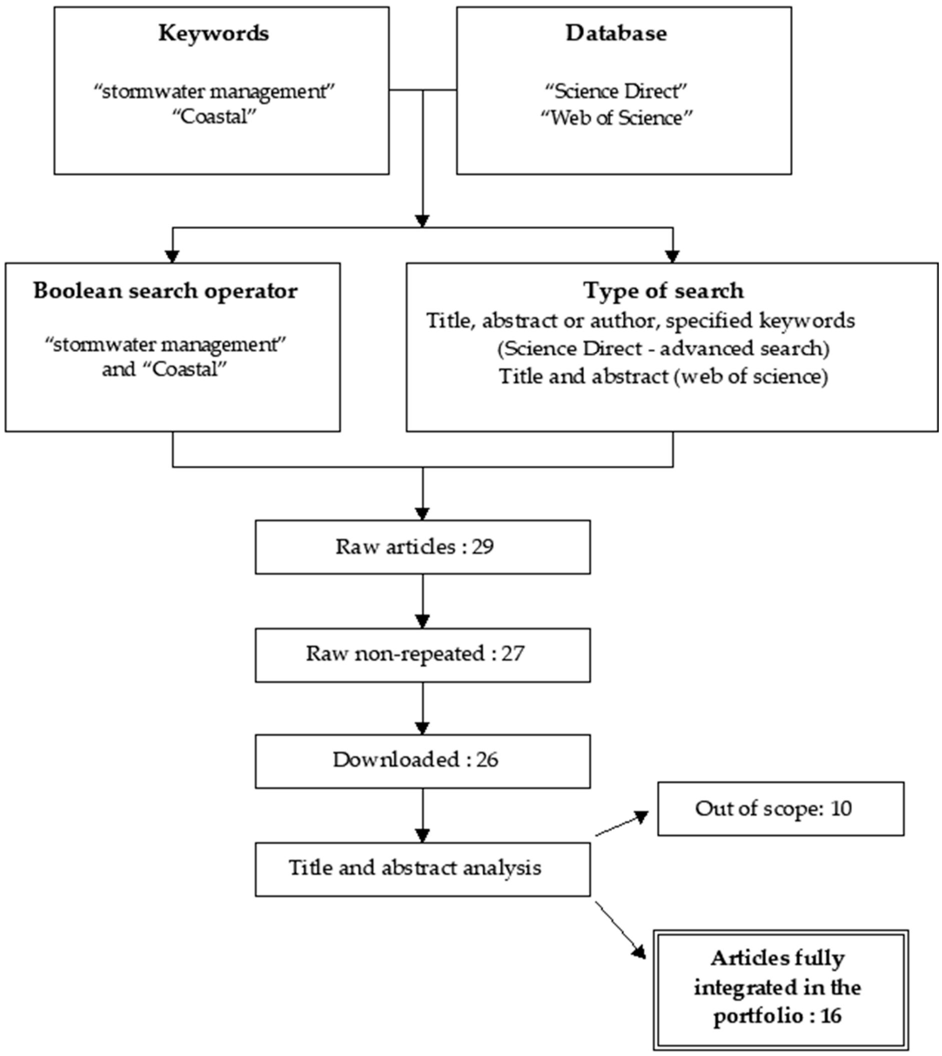

Figure 1. Methodological flowchart.

2.2. Bibliometric Analysis

A bibliometric analysis was conducted to understand how the investigation regarding SW management in coastal urban areas has been evolving.

The collected portfolio shows that the beginning of publications in this specific scope was in 2007, but by 2016, only one more article was published (Figure 2). From that year onward, the trend has been increasing, although with a noticeable drop in 2020, the period of the COVID-19 pandemic. The year 2022 did not register any papers, but the following year (2023) was the one with the most publications. Considering the extension of this trend, it is expected that, in the next years, there will be more publications related to SW drainage in coastal areas.

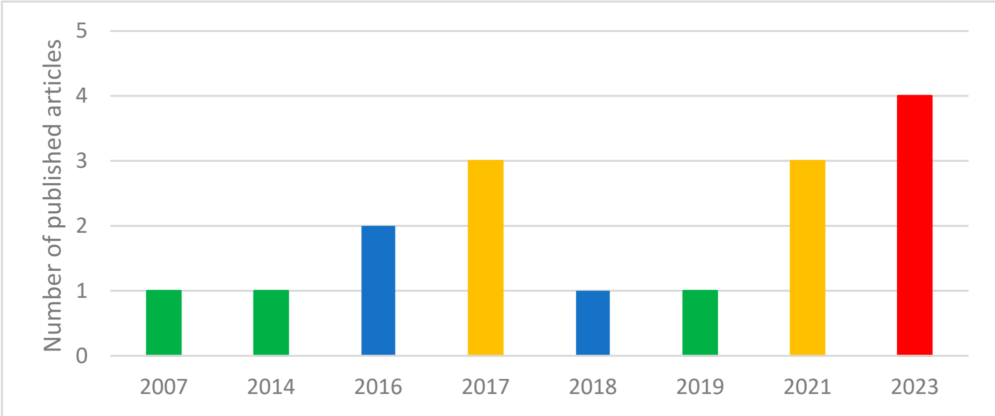

Figure 2. Year of publication of the articles that make up the portfolio.

Regarding the distribution of the portfolio's publications by the journals of the specialty, a wide distribution is noticeable (Table 1). From the 11 journals with publications on this topic, only 4 present more than one article.

Table 1. Number of articles published in each journal.

Journal	Number of Publications
Ecological Modeling	1
Ocean & Coastal Management	1
Procedia Engineering	1
Environmental Science & Policy	1
Environmental Modeling & Software	1
Ecological Engineering	2
Water Research	2
Journal of Environmental Management	2
Sustainable Cities and Society	2
Science of the Total Environment	1
Nature-Based Solutions	1
International Journal of Water Resources Development	1

On the other hand, it is interesting to know the spatial distribution of this theme. Figure 3 shows the location of the case studies presented by the authors (it should be noted that some articles address case studies in more than one location). Special incidence can be seen in the United States of America (mainly in Florida) and in Southeast Asia, where a large number of studies were carried out. Still, a wide distribution is noticeable in coastal areas around the globe, which confirms that SW management in such locations is a subject of increasing interest worldwide. In fact, as stated above, climate change has triggered a greater occurrence of extreme phenomena all over the world, so it is not surprising that the impacts on coastal areas have encouraged greater investment in research to promote better management of urban SW networks.

The portfolio that results from this research work, although not involving a large number of articles, supports the review that is intended to be made, due to the wide spatial distribution of the studies already carried out (in four continents) and to the relevance of the research which, although already very diverse for urban areas in general, with thousands of publications made in recent decades, is still restricted when focused on the specific case of coastal areas. However, the bibliometric analysis reveals its high research potential, which is verified by the publication in several specialized journals and by the growing trend over the years.

Figure 3. Spatial distribution of the studies covered in the portfolio (the values in the circles are the number of publications in each location).

3. Stormwater Management in Coastal Areas

The objective of this review, made with the articles of the collected portfolio, is to answer the following key questions:

- What are the main challenges of SW management in coastal areas?
- Which strategies and solutions are being applied and developed?

These questions were posed in order to develop a robust theoretical framework that sustains future research work in this area, and thus help to create methodologies and solutions to a development that enhances the resilience of coastal urban areas with the challenges stood by climate change.

3.1. Adjustment and Resilience

Nowadays, the concept of resilience embraces distinct aspects, including social resilience (capacity to anticipate and plan the future), ecological resilience (how fast the return to stability domain is) and engineering resilience (the ability to recover normal functionality after an extreme event). In the scope of drainage infrastructure systems, engineering resilience is the one that should be considered: it represents the ability of an infrastructure, including its interconnected ecosystems and social systems, to engage the disturbance and recover after it [5].

As stated by Joyce et al. [6], the vulnerability and adaptive capacity of a drainage system depend on the level of disturbance applied to it. This scope corresponds to the intensity and duration of rainfall, with the network reacting with a possible overflow process. In the current situation, with low or moderate rainfall, this overflow may not occur. In case of medium, high or extreme intensity, the network may have one or more flooded areas. In any case, overflow is not only dependent on the characteristics of the precipitation but also on the drainage system components. A small reaction (overflow) in the face of any precipitation can mean that the system had a high performance in terms of water retention and infiltration, for example. The authors also refer to another indicator that can be the recovery time of the system after an extreme event. The intention to develop mechanisms to assess and increase the resilience of urban drainage infrastructures can thus be assessed by these two types of reactions.

3.2. Urbanization

Flood situations are becoming more frequent and with more severe damages, as a consequence of two main factors: climate change and the significant increase in urbanization in areas in which drainage networks are old and have become undersized [7]. This increased urbanization is very common in coastal areas, due to tourism and, in most cases, SW in new urban spaces ends up in the existing downstream old networks. In fact, industrialization and rapid urbanization occurred in recent decades in many coastal cities around the globe, such as in the case presented by Mahmoud et al. [8] in the Lower Rio Grande Valley of South Texas, USA. Authors highlighted that this has created several stressors that can intensify the impacts of drainage infrastructure, such as higher and runoff volumes and peak flow.

The increasing urbanization of coastal areas increases the risk of flooding. One of the aspects that most influences this situation is the sealing of soils which, in addition to promoting a greater concentration of surface runoff, reduces the natural recharge of groundwater resources and raises the possibility of seawater intrusion. Groundwater is often considered a valuable resource to support social and economic development, while SW is seen as a threat to urban areas [9]. In certain regions, this problem is further aggravated by the scarcity of drinking water, especially in cases where surface water bodies and water aquifers are threatened. In these regions, the need to keep rainwater in the soil is even greater to avoid situations such as those reported by Islam et al. [10] in Bangladesh, where coastal populations were suffering from serious water scarcity and the contamination of groundwater (used to urban supply) with salinity due to the sea level rise as a consequence of climate change.

Thus, correct SW management is fundamental to urban populations, their assets and the general city functioning. Many SW drainage systems are not actualized and currently have problems with greater volumes generated by urban expansion. However, solutions must be diverse and not only focused on enlarging the pipe's or the network's capacity. The general management of surface runoff is fundamental to avoid expensive and unfeasible interventions and can lead to a more efficient management of SW in coastal areas.

3.3. Urban Development and Landscape Changes

SW is a result of precipitation (in the form of rain, ice or snow) and part of it becomes surface runoff while the rest is detained in the natural depressions of the landscape or infiltrates into the ground. However, the amount of surface runoff increases significantly as urbanization grows. Surface runoff flows into the nearest river or ocean and can lead to devastating situations if it is polluted [11]. On the other hand, if this drainage into the natural environment is not effective, all this runoff overflows from the networks and accumulates in urban spaces.

Huq and Abdul-Aziz [4] evaluated the individual and synergistic controls of land cover and climatic changes on SW of coastal–urban environments. They compared the historical and future runoffs and noted greater increases in runoff at and around the urban centers than at the nonurban areas in the basin. They also noted that increases in runoff were higher during the dry season and transitional months than in the wet season.

Lin et al. [12] demonstrate that high-density land uses may lead to a higher risk of urban pluvial floods if they do not have well-designed morphological spatial patterns. As they say, in many countries, it is unfeasible to detain population growth and rapid urban expansion, so specific guidance to the improvement of the morphological spatial layouts of urban land may be a key tool to promote sustainable urban living.

3.4. Impacts of Climate Change on SW Runoff

Currently, SW management is based on local weather conditions. However, the amount, timing, and intensity of precipitation events have been changing in recent decades and that, in combination with land development, can significantly affect the amount of SW runoff that needs to be managed in the future. In some regions, the combination of climate and land use change will aggravate existing SW flooding, whereas other regions in the world may be minimally affected [11].

Huq and Abdul-Aziz [4] determined the individual as combined hydro-climatic and land cover sensitivities of SW runoff in Florida, USA, and reported that rainfall was the stronger controlling driver of runoff (more than land cover), with significant seasonal variation. They also noticed a stronger and nonlinear response of runoff to concurrent changes in imperviousness of land cover and rainfall, rather than the linear sum of their individual effects. Their results show that rainfall had about 2.5 and 5 times stronger control on runoff than imperviousness and evapotranspiration, respectively. However, the study did not incorporate future projections of land cover and climate, to evaluate the potential impacts on future SW runoff, being a suggestion left by the authors for future developments. This demonstrates the need for SW systems to be managed with rainfall forecasts for the coming decades. In some regions, this means higher peak flows in intense precipitation events and probably less water in dry seasons with a higher need to preserve this resource in the cities on such periods. The evolution of existing networks must take into account these opposite sides of management strategies.

3.5. Runoff Quality

Urban SW management in coastal areas also has important quality issues that need to be addressed. According to Pinto et al. [13], about 40% of the world's population lives presently within 100 km of the coast. This means that human activities significantly influence the quantity and quality of SW that flows into coastal waterways. Most of these coastal waters provide habitat for many aquatic species and are intermittently open to the ocean, which makes them highly sensitive. Since these waters are discharged directly into the sea or indirectly through coastal waterways, all pollutants that are washed up in surface runoff reach local water resources and coastal ecosystems. A correct management of SW drainage systems in the upstream urban areas is fundamental for their sustainability, once SW affects nutrient dynamics and aquatic health. However, in coastal regions, SW control solutions are very limited when compared to the widespread research in non-coastal regions around the world [14].

SW runoff traveling through different types of land use, transports many contaminants that result in nonpoint source pollution [15]. In cities with combined sewer systems, there is an additional source of contamination coming from the overflow of SW mixed with untreated wastewater when the combined system capacity is exceeded. This situation is a reality in many coastal and interior urban areas around the world.

High rainfall and discharges aggravate the anthropogenic and hydro-climatic influences on nutrient concentration and export behavior on SW, with great implications for the aquatic ecosystem of the downstream receiving water bodies [16]. The complex nature of SW quality, influenced by catchment and rainfall characteristics, is also highlighted by Pinto et al. [13], who demonstrated physicochemical and hydrological variables with different patterns across distinct land use types at baseflow and above-baseflow conditions. They showed elevated baseflow nutrients and high annual loads of dissolved nutrients originated from urban catchments, rather than forested catchments. They also found high turbidity and total suspended solids (TSS) concentrations on industrial sites, and low turbidity on forested sites, due to suspended particulate matter. Another important aspect referred to by the authors is that TSS is strongly influenced by the range of catchment surface characteristics. They showed that SW optimization and control strategies must focus on solutions that minimize the amount of suspended solids that are transported to the receiving water.

4. Solutions and Strategies

Increasing and improving the understanding of watershed-scale SW management in coastal areas will have great benefits for public health, coastal water quality, and estuarine ecology [14]. As watershed impervious area increases, more runoff is generated from storm events, and evaporation and infiltration within the watershed decreases [14]. Solutions to improve the quality and control the excessive volumes of SW, and to reduce the impacts on downstream water bodies, require a watershed approach, instead of isolated approaches that have been common [17]. Large-scale hydrologic organization exists in landscapes shaped by water, but currently, SW management is typically carried out incrementally, resulting in watersheds that lack the influence of the characteristic hierarchical hydrologic convergence that exists in the complete watershed.

In recent years, large centralized facilities have been constructed by flood control agencies to control SW runoff, such as detention basins, culverts, and even re-engineered natural features (like changing river channels to quickly transport the runoff to downstream areas) [11]. Now, the current tendency is an integrated approach to manage SW runoff, with preventive and control practices to accomplish higher management efficiency. However, these large-scale facilities are still needed to control huge amounts of runoff generated by extreme precipitation events, as it would be impractical to handle this runoff on a decentralized basis with small-scale infiltration devices.

Besides minimizing runoff problems and preventing water contamination, a sustainable SW system is a system that increases the potential to use water resources in urban areas [11]. If designed and managed correctly, SW capture and drainage infrastructures may not only remove excess water from urban areas but also improve the aesthetics of cities namely the surroundings of roads, buildings and family dwellings.

A complete understanding of the impacts of catchment land use changes on the SW quality and quantity is necessary for the development of suitable urban SW management strategies, due to the variable nature of climatic conditions, especially precipitation, and to manage the different nutrient loads that should be expected. The study of Pinto et al. [13] demonstrates that a one-size-fits-all approach to management SW may not deliver the desired outcomes, and that tailor-made approaches are needed to comprise various flow conditions and catchment surface types. Wang et al. [18] compared distinct urban SW strategies in two coastal, developed and densely populated cities: Hong Kong, which adopted conventional SW management with a focus on pathways and receptor management, using hard engineering to control floods, and Singapore adopted holistic SW management, including incentive policies, water pricing, comprehensive governance and complete 'source-pathway-receptor' practices (shared with hard and soft engineering) to control flooding and harvest rainwater. They concluded that holistic SW management has greater cost savings and environmental benefits. It controls urban flooding and encompasses source control, rainwater use and water savings, being a sustainable and practical approach for coastal cities around the world.

4.1. Control Measures at Source

Saraswat et al. [11] divide SW runoff management practices into two categories: (1) the reduction in surface runoff volumes, and (2) the improvement of SW quality before discharge into downstream water bodies or into the ground. New strategies have been developed to minimize the negative impacts of urban SW, as its management has been evolving with time. Significative efforts are being made in the development of SW control solutions at source that are, fundamentally, infrastructures that allow the reduction in surface runoff, giving the landscape the capacity for detention and infiltration that it had before urbanization (natural setting represented in Figure 4). However, they appear included in the international bibliography in a number of concepts, namely green infrastructure (GI), nature-based solutions (NbS) and LID (low-impact development). It is important to clarify these concepts so that the solutions are correctly described and organized in order to unify their presentation. Their definitions are presented in the following points:

- EEA [19] presents GI in urban areas, as "A strategically planned and delivered network of high-quality green spaces and other environmental features". They are multifunctional resources that deliver a wide range of environmental and quality-of-life benefits for urban communities and these goals must be addressed in their design and management;
- The European Commission defined NbS as "Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions" [20];
- LID is the concept used by the United States Environmental Protection Agency to define "systems or practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of SW in order to protect water quality and associated aquatic habitat" [21]. Generally, it is an approach to land development that works with nature to manage SW at source, recreating and preserving natural features to create functional and appealing site drainage that minimizes imperviousness and treats SW as a resource instead of waste.

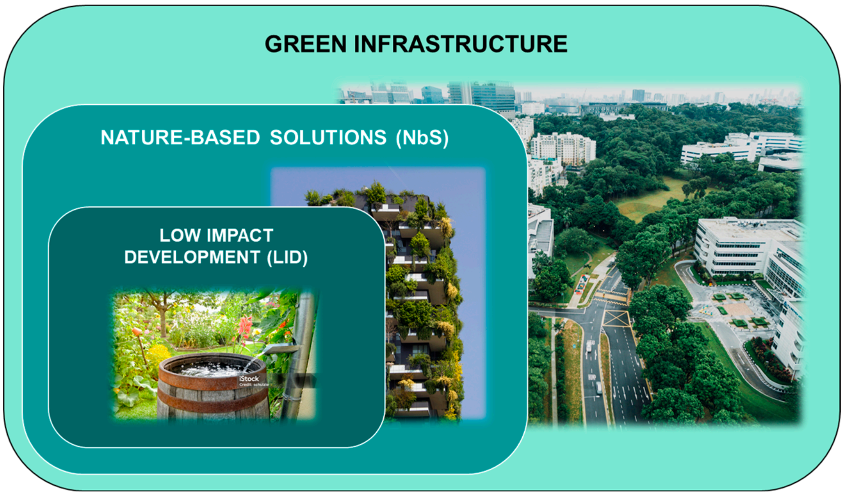

Figure 4. The interconnection of the GI, NbS and LID concepts.

Based on these definitions, it can be concluded that LID includes natural solutions with a specific goal to control SW in urban areas. Thus, the NbS concept encompasses LID solutions and all others that mimic natural processes and include other types of associated benefits like the well-being of populations in urban areas, temperature control, ecosystem restoration, etc. Finally, urban NbS, which due to their proximity are able to create a set that enhances and increases their benefits, constitute a GI. There is, in the background, a hierarchy of these concepts, and the way in which they fit into each other is represented in Figure 4.

The sustainable management of SW depends on the institutional framework of a country, its policy priorities and, of course, on its financial capability [11]. Only with these aspects working together and with community acceptance, control measures at the source such as GI are feasible as an important part of the management. On the other hand, the restoration of natural spaces is essential for community acceptance and thus the feasibility of SW management solutions requires a comprehensive understanding of site conditions.

There are many practices and solutions that have been used to follow the fundamental principles of LID to develop functional and appealing site drainage: rain gardens, vegetated rooftops, permeable pavements, bioretention facilities, and rain barrels, amongst others. Sustainable SW management, such as wetland SW treatment areas, also improves urban SW quality in addition to the benefits of water storage and peak-flow attenuation [17].

By implementing this kind of solutions that minimize imperviousness and preserve and recreate natural landscapes, SW can be managed in a way that reduces the impact of urbanization and promotes the natural movement of urban water within watersheds and the corresponding ecosystems. If they are applied on a broad scale, the restoration and maintenance of the watershed's ecological and hydrologic functions can be achieved [21].

The use of LID as an adaptation measure at the local scale can increase the storage of SW [6], promoting it to stay in the cities. They can be an important complement to conventional SW management strategies that divert flow toward centralized systems. For example, Mahmoud et al. [8] proved the benefits of bioretention for urban SW runoff reduction by comparing the size of storm events. They demonstrated its total capacity of eliminating the runoff for some small rain events, although in medium and large events, some runoff was observed. The authors pointed out that the use of local material in bioretention solutions was ideal for the infiltration capacity due to optimum media characteristics (including the porosity and hydraulic conductivity) with good results on the reduction in different pollutants.

In general, the progress of blue-green developments (including NbS) such as the Sponge City Program, has been providing several benefits to urban water, climate and ecosystem services [22]. These approaches are improving the relationship between people and urban water, and are renovating the urban landscape. However, they also have some disadvantages and challenges in their application. Wet detention ponds are nowadays the most adopted SW practice in coastal South California, as stated by Ureta et al. [15]. However, Gold et al. [14] found that the implementation of wet ponds may have distinctive effects on water quality in coastal watersheds due to the landscape's bio-geochemistry, soil type, high water table, and low relief. They concluded that, overall, watershed-scale implementation of wet ponds did not mitigate many negative effects of increased development, on SW quality.

Rainwater harvesting is also a LID practice very used worldwide with the potential for both water conservation and SW management. It is a mostly centralized solution implemented in buildings, although there are places where its coverage is at the level of a neighborhood. It has the clear advantage of providing the inhabitants with an additional reserve of water for consumption while reducing surface runoff and mitigating flood peaks by the ability to partially retain the water that occurs in a rainfall event. Yet, some studies revealed that conventional rainwater harvesting systems are not able to store large volumes of water generated by heavy rainfall events [9]. This is due to the simple fact that rainwater storage tanks must be empty when heavy storms begin; otherwise, they will have limited peak runoff reduction. To circumvent this problem, control systems can be implemented that can remotely empty reservoirs before the onset of an extreme precipitation event. If these discharges (as well as those made on a more regular basis) are made to the soils, and not to the public drainage networks, rainwater harvesting systems also have the additional advantage of compensating for the effects of the urbanized area by recharging the aquifers and, in this way, replacing the infiltration that would occur in a natural landscape. Despite being expensive systems and often with low economic viability, when considering the savings related to flood mitigation the economic benefits of rainwater harvesting might be significantly greater and motivate large-scale implementation in coastal urban areas [9].

4.2. Monitoring

Saraswat et al. [11] made an assessment of the latest practices in use to manage SW runoff and achieve urban water security. They explored the different policies and strategies adopted by Thailand, Vietnam and Japan, including case studies from Bangkok, Hanoi, and Tokyo. Their goal was to assess the advantages and disadvantages of SW runoff policies and practices, regarding hydrologic dimensions and historical measures of SW management systems. They stated that economic assessment of damage reduction and SW management must be evaluated for their effectiveness in solving the main problems. To that effect, important information must be given by regular monitoring systems before, during, and after the implementation of the chosen strategies, to assess and improve their results. In coastal areas, this monitoring must also consider the control of the water quality degradation, estuarine damage, ecological disturbance, and the loss of natural resources, as consequences of SW runoff, besides drainage problems and flooding.

4.3. The Fundamental Role of Populations

In coastal areas, tourism is a source of many challenges, so this fluctuating population must also be considered in the correct management of SW drainage systems. Penn et al. [23] stated that tourists share the responsibility to manage water resources with local residents, and through a choice experiment approach, the authors concluded that both are positively willing to pay for better strategies of SW management, but to different degrees. The study embraced different aspects such as prevention (e.g., reducing the volume or improving SW quality), public education and outreach, and monitoring and advisory services. Both tourists and residents were most favorable to make tests of water quality and educational efforts. With this kind of study, agency leaders may know which efforts for policy strategies will be more adequate for residents and tourists. In this particular case, the conclusions were encouraging since both groups had the same preferences both across and within the defined aspects.

The study made by Penn et al. [23] included several management strategies to promote better SW management in coastal areas, such as reducing the volume or improving the quality of SW, more useful monitoring and advisory services, and public education and outreach. This demonstrates the variety of aspects that must be taken into account in this management, both at an economic, social, urban planning, monitoring level, etc.

The socio-demographic characteristics of inhabitants of coastal urban areas influence their ability to accept and apply control measures at source (GI/NbS/LID), especially on their properties. The results presented by Ureta et al. [15] showed, for example, that the older population is not very interested in installing LID practices such as rain barrels, rain gardens, and rooftop disconnection in their properties. The authors also demonstrate the influence of household income on the residents' interest in their intention to include such practices in their properties. This kind of finding shows that the financial burden will be a barrier to the widespread implementation of such solutions. Taking into account that decentralized management requires that private properties are also part of the solution, an incentive plan is essential to overcome this obstacle, otherwise, inhabitants with lower income will remain unmotivated to adopt these measures. Ureta et al. [15] also revealed that people who own their properties and are exclusively in charge of their maintenance are more interested in the adoption of rooftop disconnections, rain gardens and other LID practices in the next years. This intention to implement SW control measures at source in the near future is also related to flooding-related experiences, as stated by the authors, which showed that those with the worst experiences (flooding into their houses) want to adopt bigger infrastructures like rain gardens, and those with less intense experiences (like only backyard flooding) would more likely adopt smaller solutions like rooftop disconnection.

Since anthropogenic effects have such a significant influence on urban SW management in coastal areas, as already referred to, the population will necessarily have to be a means to ensure the necessary resilience of these systems. In some places, efforts have already been made to alert locals and tourists to their role in this issue. Chan et al. [22] refer to the significant effort that the government has made among the population, to encourage their support for the Sponge City Program in China, but conclude that the commitment is dependent on the self-interest of the individuals and on the perceptions based on external forces. That is one of the main reasons why the engagement has been low. Also, in that case, people trust the government entirely, and in many cases, think that their contribution is not necessary. Also, the financial pressure felt by the families left them unaligned with such efforts.

In general, the study of Ureta et al. [15], focuses on several adoption barriers, but the perception, by residents, that green SW infrastructure practices are ineffective was the only statistically significant barrier found by the authors. This leads to an important way to develop these practices; giving the population more information about the effectiveness of these practices will increase their interest in adopting them in their houses and properties.

Various strategies, including websites, local authority leaflets, school education programs and media, are examples of means to inform domestic, tourist and business water consumers in urban areas. Also, the certification of hotels and the eco-labeling of appliances can raise awareness and help consumers to make informed choices about water efficiency and conservation [3].

4.4. Modeling

Simulations using numerical computer models are an important tool to assess the benefits and disadvantages of different alternatives to manage SW, considering the challenges of climate change. Several studies on urban SW management have been carried out with the support of these tools that help in the decision and management process by promoting an efficient and accurate method to provide indicative results that can help in population and asset protection.

With the use of numerical models, it is possible to adapt strategies to reduce flood risk in coastal areas by considering threats like sea level rise and high tide events. As stated by the Intergovernmental Panel on Climate Change [24], in this context, the concept of *risk* can be described as "the likelihood of a flood hazard occurring with an associated loss or negative impact, which can be expressed as the product of hazard, vulnerability, and exposure". They define *hazards* as "physical manifestations or occurrences of adverse events while exposure relates to elements negatively affected by hazards", and *vulnerability* as "the propensity or predisposition to be adversely affected or susceptible to harm, and a lack of capacity to cope and adapt". Although it seems that minimizing hazards and exposure is the most urgent aspect to address, vulnerability and adaptive capacity are equally important once they are tied to the concept of resilience.

Modeling scenarios in coastal areas needs to take into account the coastal tides, the sea level rise and the watershed-scale rainfall. The goal is mainly to assess the response of green and grey drainage infrastructure to current and future coastal flood threats, helping to improve drainage infrastructure resilience to flooding situations in urban areas. In the USA, Cohen and Brown [17] studied the role of hierarchy in the management and definition of SW collection and treatment systems in low-relief human-dominated watersheds using a process-based system simulation model. They demonstrated the availability of such tools to improve the characteristics of basin outflows in such landscapes.

However, the simulation of a watershed has many aspects that should be addressed with a certain level of detail. Salvan et al. [7] studied the impacts of detailed and simplified topography implementation on intense runoff modeling, using a detailed approach at a district scale, using a Mediterranean coastal city as a case study. The study focused on important questions for modeling SW drainage systems: how buildings and urban features influence overland flow, and their implications for urban flood modeling. They explored the level of detail that is needed to set up a model that is accurate and fast enough to allow operational modeling and showed that high-resolution data should be used carefully when dealing with urban hydrology and hydraulics. They pointed out a set of guidelines for modelers interested in the operational management of SW. Also, the selection of the level of topography details significantly impacts the results, both in surface drainage modeling and also in buried drainage systems. However, several effects will keep being sources of uncertainty such as surface features that evolve quickly over urban areas or that can be damaged by flood events, clogging effects, etc. [7].

In fact, there will often be SW components difficult to incorporate into numerical computer models, such as decisions made in SW management that reflect the social, economic, political, and aesthetic components of coastal cities [11].

Joyce et al. [6] developed a multi-scale modeling platform in a coastal watershed to assess the drainage infrastructure resilience with the adoption of low-impact development

(LID). They concluded that LID implementation strategies are affected by rainfall type when considering rainfall runoff reduction by peak inflow reduction. Other aspects that authors found to influence surface runoff reduction were the sub-daily rainfall patterns and, as expected for coastal areas, the effect of sea level rise on groundwater. This is a specificity of SW drainage systems that must be considered when modeling coastal areas. As the authors explained, adding infiltration-based LID alternatives to areas affected by sea level rise could result in higher groundwater tables for these areas. Results indicate that the effectiveness of LID depends on the rainfall type being considered, sub-daily rainfall patterns, and a groundwater table analysis. The major conclusion of their study was that the overall LID implementation within the watershed can alter the hydrologic response of the existing grey infrastructure to offer increased peak inflow reduction across varying rainfall types and sub-daily rainfall patterns.

Numerical models can also be used to assess the effectiveness of a single LID practice so that its results can be implemented in a large-scale model where the effects of implementing several units can be analyzed. In Texas, USA, Mahmoud et al. [8] evaluated a bioretention system planned to reduce runoff volume and pollutant loading, using a field-scale case. Its performance was compared with that of traditional asphalt pavement situated in the same parking area, over a 13-month period. Then, they used a model that evaluates multiple control practices through continuous SW runoff and quality simulation, considering a variety of rainfall intensities, land uses, soil conditions and surface types. The bioretention cell field results were used to calibrate the model outflow volumes and the results showed an average runoff volume 82% lower on the bioretention cell when compared to the traditional asphalt pavement. The study also demonstrated the influence of antecedent dry weather periods on the treatment performance of the bioretention facility.

Different types of software are available to provide SW simulations, such as the ones used by the authors of the portfolio collected for this review, namely Mike URBAN (DHI), the Interconnected Channel and Pond Routing Model v.4 (ICPR4) and The Windows Source Loading and Management Model (Win-SLAMM) [6–8]. Saraswat et al. [11] present a collection of urban stormwater models used for simulation and management (namely MOUSE, MUSIC, P8, PURRS, RUNQUAL, SLAMM, StormTac, SWMM, UVQ, WBM), analyzed according to their potential uses, spatial and temporal resolution, and the capacity to simulate capability runoff generation with different routing methods.

5. Discussion

Coastal areas present additional difficulties in relation to SW management in interior cities. Their specificities, both in terms of the current framework and in terms of adequate solutions and strategies, must be addressed in order to minimize the adverse effects of ineffective management. As presented in previous sections, concreted and sealed surfaces in urban areas avoid the infiltration of rainfall into the soil and replenish groundwater storage that would benefit urban populations at a later date. The accumulated surface runoff flows into the rivers (or merges in wastewater), being taken away from the cities. The way urban SW has been managed has been evolving: initially, through centralized collection and disposal systems to the latest development and implementation of source control solutions. However, from now on, it must also be considered that both SW and less polluted wastewater should stay in the cities to increase the availability of water resources [3]. Keeping the water in the city, allowing it to infiltrate into the soil and accumulate in water detention structures provides several benefits, such as recreational spaces and helping to create a cooling effect throughout heat waves. In addition, there are several non-structural measures that add complementary effectiveness to a more multidisciplinary and decentralized approach.

The analysis of the articles collected in the portfolio of this review demonstrated the need to promote the correct management of SW in coastal urban environments for the following reasons:

- These are often intensely urbanized areas, located at the downstream ends of the respective river basins where urban expansion has not been accompanied by the proper adaptation of existing drainage systems.
- The intensity of precipitation has been undergoing unfavorable changes, with higher intensities being recorded more frequently, which, together with uncontrolled land development, increases the amount of SW runoff that must be managed by drainage systems;
- Surface runoff, now enhanced by the high impermeability of urban areas, drags pollutants that affect water resources and marine ecosystems, threatening the quality of life of those who use them;
- Decreased SW infiltration into soils reduces groundwater, paving the way for saline water intrusion.

Being a complex system, whose management depends on diversified factors, there is no single solution that ensures the resilience of coastal urban areas. Improving the man-made environment looks like the most adequate way to manage stormwater in cities, once it is not feasible to alter the natural environment. The majority of the presented management strategies focus on the mitigation of environmental damage and risk by replicating the pre-urbanized runoff hydrograph. From the SW quality perspective, the source tracking of pollutants and the implementation of LID solutions at specific locations, are good strategies to minimize downstream pollution.

It is necessary to implement methodologies adapted to each location since. As mentioned by Pinto et al. [13] a one-size-fits-all approach to managing SW may not provide the desired outcomes, because the urban water cycle is a complex system very influenced by weather conditions. Tailor-made approaches designed at a catchment scale and considering its characteristics (including the receiving downstream water bodies) are the way forward to effective SW management.

Such methodologies should be multidisciplinary in nature, including the implementation of control measures at source, which work in a complementary way to existing drainage systems (properly adapted) and contribute to the sustainability and availability of groundwater. Also, the interaction between SW runoff and pipe flow is crucial to ensuring efficient drainage, so the maintenance of drainage systems must not be discarded. The adaptation of existing drainage systems should include control structures prepared to receive the runoff of heavy rainfall.

This multidisciplinary management should also include non-structural procedures that raise awareness and encourage people's participation. In the specific case of coastal areas, these measures must include tourists and the floating population. A crucial factor in the effectiveness of SW management practices is community acceptance, and many studies showed that when a community is more aware of the benefits, they are more willing to contribute, for example, to their maintenance and the report of operation problems. Although there has been an effort from many institutions to promote the use of GI/NbS/LID practices due to their multiple environmental benefits, a significant part of the population still does not understand and value their benefits. Issues related to residents' previous experiences, income and standard of living influence the acceptance of measures in their properties, so incentive policies will be key to this issue.

Monitoring technologies and decision support tools should also be included, taking into account the variability of network discharge conditions (with tidal levels and rising average sea level) and the development of alert systems that work with control measures at source and with populations. The modeling and simulation of coastal zones are extremely important, once the combination of different factors at the same time (like rainfall variations, imperviousness, evaporation, etc.) has greater impacts on the runoff than the action of each one separately. However, coastal urban models have additional challenges related to tidal oscillation and groundwater levels. It is important that models work with climate projections to understand what will happen to the networks in the future and to address some important aspects, such as:

1. How will drainage systems and LID practices, influence the reaction of the watershed during different precipitation intensities?
2. What factor will interfere the most with the effectiveness of the structural measures that can be applied in a determined watershed? What methods or criteria can be addressed to raise that effectiveness?
3. How will the increase in flooding stress and sea-level rise, impact the traditional drainage systems and the effectiveness of LID practices and flood control structures?

Urban SW management is a very complex task, where multiple factors go beyond mathematical models and treatment technologies. The occurrence of large quantities of water and the degradation of the receiving water environment are inevitable with urban development if adequate compensation measures are not taken. Such technologies and approaches can help capture SW for treatment and reuse before discharging it to the downstream natural environment and thus achieve urban water sustainability. Together with the existing infrastructures, the support of populations and the adoption of climate-resilient adaptation strategies for urban planning, it should be possible to achieve optimal urban water cycle management. As stated by Pinto et al. [13], tomorrow's cities will have a new way of thinking from the users' and managers' point of view, well supported by new technological innovations and institutional capacity to capture and retain water in urban areas.

6. Conclusions and Recommendations

Urban SW problems are not only related to floods but also to pollution control and groundwater management. In coastal areas, these problems are amplified by the impacts on marine ecosystems and the salinization of groundwater sources.

In coastal regions where access to drinking water is scarce, the impacts of uncontrolled SW management can also affect the supply to populations. Maintaining rainwater in cities is a way to minimize this problem, as long as it promotes soil infiltration and consequent recharge of groundwater. On the other hand, enhancing the infiltration of water into the soil is one of the most effective measures to control surface runoff that has caused flooding in several coastal areas around the world. The accumulation of large volumes of SW on urban surfaces has two main causes: the increase in the occurrence of heavy rainfall phenomena and the high sealing of soils, due to growing urbanization.

The literature review carried out in this study reveals a multidisciplinary approach to minimize the main challenges related to SW management in coastal areas (urban flooding, SW pollution and groundwater salinization), which includes the adaptation of existing infrastructures, complementing them with control solutions at source, correct urban planning and the involvement of populations. For an effective management of urban SW drainage in coastal areas, this approach must be carried out on a watershed scale, duly supported by reliable decision support tools and monitoring systems, taking advantage of this resource.

Climate change effects on the design of SW management systems in coastal areas must be considered taking into account two fundamental aspects: the future precipitation patterns that are provided by prestigious institutions (realistic forecasts, eventually validated by historical tendency analysis) and by preparing SW networks to deal with different types of events: the system must be ready to retain and infiltrate regular rainfall events, the networks must be effective when flowing intense precipitation and the landscape must be prepared to receive and control extreme events. As future developments in this research area, it is expected the development of these monitoring systems and methodologies that promote this integrated management of coastal basins is foreseen.

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