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Understanding Urban Surfaces: Nature-Based Solutions (NbS) for Stormwater Management

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Abstract

Urban areas often encounter significant challenges in stormwater management due to the prevalence of impermeable surfaces, such as asphalt, concrete, and buildings, which hinder natural water cycle. Existing stormwater management solutions are frequently neither viable nor adaptable for communities. These approaches are often costly, time-intensive, and fail to account for climate change adaptability, as well as community consultation and participation. The primary objective of this study is to analyze urban land use and land cover (LULC) to develop a tool that helps communities and stakeholders identify nature-based solutions for stormwater management, customized to their specific and localized context. A thematic analysis was conducted on the Urban LULCs of two urban areas in Puerto Rico—Bayamón and Ponce—to develop a comprehensive taxonomy of urban LULC. This analysis provided a deeper understanding of the urban surfaces in Puerto Rico, identifying 15 distinct types of urban LULC through a visual characterization conducted at a 1:1000 scale using Landsat 8 images. Through a literature review, 22 specific nature-based solutions were identified, and categorized based on water/surface relationship (shallow infiltration, storage, runoff management, and deep infiltration). This tool is designed to transform urban spaces by prioritizing surfaces that effectively manage water, mitigate flooding risks, and improve water quality, thereby enhancing the sustainability of urban environments from an individual/community scale. It introduces an array of alternatives to traditional urban water management, expanding the possibilities for more sustainable and context-sensitive approaches. By linking surface taxonomy to water management, the study provides a valuable resource for strengthening urban resilience against climate variability and extreme weather events by gaining a deeper understanding of water behavior in our communities.

Keywords

Community Tool, Nature-Based Solutions, Urban Land-Use/Land Cover, Participatory Water Management, Climate Change Adaptation

1. Introduction

Urban areas are defined as regions with specific population densities, economic activities, and spatial characteristics, all interwoven to sustain human operations within the Anthropocene.

These areas epitomize the convergence of human necessities and livelihoods, driving a need to modify natural systems to fulfill fundamental requirements. Scholars argue that urbanization represents the most definitive manifestation of changes in global human settlement patterns, reflecting a transition toward landscapes dominated by anthropogenic influence [1]. Urban settlements, in contrast to rural or underdeveloped areas, play a pivotal role in fostering economic growth, promoting social and cultural diversity, and ensuring access to essential services and infrastructure [2]. These contributions underscore the dual role of urban areas as engines of development and key drivers of environmental transformation. Globally, urbanization has been marked by a relentless upward trajectory in population. From 1950 to 2020, the global urban population rose dramatically from 0.8 billion (29.6%) to 4.4 billion (56.2%) and is projected to reach 6.7 billion (68.4%) by 2050 [3]. This growth places immense strain on natural resources and ecosystem services, increasing the urgency to address the environmental and social challenges posed by urban expansion. The expanding urban footprint transforms natural landscapes through land-use changes, deforestation, and the proliferation of impervious surfaces, significantly disrupting ecological processes.

As urban populations grow, the demand for food, water, energy, and shelter among other ecosystem services escalates, compounding pressures on finite natural resources. This transformation leads to the loss of critical ecosystem services (ESs) such as air and water filtration, carbon sequestration, flood regulation, and biodiversity support. As forests, wetlands, and agricultural lands are converted into built environments, the capacity of these natural systems to provide essential ecological functions diminishes, exacerbating urban heat island effects, increasing stormwater runoff, reducing soil permeability, and contributing to climate change. Additionally, this shift can lead to social and economic consequences, such as food insecurity, displacement, and a decline in overall environmental resilience. Effective urban planning and governance are critical to addressing these challenges, yet they remain inadequate in many contexts.

Su concludes that ecosystem services (ESs) are the essential things that natural ecosystems do to keep people alive [4]. They include providing, regulating, supporting, and cultural services. Although these services are renewable, the rate at which we consume them, especially in urban areas, often outpaces the time required for natural systems to replenish. Water resources, for example, being renewable due to their cyclical nature, face variability influenced by climate and land surfaces, leading to a highly heterogeneous hydrological cycle and water resources in both space and time [5]. Climate regulating ecosystem services (CRES) are highlighted as a crucial measure to fight climate change, but the provision of these services is strongly influenced by changes in land use and land cover [6]. Faced with a changing climate, traditional methods for handling stormwater are revealing their limitations. Relying exclusively on extensive infrastructural stormwater management is becoming increasingly impractical due to its constraints. Climate change introduces uncertainties such as altered precipitation patterns and increased frequency of extreme weather events, making static infrastructure less adaptable. Traditional engineering approaches are incapable of meeting all the sustainability challenges posed by the growing urban population and consumption [7], with a growing recognition of the need to complement/replace with the use of natural systems to attenuate runoff and manage water on-site facilitating adaptation to climate change [8]. The interconnectedness of ecosystems and hydrological cycles underscores that infrastructure alone cannot comprehensively address the intricate and evolving challenges posed by climate change. Relying solely on traditional infrastructure for water management is insufficient for addressing climate change adaptation, given the complex and multi-dimensional nature of climate-related challenges that static measures alone cannot effectively tackle. Physical structures like dams, levees, and drainage systems play a role in water management, but they have significant limitations when faced with the complexities of a changing climate, including increased precipitation, sea level rise, biodiversity loss, excessive heat, and droughts. While gray infrastructure is generally static, green infrastructure is dynamic, continuously evolving and adapting to changing conditions. Gray infrastructure can exacerbate the negative effects of development, whereas green infrastructure mitigates societal impacts by reducing heat, air, and noise pollution. It achieves this by providing shade, dispersing and diluting airborne pollutants, and buffering noise [9].

Instead of developing stormwater management actions based on predictions, and anticipatory approaches, Nature-Based Solutions (NbS) are centered around developing strategic actions whose social, ecological, and economic effects transcend one specific risk. These innovative approaches focus on the treatment of stormwater as close to the source as possible, sustainably integrating quantity and quality control [10]. Integrating nature-based solutions (NbS) into urban planning offers a transformative approach to harmonizing development with ecological stewardship. Leveraging ecosystem services, NbS can address challenges such as stormwater management, air quality, and energy efficiency, making cities more sustainable and livable. As urbanization continues to shape the global landscape, a paradigm shift is essential in how cities are planned and managed. Sustainable urban practices, including the integration of NbS and equitable resource distribution, can transition cities from drivers of ecological degradation to leaders in environmental restoration and resilience. Moving toward a predominantly urban future requires strategies that align development with natural systems, ensuring cities thrive without compromising the planet's ecological integrity.

2. Materials and Methods

This study examines urban land use and land cover (LULC) in Puerto Rico to understand the interaction between urban surfaces and water towards designing a community nature-based solution selection tool. In order to create a customized taxonomy of urban LULCs, this research integrates spatial analysis, thematic analysis, and on-site soil testing, leading to the development of a user-friendly tool that facilitates participatory water management and sustainable urban planning practices. The tool enables stakeholders—such as governments, municipalities, water management agencies, local communities, and individuals—to make informed, sustainable decisions for addressing stormwater challenges. This study aims to address the lack of accessible tools, resources, and frameworks at the community level, which exacerbates the vulnerability of urban areas to changing climatic conditions [11] while filling the gaps in our knowledge about urban LULCs and how they affect water systems. It supports collaborative approaches to managing stormwater in cities, and it gives stakeholders the chance to take the lead and make things happen.

A specific study area was selected based on community-reported flooding issues identified using Volunteered Geographic Information (VGI) from online platforms and social media. Volunteered geographic information (VGI), defined as the "act of having simple citizens produce geographic information, either intentionally or unintentionally", emerged from Web 2.0 technologies [12]. Research was made using the query "inundación" (flooding) between December 1, 2022, and December 1, 2023 using (2) local news center social media platforms, Telemundo y Metro. The area(s) with most community reporting were selected and the findings were geolocated using QGIS, allowing for the identification of clusters that informed the selection of a 2.5 km radius as the study area for further analysis. Spatial data was enriched using the USDA-NRCS Farm Planning Tool, which provided layers such as the Land Use Plan (PUT). The "Ley de Planificación de Puerto Rico" (Law No. 75 of June 24, 1975), establishes that Puerto Rico's land use plans must align with broader urban planning and conservation goals, ensuring coherent land development across municipalities [13] and The Puerto Rico Gap Analysis, a comprehensive study designed to identify the gaps in biodiversity conservation across the island. This analysis evaluates the current distribution of species, natural habitats, and protected areas to assess how well these areas conserve Puerto Rico's biodiversity. By comparing existing conservation efforts against the habitat needs of various species, the Gap Analysis helps in identifying regions that lack sufficient protection, thereby guiding future land management, conservation strategies, and policy-making. It provides valuable information for prioritizing areas that require immediate conservation attention, contributing to the island's sustainable land use and biodiversity preservation [14]. Based on the data in these two planning tools, urban LULCs were put into groups, which made it easier to create a taxonomy that fits Puerto Rico's urban environment.

To validate the Urban LULC taxonomy, a visual characterization was conducted using October 2023 Landsat 8 images at a 1:1000 scale, obtained from the USGS Earth Explorer platform.

Urban stormwater management aims to lessen the bad effects of flooding and improve water resource use at the block or community level [15] so it's important to understand urban soils and surfaces at a meso level. On-site texture tests were conducted on randomly selected impervious urban LULCs. Soil samples were collected from April 30 to May 2, 2024, using a soil sampler probe across seven sites in both municipalities. A total of 7 urban soil samples were examined for texture, with observations documented through photographs and text. On-site soil texture was developed using Thien's (1979) tactile method, which classifies soils based on moisture, ball formation, and ribbon length. This analysis provided insights into soil profiles and texture, hydrologic behavior, and water-holding capacities. The information gathered made it easier to find Hydrologic Soil Groups (HSG) (NRCS, 2017) so that we could learn more about how water behaves in cities. Leveraging the HSG tool, traditionally used for soil conservation in agriculture, provided valuable insights into water/surface relationships to enhance urban soil management. The selection of specific Nature-Based Solutions (NbS) for each Water/Surface (W/S) relationship was made based on the hydrological behavior, surface permeability, and ecosystem service potential of different urban land cover types. Impervious surfaces, such as roads and rooftops, generate high runoff volumes due to limited infiltration capacity, necessitating the implementation of solutions like green roofs, permeable pavements, and bioswales to enhance water absorption and reduce stormwater surges. In contrast, semi-pervious surfaces, such as compacted soils and urban green spaces, exhibit moderate infiltration rates, making them suitable for interventions such as rain gardens and urban wetlands, which further improve water retention and filtration.

For highly pervious surfaces, such as natural soils and vegetated areas, NbS selection prioritizes conservation-based strategies, including afforestation, soil restoration, and retention ponds, to maximize groundwater recharge and flood mitigation. The decision-making process also integrates regulatory requirements, urban planning constraints, and long-term sustainability goals to ensure that each NbS is both contextually appropriate and effective in optimizing water management while enhancing ecological and social benefits.

3. Findings and Discussion

During the site selection process, a total of 11 municipalities were identified based on 37 VIG on flooding incidents between December 30, 2022 and December 30, 2023. The Bayamón and Ponce study areas were selected with a total of (11) VIG for each one of them. The VGI data for each selected study area was georeferenced and clustered using QGIS to identify the highest concentration of community reports, defining a 2.5 km radius for analysis in both municipalities (**Figure 1**).

Further spatial analysis was conducted in the two selected study areas. The first, Plan de Uso de Terreno (PUT) or Land Use Plan, is a strategic document guiding the development, conservation, and management of land resources in Puerto Rico. The second, the Puerto Rico Gap Analysis, is a comprehensive study identifying gaps in biodiversity conservation across the island. Figure 2. presents a comparison of the taxonomy used in the respective documents. The Plan de Uso de Terreno (PUT) identifies only three urban LULC categories, whereas the Puerto Rico Gap Analysis distinguishes seven within the same areas.

Figure 1. Left: Ponce 2.5 km Study Area, Right: Bayamón 2.5 km Study Area Blue dots represent identified VGI data, blue lines represent flowing rivers and dotted blue lines represent channelized rivers (Burgos-López, 2024).

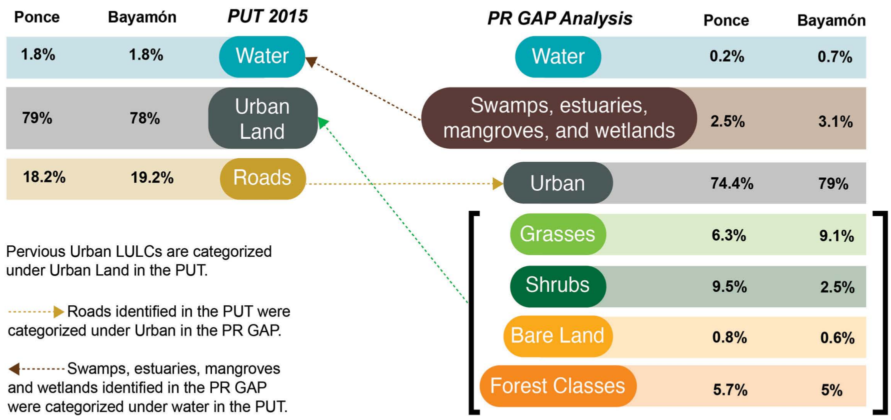

Figure 2. Comparison between the Urban LULC as per established in current planning tools at a local level: Plan de Uso de Terrenos and the PR GAP Analysis (Burgos-López, 2024).

Through further visual characterization of the Landsat 8 images, 15 urban LULC types were identified in Bayamón and Ponce, grouped into pervious and impervious surfaces. Soil samples on the identified pervious surfaces were collected throughout both municipalities from April 30 and May 2, 2024 with a total of (7) urban soil samples on (7) sites (Figure 3). These include backyards and gardens, abandoned structures, cemeteries, vacant lots, flowing rivers, urban agriculture, parking areas, single roofs, planting strips, open/natural areas, plazas/public spaces, drainage channels, building roofs, streets and sidewalks, and channelized water bodies. These are listed in Table 1 based on perviousness. Eight LULCs were classified as pervious surfaces, retaining their capacity to provide critical ecosystem services including infiltration for water management.

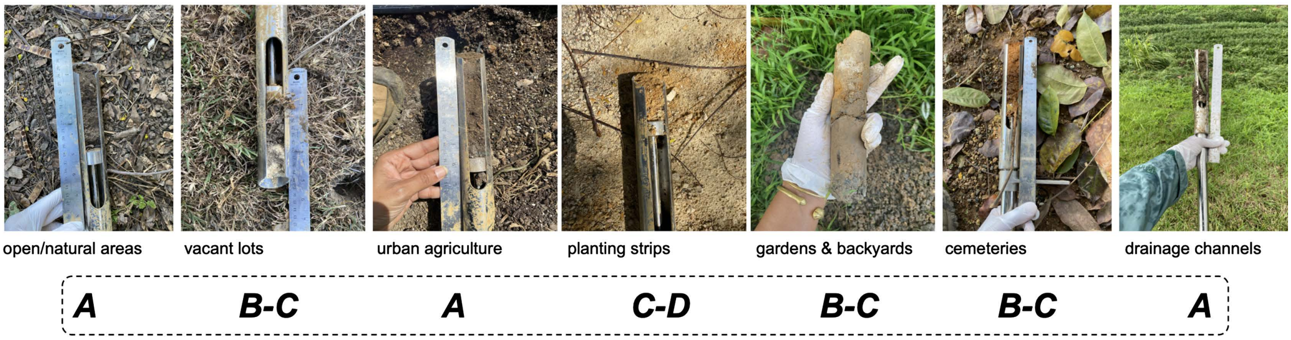

Figure 3. Soil samples taken ate the 7 pervious areas in Ponce and Bayamón with the respective Hydrological Soil Group (HSG).

Table 1. Identified urban LULCs divided by surface perviousness.

Urban LULCs	
Impervious	Pervious
Parking Areas	Open/Natural Areas
Streets and Sidewalks	Planting Strips
Single Unit Roofs	Gardens and Backyards
Abandoned Structures	Flowing Rivers
Building Roofs	Drainage Channels
Channelized Water Bodies	Cemeteries
Plazas/Public Spaces	Urban Agriculture
	Vacant Lots

At the selected sites, the probe—a Homier 40-inch (1 Meter) Soil Sampler Probe 304 Stainless Steel with Ejector and Foot Pedal was inserted vertically, and rotated slightly for uniform sampling, then the core was retrieved while maintaining the integrity of the soil structure in order to document layers. Qualitative observations, including depths and visual characteristics, were recorded, and documented through photographs and text. Although there were 7 impervious surface types compared to 8 pervious surface types, the impervious surfaces were contiguous. In contrast, the pervious surfaces were more diverse but fragmented, forming smaller, disconnected urban soil systems. Among the identified urban LULCs, notable impervious surfaces included large-scale commercial roofs and parking areas, such as Plaza del Caribe in Ponce, which contributes approximately 39 hectares of impervious surface, and Plaza del Sol in Bayamón, with 15 hectares (Figure 4).

Water bodies, including flowing rivers, channelized watercourses, and drainage channels, were observed as significant but highly altered urban features. Examples include Río Bayamón and Río Portugués, where large-scale flood control infrastructure was implemented, often reducing natural connectivity and ecological health. Green corridors along these water bodies, while present, varied significantly in density and biodiversity between municipalities, with Bayamón exhibiting more robust ecological features compared to Ponce.

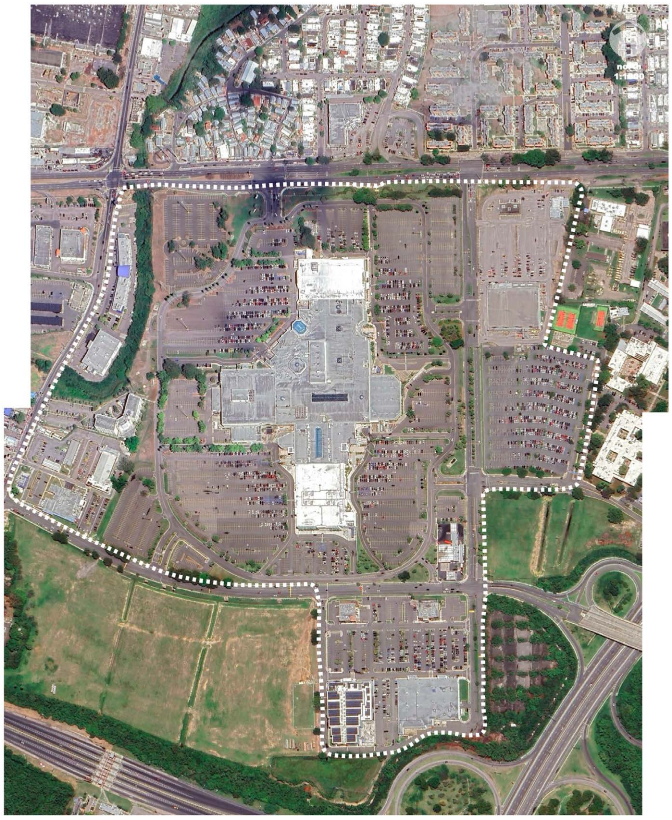

Figure 4. Contiguous impermeable surfaces (parking area, street and sidewalks and building roofs) totaling 39 acres approximately. NTS. (Burgos-López, 2024).

The soil sampling and W/S (water/surface) relationship analysis provided insights into urban stormwater dynamics. Categories like backyards and vacant lots demonstrated shallow infiltration potential, while others, such as planting strips, indicated soil compaction conditions with limited water retention capabilities. Urban agriculture and open/natural areas demonstrated the lowest runoff potential, making them highly effective for managing water in urban environments. These soil types are particularly suited for enhancing infiltration and reducing stormwater challenges in urban settings. Impervious LULCs, including single-unit roofs, building roofs, and paved parking areas, primarily contributed to runoff. The study also pinpointed crucial problems in green spaces, including the conversion of open/natural areas into impermeable developments, which intensifies runoff and diminishes infiltration opportunities. Despite these challenges, eight pervious LULCs indicate that NbS still has significant potential in urban Puerto Rican contexts. Once the taxonomy of urban LULCs was finished and water/surface relationships were assigned to each category, the next step was to find nature-based solutions (NbS) that would work for each water/surface relationship (**Figure 5**). A general overview of each NbS is provided below, categorized according to their associated water/ surface relationships as detailed in the table. This overview includes a definition of each solution, the relevant legal and regulatory framework, cost considerations, and management requirements. These elements form the basis for identifying optimal NbS tailored to specific site conditions, emphasizing the critical role of understanding water/surface dynamics in urban planning and sustainable water management.

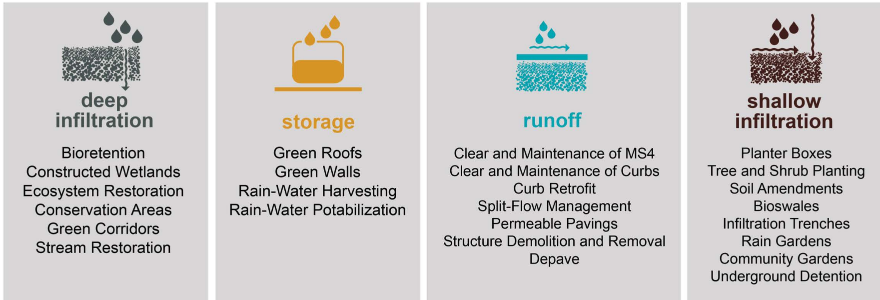

Figure 5. Nature-based solutions organized as per water/surface relationships.

The study identified four primary W/S relationships—runoff, shallow infiltration, storage, and deep infiltration—using this classification to organize NbS. These relationships underscore how urban surfaces interact with water and offer actionable insights for stormwater management.

Runoff-heavy areas require solutions such as permeable pavements, asphalt/structure removal, and curb retrofits. Shallow infiltration can be enhanced through street trees, planter boxes, and urban agriculture, while storage-focused areas benefit from green roofs and rainwater harvesting systems. Deep infiltration is supported by bioretention systems, constructed wetlands, and ecosystem restoration initiatives. For instance, runoff management solutions like bioswales and infiltration trenches were highlighted for their ability to reduce surface water accumulation, mitigate flooding risks, and improve water quality. These solutions are particularly applicable to impervious LULCs like parking lots and streets. Storage-focused solutions, including green roofs and rainwater harvesting, were emphasized for their potential to reduce peak runoff volumes and offer additional water resources. In deep infiltration contexts, bioretention cells and constructed wetlands demonstrated long-term efficacy in improving water quality and recharging groundwater. Implementation costs for NbS varied widely. Green roofs were noted for their higher upfront costs but long-term durability and energy-saving potential. Rainwater harvesting systems, including community-based initiatives, offered cost-effective management solutions with scalability. Soil amendments, bioswales, and tree planting programs were recommended for shallow infiltration areas, particularly in degraded soils, to restore hydrological function and increase biodiversity. The analysis revealed significant challenges in urban water management, including limited implementation of NbS due to policy gaps and inadequate maintenance of existing green infrastructure. While planning instruments like the PUT highlight urban land and water categories, they lack enforceable mandates for NbS implementation, leaving such measures discretionary for property owners. Additionally, the lack of integration between large-scale flood control projects and localized NbS has hindered the holistic management of water resources. The conversion of open/natural areas into impervious surfaces underscores the pressing need for sustainable urban planning. Just two projects around the 2.5 km radius in the study area of Bayamon transformed approximately 60 hectares of pervious green spaces into paved areas over five years (**Figure 4**), highlighting the urgency of preserving urban soils and implementing NbS. Furthermore, the lack of robust green infrastructure maintenance, particularly in channelized water bodies and planting strips, reduces ties their capacity to manage stormwater effectively.

The Nature-Based Solutions (NbS) Selection Tool

Puerto Rico's water management systems have developed through historical influences, including colonial policies, agricultural demands, urbanization, and modern regulations such as the Clean Water Act. The current framework is fragmented among ten federal and local agencies, resulting in inefficiencies, jurisdictional overlaps, and gaps in implementation. Recent updates, such as incorporating Low-Impact Development (LID) practices, demonstrate progress but lack mandatory enforcement, reducing their operational impact. Addressing these challenges requires an integrated, data-driven, and stakeholder-engaged approach to improve system resilience, optimize resource allocation, and adapt to the hydrological complexities of a changing climate.

Nature-based solutions (NbS) for water management are important to governments, agencies, and institutions, and they have been working hard to collect information to organize and describe the different strategies (see guides from the EPA, The Nature Conservancy, USACE, UN, and IPCC). However, decision-making regarding which specific NbS should be studied in a given context remains challenging. To move toward an operational framework that can guide applications of the NbS concept [16], we need to learn more about NbS and confirm the principles on which it is based. The development of the NbS Selection Tool (**Figure 6**) represents a significant advancement in addressing these challenges. This tool integrates spatial data, stakeholder input, and hydrological insights to recommend tailored NbS for specific urban contexts. By analyzing urban LULCs and their W/S relationships, the tool guides the implementation of solutions such as rain gardens, permeable pavements, and bioretention systems. It emphasizes a participatory approach, encouraging collaboration between communities, municipalities, and technical experts to co-create effective water management strategies. This tool also democratizes access to resilient infrastructure knowledge by supporting communities in taking the lead in water management needs at a local level. It facilitates decision-making at household and municipal levels by providing guidance on the selection process based on current state. Additionally, the tool bridges gaps in existing policy frameworks by offering actionable recommendations that align with local hydrological and urban conditions.

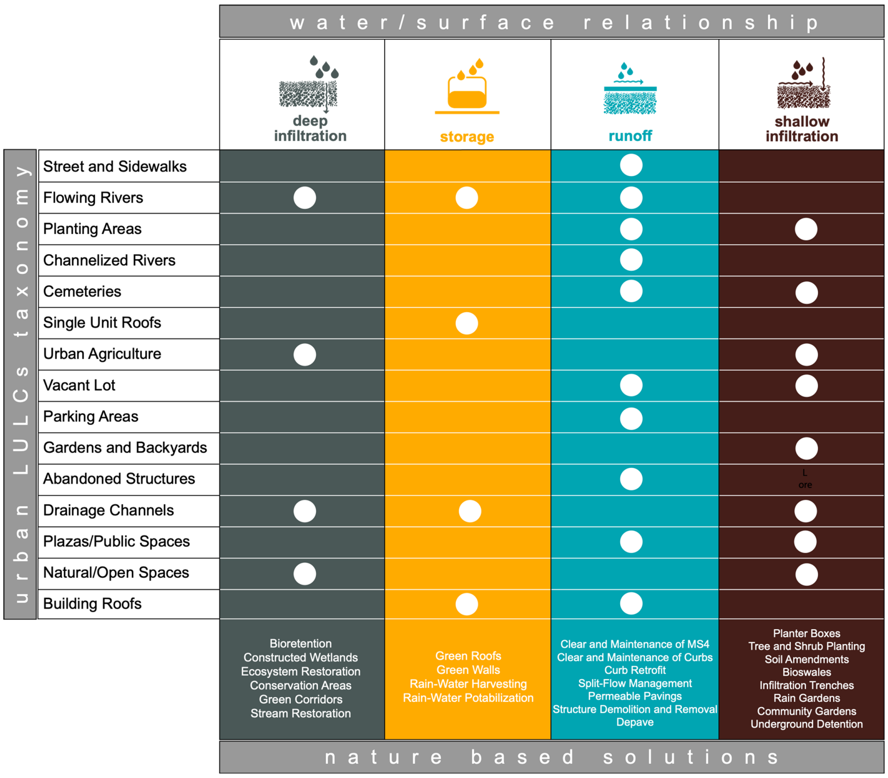

Figure 6. Nature-based solution selection tool (Burgos-López, 2024).

4. Conclusions

The primary consequence of urbanization is the transformation of natural landscapes into impervious surfaces, which disrupts natural hydrological cycles, exacerbates flooding, intensifies urban heat islands, and diminishes ecosystem services. This contrast—an anthropogenic disruption of the water cycle between pervious and impervious surfaces in the urban landscape—highlights the potential of exposed urban soils to sustain essential ecosystem benefits, helping to offset the high demand for ecosystem services in urban environments. Urbanization presents both challenges and opportunities for sustainable development. The density and resource concentration of urban areas provide unique platforms for innovative solutions to global challenges. Compact cities can lower per capita resource consumption and emissions, while mixed-use development and efficient public transit reduce reliance on private vehicles. Green infrastructure, such as urban parks, green roofs, and permeable pavements, helps mitigate urban heat islands, enhance biodiversity, and improve water management, increasing cities' resilience to climate change. These findings highlight opportunities for targeted management and preservation of urban pervious surfaces to enhance sustainability. Through spatial analysis and on-site assessments in the study areas of Bayamón and Ponce, this study confirmed these effects. It showed that urban land use, land cover (LULC) and water management are complicated and affect each other in many ways. While the study provided valuable insights, the limited diversity of urban land use types in the two municipalities underscores the need to expand the analysis to include additional areas to develop a more comprehensive tool for managing urban surfaces.

In contrast, this study expands the classification to 15 categories, providing a more detailed and comprehensive understanding of urban LULC. The findings suggest that at the decision-making level, urban LULC characteristics are not being thoroughly analyzed or considered. Instead, management approaches remain surface-level, overlooking the crucial ecosystem services provided and sustained by the soil beneath urban surfaces.

Recognizing the limitations in the current soil sampling analysis, it is essential to continue collecting soil samples from the seven previously identified urban LULC categories. This will enhance understanding of soil hydrodynamics, including infiltration rates, water retention capacity, and the role of different soil types in regulating stormwater. Such ongoing analysis generates critical data to refine and optimize Nature-Based Solutions (NbS) for stormwater management, ensuring that interventions are site-specific and effectively leverage the soil's capacity to support ecosystem services.

Urban hydrology in Puerto Rico has shifted significantly due to high-value urban land being converted into single-use, car-dependent developments. Impervious surfaces have replaced previously found infiltration zones in open natural spaces and vacant lots, leading to an increase in stormwater runoff. Responsibility for managing this runoff is transferred entirely to public entities like Municipal Separate Storm Sewer Systems (MS4s) and the Department of Natural Resources, despite originating from privately developed properties. This disparity highlights the need for policies that enforce accountability, non-extractive and sustainable urban development practices. Additionally, current planning tools, such as the *Plan de Uso de Terrenos* (*PUT*), fail to recognize the hydrological and ecosystem contributions of pervious surfaces, categorizing them uniformly as "urban land." This oversimplification disregards their role in stormwater infiltration, urban cooling, and climate resilience, exacerbating the environmental challenges associated with urbanization.

Transportation infrastructure also plays a significant role in shaping urban dynamics. Roads and highways, which constitute approximately 20% of the study areas, contribute substantially to surface runoff, heat island effect and ecosystem fragmentation. There haven't been any high-density, mixed-use projects with green infrastructure built into suburban developments near transit hubs in Bayamón and Ponce. This has hurt the potential of transit-oriented development (TOD) to reduce impervious surfaces and encourage sustainable urban growth. TOD offers a crucial opportunity to minimize impermeable surfaces, reduce reliance on private vehicles, and integrate green infrastructure to enhance urban livability and environmental sustainability [17]. However, these opportunities remain underutilized as developments continue to prioritize car-centric designs.

Urban agriculture, vacant lots, and abandoned spaces present untapped opportunities for enhancing urban ecosystem services. The study highlights the potential of urban soils, such as those in the Huerto Urbano Callejón Trujillo in Ponce, to support deep infiltration and food production, addressing both stormwater management and food security in a region where 85% of food is imported. Abandoned properties and vacant lots present significant opportunities for implementing Nature-Based Solutions (NbS), converting underutilized urban spaces into functional assets that enhance resilience and sustainability. Incorporating high-quality agricultural soils and green infrastructure into these areas can improve water infiltration, restore soil health, reduce urban runoff, and mitigate flooding risks [18]. Additionally, these transformations contribute to lowering carbon emissions by enhancing carbon sequestration, reducing the urban heat island effect through increased vegetation, and promoting sustainable land use practices that foster healthier urban ecosystems.

The study also underscores the importance of addressing climate justice in urban planning. Many vulnerable communities in flood-prone areas, such as those near rivers in Ponce, are exposed to environmental hazards, further exacerbating social and environmental inequities [1]. These settlements, often located in areas with poor environmental quality, face heightened risks from flooding and climate-related disasters. Comprehensive strategies that integrate NbS into urban

planning is critical for enhancing climate resilience and addressing these disparities. Innovative approaches like sponge cities and Room for the River initiatives, which emphasize restoring natural hydrological functions [19], offer promising models for sustainable urban development.

To address these challenges effectively, it is essential to implement policy reforms that mandate the preservation and restoration of pervious surfaces and promote NbS. Taxation on large impervious surfaces could provide financial incentives for sustainable urban practices and generate revenue for urban greening and stormwater management initiatives. Promoting NbS, such as rain gardens, green roofs, and urban tree planting, can mitigate urban heat islands, enhance biodiversity, and improve water management [20]. Expanding community-driven projects, such as urban agriculture and depaving initiatives, further leverage underutilized spaces for sustainable development.

Mainstreaming nature-based solutions (NbS) requires interdisciplinary collaboration, integrating applied science, systems ecology, and community participation to develop context-specific solutions for effective water management. Tools such as the NbS Selection Tool developed in this study provide a framework for communities and stakeholders to evaluate, prioritize, and implement strategies that optimize stormwater management while reducing dependence on traditional gray infrastructure. By delivering critical data on hydrological performance, cost-efficiency, and long-term maintenance requirements, applied science ensures that these solutions are both technically viable and sustainable [21]. This integrated approach not only enhances urban resilience and adaptive capacity but also promotes co-benefits such as biodiversity conservation, carbon sequestration, and urban cooling, strengthening the multifunctional role of urban green infrastructure. The world's urban landscapes, including Puerto Rico, face significant challenges due to the impacts of urbanization and climate change. However, by integrating

NbS into urban planning, fostering community engagement, and adopting innovative practices, stakeholders can create resilient urban environments that address current challenges and prepare for future impacts.

Note

The protocol, approved on April 2, 2024, under number B03-138-24, outlines a systematic approach for achieving the project's goal while ensuring compliance with the Institutional Review Board (IRB) and other mandatory procedures established by the Ana G. Méndez University. This adherence to ethical standards and regulatory guidelines guarantees that the research is conducted responsibly, with respect for participant rights and data integrity throughout the data collection and analysis process.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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