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Research Article

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The Role of Stormwater Management in the Context of Gray, Green and Blue Infrastructure Paradigm

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Abstract Stormwater management is a crucial aspect of urban planning and environmental sustainability. It consists of the implementation of strategies and systems designed to manage both the quantity and quality of stormwater runoff. This management is vital in preventing flooding, reducing erosion, improving water quality, and enhancing the aesthetic and ecological values of urban environments. Gray infrastructure refers to the conventional engineered systems and structures designed for essential services like water management, waste management, and transportation. Green infrastructure is an approach that employs natural processes and elements to provide environmental services and benefits. These systems are designed to be sustainable, with the objective of reducing urban heat, controlling flooding, and promoting healthier urban living environments by mimicking natural processes. It encompasses the integration of plants, water, and soils into urban and rural settings, with the aim of managing water runoff, improving air and water quality, and enhancing urban biodiversity. The term blue infrastructure is used to describe the water-based elements within urban and rural landscapes that have been designed with the objective of managing and utilizing water resources in a sustainable manner. This encompasses both natural and artificial water bodies, such as rivers, lakes, wetlands and constructed features, including canals and water retention ponds. In this context, the concepts of gray, green, and blue infrastructure play significant roles in the notion of stormwater management. This study focuses on the aspect of paradigm of gray, green and blue infrastructure with an emphasis on stormwater management.

Keywords Blue infrastructure, Gray infrastructure, Green infrastructure, Stormwater management.

1. Introduction

The rapid increase in population, particularly in urban areas, has led to an increase in environmental problems, damage to habitats, and deterioration of ecological functions and processes. While the need for drinking and potable water increases, the environments that ensure the natural water cycle are becoming impermeable. Therefore, water resources management is essential to provide water to the growing population and to meet the restrictions on the use of water resources. Water resources management refers to the most efficient and systematic use of water by people [1].

Stormwater management is the application of various green infrastructure systems with the objective of reducing runoff and improving water quality. Stormwater refers to rainwater or snowmelt runoff from streets, green spaces and various other areas. When stormwater is absorbed into the ground in designated areas, it is filtered and eventually replenishes aquifers or flows into streams and rivers [2].

As a result of increasing urbanization, floods and overflows threaten millions of people in various cities around the world. Instead of traditional methods of combating urban floods, the current financial crises in local governments, which are effective all over the world, have been effective in the development of alternative approaches [3].

2. Concepts of Infrastructure

The concepts of infrastructure represent different approaches to urban planning and environmental management, each focusing on particular aspects of how cities and landscapes are built and function, have been the center and driving force for developing different approaches. Gray infrastructure is essential for basic urban operations; green infrastructure offers sustainable, eco-friendly solutions to urban challenges; and blue infrastructure emphasizes the importance of water systems for ecological and human health. Together, these infrastructure types represent a holistic approach to sustainable urban development.

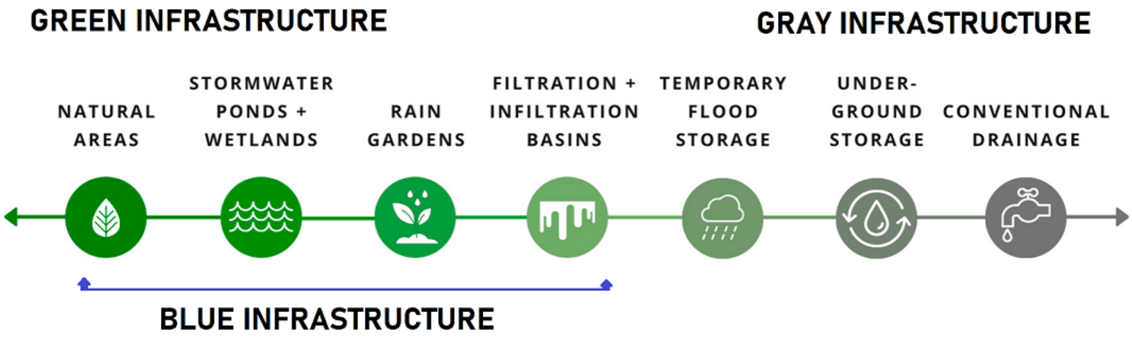

Figure 1: Gray-Green-Blue Infrastructure spectrum. Adapted from Taguchi et al. [4]

2.1. Gray Infrastructure

Gray infrastructure is defined as the basic engineering structures that support essential urban and industrial functions. These infrastructures are critical to the stability and productivity of modern societies. The term gray infrastructure is often used as a contrast to the term "green infrastructure", which includes more natural processes and elements. The aforementioned infrastructures include water and sewerage facilities, transport networks, energy infrastructure and waste management systems. The term "gray infrastructure" encompasses a range of essential engineering structures, including water and sewerage systems, their pipelines, treatment plants and pumping stations. These systems are necessary for the collection, transport, treatment and disposal of water and sewage [5]. While gray infrastructure can be beneficial, it also poses significant environmental and sustainability challenges. The construction and operation of these facilities often results in significant ecological footprints, including high energy use, greenhouse gas emissions and landscape change [6]. The pervasive utilization of gray infrastructure has the consequence of increasing the extent of impervious surfaces, including roads, car parks and roofs. This, in turn, can give rise to an intensification of stormwater runoff and a reduction in infiltration, which can result in urban flooding, erosion and a deterioration in water quality [7]. The construction and operation of gray infrastructure, such as dams, reservoirs and channel modifications, can have a significant impact on natural hydrological processes, including flow patterns, sediment transport, groundwater recharge and the impact on baseflow. These changes can have a cascading effect on aquatic ecosystems and riparian habitats. Despite the numerous advantages and necessities associated with gray infrastructure projects, they can also result in significant environmental consequences, including the loss of habitats, deterioration of water quality, reduction in biodiversity, and degradation of ecosystems. To mitigate these adverse effects and enhance ecological resilience, it is essential to implement careful planning, environmental assessment, and effective mitigation measures [8]. The lifespan of gray infrastructure assets is finite, necessitating regular inspection, maintenance, repair and replacement to ensure structural integrity, functionality and safety. This presents significant challenges for asset management, funding allocation and long-term sustainability [9]. Despite the implementation of engineering design standards and risk management practices, gray infrastructure systems remain susceptible to the impact of extreme weather events, such as hurricanes, floods, droughts and storms. These events can exceed the design capacities of the systems, leading to system failures, widespread damage, disruption and economic losses [10]. The construction, operation and maintenance of gray infrastructure projects require significant capital investments, operating expenses and life-cycle costs that can strain public budgets, increase user charges and limit funding for other essential infrastructure and services [9].

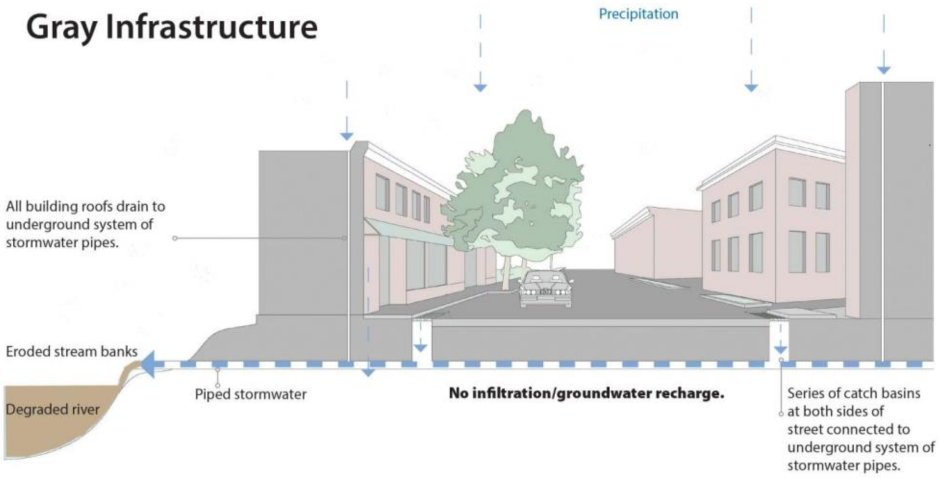

Figure 2: Gray Infrastructure runoff [11]

2.2. Green Infrastructure

Green infrastructure is defined by the European Commission as a strategically planned network of natural and semi-natural areas designed to provide a wide range of ecosystem services such as water filtration, air quality, recreational space and climate mitigation and adaptation [12]. This infrastructure includes components such as parks, forests, wetlands, green roofs, rain gardens, permeable pavements. Each component serves specific functions and collectively contributes to the ecological and social health of urban environments. It began to emerge in academic literature and planning discourse in the 1990s, particularly in the context of ecosystem-based approaches to sustainable urban development and infrastructure planning and design. The concept gained traction in the early 2000s as the potential for integrating natural and semi-natural features into urban landscapes to address environmental challenges such as stormwater management, biodiversity loss and climate change mitigation [13]. Green infrastructure has a number of basic functions and benefits. Green infrastructure systems such as rain gardens, green roofs and permeable surfaces are effective in managing stormwater runoff. These systems absorb and filter stormwater, which reduces flooding, erosion and the load on sewerage systems and improves water quality [14]. Green infrastructure plays a pivotal role in supporting biodiversity in urban areas. It provides essential habitats, migration corridors and gene pools for a multitude of species, thereby integrating biodiversity within the ecosystem. This integration is of paramount importance for ecosystem services, as it can also enhance the resilience of ecosystems to environmental changes [15]. Green infrastructure helps mitigate climate change by sequestering carbon dioxide. Furthermore, features such as green roofs and increased tree cover can reduce urban
heat island effects and thus help cities adapt to rising temperatures [16]. The implementation of green infrastructure poses several challenges, such as land use conflicts, maintenance costs and the need for interdisciplinary cooperation. Urban planners, environmental engineers and landscape architects need to work together to effectively integrate green infrastructure into existing urban landscapes. In addition, the long-term maintenance and ecological integrity of these systems must be ensured to ensure sustainable benefits [17].

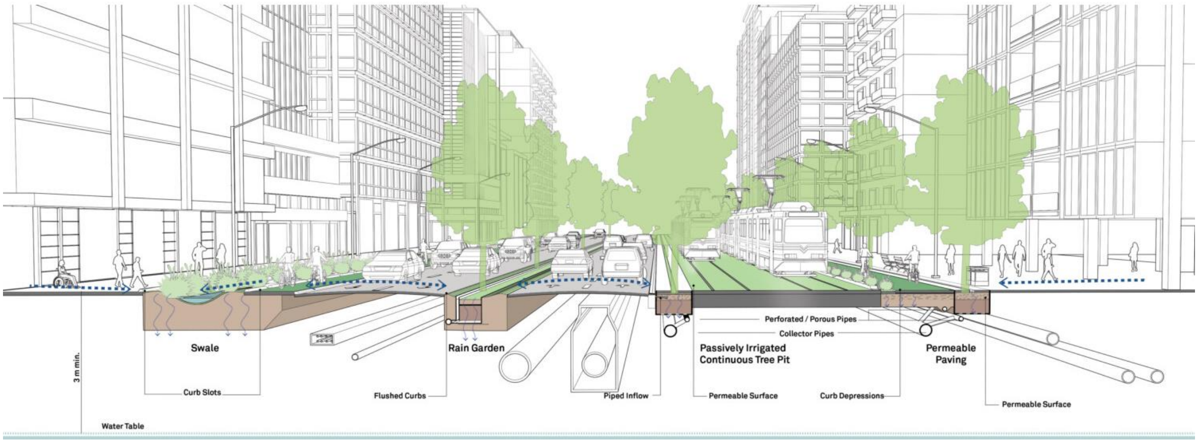

Figure 3: Green Infrastructure in Urban setting [18]

2.3. Blue Infrastructure

Blue infrastructure refers to water-based elements of urban and rural landscapes used to address environmental challenges, increase biodiversity and provide ecological and recreational benefits. It is an important component of urban ecological planning, focusing on the integration of water into urban environments to address the impacts of climate change and urban sustainability. Blue Infrastructure includes both natural and artificial water-based systems in urban contexts to manage stormwater, reduce urban heat island effects, and enhance urban liveability and biodiversity [19][20]. Blue infrastructure involves the use of water sensitive design techniques to manage urban runoff and improve water quality. Techniques such as biofiltration systems, canals and permeable pavements allow stormwater to infiltrate and be filtered at source, reducing surface runoff and pollutant loads [21]. Blue infrastructure helps to conserve aquatic ecosystems in urban settings by also maintaining or improving hydrological connectivity. This includes the restoration of interconnected waterways and the integration of wetlands, which play an important role in supporting biodiversity and providing habitat for a variety of species [22]. Blue infrastructure also provides significant socio-cultural benefits. Urban water bodies are often at the centre of recreational activities and can be focal points in urban landscapes, contributing to the aesthetic value of the area and supporting community well-being and social harmony [23]. In conclusion, while blue infrastructure plays a crucial role in urban environmental management and climate adaptation, its success requires careful integration into urban planning, regular maintenance, and continuous evaluation and necessary interventions to adapt to emerging challenges and opportunities.

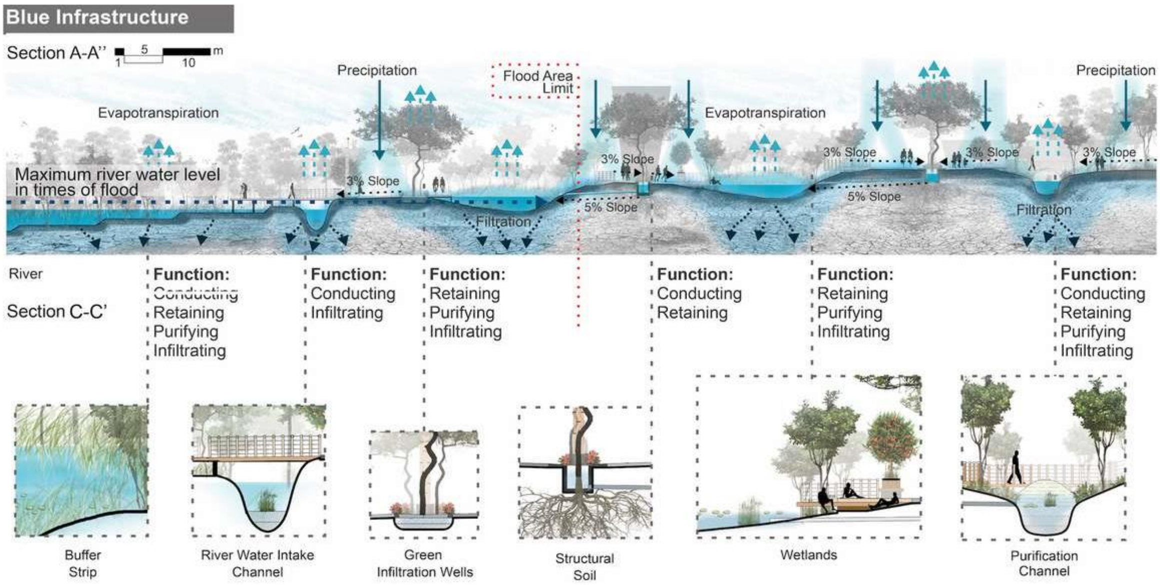

Figure 4: Blue infrastructure components and functions [24]

3. The Paradigm of Gray, Green and Blue Infrastructures as Stormwater Management Concept

Stormwater refers to water resulting from all precipitation, including meltwater from heavy rain, hail and snow. Stormwater can infiltrate the soil, become groundwater, be stored in ponds and puddles on depressed land surfaces, evaporate back into the atmosphere, or turn into surface runoff [25]. The management of the quantity and quality of rainwater and meltwater is called "Stormwater Management". It includes techniques and strategies to reduce and control the undesirable effects of stormwater runoff on the environment and infrastructure [26]. Combining gray, green, and blue infrastructures provides a more sustainable and resilient approach to stormwater management. Such integration allows cities to optimize functionality; while gray infrastructure is efficient for quick water conveyance, integrating it with green and blue infrastructures allows for better long-term water management and environmental protection; enhance resilience by diversifying the methods of stormwater management, cities can improve their resilience to a range of hydrological impacts from climate variability and change; improve water quality as green and blue infrastructures can naturally filter pollutants from stormwater, thereby improving water quality that benefits both human populations and wildlife; and provide social benefits, as urban green and blue spaces are valuable for recreation and can improve overall quality of life. The gray, green and blue infrastructure stormwater management paradigm reflects a shift from traditional approaches to more integrated, sustainable practices that align with broader environmental and social objectives. This paradigm shift is underpinned by a growing recognition of the limitations of traditional (gray) infrastructure systems and the benefits of incorporating natural and semi-natural elements into urban planning and design.

4. Discussion

Traditionally, stormwater management has been dominated by gray infrastructure, designed to move stormwater away from the built environment as quickly as possible to prevent flooding. This approach is based on engineering solutions that emphasise efficiency and immediate water removal, including sewers, drains, pipes and concrete channels. While effective in preventing waterlogging and flood damage in urban areas, this approach often leads to environmental degradation, such as water pollution and disruption of natural water cycles, requiring a paradigm shift towards more sustainable practices. The paradigm of green infrastructure represents a shift towards the utilization of vegetation and other natural processes to manage stormwater. This approach integrates the landscape into stormwater management, utilising it to absorb, filter, and slowly release stormwater back into the environment. This paradigm not only addresses the limitations of gray infrastructure but also contributes to healthier urban environments. Blue infrastructure paradigm focuses on the management, enhancement, and creation of water-based environments within urban settings. It includes the restoration of natural water bodies and the creation of new ones that manage stormwater and provide ecosystem services. This approach emphasizes the role of water in urban ecosystems, promoting both environmental sustainability and quality of life. The direction of these paradigm shifts indicates that future systems will be more flexible and adaptable.It's important to acknowledge Stormwater management concept not as static rigid solution, but as an adaptable and evolving system to better serve tomorrow's problems.

5. Conclusion

The contemporary paradigm of stormwater management advocates for the integration of gray, green, and blue infrastructures to create synergistic effects that enhance the resilience and sustainability of urban environments. This integrative approach acknowledges the shortcomings of solely relying on gray infrastructure, views stormwater as a resource rather than a waste product, values the multifunctional benefits of green and blue infrastructures, and strives for a holistic water management strategy that supports sustainable urban and rural development. This paradigm shift is of utmost importance for the effective adaptation to the challenges of urbanisation and climate change. It is crucial for ensuring that urban and rural environments can manage stormwater effectively while enhancing the ecological and social fabric of cities. Stormwater management evolves over time with more intelligent and efficient green-blue infrastructure approaches. It's role in their context has significantly moved over from gray to green-blue since its emergence. Therefore it is crucial to plan and apply stormwater management systems based on latest concepts and developments to maximize the efficiency and benefits of used approach.

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