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Green Stormwater Infrastructures: A Sustainable Strategy for Mitigating the Ultra-Urban Impacts of Megacity Dhaka

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Abstract

The megacity of Dhaka, Bangladesh, is becoming increasingly exposed to the negative consequences of rapid and uncontrolled development, such as chronic waterlogging, frequent flooding, and the intensification of the urban heat island effect. The expansion of impermeable surfaces, as well as the encroachment on natural drainage systems such as canals and wetlands, all contribute significantly to these difficulties. Traditional "gray" infrastructure has proven insufficient to accommodate the volume and complexity of stormwater management in this ultra-urban environment. This review paper investigates the potential of Green Stormwater Infrastructure (GSI) as a sustainable and resilient alternative. Using a variety of global and regional studies, the article assesses the suitability and effectiveness of GSI practices—such as rain gardens, tree trenches, permeable pavements, bioswales, and green roofs in densely populated areas like Dhaka. The review focuses on GSI's multifunctional benefits, such as improved stormwater regulation, water quality, air quality, urban heat mitigation, and the return on investment for restoration of important ecosystem services. The findings highlight the importance of incorporating GSI into Dhaka's urban planning framework to promote long-term environmental sustainability and urban resilience.

Keywords

Green Stormwater Infrastructures, Heat Island Effect, Urban Flooding, Sustainable Stormwater Management, Climate Resilience

1. Introduction

Dhaka, the capital of Bangladesh, is among the world's rapidly rising cities, with impervious surfaces increasing concurrently. In 2020, impervious surfaces cov-

ered 300.749 square miles, constituting 51.02% of the total land area. Furthermore, imperviousness in Dhaka rises over time. Between 1990 and 2020, the impervious surface area in Dhaka City expanded by 29% [1]. A high degree of imperviousness is a characteristic of ultra-urban areas, which are defined by the high density of paved surfaces or buildings. The majority of the land area is occupied by buildings, parking facilities, urban streets, highways, or walkways, with imperviousness typically exceeding 50 percent in ultra-urban areas [2]. Dhaka city is classified as an ultra-urban area due to impervious surfaces exceeding 50%, with a trend of gradual increase. Megacities, also known as super cities, refer to urban areas with a population of more than 10 million people [3] and Dhaka placed as a Megacity due to its population of 24.7 million [4]. Dhaka, the capital of Bangladesh and an ultra-urban megacity, is affected by an urban heat island (UHI) due to its extensive impervious surfaces. Urban heat islands (UHIs) have become a major challenge for cities and local authorities in their quest for climate resilience. With the intensification of global warming and growing urbanization, the areas impacted by UHIs where temperatures can exceed those of the surrounding areas by several degrees represent an increased risk to the health and quality of life of residents, as well as biodiversity, and can also hinder action to reduce energy consumption [5]. The examination of LST (Land surface temperature) [6] in Dhaka indicates alarming trends, underscoring the immediate necessity for interventions to combat the Urban Heat Island (UHI) effect, a phenomenon wherein concrete, asphalt, and steel absorb and retain heat, transforming cities into heat traps. Dhaka's explosive, unplanned growth has stripped the city of its natural cooling systems. Between 1989 and 2020, Dhaka lost 47% of its dense vegetation and healthy green cover shrank from 17% (5,202 hectares) to just 2% (612 hectares) [7]. An escalation in temperature variability is expected to be a significant outcome of climate change for Bangladesh. Employing a regional climate model (RCM), its anticipated that a substantial rise in temperature extremes until the conclusion of the twenty-first century [8]. The heat island effect will emerge as a significant issue for the metropolis of Dhaka in the future. Moreover, in urban and urbanized regions, impermeable surfaces like pavements and roofs inhibit the natural absorption of precipitation in the soil. Conversely, water swiftly flows into storm drains, sewer systems, and drainage ditches, potentially resulting in floods, erosion, turbidity, overflow of storm and sanitary sewer systems, and damage to infrastructure [9]. Since the 1950s, Dhaka has consistently encountered severe flooding. Nevertheless, the embanked region of Dhaka West encounters urban flooding, obstructed drainage systems, and heightened susceptibility to severe rainfall. Over the years, land development initiatives in both the western and eastern sectors of Dhaka City have resulted in encroachment into these areas, obstructing primary drainage routes and exacerbating waterlogging in the west and monsoon floods in the east [10]. With the ongoing increase in global temperatures, we anticipate a rise in both the frequency and intensity of heavy precipitation events. Stormwater flooding impacts Dhaka metropolis, while the large im-

pervious surface exacerbates the heat island effect. In these circumstances, green stormwater infrastructure, referred to as GSI or green tools, mitigates overflows by diminishing the volume of runoff entering sewers. Stormwater is absorbed by vegetation and soil, subsequently evaporating into the atmosphere or being discharged into sewers at a reduced rate. Vegetation and other natural components offer advantages for individuals and the ecosystem while simultaneously regulating rainwater [11]. Green stormwater infrastructure (GSI) measures, such as green roofs, trees, bioretention zones, and permeable pavement, provide shade, diminish heat-absorbing surfaces, and release water vapor, thereby cooling hot air and mitigating the urban heat island (UHI) effect. Research indicates that, at adequate scale, Green Stormwater Infrastructure (GSI) practices can reduce ambient air temperatures by 0.5 to 1.8˚F [12].

2. Green Stormwater Infrastructures

2.1. What Are Green Stormwater Infrastructures (GSI)?

Green stormwater infrastructure (GSI) is a system of natural and semi-natural systems that control rainwater at its source. This technique is different from typical "gray" infrastructure like pipes and sewers, which just remove rainwater. GSI imitates the natural hydrological process to reduce runoff, clean up pollutants, and provide a number of benefits for the environment, society, and the economy. Traditional gray infrastructure focuses on moving water, while Green Stormwater Infrastructure (GSI) calls for a decentralized, multi-faceted approach based on natural processes. Green Stormwater Infrastructure (GSI) methods let rainwater soak into the ground, which helps to refill local aquifers. As stormwater moves through soil and plants, it naturally cleans itself before it may pollute waterways nearby. Plants and trees take in and release water vapor into the air, which helps reduce the amount of runoff. Some GSI parts are made to hold large amounts of water for a short time during heavy rains to help prevent flooding. There are a number of ways to do GSI that can be used in both public and private settings. Rain gardens are designed to be low-lying places that collect and clean rainwater runoff from roofs, roads, and parking lots. Green roofs are covered in plants and a substrate that holds and controls rainwater. Bioswales are channels or landscape features that are covered in plants and carry and clean up rainwater runoff. There are interconnected trenches, called runoff tree trenches, that are under a sidewalk. They collect and filter runoff so that the roots of street trees can soak it up [13]-[17].

2.2. GSI Reduce Urban Heat Island (UHI) Effect in Ultra-Urban City

Green Stormwater Infrastructure (GSI) uses natural methods, including rain gardens, bioretention ponds, trees, and swales, to catch and hold rain where it falls. It offers several benefits for the public, such as better water quality, less urban heat and stormwater flooding, lower carbon emissions, more wildlife habitats, and better physical and mental health for residents. GSI can give you these benefits at or

below the cost of typical choices, which is a big deal [18]. The U.S. EPA says that tree groves can make the air in cities up to 9˚F cooler than the air in nearby areas. Green roofs are a fantastic way to reduce heat islands since they cool the air directly and indirectly. They improve air quality by lowering temperatures, soaking up pollutants, and stopping further air pollution from happening [19]. Green stormwater infrastructure (GSI) helps reduce the urban heat island (UHI) effect in cities that are well-built up, mostly by providing shade and helping water evaporate. GSI lessens the heat-retaining properties of concrete, asphalt, and other non-permeable surfaces by adding natural elements to areas with many buildings. In big cities where there isn't much room, GSI programs are carried out in a planned way to address stormwater management and lowering the temperature [19].

2.3. GSI Reduce Urban Stormwater Flooding

Green stormwater infrastructure (GSI) helps keep cities from flooding by using natural processes to collect, filter, and soak up water. This method works against the effects of hard surfaces like concrete and asphalt. GSI controls rainwater closer to its source, which lowers the amount of runoff that enters and overwhelms typical "gray" drainage systems. These systems are often too small for heavy and frequent storms [20]. Bioswales and rain gardens are shallow, vegetated basins or channels that catch and clean up rainwater from places that can't hold water. They utilize a particular combination of soil and native plants with deep roots to help the earth soak up more water. Tree trenches in cities are made up of a connected trench filled with gravel and layers of soil. They catch and retain runoff, which tree roots then absorb and the soil filters [21].

2.3. GSI Improve Air Quality

Green stormwater infrastructure (GSI) cleans the air in cities by filtering out pollutants, lowering the temperature, and saving energy. GSI features make cities healthier and easier to breathe by adding plants and natural processes to the design. Green roofs are layers of plants, growing medium, and drainage materials on top of roofs. They trap pollutants and cool buildings by letting water evaporate, which cuts down on energy use and emissions. Street trees and other plants in cities take gases and small particles out of the air [22]. The EPA estimates that urban trees in the United States remove over 700,000 metric tons of air pollutants annually. Plants like trees, shrubs, and grasses that are employed in GSI systems can take in air pollutants, including nitrogen dioxide, ozone, and particulate matter, through their leaves and surfaces. These plants also provide off oxygen and assist in minimizing the urban heat island effect, which can indirectly lower the amount of ground-level ozone that forms. GSI also lowers dust and other pollutants in the air by adding more green cover. This makes the air cleaner and healthier for people who live in the city [23].

2.4. Efficiency of GSI for Particular Challenges

Green Stormwater Infrastructure (GSI) solutions can be customized to tackle urban issues, like monsoon flooding and urban heat. The most successful Green Stormwater Infrastructure (GSI) solutions for street-level monsoon flooding are those that rapidly and efficiently handle substantial amounts of stormwater. This category encompasses bioswales, vegetative channels that decelerate and filter runoff; permeable pavements, which permit water infiltration through surfaces such as roadways and sidewalks; and rain gardens, shallow, planted depressions that collect runoff from impermeable surfaces. Conversely, to mitigate urban heat island effects in densely populated residential zones, the implementation of Green Stormwater Infrastructure (GSI) that enhances vegetation and facilitates evapotranspiration is most efficacious. These encompass green roofs that insulate structures and lower ambient temperatures, urban tree canopies that offer shade and diminish heat retention, and vertical gardens that introduce vegetation to walls in limited spaces. Pocket parks and green courtyards facilitate cooling by establishing shaded, vegetated areas within apartment buildings.

3. Case Studies of Effective GSI Implementation

3.1. Cases in the North American Region

Philadelphia's Green City, Clean Waters initiative, which is known all throughout the country, is the main way the city deals with urban heat islands and stormwater flooding. The Philadelphia Water Department (PWD) has been working on this 25-year project since 2011. It uses green stormwater infrastructure (GSI) to manage precipitation where it falls, which takes some of the burden off the city's old, combined sewage system. GSI is carefully built for neighborhoods that are already hot, like North and West Philadelphia, where the UHI impact has gotten worse since there isn't enough green space, which is a result of redlining in the past. Rain gardens and vegetated basins, or bioswales, are put in the right places to collect and filter runoff from streets and parking lots so that it can sink into the earth [24]. Additionally, the integrated GSI systems on Villanova University's campus have proven to be successful in reducing the urban heat island effect. Several studies revealed that any type of green stormwater infrastructure (GSI) can reduce ambient temperatures more effectively than a parking lot alone [25] [26]. Additionally, the presence of rain gardens and other forms of green infrastructure on the campus of Villanova University resulted in a decrease in the amount of stormwater that was discharged into the surrounding environment [27]. The nature-based solution strategies employed in Philadelphia and Villanova, such as rain gardens, green roofs, and permeable pavements, are adaptable elements that can be implemented in Dhaka's densely populated metropolitan areas to reduce runoff and enhance water quality. Philadelphia's focus on public engagement and education can serve as a model for analogous awareness initiatives in Dhaka to advocate for sustainable water practices. Furthermore, the advantages of urban aesthetics and biodiversity are as significant in Dhaka's crowded and polluted setting.

3.2. Cases in the South Asian Region

The city of Bengaluru in India is an excellent example of a South Asian megacity that has successfully implemented Green Stormwater Infrastructure (GSI). The city has progressively adopted nature-based solutions to tackle challenges such as urban flooding, water scarcity, and environmental deterioration. Bengaluru's strategy encompasses the restoration of traditional water bodies, the establishment of rain gardens, and the promotion of permeable pavements and green roofs in both public and private developments. These initiatives constitute a comprehensive approach aimed at augmenting urban resilience and sustainability via multifunctional green infrastructure that facilitates flood management, groundwater replenishment, and enhanced urban microclimates [28]. Despite challenges like maintenance, spatial limitations, and institutional coordination, Bengaluru's actions illustrate the feasibility of effectively adapting GSI in other South Asian urban environments, such as Dhaka [29] [30].

4. Is Dhaka Poised to Become the Next GSI-Focused City?

Dhaka can use Green Stormwater Infrastructure (GSI) to considerably improve its ability to deal with its continuous flooding problems [31]. These problems are made worse by climate change and rapid, unplanned urbanization. GSI doesn't only use "gray" infrastructure, such as pipelines and sewers. It also uses natural systems like bioswales, rain gardens, green roofs, and permeable pavements to soak up and clean rainwater where it falls. This strategy would help restore the city's natural drainage capacity, which has been affected by the encroachment on canals and floodplains. It would also lessen the quantity of runoff during heavy monsoon rains. GSI can do more than merely stop floods. It can also filter the air and water naturally, provide more tree canopy to lower the urban heat island effect, and make important green spaces that can improve the health of the community and the variety of life. Because Dhaka has a lot of people living there, good green infrastructure focuses on modest, vertical solutions that make the most of small spaces and are healthy for the environment. By incorporating vegetation into the built environment, vertical green infrastructure (VGI) enhances urban sustainability and quality of life. These systems, also known as vertical greening systems, use a variety of technologies to cover walls, screens, and building facades with vegetation. From lowering the urban heat island effect to enhancing air quality and building insulation, VGI provides a plethora of ecological, social, and financial advantages [32]. Corporate and office buildings could use rooftop farming, green facades, living walls, and green roofs as VGI. In Dhaka, where horizontal space is limited, vertical greenery can be implemented on residential, commercial, and institutional buildings to create microclimates, reduce energy consumption by insulating buildings, and manage stormwater runoff. Since some living walls are self-supporting and not affixed to a building, they can serve as green barriers or dividers. Green roofs and rooftop farming are great because they lower the urban heat island effect, clean the air by getting rid of pollutants, help with

stormwater management to stop flooding, and even give you fresh food. Lemongrass, basil, and mint are all great options for rooftop gardens since they are aromatic, quick-growing, and easy to care for. Lemongrass has multiple uses, including as a mosquito repellant and in tea. Vertical gardens and green walls are the same thing: they install plants on the outside of buildings to cool them down and filter out noise and air pollution. It would also be easy to put tree trenches and rain gardens in public parks and recreation places. Dhaka South City Corporation (DSCC) administers 27 parks throughout its 75 wards, whereas Dhaka North City Corporation (DNCC) supervises 23 parks within its 54 wards. The total number of parks governed by the city administration in Dhaka now stands at 50 [33]. City corporations' public parks would be a wonderful option to install rain gardens, tree trenches and bioswales to reduce stormwater flooding. Rasulbagh Children's Park (DSCC) in Dhaka South City Corporation, for example, has rain gardens, rainwater collection trenches, and natural vegetation like Sofeda and Chalta trees, all of which are intended to regulate stormwater runoff and avoid localized floods during monsoon season [34]. Another positive example is Justice Shahbuddin Ahmed Park (DNCC, Gulshan), which is part of Dhaka North City Corporation's redevelopment initiative, with landscaped gardens, rainwater harvesting systems, and waterside walks. Though not expressly branded as "rain gardens," the park has stormwater-sensitive landscaping that performs similarly [35].

5. Challenges

Dhaka could face numerous challenges in implementing green stormwater infrastructure (GSI) due to the city's increasing urbanization, unregulated construction, and abundance of grey infrastructure. When it rains a lot, urban floods are worsened by the growth of structures and paved areas, which hinder water's ability to soak in and drain away. According to studies, many open spaces and sources of water are disappearing from places like Hatirjheel-Begunbari, and by 2040, more than 90% of the land will be covered by structures [36]. The urban sprawl of Dhaka has resulted in the encroachment of wetlands, the loss of agricultural land, and the emergence of unplanned settlements. In certain regions, the population density of the city surpasses 47,000 individuals per square kilometer [37]. However, despite the hindrance, public awareness and low-cost, small-scale pilot initiatives could prove effective to reshape the city in a sustainable manner.

6. Conclusion

Dhaka city would greatly benefit from implementing green stormwater infrastructure to tackle the combined issues of urban flooding and the heat island effect. By integrating solutions such as green roofs, permeable pavements, rain gardens, and tree trenches into its urban planning, Dhaka can boost stormwater absorption, reduce surface runoff, and decrease city temperatures through increased vegetation and evapotranspiration. Given the proliferation of office and corporate struc-

tures in Dhaka City, green roofs may serve as a flexible and pragmatic option. Additionally, rain gardens and tree trenches can effectively alleviate monsoon waterlogging due to their superior infiltration capabilities, and they may be utilized in urban parks, public schools, and recreational spaces. Implementing green stormwater infrastructures is not solely an environmental necessity; it is a strategic investment in Dhaka's future. To effectively promote the need for Green Stormwater Infrastructure (GSI) in Dhaka, building codes must require the incorporation of GSI components, including green roofs, rainwater harvesting systems, and permeable pavements, in new constructions and significant restorations. These codes must be customized to local climatic and urban situations, guaranteeing their practicality and enforceability. Financial incentives, like tax rebates, development bonuses, or diminished sanitary fees, might motivate private developers to voluntarily incorporate Green Stormwater Infrastructure (GSI). Furthermore, GSI should be integrated into RAJUK's urban resilience projects and the climate action plans of city corporations, in accordance with overarching objectives like flood control, climate resilience, and enhanced urban livability.

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Conflicts of Interest

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

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