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Research Article

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The Potential Uses of Rain Gardens in Mitigating Nonpoint Source Pollution: An Integrative Approach

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Abstract Nonpoint Source (NPS) pollution represents a significant challenge to water quality on a global scale. Characterized by diffuse contamination from various dispersed sources such as agricultural landscapes, urban environments, and highways, presents significant challenges to maintaining water quality. Traditional stormwater management techniques frequently prove inadequate in effectively addressing this type of pollution. This study focuses on the potential uses of rain gardens, a sustainable stormwater management solution, in mitigating NPS pollution. Rain gardens are shallow depressions planted with native vegetation that have been engineered to intercept, treat, and infiltrate stormwater runoff. They employ natural processes to decrease pollutant loads entering aquatic systems. The design of these gardens is critical and involves considerations such as the size relative to the catchment area, soil composition conducive to filtration and microbial activity, and the selection of appropriate plant species that can thrive in fluctuating water conditions. The functionality of rain gardens encompasses several key mechanisms. These include filtration and adsorption, whereby soil particles capture and retain pollutants such as phosphate, nitrate and heavy metals; biological uptake, through which plants absorb nutrients, thus preventing them from contributing to eutrophication downstream; and microbial degradation, whereby soil microorganisms break down organic pollutants, including hydrocarbons and pesticides. These findings substantiate the role of rain gardens in enhancing stormwater management and ecological health.

Keywords Green infrastructure, Rain garden, Stormwater management, Water quality, Pollution removal

1. Introduction

Nonpoint source pollution (NPS) is defined as the contamination of water bodies from a multitude of sources, including agricultural runoff, urban stormwater, and scattered residential areas. This makes it a complex environmental issue to manage [1]. Innovative approaches, particularly green infrastructure solutions such as rain gardens, have been identified as effective tools to address NPS by treating stormwater at its source [2]. Rain gardens are engineered features designed to collect and treat stormwater runoff through natural processes. Typically, they are shallow depressions filled with permeable soil and planted with native vegetation capable of withstanding high moisture and occasional inundation. The design criteria involve aspects such as size relative to the drainage area, soil composition, and appropriate plant species, which are critical for their pollutant removal efficiency [3][4].

2. Nonpoint Source Pollution (NPS)

The term, which is more precisely defined as diffuse pollution in Europe and accepted as non-point source pollution in the USA, refers to pollution that does not originate from a single identifiable source. It is a type of pollution that arises from numerous dispersed sources, making it challenging to control and manage. This type of pollution typically results from stormwater or snowmelt runoff flowing through the ground. As the runoff flow progresses, it carries away natural and man-made pollutants, transporting them to lakes, rivers, wetlands, coastal waters, and even groundwater resources. Diffuse or non-point sources of pollution are often insignificant individually, but collectively can cause significant environmental damage. Diffuse pollution is the process of transporting potential pollutants resulting from a range of activities that individually have no impact on the aquatic environment, but when combined can have a significant impact on a watershed scale. The management of non-point (diffuse) source pollution comprises a set of measures implemented to combat this situation [1][5]. Agricultural runoff is the leading source of nonpoint pollution in numerous regions. Runoff from agricultural lands can carry nutrients, primarily nitrogen and phosphorus, that contribute to eutrophication in water bodies. Eutrophication can lead to algal blooms that produce toxins, some of which can be harmful and affect aquatic life and human health [6]. Urban Runoff is when impermeable surfaces such as roads, driveways and roofs prevent stormwater from naturally drain into the soil. Instead, water flows rapidly, collecting contaminants such as oils, heavy metals, and chemicals from various surfaces and carrying them into water systems and eventually into water bodies [7]. The drainage or runoff from abandoned mining operations frequently contributes to nonpoint source pollution. For instance, in strip mining, the upper layers of soil and vegetation are removed to reveal the desired ore. Erosion may occur if an area where strip mining takes place is not properly reclaimed after mining activities have ended. Furthermore, the mixing of air, water, and sulfur-containing rocks can cause chemical reactions that result in the formation of sulfuric acid and iron hydroxide. The acidic flow dissolves heavy metals such as copper, lead and mercury, which can also pollute streams and other water resources [8]. The U.S. Clean Water Act (CWA) is also an example of water conservation practices around the world, providing the foundation for regulating the discharge of pollutants into United States waters and establishing quality standards for surface waters. Specifically, CWA Section 319 aims to prevent nonpoint pollution by providing funding and support to states to implement management programs that address nonpoint pollution [9]. It is evident that urban and rural stormwater management systems play a pivotal role in the management of non-point pollution. In addition to stormwater management and related practices, public awareness activities are also carried out to reduce pollutant load on urban and rural areas [10].

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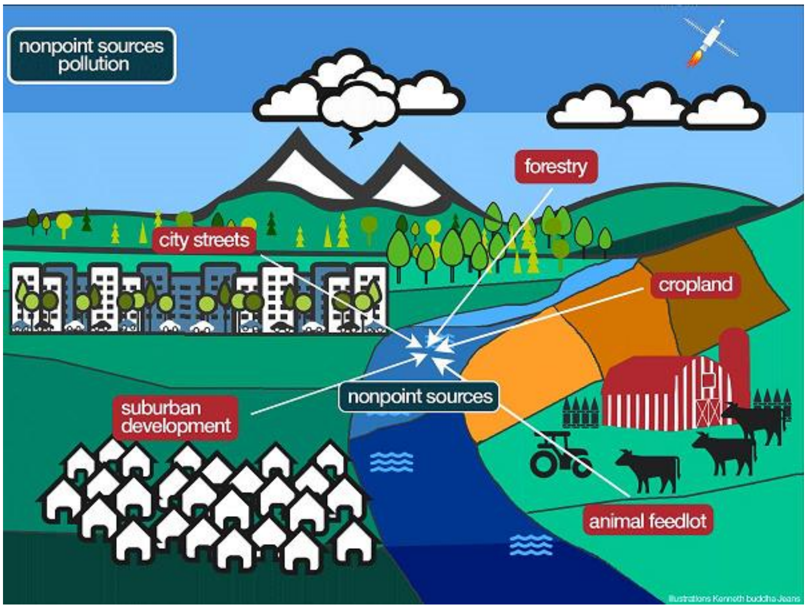

Figure 1: Nonpoint Source Pollution diagram [11]

3. Use of Rain Gardens in Mitigating Nonpoint Source Pollution

Rain gardens are shallow depressions planted with native vegetation. They are engineered to intercept, treat, and infiltrate stormwater runoff, using natural processes to decrease pollutant loads entering aquatic systems. The design of these gardens is critical, and it involves considerations such as the size relative to the catchment area, soil composition conducive to filtration and microbial activity, and the selection of appropriate plant species that can thrive in fluctuating water conditions. The functionality of rain gardens encompasses several key mechanisms. These include filtration and adsorption, whereby soil particles capture and retain pollutants such as phosphates, nitrates and heavy metals. Biological uptake is another mechanism, whereby plants absorb nutrients, thus preventing them from contributing to eutrophication downstream. Finally, microbial degradation is a further mechanism, whereby soil microorganisms break down organic pollutants, including hydrocarbons and pesticides. [3][4][12]. Rain gardens can be crucial in both urban and rural settings for mitigating the nonpoint source pollution. In urban and suburban settings, most of the nonpoint source pollution originates from ordinary households and vehicles. Small sized rain gardens located at streets and drains as shown in "*Figure 2"* can be very effective for capturing and removing the pollutants before they mix into water bodies and become a major problem.

Figure 2: A Rain Garden in New York City streets [13]

In rural settings, as area selection and usage become easier due to large open spaces, larger sized multiple rain gardens strategically placed at the points of possible flood runoff routes, can be effective in mitigating nonpoint source pollution by reducing the volume of the runoff and by filtering the pollutants carried within.

Figure 3: Stormwater in Rural Areas [14]

Active mining operations considered as point source pollution. However, drainage and runoff from abandoned mining operations frequently cause to nonpoint source pollution [8]. Mining operations frequently result in the destruction of flora, alterations to the topography of the site, and the failure to restore the site to its original vegetation and natural landscape forms that can cause erosion and various surfaced ores that can produce various chemical reactions as a result from these operations can contribute to significant nonpoint source pollution loads on water bodies. Similar to the rural settings, strategically placed rain gardens around mining sites, can effectively catch runoff and mitigate the pollution loads before they reach the streams and water bodies.

Figure 4: Stream impacted by acid mine drainage from an abandoned coal mine [15]

4. Discussion

One of the primary challenges associated with rain gardens is the necessity for accurate design and adequate sizing relative to their catchment areas. Incorrect sizing can result in inadequate treatment of runoff, as the garden may become overwhelmed during heavy rainfall events. The effectiveness of a rain garden is largely dependent on its ability to hold and treat the anticipated volume of stormwater. Overflows can occur if the rain garden is not adequately sized or designed, leading to unfiltered runoff entering waterways. Using multiple rain gardens in possible overflow direction can be an efficient way to increase the capacity of total system and can be used as an upgrade if the initial system overloads over time. The type of soil used in rain gardens can be of vital importance, as it affects both the rate of water infiltration and the capacity to remove pollutants. Soils with a high clay content can impede the infiltration of water, leading to the formation of standing water that can become a breeding ground for mosquitoes. Conversely, very sandy soils may allow water to infiltrate too quickly, reducing the garden’s ability to remove pollutants. Achieving the optimal balance in soil composition is essential for the rain garden to perform at its best, but this can be challenging in urban areas where soil quality is usually poor. The type and concentration of pollutants in runoff can also challenge rain gardens. High concentrations of certain chemicals or varied pollution types can exceed the treatment capacity of a rain garden. Heavy metals, for example, can accumulate in the soil and potentially affect plant health, while oil and other hydrocarbons from road runoff may require specific types of plants and soil microbes to achieve effective degradation.

5. Conclusion

Rain gardens represent a critical component of urban stormwater management strategies aimed at mitigating Nonpoint Source (NPS) Pollution. Despite the challenges associated with their design, maintenance, and public perception, the benefits they offer in terms of water quality improvement, ecosystem biodiversity, and aesthetic enhancement are substantial. These systems not only reduce the volume of runoff and filter harmful pollutants but also contribute to urban beautification and provide vital habitats for local wildlife. To enhance the effectiveness and adoption of rain gardens, it is imperative to address the challenges they face through improved design techniques, community engagement, and policy support. Landscape architects, urban planners and engineers need to focus on optimizing rain garden designs to suit specific local conditions, including soil type, rainfall patterns, and pollutant loads. This entails employing advanced modeling tools to predict stormwater runoff and pollutant removal efficiencies accurately and tailoring designs to maximize these aspects.

Furthermore, ongoing maintenance must be streamlined and standardised in order to reduce the burden on property owners and municipalities. The establishment of clear guidelines and the provision of regular workshops or resources can assist in maintaining the functionality of these systems over the long term. Public education plays a pivotal role in shifting perceptions about rain gardens. By promoting their environmental and aesthetic benefits, communities can be encouraged to embrace these features as integral parts of the urban landscape. The support from local governments, including incentives for rain garden installation and maintenance, can further enhance their proliferation. It is therefore essential that policies are developed that integrate rain gardens into broader green infrastructure plans and stormwater management policies, in order to realise their full potential. The integration of rain gardens into urban landscapes represents a promising pathway toward more resilient and sustainable cities. As research continues to evolve and technology improves, the implementation of rain gardens could become more widespread, playing a pivotal role in addressing the complex challenges of urban water management.

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