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Research Article

Sustainable Enhancement of Stormwater Management Through Permeable Pavement: A Case Study of Barisal City

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Abstract

Rapid urbanization and population growth in Bangladeshi cities, Barisal in particular, have created serious environmental issues including urban water-logging. While flooding prevents the infiltration of rainwater, the extensive concreting of the open space, the boulevards, and waterbodies have become a barrier to rainwater infiltration and flooding the daily life, the infrastructure, and the contamination of water. Therefore, there is a need for stormwater management. This study examines permeable pavement systems (PPS) systems as a potentially sustainable model. PPS systems recharge groundwater, manage surface runoff, and reduce flooding in residential, commercial, and industrial areas. The hydraulic modeling revealed that a 35-inch-deep PPS system with underdrain capabilities can hold approximately 865.41 cubic feet of stormwater. The study concluded that permeable pavement systems provide a sustainable long-term solution for stormwater management when conventional drainage isn't able to manage stormwater sufficiently. This is one mere action toward achieving Sustainable Development Goal 11 towards sustainable Cities and human. Thus, this study provides the foundation for urban sustainability, resilience, public health, environmental protection, and infrastructure sustainability and durability. A PPS system will provide immediate benefits to be achieved, however over time the long-lasting benefits will build stakeholder involvement from the community at large.

Keywords

Permeable Pavement, Barisal City, Sustainable Development Goal (SDG), Waterlogging, Rigid Pavement

1. Introduction

Urban flooding and improper stormwater management are two major issues brought on by the rapid urbanization of developing nations [1-3]. During periods of intense rainfall, conventional drainage systems are frequently overwhelmed by the extensive replacement of natural permeable land with impervious surfaces, which disrupt infiltration, speed up runoff, and decrease groundwater recharge [1-3]. Unplanned urbanization, canal encroachment, and vegetation loss have negatively impacted Bangladesh's hydrological balance, leading to frequent waterlogging in the country's largest cities [4-7]. Despite being smaller than Chattogram or Dhaka, Barisal is becoming more vulnerable to flooding because of its low elevation, inadequate drainage, and growth of impermeable surfaces [4-7]. The shortcomings of traditional drainage systems that rely on antiquated rainfall data are further highlighted by climate change, which is causing more frequent high-intensity rainfall [8].

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Beyond conventional drainage expansion, sustainable solutions are needed to address these issues [9, 10]. By simulating natural hydrological processes through infiltration, detention, and evapotranspiration, Sustainable Drainage Systems (SuDS) provide an efficient method that lowers runoff and enhances water quality [9, 10]. Because they function as both traffic surfaces and stormwater infiltration media, Permeable Pavement Systems (PPS) are especially well-suited for urban settings [11, 12]. PPS is still not well-known in Bangladesh's mid-tier cities, despite its widespread use [11, 12]. In order to estimate surface runoff and create a theoretical PPS design, this study focuses on Barisal and chooses a sub-road in the vicinity of C & B Road. In order to improve urban drainage and lessen waterlogging in Barisal, the goals are to analyze the current drainage conditions, gauge the effectiveness of PPS, and suggest a long-term, climate-resilient solution.

2. Methodology

The approach taken in this study uses both qualitative and quantitative methods to gain a full understanding of stormwater management. Qualitative data was collected utilizing interviews, semi-structured surveys and observations, along with audio and photographic data to support stakeholder perspectives. The quantitative piece element drew from secondary data in the literature and statistical literature to identify the gap in research and assess existing solutions. The research was methodically organized into five chronological phases to ensure research rigor, as well as continuity from research inception to completion.

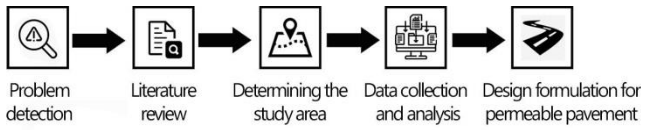

Figure 1. *Flow chart of methodology.*

3. Literature Review

3.1. Overview of Permeable Pavement Research

Permeable pavement systems (PPS), integral to Sustainable Drainage Systems (SuDS), have emerged as effective and sustainable solutions for stormwater management in urban contexts [13, 14]. Although the volume of high-quality PPS research is comparatively limited, their role in runoff mitigation and water reuse is increasingly recognized [15]. Properly maintained PPS can withstand storm events exceeding the 100-year return period, achieving infiltration rates from 130 mm/h to several thousand mm/h, with reductions in peak flow ranging from 7–43% and total runoff from 1–40% [16, 17].

3.2. Hydraulic and Environmental Performance

Reservoir depth exerts significant influence on hydraulic outcomes. Depths of 240 mm, 328 mm, and 400 mm reduce flood volume and duration by 18.29% and 71%, 98.05% and 81%, and eliminate surface flooding entirely, respectively. PPS also contribute to water quality improvements, with reported removal efficiencies of up to 49% for metals, 43% for total phosphorus, and 60% for suspended solids [14]. They are particularly suited to sidewalks, driveways, and parking lots in low-traffic zones.

3.3. Design Considerations for PPS

Design parameters include contributing drainage area, subgrade infiltration rate, base course properties, rainfall intensity, and management objectives. However, no universally accepted structural methodology currently exists [18, 19].

3.4. Design Approaches: Level 1 vs Level 2

Design strategies are typically categorized into Level 1 (baseline) and Level 2 (enhanced), with the latter providing improved outcomes in runoff reduction and nutrient removal.

Table 1. *Specifications for Permeable Design [20].*

Level 1 Design	Level 2 Design
Soil infiltration is less than 0.5 in/hr.	The rate of soil infiltration is more than 0.5 in/hr.
Need for an underdrain.	Underdrain is not mandatory.
CDA = The amount of permeable pavement plus upgraded parking, provided that the exterior area to permeable pavement ratio stays below 2:1.	CDA = The permeable pavement area.

3.5. PPS Scale Classifications and Structure

PPS are classified as micro (250–1,000 ft²), small (1,000–10,000 ft²), and large (>10,000 ft²) [20]. Structurally, they comprise a permeable surface layer underlain by multiple engineered sub-base layers tailored to functional demands.

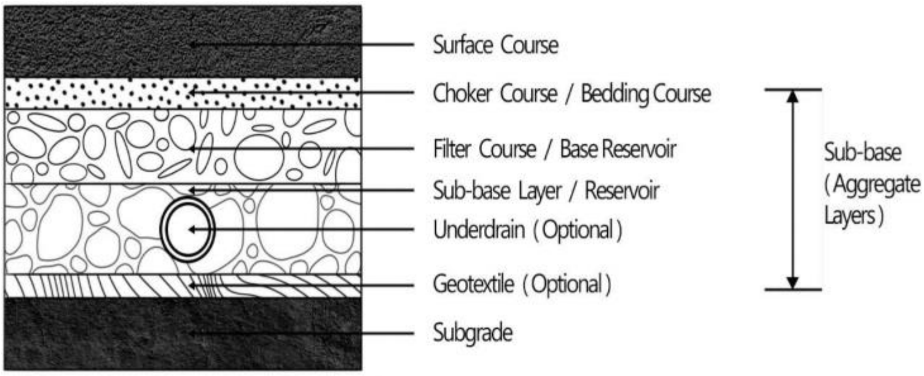

Figure 2. *General cross-section of permeable pavement.*

4. Determining the Study Area

The sub-road of Residential Area C&B Road, Ward No. 21, Barisal City, faces chronic stormwater issues. Impervious paving and lack of natural ground cause waterlogging, disrupting transport and accelerating pavement decay. Persistent flooding increases maintenance costs, highlighting the urgent need for efficient stormwater management and context-specific paving solutions.

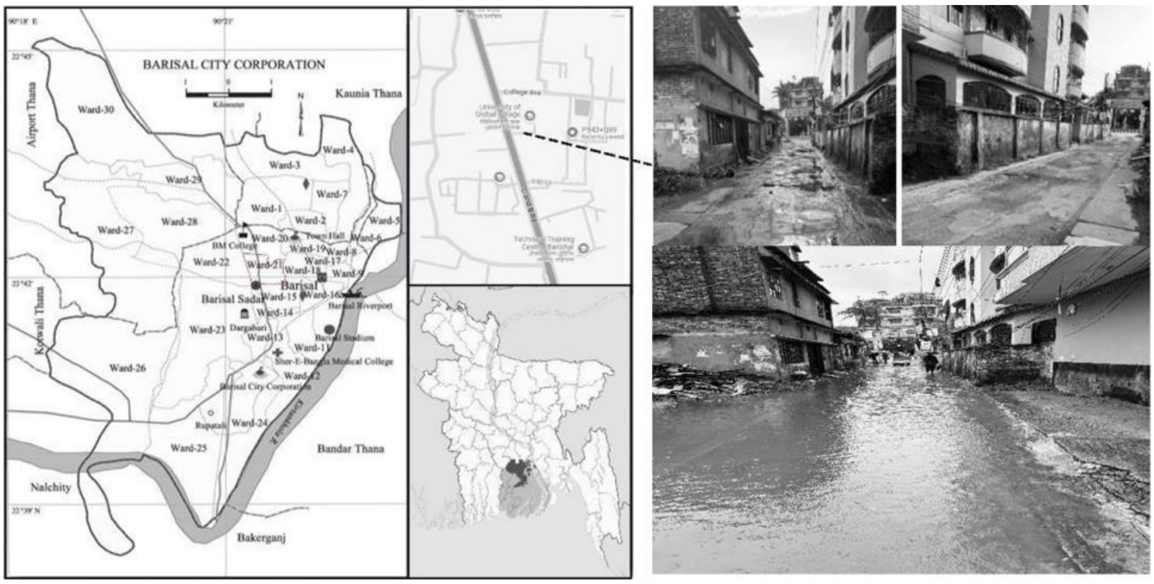

Figure 3. *Observation of selected study area.*

5. Data Collection and Analysis

5.1. Soil Condition of the Study Area

Soil type: Clay soil [21] – Hydrologic Soil Group D, Runoff coefficient of Clay soil: 0.42-0.51 [22], Infiltration rate of clay soil: 1-5 mm/hr [14].

5.2. Precipitation Data of Study Area

In all measured months, the depth of precipitation was less than 4 cm.

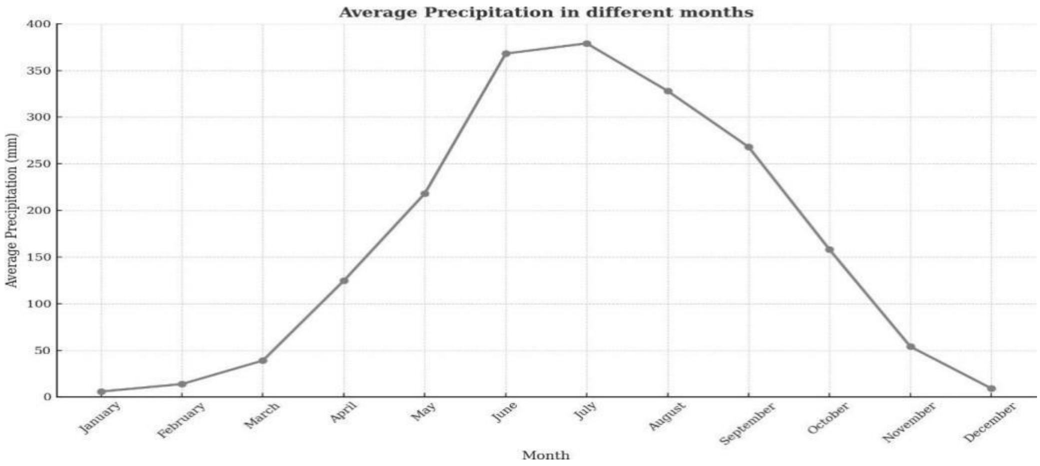

Figure 4. Precipitation data of Barisal city (2014–2023) [23].

6. Design Formulation for Permeable Pavement

A theoretical design approach is employed to develop the permeable pavement system. With the study area's soil infiltration rate below 0.5 in/hr, a Level 1 micro-scale design is adopted. The clayey soil's low permeability necessitates an underdrain system to ensure efficient drainage.

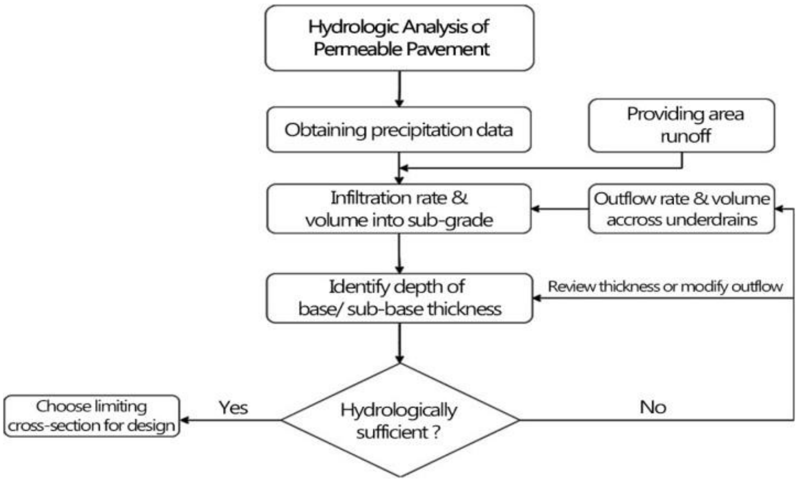

Figure 5. Flow chart of hydrologic analysis of permeable pavement system.

7. Hydraulic Design and Performance Estimation

7.1. Stormwater Runoff Calculation

Road Dimensions: width of the road = 2.8m (9ft) and length of the road = 34m (110ft).

Area of the road = (9 × 110) sq ft = 990 sq ft < 1000 sq ft Runoff Yield = 62 gallons per 100 ft^2 for 1-inch rainfall. [14].

So, the volume of runoff water = 990 × 0.62 ×14.92 (calculated for maximum value of precipitation from figure) = 9157.896 gallon = 1224.24 ft^3.

7.2. Rainfall Intensity Calculation

The rainfall intensity is calculated using the following equation [4]:

$$i_{d,T} = \frac{69.536-23.457 \ \ln(-\ln(1-\frac{1}{T})}{d^{0.686}} \quad (1)$$

Assuming a storm event, d=15 mins= 0.25 hour and design period, T=1.5 years [24].

So, the rainfall intensity, $i_{d,}$ = 174.27 mm/hr = 6.797 in/hr.

7.3. Depth of Runoff Calculation

The peak runoff flow rate is determined using the Rational Method:

$$Q = CiA \tag{2}$$

Runoff coefficient, C = 0.95 (the runoff for impermeable surfaces) [14].

Rainfall intensity, i = 6.797 in/hr.

Drainage area, A = 990 sft = 0.023 acre (as the surface area will be permeable).

According to equation (2), peak runoff flow rate, Q = 0.14 cfs.

The depth of runoff is calculated as:

$$d_c = \frac{Q}{3600} \times t \tag{3}$$

Duration of the storm, t = 15 mins = 900 s.

So, considering equation (3) the depth of runoff, d_c= 0.035ft.

7.4. Underdrain Outflow Rate Calculation

The underdrain outflow rate is given by:

$$q_u = k \times m \tag{4}$$

Hydraulic conductivity for the reservoir layer, k = assumed 100ft/day [14] Underdrain pipe slope, m = assumed 1% = 0.01.

Underdrain outflow rate, q_u = 100×0.01 = 1ft.

7.5. Depth of Base/Sub-base Reservoir Layer Calculation

$$d_p = \frac{\{(d_c \times R) + P - (\frac{1}{2} \times t_f) - (q_u \times t_f)\}}{V_r} \quad [20] \tag{5}$$

Depth of runoff from the contributing drainage area (not including the permeable surface) for the treatment volume (T_v /Ac), or other design storm, d_c = 0.035 ft.

The ratio of the contributing drainage area (Ac) (not including the permeable pavement surface) for the permeable pavement surface area (A_P), R =2 [20].

Rainfall depth for the treatment volume, P = 14.92 inch = 1.25 ft.

The infiltration rate for the clay soil, 3mm/hr (taking the average value of infiltration rate of clay soil) = 0.24ft/day.

The time to fill the reservoir layer, t_f= assumed 2 hours or 0.083 day The void ratio for the reservoir layer, v_r= 0.4 (referencing to ASTMC 29) Outflow through Underdrain, q_u = 1ft/day.

Using these values and considering equation (5), the required depth of the reservoir layer is calculated as, d_p= 2.98 ft.

7.6. Storage Volume Calculation

The storage volume is calculated using the equation:

$$vs = (dP\eta + 0.5itf) \tag{6}$$

The surface area of permeable, A_P = 990 ft^2.

$$n = \frac{0.4}{1+0.4} = 0.29$$

So, the storage volume, vs = 990 × (2.98×0.29+0.5×0.24×0.083) = 865.41 ft^3.

8. Result and Discussion

8.1. Specification of Materials for Designed PPS

Pavement Surface: Permeable Asphalt (PA), following NAPA design, construction, and maintenance guidelines.

Choker/Bedding Course: 2-inch layer of ASTM D448 No. 8 stone [20].

Reservoir Layer: 35-inch depth of ASTM D448 No. 2 stone (2½–1½ in.) [25].

Underdrain: 4–6 in. perforated PVC pipe (AASHTO M 252) with ≥1% slope.

Geotextile Layer: Needled, non-woven polypropylene, Grab Tensile ≥120 lbs (ASTM D4632), Mullen Burst ≥225 lbs/sq. [20].

8.2. Discussion

The study applied quantitative and qualitative approaches to evaluate PPS. Theoretical design indicates that, even on clay-rich soils, appropriate underdrains substantially reduce stormwater runoff. A 990 sq. ft. impervious surface generating ~1,224.24 ft³ of runoff can infiltrate up to 35 inches (2.98 ft) into the reservoir layer, assuming 0.4 void ratio with ASTM D448 No. 2 aggregates.

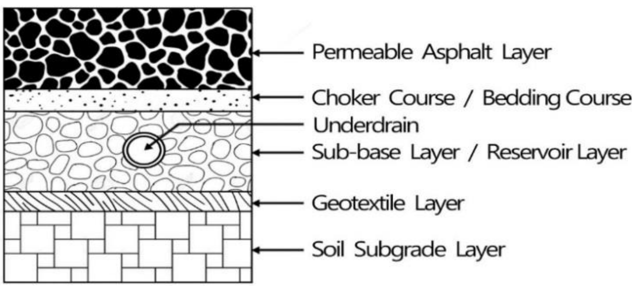

Figure 6. *Suggested design cross-section for permeable pavement.*

9. Conclusion

The implications of this research point towards the following conclusions:

1) While road infrastructure is necessary for the growth of urbanization, traditional methods of construction can actually facilitate surface runoff and limit groundwater recharge, which may exacerbate the risk of urban flooding.
2) Permeable paving with an asphalt top is an effective and environmentally sustainable solution for stormwater management in Barisal City.
3) The system was able to accommodate both infiltration and filtration and control runoff, and recharge groundwater even on subgrade soils that were clayey when adequate drainage was provided in the system.
4) The adoption and use of impermeable pavement technology will promote sustainable urban water infrastructure, as well as, support achievement of SDG 11. Desired urban flooding resilience can be achieved by expanding the use of permeable pavement used in sustainable urban.

Abbreviations

PPS	Permeable Pavement Systems
SuDS	Sustainable Drainage Systems
A_p	Surface Area of Permeable Pavement
CDA	Contributing Drainage Area
P	Rainfall Depth for Treatment Volume
R	Ratio of Contributing Drainage Area to Permeable Surface Area
η	Storage Void Ratio (Porosity-Related Factor)
NAPA	National Asphalt Pavement Association

Author Contributions

Md Ziaur Rahman Khan: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Software, Visualization, Writing – original draft, Writing – review & editing

Somen Saha: Data Curation, Methodology, Project Administration, Supervision, Visualization

Oaisul Mostofa Karim: Funding Acquisition, Investigation, Resources, Software, Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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