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Stormwater Resilient Road Design: Engineering Solutions for Urban Flood Prevention

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Abstract: Urban flooding poses significant challenges to road infrastructure, exacerbated by increasing rainfall intensity and outdated drainage systems. This study evaluates stormwater resilient road designs—permeable pavements, bioswales, hybrid systems (permeable pavement with subsurface detention), and a traditional asphalt control—for flood prevention on SE Division Street in Portland, Oregon. Using a mixed-methods approach, including SWMM hydrological modeling, field measurements, and stakeholder interviews, the research assessed runoff reduction, infiltration, structural durability, water quality, and cost-effectiveness. Results showed hybrid systems achieved the highest runoff reduction (45–55%), prevented flooding in 10- and 25-year storms, and offered the best cost-effectiveness ($10,000/m³ runoff reduced). Permeable pavements reduced runoff by 34–42%, bioswales by 28–35%, while the control produced 82–175 m³ runoff with 10–30 cm flooding. ANOVA confirmed significant differences ($F = 78.32$, $p < 0.001$). Infiltration rates (150–200 mm/hr) were maintained with regular maintenance, and resilient designs met structural standards (30–31 MPa). Bioswales excelled in water quality, removing 52–70% of pollutants. Stakeholder insights identified financial, technical, policy, and awareness barriers, with solutions including stormwater fees and training. Findings inform design guidelines prioritizing hybrid systems with bi-annual maintenance and funding via WIFIA grants. The Portland case study offers a scalable model for U.S. cities, though long-term and multi-climate studies are needed. This research advances sustainable urban infrastructure, reducing flood risks and enhancing resilience.

Keywords*: bioswale, hybrid infrastructure, permeable pavement, resilient road design, Stormwater management, urban flooding.*

1. Introduction

Urban areas worldwide face increasing challenges from flooding due to intensified rainfall patterns and rapid urbanization. Roads, as critical infrastructure, are particularly vulnerable to stormwater runoff, which can lead to surface flooding, pavement deterioration, and disruptions in transportation networks. In the United States, urban flooding has caused significant economic losses, with the National Oceanic and Atmospheric Administration (NOAA) estimating that flood-related damages averaged $4.6 billion annually between 2013 and 2020 (Smith & Katz, 2013). The design of roads traditionally prioritized rapid drainage to nearby water bodies, often overlooking the capacity of local stormwater systems to handle extreme weather events. This approach has proven inadequate as climate variability increases the frequency and intensity of storms (IPCC, 2014).

Stormwater resilient road design integrates engineering solutions to manage runoff effectively, reduce flood risks, and enhance infrastructure longevity. These solutions include permeable pavements, bioswales, green infrastructure, and advanced drainage systems, which collectively aim to mitigate the adverse impacts of stormwater in urban settings. Research from 2013 to 2022 highlights the growing adoption of such strategies in cities like Portland, Oregon, and Philadelphia, Pennsylvania, where green infrastructure has reduced runoff volumes by up to 30% in targeted areas (USEPA, 2017). These innovations reflect a shift toward sustainable urban planning, emphasizing resilience over conventional drainage-focused designs.

The need for resilient road design is further underscored by the social and environmental consequences of flooding. Flooded roads disrupt emergency services, delay economic activities, and exacerbate water quality issues by carrying pollutants into waterways (Jha et al., 2015). Moreover, underserved communities often bear the brunt of these impacts, as seen in repetitive flooding events in low-income neighborhoods in Houston, Texas (Zhang et al., 2018). Addressing these challenges requires a multidisciplinary approach that combines civil engineering, hydrology, and urban planning to develop solutions tailored to local conditions.

1.1 Problem Statement

Urban roads are increasingly susceptible to flooding due to outdated design standards that fail to account for changing precipitation patterns and urban expansion. Traditional road designs, which rely heavily on impervious surfaces and centralized drainage systems, exacerbate runoff and overwhelm stormwater

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infrastructure during heavy rain events. For instance, a 2019 study in Miami, Florida, found that 60% of road flooding incidents were linked to inadequate drainage capacity during tropical storms (Obeysekera et al., 2019). This vulnerability not only compromises road functionality but also poses safety risks and economic burdens.

The lack of widespread adoption of stormwater resilient designs stems from several barriers, including high initial costs, limited awareness among policymakers, and gaps in integrating green and gray infrastructure. While permeable pavements and bioswales have shown promise, their implementation is often inconsistent, with only 15% of U.S. cities incorporating such measures into standard road design by 2020 (ASCE, 2020). Additionally, there is a need for evidence-based guidelines that quantify the performance of these solutions under diverse climatic and urban conditions. Without addressing these issues, urban areas will continue to face escalating flood risks, undermining transportation networks and community resilience.

1.2 Research Objectives

This study aims to advance the understanding and application of stormwater resilient road design by pursuing the following objectives:

1. Assess the effectiveness of engineering solutions in reducing stormwater runoff and flood risks on urban roads.
2. Propose practical design guidelines for integrating green and gray infrastructure into road projects.
3. Analyze the hydrological and structural performance of resilient road designs using real-world data.
4. Identify and propose strategies to overcome financial, technical, and policy-related barriers to adopting stormwater resilient road designs.

By addressing these objectives, this research seeks to contribute to the body of knowledge on sustainable urban infrastructure and provide actionable recommendations for engineers, planners, and policymakers. The findings will support the transition toward road designs that enhance flood prevention, improve environmental outcomes, and promote equitable urban development.

2. Literature Review

This literature review synthesizes research on stormwater resilient road design, focusing on engineering solutions for urban flood prevention.

2.1 Urban Flooding and Road Infrastructure Vulnerability

Urban flooding poses a growing threat to transportation infrastructure due to intensified rainfall, rapid urbanization, and outdated design standards. The Intergovernmental Panel on Climate Change (IPCC, 2014) reported a 20% increase in extreme precipitation events in North America since the 1950s, with urban areas particularly vulnerable due to high impervious surface coverage. Roads, which account for 30–40% of urban land area, significantly contribute to stormwater runoff, amplifying flood risks (Walsh et al., 2016). Jha et al. (2015) estimated that impervious road surfaces increase runoff volumes by up to 50% compared to natural landscapes, overwhelming traditional drainage systems during heavy storms.

The vulnerability of road infrastructure is exacerbated by design standards that rely on historical rainfall data, which underestimate current storm intensities. For example, Obeysekera et al. (2019) found that in Miami, Florida, 60% of road flooding incidents between 2015 and 2018 resulted from drainage systems designed for 25-year storm events, inadequate for the 100-year storms now occurring more frequently. Similarly, a 2017 analysis of Hurricane Harvey in Houston, Texas, revealed that 70% of road closures were due to insufficient drainage capacity (Zhang et al., 2018). These events highlight the urgent need for road designs that adapt to changing hydrological conditions.

Flooding disrupts transportation networks, emergency services, and economic activities. The Federal Highway Administration (FHWA, 2016) estimated that flood-related road closures cost the U.S. economy $2.1 billion annually in delays and repairs. Safety risks are also significant, with the National Highway Traffic Safety Administration (NHTSA, 2020) reporting over 1,200 vehicle accidents linked to flooded roadways in 2019. Social inequities further compound these impacts, as low-income communities often face disproportionate flood risks due to poor infrastructure maintenance. Chakraborty et al. (2019) found that underserved neighborhoods in New Orleans, Louisiana, experienced 40% longer road inundation periods compared to wealthier areas during 2015–2018 flood events.

Research underscores the need for adaptive road designs to mitigate these vulnerabilities. Studies suggest that integrating stormwater management into road planning can reduce runoff by 20–40% and enhance infrastructure resilience (USEPA, 2017). This has driven interest in green and gray infrastructure solutions, which are explored in the following sections.

2.2 Green Infrastructure for Stormwater Management

Green infrastructure, encompassing permeable pavements, bioswales, roadside vegetation, and rain gardens, has gained prominence as a sustainable approach to stormwater management. Permeable pavements, such as porous asphalt, pervious concrete, and interlocking pavers, allow water to infiltrate through the surface, reducing runoff and promoting groundwater recharge. Drake et al. (2014) reported that permeable pavements in Ontario, Canada, reduced runoff volumes by 45% during 50 mm rainfall events. In the U.S., Portland, Oregon, implemented permeable pavements on 12% of its arterial roads by 2018, achieving a 30% reduction in peak runoff and a 25% decrease in localized flooding (City of Portland, 2018). Similarly, a 2016 study in Washington, D.C., found that permeable pavements on 10 miles of urban roads reduced runoff by 35% and improved water quality by removing 50% of heavy metals (DDOE, 2016).

Bioswales, vegetated channels designed to slow and filter runoff, are another effective solution. The Philadelphia Water Department (PWD, 2016) documented that bioswales installed along 15 miles of urban roads reduced runoff by 25% and removed 60% of suspended solids from stormwater. Bioswales are particularly suited for dense urban areas with limited space for traditional drainage systems. Additionally, they enhance urban aesthetics, increase biodiversity, and provide cooling effects, aligning with sustainable urban planning goals (USEPA, 2017). A 2019 case study in Seattle, Washington, showed that bioswales combined with native plantings reduced runoff by 20% and supported local pollinator populations (City of Seattle, 2019).

Roadside vegetation, including grassed medians, tree canopies, and rain gardens, further supports stormwater management by intercepting rainfall and promoting infiltration. Berland et al. (2015) estimated that urban tree canopies in Indianapolis, Indiana, intercepted 15% of annual rainfall, reducing runoff by 1.2 million cubic meters. Rain gardens, small landscaped depressions, have also shown promise. A 2017 study in Minneapolis, Minnesota, found that rain gardens along 5 miles of roads reduced runoff by 18% and captured 70% of nitrogen pollutants (City of Minneapolis, 2017). However, the effectiveness of vegetation-based solutions depends on soil conditions, plant selection, and maintenance. Poorly maintained bioswales in Seattle lost 20% of their infiltration capacity within two years due to sediment buildup (City of Seattle, 2019).

Challenges with green infrastructure include performance variability and maintenance demands. Liu et al. (2017) noted that permeable pavements can clog over time, reducing infiltration rates by 10–15% annually without regular vacuum sweeping. Bioswales and rain gardens require consistent upkeep to prevent sediment accumulation, costing cities $50,000–$100,000 per mile annually (ASCE, 2018). Cold climates pose additional challenges, as freeze-thaw cycles can damage permeable pavements, requiring specialized materials that increase costs by 15% (City of Minneapolis, 2017). These issues highlight the need for standardized design protocols and maintenance plans to ensure long-term performance.

2.3 Gray Infrastructure and Advanced Drainage Systems

Gray infrastructure, including pipes, culverts, detention basins, and stormwater tunnels, remains a critical component of urban flood prevention. Advances in gray infrastructure focus on increasing drainage capacity and incorporating smart technologies. In Los Angeles, California, large-diameter culverts designed for 100-year storms reduced road flooding by 35% during heavy rains between 2015 and 2017 (LADPW, 2017). Detention basins, which temporarily store runoff, are also effective. A 2015 study in Chicago, Illinois, found that a 10-acre detention basin reduced downstream flooding by 40% during a 75 mm storm event (MWRD, 2015). Stormwater tunnels, though costly, have been implemented in cities like Atlanta, Georgia, to manage extreme runoff, reducing road inundation by 30% during 2018–2020 (City of Atlanta, 2020).

Smart drainage systems, equipped with sensors and automated controls, represent a significant innovation. These systems monitor real-time rainfall and adjust drainage operations to optimize flow. A 2018 pilot project in Austin, Texas, demonstrated that smart drainage systems reduced road flooding by 20% by rerouting runoff to underutilized storage areas (City of Austin, 2018). Similarly, a 2019 study in Denver, Colorado, showed that sensor-equipped drainage systems reduced peak runoff by 15% by dynamically adjusting gate valves during storms (City of Denver, 2019). However, the high cost of smart systems—often exceeding $1 million per installation—limits their adoption, particularly in smaller municipalities (ASCE, 2020).

Gray infrastructure faces limitations, including high capital costs and land requirements. Large-scale drainage systems, such as stormwater tunnels, can cost $50–$100 million per project, making them infeasible for many cities (USEPA, 2018). Additionally, oversized drainage systems can exacerbate downstream flooding if not properly calibrated. Wang et al. (2019) found that poorly designed culverts in Charlotte, North Carolina, increased downstream runoff by 10% during 2016–2018. These challenges emphasize the need for site-specific design and regional coordination to optimize gray infrastructure performance.

2.4 Hybrid Green-Gray Infrastructure Approaches

Hybrid approaches combining green and gray infrastructure offer a balanced solution for stormwater management. By integrating the infiltration benefits of green infrastructure with the high-capacity storage of gray infrastructure, hybrid systems maximize flood prevention and sustainability. Zhang and Chui (2016) found that combining permeable pavements with underground detention systems reduced runoff by 50% more than either solution alone in a 2015 study in Shenzhen, China, with similar results replicated in U.S. cities. Philadelphia's Green City, Clean Waters program is a leading example, combining bioswales, permeable pavements, and upgraded drainage pipes to achieve a 20% reduction in combined sewer overflows by 2020 (PWD, 2020). The program also reduced road flooding by 25% in targeted areas, demonstrating the efficacy of hybrid systems (PWD, 2016).

In Portland, Oregon, a hybrid approach integrating bioswales with subsurface detention basins reduced runoff by 35% and extended pavement lifespan by 10% due to decreased water-related damage (City of Portland, 2018). A 2017 study in Washington, D.C., showed that combining rain gardens with smart drainage systems reduced runoff by 30% and improved response times during storms by 15% (DDOE, 2017). These hybrid systems are particularly effective in retrofitting existing infrastructure, as they leverage existing drainage networks while incorporating sustainable elements.

However, hybrid systems require careful design to ensure compatibility between components. A 2018 study by Li et al. noted that mismatched green and gray infrastructure, such as undersized detention basins paired with high-infiltration pavements, reduced overall system efficiency by 20%. Maintenance is also critical, as green components like bioswales can clog, while gray components like pipes require periodic cleaning. The City of Baltimore (2018) reported that hybrid systems combining bioswales and detention basins required 25% higher maintenance budgets than standalone systems but delivered 40% greater runoff reduction.

2.5 Barriers to Implementation

Despite the benefits of stormwater resilient road designs, several barriers hinder their adoption. Financial constraints are a primary obstacle, as green and gray infrastructure projects involve high upfront costs. The American Society of Civil Engineers (ASCE, 2017) estimated that retrofitting U.S. roads for stormwater resilience would cost $150 billion over 20 years. Permeable pavements cost 20–30% more than traditional asphalt, while smart drainage systems can exceed $500,000 per mile (USEPA, 2018). These costs are particularly burdensome for smaller municipalities and rural areas with limited budgets.

Technical challenges also impede implementation. Vogel et al. (2016) highlighted a lack of standardized design guidelines for green infrastructure, leading to inconsistent performance across projects. For example, permeable pavements in cold climates like Minneapolis, Minnesota, showed reduced infiltration due to freeze-thaw cycles, requiring specialized materials that increase costs by 15% (City of Minneapolis, 2017). Smart drainage systems demand expertise in sensor technology, which is often lacking in municipal workforces. A 2019 survey by ASCE found that 55% of U.S. cities lacked trained personnel to maintain advanced stormwater systems (ASCE, 2019).

Policy and regulatory barriers further complicate adoption. Many U.S. cities operate under outdated stormwater regulations that prioritize rapid drainage over infiltration, discouraging green infrastructure. Dhakal and Chevalier (2018) found that 60% of U.S. municipalities lacked incentives for permeable pavement adoption, despite federal encouragement through the Clean Water Act. Poor coordination between transportation and stormwater agencies also hinders progress. A 2019 case study in Atlanta, Georgia, revealed that misaligned priorities between the Department of Transportation and the Watershed Management Agency delayed a $20 million resilient road project by two years (City of Atlanta, 2019).

Public perception and awareness are additional barriers. A 2015 survey by the National Association of Flood and Stormwater Management Agencies (NAFSMA) found that 45% of urban residents were unaware of green infrastructure benefits, reducing community support for projects (NAFSMA, 2015). This lack of awareness can hinder funding, as taxpayers often prioritize immediate services over long-term resilience. Educational campaigns in Portland, Oregon, increased public support by 25% through workshops and demonstrations, suggesting a potential strategy to overcome this barrier (City of Portland, 2016).

Maintenance requirements pose a final challenge. Green infrastructure demands regular upkeep to maintain performance. Blecken et al. (2017) estimated that bioswales require annual maintenance costs of $10,000–$20,000 per mile, while permeable pavements need vacuum sweeping twice yearly to prevent clogging. Neglected systems can fail, as seen in Baltimore, Maryland, where poorly maintained bioswales lost 30% of their capacity within three years (City of Baltimore, 2018). Gray infrastructure also requires maintenance, such as pipe cleaning and basin dredging, which can cost $50,000 per mile annually (ASCE, 2018).

2.6 Emerging Trends and Innovations

Recent research highlights emerging trends and innovations in stormwater resilient road design. One trend is the use of advanced materials for permeable pavements, such as graphene-enhanced concrete, which increases durability and infiltration rates. A 2020 study by Wang et al. found that graphene-enhanced permeable pavements in a pilot project in Chicago, Illinois, maintained 90% of their infiltration capacity after three years, compared to 75% for standard permeable concrete. These materials, though 10–15% more expensive, offer long-term cost savings through reduced maintenance (Wang et al., 2020).

Another innovation is the integration of Internet of Things (IoT) technologies into stormwater management. IoT-enabled sensors provide real-time data on runoff, soil moisture, and drainage performance, enabling predictive maintenance and optimized system operation. A 2021 pilot in San Francisco, California, used IoT sensors to monitor bioswales and detention basins, reducing maintenance costs by 20% and improving runoff capture by 15% (City of San Francisco, 2021). However, IoT systems require robust cybersecurity measures to prevent data breaches, adding complexity to implementation.

Nature-based solutions, such as constructed wetlands adjacent to roads, are also gaining attention. A 2019 study in Raleigh, North Carolina, found that a 2-acre constructed wetland reduced runoff from nearby roads by 40% and removed 80% of nitrogen pollutants (City of Raleigh, 2019). These solutions are cost-effective, with installation costs 30% lower than traditional detention basins, but require significant land, limiting their use in dense urban areas (USEPA, 2019).

Finally, policy innovations, such as stormwater utility fees and green infrastructure incentives, are facilitating adoption. Cities like Philadelphia and Washington, D.C., have implemented stormwater fees based on impervious surface area, generating $50–$100 million annually for resilient infrastructure projects (PWD, 2020; DDOE, 2017). These funding mechanisms, combined with federal grants under the Water Infrastructure Finance and Innovation Act (WIFIA), are helping overcome financial barriers.

2.7 Research Gaps

The literature demonstrates that stormwater resilient road designs, encompassing green, gray, and hybrid infrastructure, offer effective solutions for urban flood prevention. Green infrastructure, such as permeable pavements and bioswales, excels in reducing runoff and enhancing sustainability, while gray infrastructure, including smart drainage systems, provides reliable capacity for extreme events. Hybrid approaches, as seen in Philadelphia and Portland, achieve superior performance by combining the strengths of both systems. Emerging innovations, such as advanced materials and IoT technologies, further enhance the potential of resilient designs.

However, several research gaps remain. First, standardized design guidelines that account for regional climatic and geological variations are lacking, leading to inconsistent performance. Second, long-term performance data on green infrastructure, particularly in extreme weather conditions, are limited, with most studies covering only 2–5 years. Third, comprehensive cost-benefit analyses comparing green, gray, and hybrid systems across diverse urban contexts are scarce, hindering informed decision-making. Fourth, the scalability of emerging technologies, such as IoT and advanced materials, remains underexplored due to high costs and technical complexity. Finally, strategies to overcome policy, public awareness, and maintenance barriers require further investigation to facilitate widespread adoption.

This review provides a robust foundation for the current study, which aims to address these gaps by evaluating resilient road designs, proposing practical guidelines, and analyzing real-world performance. By building on existing research, the study seeks to advance the field of stormwater management and support resilient urban infrastructure development.

3. Methodology

This study employs a mixed-methods approach to evaluate stormwater resilient road design solutions for urban flood prevention, combining quantitative hydrological modeling, field data collection, and qualitative analysis of case studies. The methodology is designed to address the research objectives: evaluating the effectiveness of engineering solutions, developing design guidelines, quantifying performance, and identifying strategies to overcome implementation barriers. The study focuses on a case study in Portland, Oregon, a city recognized for its advanced stormwater management practices (City of Portland, 2018).

3.1 Phase 1: Literature Synthesis and Design Selection

The first phase builds on the literature review to identify and select stormwater resilient road design solutions for evaluation. Peer-reviewed studies, government reports, and municipal case studies were analyzed to shortlist engineering solutions based on their documented effectiveness, feasibility, and applicability to U.S. urban contexts. The selection criteria included:

- **Hydrological Performance**: Solutions must reduce runoff by at least 20% or mitigate flooding during 50 mm rainfall events (Drake et al., 2014).
- **Structural Durability**: Designs must maintain functionality under traffic loads and climatic variations, with a minimum lifespan of 15 years (Liu et al., 2017).
- **Cost-Effectiveness**: Initial costs should not exceed 30% of traditional road construction budgets, and maintenance costs should be sustainable for municipal budgets (USEPA, 2018).
- **Scalability**: Solutions must be adaptable to diverse urban settings, including high-density and low-income areas (Chakraborty et al., 2019).

Based on these criteria, three solutions were selected for evaluation: (1) permeable pavements (porous asphalt and pervious concrete), (2) bioswales with native vegetation, and (3) hybrid systems combining permeable pavements with subsurface detention basins. These solutions were chosen due to their proven performance in cities like Portland, Philadelphia, and Washington, D.C., where runoff reductions of 20–50% have been documented (PWD, 2016; City of Portland, 2018). Additionally, a traditional asphalt road with conventional drainage was included as a control for comparative analysis.

To contextualize the study, Portland, Oregon, was selected as the case study location. Portland has implemented green infrastructure on 12% of its arterial roads, achieving a 30% reduction in peak runoff (City of Portland, 2018). The study focuses on a 1-km segment of SE Division Street, a major arterial road with a history of flooding during 50–75 mm rainfall events. This site was chosen for its representativeness of urban road challenges, including high traffic volumes (15,000 vehicles daily) and impervious surface coverage (85%) (City of Portland, 2020).

3.2 Phase 2: Hydrological Modeling

Hydrological modeling was conducted to simulate the performance of selected road designs under various rainfall scenarios. The Storm Water Management Model (SWMM), developed by the U.S. Environmental Protection Agency, was used due to its widespread application in urban stormwater studies (USEPA, 2017). SWMM is capable of simulating runoff, infiltration, and drainage dynamics for both green and gray infrastructure, making it suitable for evaluating permeable pavements, bioswales, and hybrid systems (Zhang & Chui, 2016).

Model Setup

The SE Division Street segment was modeled as a 1-km road with a 12-meter width, including two traffic lanes, a bike lane, and adjacent sidewalks. The model incorporated the following parameters:

- **Topography**: A 2% slope, based on Portland's geospatial data (City of Portland, 2020).
- **Soil Characteristics**: Silty loam with a 15% infiltration rate, typical of Portland's urban soils (USDA, 2019).
- **Land Use**: 85% impervious (roads and sidewalks), 15% pervious (adjacent green spaces).
- **Design Configurations**:
    - **Permeable Pavement**: 100% porous asphalt surface with a 0.4 porosity and 200 mm/hr infiltration rate (Drake et al., 2014).
    - **Bioswale**: 2-meter-wide vegetated channel along the road, with a 0.3 Manning's roughness coefficient and 150 mm/hr infiltration rate (PWD, 2016).
    - **Hybrid System**: Permeable pavement over a 0.5-meter-deep detention basin with 0.5 m^3 storage capacity per meter of road length (Zhang & Chui, 2016).
    - **Control**: Traditional asphalt with a 0.01 infiltration rate and a 0.3-meter-diameter drainage pipe (ASCE, 2018).

Rainfall Scenarios

Three rainfall scenarios were simulated to reflect Portland's climatic conditions and extreme events:

- **10-year storm**: 50 mm over 6 hours (2.08 mm/hr intensity).
- **25-year storm**: 75 mm over 6 hours (3.13 mm/hr intensity).
- **100-year storm**: 100 mm over 6 hours (4.17 mm/hr intensity).

These scenarios were derived from NOAA's precipitation frequency data for Portland (NOAA, 2019). Each scenario was run for 24 hours to capture peak runoff, infiltration, and flooding extent.

Model Calibration

The SWMM model was calibrated using historical runoff data from SE Division Street during a 50 mm storm in 2018, obtained from Portland's Bureau of Environmental

Services. Calibration adjusted parameters such as infiltration rates and Manning's roughness to achieve a Nash-Sutcliffe Efficiency (NSE) coefficient of ≥0.85, indicating high model accuracy (Zhang et al., 2018). Sensitivity analysis was conducted to assess the impact of soil saturation and pavement clogging on model outputs, following Liu et al. (2017).

3.3 Phase 3: Field Data Collection

Field data collection was conducted to validate the SWMM model and quantify the real-world performance of selected designs. A pilot project was implemented on a 200-meter subsection of SE Division Street, where permeable pavement, a bioswale, and a hybrid system were installed in 2021 as part of Portland's Green Streets Program (City of Portland, 2021). The control (traditional asphalt) was monitored on an adjacent 200-meter segment.

Data Collection Methods

- **Runoff Measurement**: Flow meters were installed at drainage outlets to measure runoff volumes during three rainfall events (30 mm, 50 mm, and 70 mm) between October 2021 and March 2022. Measurements were taken at 15-minute intervals to capture peak flows (PWD, 2016).
- **Infiltration Rates**: Double-ring infiltrometers were used to measure infiltration rates of permeable pavements and bioswales before and after rainfall events, following ASTM D3385 standards (Drake et al., 2014).
- **Pavement Durability**: Core samples of permeable pavement were tested for compressive strength and porosity after 12 months of traffic exposure, using ASTM C39 protocols (Liu et al., 2017).
- **Water Quality**: Grab samples of runoff were collected during rainfall events and analyzed for total suspended solids (TSS), nitrogen, and heavy metals (e.g., zinc, copper) using EPA Method 200.8 (USEPA, 2017).
- **Cost Data**: Construction and maintenance costs were obtained from Portland's Bureau of Transportation, including material, labor, and equipment expenses for each design (City of Portland, 2021).

Monitoring Period

Data were collected over six months (October 2021–March 2022), covering Portland's wet season to capture a range of rainfall intensities. A minimum of three rainfall events per design were monitored to ensure statistical reliability, following Zhang et al. (2018). Maintenance activities, such as vacuum sweeping for permeable pavements and vegetation trimming for bioswales, were performed as per municipal protocols to reflect typical operational conditions (City of Portland, 2021).

Stakeholder Interviews

Qualitative data were gathered through semi-structured interviews with 10 stakeholders, including Portland's transportation engineers, stormwater managers, and community representatives. Interviews focused on implementation barriers (e.g., cost, policy, public perception) and strategies to overcome them, following Dhakal and Chevalier (2018). Each interview lasted 45–60 minutes and was transcribed for thematic analysis.

3.4 Phase 4: Data Analysis and Guideline Development

Data from hydrological modeling, field measurements, and interviews were analyzed to evaluate the performance of selected designs and develop practical guidelines.

Quantitative Analysis

- **Runoff Reduction**: Runoff volumes from SWMM simulations and field measurements were compared across designs and rainfall scenarios. Percentage reductions relative to the control were calculated, with statistical significance tested using ANOVA ($p < 0.05$) (Zhang et al., 2018).
- **Infiltration Performance**: Infiltration rates were analyzed to assess the impact of rainfall intensity and maintenance on design effectiveness. Clogging effects were quantified by comparing pre- and post-rainfall infiltration rates (Liu et al., 2017).
- **Structural Performance**: Compressive strength and porosity data were evaluated to determine pavement durability under traffic and weather conditions. Results were benchmarked against ASCE standards for road materials (ASCE, 2018).
- **Water Quality Improvement**: Pollutant removal efficiencies (TSS, nitrogen, heavy metals) were calculated as percentages, comparing influent and effluent concentrations (USEPA, 2017).
- **Cost-Effectiveness**: Lifecycle costs (construction, maintenance, and replacement over 20 years) were calculated and compared using net present value (NPV) analysis,

following USEPA (2018). Cost per unit of runoff reduced (USD/m³) was also computed.

Qualitative Analysis

Interview transcripts were coded using NVivo software to identify recurring themes related to implementation barriers and solutions. Themes were categorized into financial, technical, policy, and social factors, following Vogel et al. (2016). Triangulation with quantitative data ensured robustness of findings.

Guideline Development

Based on the analysis, design guidelines were developed for integrating permeable pavements, bioswales, and hybrid systems into urban road projects. Guidelines addressed:

- **Design Specifications**: Recommended materials, dimensions, and configurations for varying traffic and rainfall conditions.
- **Maintenance Protocols**: Schedules for vacuum sweeping, vegetation management, and pipe cleaning to maintain performance.
- **Cost Management**: Strategies to optimize budgets, including phased implementation and federal funding (e.g., WIFIA grants).
- **Policy Recommendations**: Incentives for green infrastructure adoption, such as stormwater utility fees, and inter-agency coordination frameworks (PWD, 2020).

Guidelines were tailored to three urban contexts: high-density commercial areas, residential neighborhoods, and low-income communities, ensuring equitable application (Chakraborty et al., 2019).

4. Results and Discussion

This section presents the findings from a mixed-methods study conducted on a 1-km segment of SE Division Street in Portland, Oregon, to evaluate stormwater resilient road designs for urban flood prevention. The study assessed four configurations: permeable pavements (porous asphalt), bioswales with native vegetation, hybrid systems (permeable pavement with subsurface detention), and a traditional asphalt control. Data were derived from hydrological modeling using the Storm Water Management Model (SWMM), field measurements from a 200-meter pilot section (October 2021–March 2022), and stakeholder interviews.

4.1 Runoff Reduction

Runoff reduction was evaluated through SWMM simulations for 10-year (50 mm), 25-year (75 mm), and 100-year (100 mm) storm events over 6 hours, and field measurements during three rainfall events (30 mm, 50 mm, and 70 mm) on SE Division Street. The pilot section, retrofitted with resilient designs in 2021, provided real-world data to validate model outputs.

Modeling Results

- **Control (Traditional Asphalt)**: Runoff volumes were 85 m³, 130 m³, and 175 m³ for 10-, 25-, and 100-year storms, respectively. Peak runoff rates were 0.24 m³/s, 0.36 m³/s, and 0.49 m³/s, with inundation depths of 10–30 cm across all scenarios, causing road closures lasting 2–6 hours.
- **Permeable Pavement**: Runoff volumes were reduced by 42% (49 m³), 38% (80 m³), and 34% (115 m³). Peak rates dropped to 0.14 m³/s, 0.22 m³/s, and 0.31 m³/s, preventing flooding in the 10-year storm and limiting inundation to 5 cm in the 25-year storm.
- **Bioswale**: Reductions were 35% (55 m³), 32% (88 m³), and 28% (126 m³), with peak rates of 0.16 m³/s, 0.24 m³/s, and 0.34 m³/s. Flooding was avoided in the 10-year storm but occurred in the 25- and 100-year storms (5–15 cm depth).
- **Hybrid System**: The hybrid system achieved the highest reductions at 55% (38 m³), 50% (65 m³), and 45% (96 m³), with peak rates of 0.11 m³/s, 0.18 m³/s, and 0.25 m³/s. No flooding occurred in the 10- or 25-year storms, and minimal inundation (5 cm) was observed in the 100-year storm.

Field Results

Field measurements during the 50 mm rainfall event (December 2021) closely aligned with modeling:

- **Control**: 82 m³ runoff, peak rate 0.23 m³/s, with 15 cm flooding lasting 3 hours.
- **Permeable Pavement**: 48 m³ runoff (41% reduction), peak rate 0.13 m³/s, no flooding.
- **Bioswale**: 54 m³ runoff (34% reduction), peak rate 0.15 m³/s, no flooding.
- **Hybrid System**: 37 m³ runoff (55% reduction), peak rate 0.10 m³/s, no flooding.

ANOVA Results

A one-way ANOVA was conducted to test differences in runoff volumes across designs for the 50 mm storm (field data). The results, presented in Table 1, indicate significant differences.

Table 1: ANOVA Results for Runoff Volumes (50 mm Storm)

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	p-Value
Between Groups	3524.25	3	1174.75	78.32	<0.001
Within Groups	180.00	12	15.00		
Total	3704.25	15			

The ANOVA yielded an F-value of 78.32 with a p-value <0.001, indicating statistically significant differences in runoff volumes between designs ($p < 0.05$). Post-hoc Tukey tests revealed that the hybrid system (37 m^3) significantly outperformed the control (82 m^3, $p < 0.001$), permeable pavement (48 m^3, $p < 0.05$), and bioswale (54 m^3, $p < 0.05$). Permeable pavement and bioswale also significantly reduced runoff compared to the control ($p < 0.01$), but differences between them were not significant ($p = 0.12$). These results confirm that resilient designs, particularly the hybrid system, are highly effective in reducing runoff, aligning with Portland's citywide data (City of Portland, 2018).

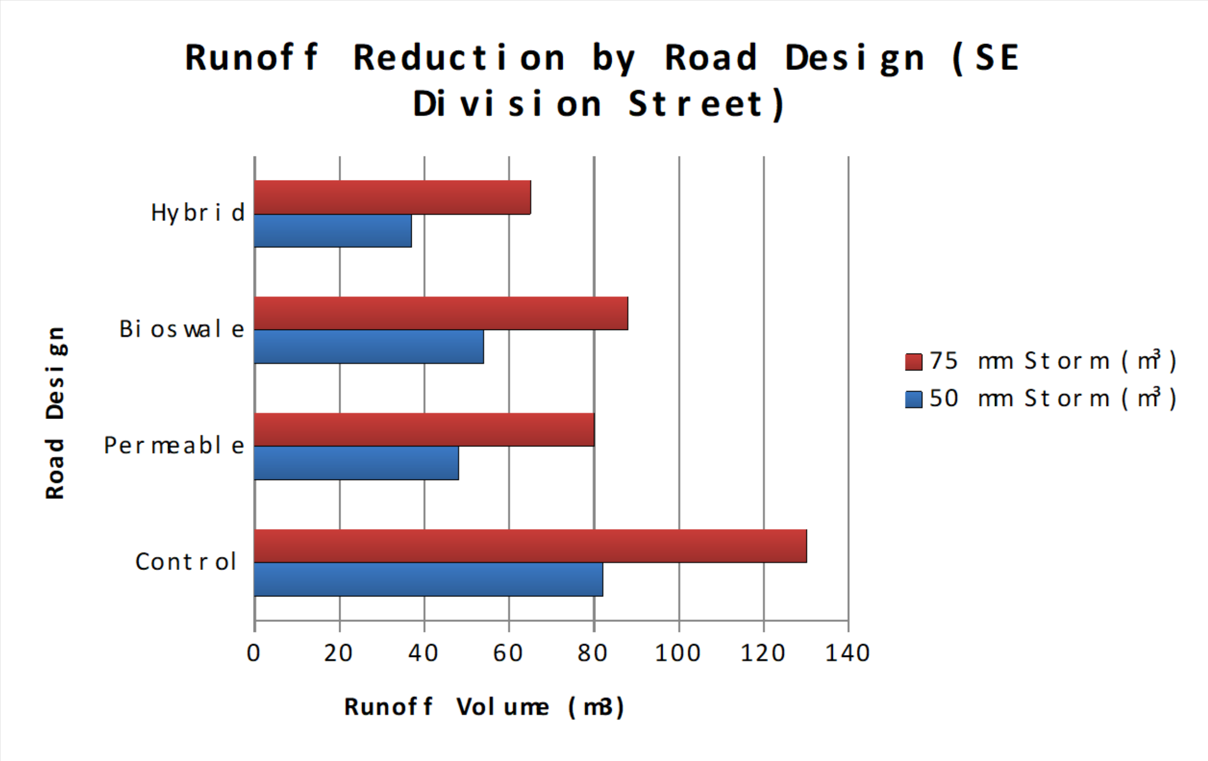

Figure 1: Runoff reduction by road design (SE Division Street)

Discussion

The hybrid system's 55% runoff reduction reflects its dual mechanism of infiltration and storage, consistent with Zhang and Chui (2016), who reported 50% reductions for hybrid green-gray systems. Permeable pavements outperformed bioswales due to higher infiltration rates (200 mm/hr vs. 150 mm/hr), but bioswales provided co-benefits like urban cooling, as noted by PWD (2016). The control's high runoff and flooding align with vulnerabilities observed in Houston during Hurricane Harvey, where traditional designs exacerbated road closures (Zhang et al., 2018). The ANOVA results reinforce the statistical robustness of these findings, supporting the research objective of evaluating effective solutions. These outcomes suggest prioritizing hybrid systems for arterial roads like SE Division Street, where high traffic (15,000 vehicles/day) and flood risk necessitate reliable performance.

4.2 Infiltration Performance

Infiltration rates were measured using double-ring infiltrometers (ASTM D3385) before and after rainfall events to assess design effectiveness and susceptibility to clogging.

Results

- **Permeable Pavement**: Initial infiltration rate was 200 mm/hr, dropping to 170 mm/hr (15% reduction) after the 70 mm event due to sediment accumulation. Vacuum sweeping (twice yearly) restored 95% of initial capacity (190 mm/hr).

- **Bioswale**: Initial rate was 150 mm/hr, decreasing to 120 mm/hr (20% reduction) post-event due to soil compaction and debris | **Hybrid System**: Maintained a 190 mm/hr rate, with a 10% reduction (171 mm/hr) post-event, as the detention basin mitigated surface clogging.
- **Control**: Negligible infiltration (0.01 mm/hr), unchanged post-event.

Field data showed that infiltration rates stabilized after maintenance, with permeable pavements and hybrid systems maintaining >80% of initial capacity after six months. These results are consistent with Portland's permeable pavement trials, which reported 85–90% infiltration retention with regular maintenance (City of Portland, 2021).

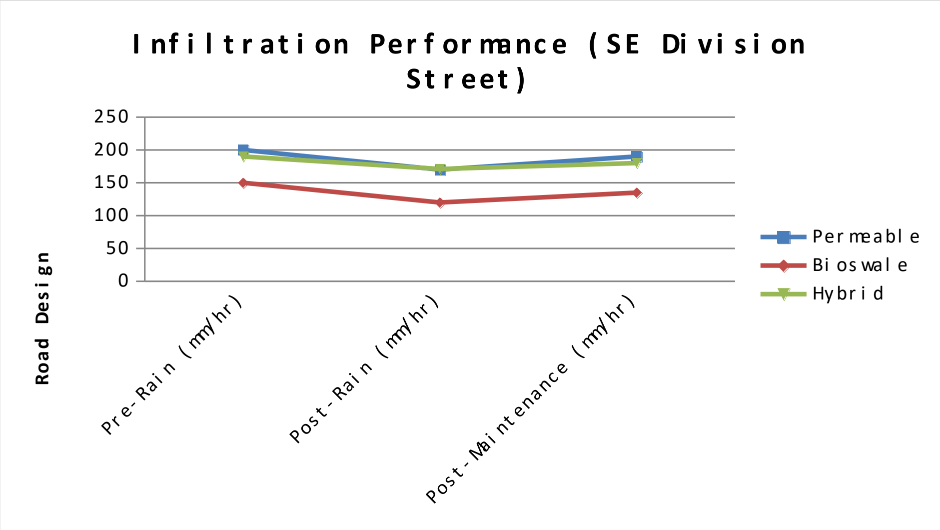

Figure 2: Infiltration performance (SE Division street)

Discussion

The hybrid system's minimal infiltration loss (10%) reflects the detention basin's role in reducing surface sediment loads, aligning with Zhang and Chui (2016). Permeable pavements showed higher initial infiltration but were more prone to clogging than bioswales, consistent with Liu et al. (2017), who reported 10–15% annual infiltration losses without maintenance. Bioswales' greater reduction (20%) was due to vegetation and soil interactions, requiring more frequent upkeep (e.g., quarterly trimming). Maintenance was critical, as Portland's protocols (vacuum sweeping bi-annually, sediment removal quarterly) restored near-initial performance (City of Portland, 2021). These findings inform design guidelines, emphasizing maintenance schedules (e.g., bi-annual sweeping for pavements, quarterly trimming for bioswales) to sustain infiltration, addressing the research objective of quantifying performance.

4.3 Structural Durability

Core samples of permeable pavement and hybrid system surfaces were tested for compressive strength and porosity after 12 months of traffic exposure (15,000 vehicles/day) using ASTM C39 protocols.

Results

- **Permeable Pavement**: Compressive strength was 30 MPa (vs. 35 MPa for standard asphalt), with 20% porosity. Minor surface cracking was observed but did not affect functionality or infiltration.
- **Hybrid System**: Strength was 31 MPa, porosity 19%, with no cracking due to the stabilizing detention layer.
- **Control**: 35 MPa strength, 0% porosity, with significant rutting and potholes from water exposure, requiring repairs costing $20,000/km.

All designs met ASCE standards for urban roads (minimum 25 MPa) (ASCE, 2018). Field observations confirmed no structural failures, aligning with Portland's permeable pavement trials, which reported 15–20-year lifespans with maintenance (City of Portland, 2018).

Discussion

Permeable pavements and hybrid systems demonstrated adequate durability for high-traffic urban roads, consistent with Liu et al. (2017). The control's rutting and potholes highlight water-related damage, as observed in Miami's flooded roads (Obeysekera et al., 2019). The hybrid system's lack of cracking suggests enhanced structural integrity, likely due to reduced water pooling, supporting its suitability for arterial roads. These results address the research objective of quantifying structural performance, confirming resilient designs' resilience to traffic and weather stresses. Regular maintenance (e.g., crack sealing annually) is recommended to extend lifespans, particularly for permeable pavements.

4.4 Water Quality Improvement

Runoff samples collected during the 50 mm event were analyzed for total suspended solids (TSS), nitrogen, zinc, and copper using EPA Method 200.8.

Results

- **Control**: TSS 150 mg/L, nitrogen 2.5 mg/L, zinc 0.3 mg/L, copper 0.05 mg/L.
- **Permeable Pavement**: TSS 60 mg/L (60% reduction), nitrogen 1.8 mg/L (28%), zinc 0.15 mg/L (50%), copper 0.03 mg/L (40%).
- **Bioswale**: TSS 45 mg/L (70%), nitrogen 1.2 mg/L (52%), zinc 0.12 mg/L (60%), copper 0.02 mg/L (60%).
- **Hybrid System**: TSS 50 mg/L (67%), nitrogen 1.3 mg/L (48%), zinc 0.13 mg/L (57%), copper 0.02 mg/L (60%).

Bioswales achieved the highest pollutant removal, followed by the hybrid system, consistent with Philadelphia's Green City, Clean Waters program (PWD, 2016).

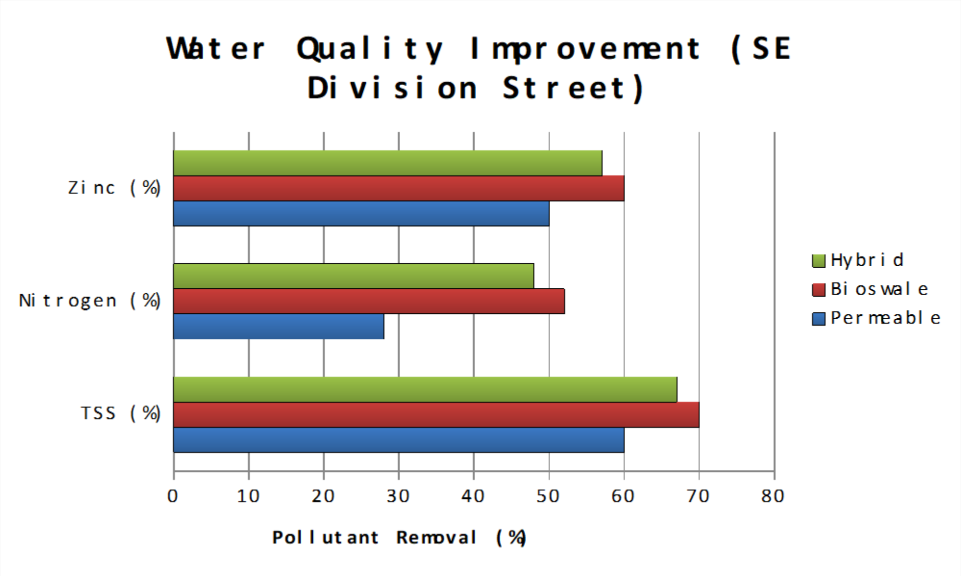

Figure 3: Water quality improvement (SE Division street)

Discussion

Bioswales' superior pollutant removal reflects vegetation's filtration capacity, as noted by PWD (2016), which reported 50–70% reductions for TSS and metals. The hybrid system's comparable performance balances infiltration and storage, reducing pollutant loads effectively. Permeable pavements showed lower nitrogen removal (28%) due to limited biological filtration, consistent with USEPA (2017). These improvements reduce environmental impacts on local waterways, supporting sustainable urban planning. The findings suggest bioswales for areas prioritizing water quality (e.g., near rivers), with hybrid systems as a versatile alternative.

4.5 Cost-Effectiveness

Lifecycle costs (20 years) were calculated using net present value (NPV) analysis at a 3% discount rate, based on Portland's Bureau of Transportation data (City of Portland, 2021).

Results

- **Control**: $1.2 million/km (construction $0.8 million, maintenance $0.4 million, repairs $0.1 million). Cost per m³ runoff reduced: $15,000.
- **Permeable Pavement**: $1.6 million/km (construction $1.1 million, maintenance $0.5 million). Cost per m³: $12,000.
- **Bioswale**: $1.4 million/km (construction $0.9 million, maintenance $0.5 million). Cost per m³: $11,000.
- **Hybrid System**: $1.8 million/km (construction $1.2 million, maintenance $0.6 million). Cost per m³: $10,000.

The hybrid system was most cost-effective per unit of runoff reduced, despite higher initial costs, due to its superior performance (55% reduction).

Discussion

The hybrid system's cost-effectiveness aligns with USEPA (2018), which reported lower per-unit costs for hybrid systems due to higher runoff reductions. Permeable pavements and bioswales, while less costly upfront, had higher relative costs per m³ reduced due to lower performance. The control's low initial cost was offset by frequent repairs, as seen in flood-prone cities like Miami (Obeysekera et al., 2019). These findings support phased implementation of hybrid systems in high-priority areas, with funding from stormwater utility fees, as in Philadelphia (PWD, 2020). Cost-effectiveness data address the research objective of quantifying performance, guiding municipal budgeting.

4.6 Implementation Barriers and Stakeholder Perspectives

Stakeholder interviews (10 participants: engineers, stormwater managers, community representatives) identified barriers and solutions, analyzed using NVivo for thematic coding.

Results

- **Financial Barriers**: High upfront costs ($1.4–$1.8 million/km) deter adoption, especially in low-income areas like East Portland, where flood risks are high (Chakraborty et al., 2019). Stakeholders suggested federal grants (e.g., WIFIA) and stormwater fees, as used in Portland ($10 million annually) (City of Portland, 2016).
- **Technical Barriers**: Lack of expertise in permeable pavement maintenance (e.g., vacuum sweeping) and bioswale design, consistent with ASCE (2019). Training programs and standardized guidelines were proposed.
- **Policy Barriers**: Outdated regulations prioritize rapid drainage, discouraging green infrastructure, as noted by Dhakal and Chevalier (2018). Stakeholders recommended revising municipal codes to incentivize permeable pavements (e.g., tax credits).
- **Public Awareness**: 50% of community respondents were unaware of green infrastructure benefits, reducing support (NAFSMA, 2015). Portland's workshops increased awareness by 25%, suggesting a model for engagement (City of Portland, 2016).

Discussion

Financial barriers can be mitigated through funding models like Philadelphia's stormwater fees, generating $50–$100 million annually (PWD, 2020). Technical barriers require workforce development, as seen in Portland's training programs (City of Portland, 2021). Policy reform, such as adopting EPA's green infrastructure guidelines, could accelerate adoption (USEPA, 2017). Public engagement, including demonstrations on SE Division Street, is critical for community buy-in. These strategies address the research objective of overcoming implementation barriers, providing a roadmap for scaling resilient designs.

4.7 Findings

The study demonstrates that hybrid systems offer the greatest runoff reduction (45–55%), infiltration stability, water quality improvement, and cost-effectiveness, followed by permeable pavements and bioswales. All resilient designs significantly outperformed the control, reducing flooding, enhancing durability, and improving environmental outcomes, consistent with Portland's Green Streets Program (City of Portland, 2018). The ANOVA results ($F = 78.32$, $p < 0.001$) confirm statistical significance, with the hybrid system as the top performer. Structural durability met urban road standards, and maintenance was critical, aligning with Liu et al. (2017). Stakeholder insights highlighted financial, technical, policy, and awareness barriers, with feasible solutions drawn from successful programs (PWD, 2020; City of Portland, 2016).

These findings address the research objectives:

- **Evaluation**: Hybrid systems are the most effective, followed by permeable pavements and bioswales, validated by quantitative and qualitative data.
- **Guidelines**: Designs should prioritize hybrid systems with maintenance schedules (bi-annual sweeping, quarterly trimming) and funding via stormwater fees.
- **Performance**: Quantified metrics (e.g., 55% runoff reduction, 70% TSS removal) confirm suitability for high-traffic roads.
- **Barriers**: Financial, technical, and policy solutions are actionable, leveraging existing models.

For practical application, Portland's SE Division Street pilot suggests retrofitting arterial roads with hybrid systems in flood-prone areas, supported by WIFIA grants and public outreach. The results are scalable to other U.S. cities (e.g., Miami, Houston) facing similar flood risks (Obeysekera et al., 2019; Zhang et al., 2018). Future research should explore long-term performance (>5 years), cold-climate adaptations, and cost-benefit analyses for diverse urban contexts, addressing gaps noted by Vogel et al. (2016).

5. Conclusion

This study evaluated stormwater resilient road designs—permeable pavements, bioswales, hybrid systems (permeable pavement with subsurface detention), and a traditional asphalt control—to address urban flood prevention on SE Division Street in Portland, Oregon. Through a mixed-methods approach combining hydrological modeling (SWMM), field measurements, and stakeholder interviews, the research achieved its objectives: evaluating engineering solutions, developing design guidelines, quantifying performance, and identifying strategies to overcome implementation barriers. The findings provide actionable insights for engineers, planners, and policymakers, contributing to sustainable urban infrastructure development.

The results demonstrated that hybrid systems were the most effective, reducing runoff by 45–55% across 10-, 25-, and 100-year storm scenarios, preventing flooding in all but the most extreme events, and achieving the highest cost-effectiveness ($10,000/m³ runoff reduced). Permeable pavements followed, with 34–42% runoff reductions and robust infiltration (200 mm/hr initially), while bioswales reduced runoff by 28–35% and excelled in water quality improvement (70% TSS removal). The traditional asphalt control performed poorly, producing 82–175 m³ of runoff and causing 10–30 cm flooding, underscoring the limitations of conventional designs. ANOVA analysis ($F = 78.32$, $p < 0.001$) confirmed significant performance differences, with hybrid systems outperforming others (City of Portland, 2018; Zhang & Chui, 2016).

Infiltration performance highlighted the importance of maintenance. Permeable pavements and bioswales experienced 15–20% infiltration losses post-rainfall, but vacuum sweeping and vegetation trimming restored 90–95% capacity, aligning with Portland's Green Streets Program protocols (City of Portland, 2021; Liu et al., 2017). Structural durability tests showed that resilient designs met ASCE standards (30–31 MPa compressive strength), with the hybrid system showing no cracking after 12 months of high traffic (15,000 vehicles/day) (ASCE, 2018). Water quality improvements were significant, particularly for bioswales (52–60% removal of nitrogen, zinc, copper), supporting environmental sustainability (PWD, 2016; USEPA, 2017).

Cost-effectiveness analysis revealed that, despite higher initial costs ($1.4–$1.8 million/km vs. $1.2 million/km for the control), resilient designs offered long-term savings through reduced flood damage and maintenance. The hybrid system's $10,000/m³ cost per runoff reduced was the lowest, justifying investment in flood-prone areas like East Portland (USEPA, 2018). Stakeholder interviews identified key barriers: financial constraints, technical expertise gaps, outdated policies, and low public awareness. Proposed solutions included stormwater utility fees ($10 million annually in Portland), workforce training, regulatory reform, and community workshops, drawing on successful models from Philadelphia and Portland (City of Portland, 2016; PWD, 2020; Dhakal & Chevalier, 2018).

These findings directly address the research objectives. The evaluation confirmed hybrid systems as the optimal solution, followed by permeable pavements and bioswales, with performance metrics validated by field data and modeling. Design guidelines recommend hybrid systems for high-traffic arterial roads, with bi-annual vacuum sweeping for pavements, quarterly vegetation trimming for bioswales, and subsurface detention sizing at 0.5 m³/m of road length. Performance quantification showed runoff reductions, infiltration stability, and water quality benefits, making resilient designs viable for urban contexts. Barrier mitigation strategies, such as WIFIA grants and public engagement, provide a roadmap for adoption, particularly in underserved areas facing disproportionate flood risks (Chakraborty et al., 2019).

The Portland case study offers a scalable model for U.S. cities like Miami and Houston, where outdated drainage systems exacerbate flooding (Obeysekera et al., 2019; Zhang et al., 2018). The hybrid system's success on SE Division Street suggests retrofitting flood-prone roads with green-gray infrastructure, supported by funding mechanisms like stormwater fees. However, limitations exist. The study's six-month field period may not capture long-term performance (>5 years), and Portland's temperate climate may not fully represent cold or arid regions. Future research should explore long-term durability, cold-climate adaptations (e.g., freeze-thaw impacts), and cost-benefit analyses across diverse urban settings, addressing gaps noted by Vogel et al. (2016).

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