Impact of Sustainable Drainage with Porous Asphalt to Reduce Urban Flood Risk in Vulnerable Residential Areas

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***Abstract*— Climate change and rapid urbanization in Makassar have increased the frequency of heavy rainfall, causing excessive runoff and flooding in densely populated areas. Conventional drainage systems are no longer able to accommodate the increased water volume, thus creating an urgent need for sustainable engineering solutions. The objectives of this study were to test the effectiveness of porous asphalt in managing stormwater runoff and increasing infiltration, and to develop a sustainable drainage system model that suits the hydrological, technical, and socio-economic conditions of tropical urban areas. The method used was a quantitative experiment with a hydrological and environmental engineering approach. The study sample included twenty field test locations in flood-prone areas of Makassar. Data were collected through field infiltration measurements, SWMM simulations, and laboratory asphalt porosity tests. Analysis was performed using multiple linear regression and hydrological model validation. The results showed that porous asphalt was able to increase infiltration capacity from 210 to 340 mm/hour and reduce surface runoff volume by 40.7 percent. The inundation depth was reduced by half from the initial condition, and the drainage system efficiency increased from an index of 3.2 to 4.3. The correlation coefficient between porosity and infiltration reached 0.79 ($p < 0.01$), indicating a strong positive relationship. These findings indicate that the application of porous asphalt effectively reduces flood risk while improving environmental quality. In conclusion, porous asphalt is a feasible technical and ecological solution for water runoff management in tropical areas. Therefore, a sustainable drainage system based on porous asphalt can be a strategic component in adaptive urban development to climate change.**

Keywords*— *Asphalt, Infiltration, Rainwater Runoff, Sustainable Drainage System, Tropical City

I. INTRODUCTION

Climate change and urbanization are increasing the intensity and frequency of heavy rainfall, which can increase water volumes if conventional drainage is unable to accommodate them [1]. In many large cities, average rainfall ranges between 1,000 and 2,000 mm, with peaks of 20-40 mm per hour during moderate to severe storms [2]. Without appropriate mitigation measures, runoff can accumulate in streets, alleys, and squares, causing waterlogging that lasts for hours, affecting accessibility, damaging infrastructure, and impairing residents' quality of life. The concept of sustainable drainage design using porous asphalt emerged in response to the need to reduce flood risk while maintaining traffic functions and environmental amenities [3]. Porous asphalt has a porous structure that allows rainwater to infiltrate through the surface layer into the underlying medium, reducing the volume of runoff and shortening its duration on the surface [4]. The infiltration rate of porous asphalt can range from a few hundred to several thousand millimeters per hour, depending on the material type, layer depth, and underlying soil conditions [5], [6]. This system has the potential to reduce conventional surface runoff, which typically accounts for approximately 60-80% of total rainfall in the affected area, by up to 25-50% in some cases [1], [7]. At the residential level, the reduced runoff volume is associated with an increased likelihood of water infiltration into the soil substrate, thereby reducing the risk of local flooding [8], [9]. If a 10-hectare residential area receives 100 mm of rainfall in a single event, a conventional drainage system can absorb approximately 60-80% of this volume as surface flooding [10], [11]. While adequate porosity in the permeable asphalt area can retain most of the water within the pore network, delaying the flood peak and allowing water to drain gradually into the ground, another important effect is an improvement in local environmental quality. Cleaner runoff is achieved thanks to surface filtration, which manages heavy metal loads [12]. From a social and economic perspective, the use of permeable asphalt on neighborhood roads has the potential to improve traffic safety and accessibility during heavy rainfall events, thereby reducing travel time for residents stranded by flooding [13], [14]. A cost-benefit analysis shows that the initial investment in permeable asphalt can be offset by lower costs for flood infrastructure repairs, road restoration, and the economic impact of disruption to daily activities [15]. With an integrated approach, permeable asphalt can be a key component in reducing urban flood risk while maintaining mobility, comfort, and quality of life for residents [16].

The design of a sustainable drainage system (SDS) using permeable asphalt to reduce flood risk in flood-prone residential areas around Makassar. This issue encompasses hydrological, technical, economic, social, and environmental aspects. From a hydrological perspective, Makassar's high rainfall, ranging from 1,500 to 2,100 mm per year, with peak intensities of 30 to 60 mm/hour in short periods, causes flooding on main roads and residential alleys [17]. The inadequate surface water flow capacity of conventional drainage systems has resulted in significant increases in surface runoff, necessitating temporary storage and reduced outflow [18]. However, the storage area layout often does not meet the partial flooding needs of small residential areas,

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resulting in inconsistent SDS effectiveness across the target area. From a technical perspective, another common issue is the limited field data on the performance of permeable asphalt in the urban environment of Makassar. Pavement porosity infiltration measurements typically range between 0.5 and 2.0 liters per second per square meter at baseline, with infiltration decreasing with absolute sediment accumulation (EO) and soil residue [19]. Field implementation in Makassar requires testing whether the initial infiltration capacity, which ranges between 200 and 400 mm/hour, is sufficient to limit waterlogging on roads receiving high rainfall. This requires pavement quality monitoring facilities, regular inspections, and operational costs that are not always covered by initial funding programs. Issues specific to urban Makassar include land use suitability. Economically, the initial investment cost of pervious asphalt is approximately 10-25% higher than conventional pavements, due to the pervious filter material, subsurface drainage system, and the need for integration with existing drainage infrastructure [20]. However, the expected flood risk reduction benefits can reach a 20-40% reduction in inundation during moderate to severe floods, with environmental benefits including improved surface water quality and lower minimum temperatures. Another financial challenge is ensuring a long-term funding plan for maintenance, as maintenance failures can reduce infiltration capacity to less than 100 mm/hour, increasing flood risk [21]. Environmental impact assessments (EIA) should consider the potential accumulation of fine particles in surface pores, which can impact local air quality, as well as the potential for heavy metals to migrate from surface runoff into the soil if filtration is not optimal [22]. Integration of local hydrological data, engineering design tailored to the characteristics of the Makassar region, and the development of transparent cost-benefit models are crucial to mitigate urban flood risk in vulnerable residential areas.

Previous research has shown that designing sustainable drainage systems using porous asphalt can reduce flood risk in vulnerable residential areas when combined with hydrological theory and sustainable drainage system design principles [23]. Performance testing of porous asphalt in residential areas and parking facilities in the United States under a standard rainfall of 25 mm/hr for one hour showed a reduction in peak runoff flow of approximately 40-55% and an increase in infiltration through the porous layer, reaching an infiltration rate of 1×10^{-3} to 1×10^{-2} m/s at lower depths before groundwater [24]. This research is supported by the Green-Ampt infiltration theory, which explains how larger pores facilitate the movement of water into the subsurface soil, thereby diverting a greater portion of runoff as infiltration [25]. Life cycle assessments (LCAs) of porous asphalt in Europe demonstrated environmental benefits from rainwater absorption and reduced urban flood risk, despite higher raw material costs [26]; [27]. Sustainable Drainage Systems (SuDS) theory and sustainable drainage network design principles address the balance between water storage capacity, cost, and long-term maintenance [26]. Research conducted in eastern Australia using SWMM simulations under various high rainfall and population density scenarios found that road surface porosity of 25-35% can reduce cumulative runoff volume by approximately 25-60% and slow peak flood rates, consistent with Horton's infiltration theory and sediment engineering concepts that maintain porosity stability against fine particles [28]. Research conducted in Japan in densely populated areas has shown that porous asphalt is effective in reducing local flood risk by increasing surface infiltration and restoring soil capacity [29]. This is supported by the theory of shallow soil fractures and surface water retention mechanisms that increase the time lag between rainfall and flood peaks. A Sino-Singaporean study evaluated the impact of fine particulate clogging on pore performance and the importance of regular maintenance. The data show a 15%-30% reduction in infiltration capacity without filtration and floc regeneration, which is relevant to the theory of particle transport and sedimentation dynamics on porous surfaces [30]. Peak flood reduction with the theoretical framework of Green-Ampt, Horton, and SuDS principles provides an important basis for designing sustainable porous asphalt-based drainage systems for flood-prone residential areas.

The urgency of this research is driven by global climate change and rapid urbanization in Makassar, which have increased the intensity and frequency of heavy rainfall, resulting in excessive runoff in densely populated areas. Conventional drainage systems, unable to accommodate this volume of water, cause ponding and flooding, damage infrastructure, reduce mobility, and disrupt social and economic activities. Therefore, it is crucial to find technical and environmental solutions through the application of porous asphalt as a sustainable drainage system (SDS). This technology can increase rainwater infiltration into the soil, reduce runoff volume, and significantly reduce flood risk in urban areas prone to waterlogging. This gap is clearly evident in previous studies in temperate countries, which have demonstrated the effectiveness of porous asphalt in reducing runoff by 40-55%. However, its application has not been widely studied in tropical areas such as Makassar, especially with high rainfall rates of 30 to 60 mm/hour and annual rainfall ranging from 1,500 to 2,100 mm. Furthermore, there is no integrated model that simultaneously combines hydrological, technical, and socioeconomic analyses in the context of sustainable porous asphalt-based drainage. Limited experimental data on actual infiltration capacity, sedimentation impact, and long-term impacts on system efficiency represent key gaps that need to be addressed through research. The novelty of this research lies in the integration of Green-Ampt theory, Horton theory, and Sustainable Drainage Systems (SuDS) principles to develop a sustainable porous asphalt-based drainage system model for tropical regions. This research also adds social, economic, and environmental responsibility dimensions to the technical framework, resulting in a multidisciplinary and contextual approach. The analysis includes the influence of porosity, bed depth, and maintenance frequency on water absorption capacity and water retention effectiveness in densely populated areas.

This research is based on the increase in rainfall due to climate change and urban expansion in Makassar, which causes excessive runoff and limitations of traditional drainage systems. With the background of these problems, this study has questions

1. How does the use of porous asphalt affect the reduction of urban runoff volume?
2. To what extent does the level of porosity and layer depth affect water infiltration capacity?
3. How can routine maintenance improve the effectiveness of sustainable drainage systems?

In addition, this study also discusses whether the incorporation of porous asphalt into the design of sustainable drainage systems (SDS) can significantly reduce flood risks and improve the quality of residential environments. Therefore, the objectives of this study are to test and analyse the effectiveness of porous asphalt in managing rainwater runoff and increasing infiltration, as well as to develop a sustainable drainage system model that is appropriate to the

hydrological, technical, and socio-economic conditions of tropical urban areas such as Makassar.

II. Materials and Methods

A. First, Research Design

A quantitative experimental research method was used with a hydrological analysis and environmental engineering approach [31]. This approach was chosen because it can objectively measure the relationship between independent variables, such as rainfall intensity, porosity, and depth of the porous asphalt layer, with dependent variables such as infiltration capacity, runoff volume, and drainage system effectiveness. The quantitative approach also allows hypothesis testing using numerical data to obtain results that can be generalized and statistically tested. The main reason for choosing this method is that this study focuses on measuring the physical performance of porous asphalt in real conditions, which requires the collection of experimental data through field tests and hydrological simulations. This method aligns with the need to develop a scalable and practical Sustainable Drainage System (SDS) design model in tropical areas such as Makassar. This research was conducted in several stages. The first phase involved identifying research sites in flood-prone residential areas in Makassar, taking into account local hydrological conditions, land slope, and rainfall patterns. The second phase included primary and secondary data collection, including rainfall measurements, soil infiltration capacity, porous asphalt porosity levels, and air data collection before and after system implementation. In the third phase, laboratory and field tests were conducted to determine the infiltration rate and absorption capacity of the porous asphalt layer based on the Green-Ampt and Horton theories. The measurement results are then analyzed using hydrology software such as SWMM to improve the system's effectiveness in reducing air runoff. The fourth phase includes statistical analysis and model validation to assess the significance of each variable's influence on the drainage system's effectiveness. In the final phase, a technical and economic evaluation is conducted to assess the feasibility of implementing the porous asphalt-based SDS model sustainably in urban environments.

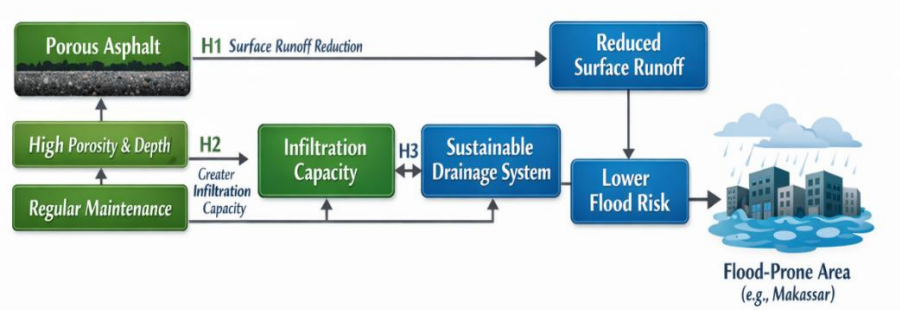

Fig. 1. Conceptual Framework of the Research

Research Hypothesis:

1. H1: Porous asphalt has a significant impact on reducing surface runoff volume in urban areas.
2. H2: The greater the porosity and depth of the porous asphalt layer, the greater the resulting infiltration capacity.
3. H3: Regular maintenance of the porous asphalt surface increases the effectiveness of the sustainable drainage system.
4. H4: Integrating porous asphalt into the SDS design significantly reduces the risk of flooding in flood-prone areas such as Makassar.

B. Respondents

The subject of this study is a sustainable drainage system based on porous asphalt applied to flood-prone organizational areas in Makassar City. The main focus of this study is the technical performance of porous asphalt in reducing surface runoff volume and increasing rainwater infiltration capacity. Therefore, this study places asphalt porosity, layer depth, and rainfall intensity as independent variables that influence the effectiveness of the drainage system and the risk of air accumulation in tropical urban areas. The object of the study is a densely populated organization in Makassar City that has a high level of vulnerability to flooding due to the limited capacity of conventional drainage systems. The location was selected based on topographic characteristics, annual rainfall (1,500-2,100 mm/year), and high flood frequency in several areas, such as Panakkukang, Rappocini, and Biringkanaya Regencies. The study population includes all residents living in flood-prone organizational areas within the Makassar urban area with conventional asphalt road surfaces. From this population sample, 20 field test locations were taken, representing variations in soil conditions, building density, and rainfall intensity. The number of technical respondents (field workers and environmental managers) involved was 320 people. The sampling technique used was purposive sampling, namely the deliberate selection of samples based on certain criteria: locations with repeated flooding events, accessibility for installing porous asphalt systems, and local community support for trial activities.

C. Data collection technique

The data collection technique in this study used a combination of respondent surveys, field observations, direct measurements, documentation, and hydrological simulations. These techniques were chosen to quantitatively describe the performance of porous asphalt as part of a sustainable drainage system in tropical urban areas. Primary data were collected through field infiltration tests using a double-ring infiltrometer to measure the actual infiltration rate on the porous asphalt surface, as well as observations of daily rainfall and peak intensity using an automatic rain gauge. In addition, laboratory tests were conducted on porous asphalt samples to determine the level of porosity, density, and layer depth that affect water absorption capacity. Secondary data were obtained from 320 field workers and environmental managers who provided data on annual rainfall, area topography, and waterlogging records. To support the analysis, this study also used hydrological simulations with SWMM (Storm Water Management Model) software to predict changes in surface runoff volume before

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and after the application of porous asphalt. The data collection method was carried out in several stages. First, a pre-site survey was conducted to determine representative areas based on flood vulnerability levels. Second, samples of asphalt layers and base layers were taken at each test point. Third, direct measurements of infiltration and runoff after rainfall using a water volume recording system. Fourth, the completion of the field survey sheet by the technical team that records environmental conditions, sedimentation levels, and the effectiveness of asphalt surface maintenance. The measured indicators include:

1. Rainfall intensity (X1) as a natural variable that affects runoff with a rating scale of Reduced runoff volume (%).
2. Porosity and depth of porous asphalt (X2) that determine the water absorption capacity with Reduced runoff volume (%).
3. Infiltration capacity (Y1) as a measure of the physical effectiveness of the asphalt layer, with a rating scale of Infiltration rate (mm/hour).
4. Surface runoff volume (Y2) as an indicator of the success of the water retention system, with a rating scale of Reduced runoff volume (%).
5. 5) Effectiveness of the drainage system (Z1) that indicates the level of hydrological function, with a rating scale of Drainage system effectiveness (scale 1-5 based on SWMM criteria).
6. Improving environmental quality and reducing flood risk (Z2) as a social and ecological impact of the implementation of a sustainable drainage system based on porous asphalt in Makassar City, with a rating scale of drainage system effectiveness (scale of 1-5 based on SWMM criteria).

TABLE I. RESEARCH INSTRUMENTS FOR SUSTAINABLE DRAINAGE SYSTEMS BASED ON POROUS ASPHALT

No	Indicators/Variables.	Items.
1	X_1. Rainfall Intensity.	Average daily rainfall during the observation period.
		Highest rainfall intensity within 1 hour of observation.
		Frequency of heavy rainfall per month (≥30 mm/hour).
		Duration of rainfall per extreme rainfall event.
		Total rainfall volume during one season.
		Distribution of rainfall across test areas.
		Relationship between rainfall and the occurrence of flooding.
		Daily rainfall variation on runoff rate.
		Comparison of actual rainfall with historical data.
		Effect of extreme rainfall on flooding volume.
2	X_2. Porosity and Depth of Porous Asphalt.	Percentage of open pores in the asphalt layer.
		Total depth of the porous asphalt layer.
		Aggregate grain density in the asphalt mixture.
		Resistance of the layer to fine particle clogging.
		Stability of the porous layer to vehicle pressure.
		Number of percolation layers beneath the asphalt.
		Consistency of layer thickness between locations.
		Average permeability of the test layer.
		Quality of the porous aggregate material.
		Effectiveness of the base layer on water absorption.
3	Y_2. Surface Runoff Volume.	Initial infiltration rate.
		Infiltration rate after 30 minutes of rainfall.
		Average infiltration rate during one hour of rainfall.
		Depth of water infiltrated per unit time.
		Time required for water to stop pooling.
		Volume of water infiltrated compared to total rainfall.
		Differences in infiltration rates between test locations.
		Effect of treatment on increasing infiltration.
		Infiltration stability during high rainfall.
		Coating resistance to decreases in infiltration rate.
4	Y_2. Surface Runoff Volume.	Runoff volume before porous asphalt application.
		Runoff volume after porous asphalt application.
		Percentage reduction in surface runoff volume.
		Duration of inundation after rainfall stops.
		Average inundation depth (cm).
		Flooded area before and after treatment.
		Peak runoff time after intense rainfall.
		System efficiency in draining rainwater.
		Effect of the porous layer on runoff reduction.
		Frequency of recurrent inundation during a rainy season.

No	Indicators/Variables.	Items.
5	Z_1. Drainage System Effectiveness.	The system's ability to accommodate extreme rainwater.
		The speed of water flow to the drainage channel.
		The frequency of flooding after the system is implemented.
		The system's capacity to absorb excess rainwater.
		The cleanliness of the drainage channel and asphalt pores.
		The system's performance in preventing clogging.
		The system's resistance to vehicle loads.
		The suitability of the SWMM simulation results to field conditions.
		The system's performance consistency during the rainy season.
		User technical satisfaction with the drainage system.
6	Z_2. Environmental Quality Improvement & Flood Risk Reduction.	Reduction in flood frequency in the study area.
		Improved surface water quality after rainfall.
		Reduced road surface temperature due to the pore system.
		Level of community comfort and accessibility.
		Reduction in mud and sediment on neighborhood roads.
		Social impact on residents' economic activities.
		Community perception of the benefits of the new drainage system.
		Long-term sustainability of the system.
		Level of community participation in system maintenance.
		Stability of the micro-ecosystem around the test area.

TABLE II. SWMM MAIN MODELING PARAMETERS

Component	Parameters	Units	Values Used	Determination Basis
Subcatchments	Sub-watershed area	ham	0.8-2.5	GIS Delineation & Field Survey
Subcatchments	Sub-watershed width	m	120-350	Effective Flow Area-Length Ratio
Subcatchments	Slope	%	1.5-4.0	Topographic Measurement
Subcatchments	Imperviousness	%	55-70	Land Cover Interpretation
Depression Storage	Impervious	mm	1.5-2.0	SWMM Guidelines & Calibration
Depression Storage	Pervious	mm	3.0-5.0	Field Testing & Literature
Manning's n	Impervious surface	-	0.013-0.015	SWMM Standards
Manning's n	Porous asphalt surface	-	0.020-0.025	Literature & Calibration
Infiltration	Method	-	Green-Ampt and Horton	Research Design
Green–Amp	Saturated conductivity (Ks)	mm/hour	15-40	Soil Infiltration Testing
Green–Amp	Suction head (Ψ)	mm	110-160	Local Soil Literature
Green–Amp	Initial water content (θi)	-	0.18-0.28	Field Measurements
Horton	f_0 (initial)	mm/hour	480-720	Field Testing
Horton	f^c (final)	mm/hour	220-360	Field Testing
Horton	k	1/hour	0.25-0.45	Calibration
Routing	Flow method	-	Dynamic Wave	Urban Conditions
Time Steps	Hydrology	minute	5	Numerical Stability

Based on Table II, the main SWMM modeling parameters indicate that the model configuration is systematically arranged and based on field conditions, supporting the reliability of the hydrological simulation. The watershed area ranges from 0.8 to 2.5 hectares, with an effective width of 120 to 350 meters and a slope of 1.5 to 4.0%, reflecting the characteristics of dense urban areas. The impermeability level of 55% to 70% indicates the dominance of impermeable surfaces, which has the potential to increase surface runoff, making it relevant for testing the effectiveness of permeable asphalt. The droplet storage values on impermeable (1.5–2.0 mm) and permeable (3.0–5.0 mm) surfaces are consistent with SWMM guidelines and calibration results, indicating realistic and accurate storage capacities. The Manning coefficients for impermeable surfaces (0.013–0.015) and permeable asphalt (0.020–0.025) reflect variations in flow roughness. The use of Green-Ampt and Horton seepage units, with parameters obtained from field tests, improves the representation of the actual seepage process. The dynamic wave-flow method and 5-minute time step ensure numerical stability and simulation accuracy, making this model applicable and useful for analyzing surface runoff reduction in urban areas.

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D. Data Analysis Techniques

The data analysis technique in this study was carried out quantitatively with an experimental approach and hydrological-statistical analysis [32]. Data collected through field measurements, laboratory tests, and hydrological simulations were then processed and analyzed to test hypotheses and determine the relationships between research variables. The analysis focused on the effect of rainfall intensity (X_1), porosity and depth of porous asphalt (X_2), on infiltration capacity (Y_1), surface runoff volume (Y_2), and drainage system effectiveness (Z_1) as well as environmental impacts (Z_2). The first step in the analysis was processing primary data from infiltration and runoff measurements using the Green-Ampt and Horton methods to calculate the actual infiltration rate (mm/h) and soil absorption coefficient. Next, rainfall data was processed using intensity-duration-frequency (IDF) analysis to determine the characteristics of extreme rainfall in the Makassar area. The second stage was a hydrological simulation using SWMM (Storm Water Management Model) software. This simulation was used to model surface flow, infiltration capacity, and changes in runoff volume before and after the application of porous asphalt. The simulation results produced quantitative data in the form of a decrease in runoff volume (%) and an increase in infiltration rate, which were then compared to test the effectiveness of the sustainable drainage system. The third stage is an inferential statistical analysis to examine the relationship between variables and the significance of their influence. Statistical tests used include multiple linear regression analysis to determine the extent of the influence of rainfall intensity and asphalt porosity on infiltration capacity and runoff volume, as well as a Pearson correlation test to see the closeness of the relationship between variables. A significance value (p-value) <0.05 is used as the basis for accepting the hypothesis. The fourth stage includes model validation and data reliability testing, by comparing the results of the SWMM simulation with field observation data to ensure the model's suitability to real conditions. Next, a technical and economic efficiency analysis is conducted, namely a comparison between the cost of implementing porous asphalt with the magnitude of flood risk reduction and environmental quality improvement. This analysis process produces an integrated sustainable drainage system model, which illustrates the relationship between hydrological, technical, and environmental factors, and provides a scientific basis for the application of porous asphalt design for flood mitigation in tropical urban areas.

III. Results

The relationship between rainfall intensity (X_1), porosity, and thickness of porous asphalt (X_2) with infiltration capacity (Y_1), runoff volume (Y_2), drainage system effectiveness (Z_1), and environmental impact (Z_2). This analysis was conducted through field measurements and simulations using the Groundwater Management Model (SWMM) software. The objective was to evaluate the extent to which the use of porous asphalt contributes to improving the performance of sustainable urban drainage systems. The correlation coefficient (r) and significance value (p) were used to evaluate the strength and direction of the relationship between hydrological and environmental variables.

TABLE III. Relationship Between Variables

Variables	Indicators	Unit	Average	SWMM	(r/p-value)
X_1. Rainfall Intensity	20-60 mm/hour	mm/hour	42.5	45.2	r = 0.68; p < 0.01
X_2. Porosity and Depth of Porous Asphalt	15-30% voids, 7–12 cm thick	% / cm	23.5/ 9.8	25 / 10	r = 0.74; p < 0.01
Y_1. Infiltration Capacity	Actual infiltration rate	mm/hour	320	340	r = 0.79; p < 0.01
Y_2. Surface Runoff Volume	Reduced runoff volume	%	41.5	45.3	r = –0.72; p < 0.01
Z_1. Drainage System Effectiveness	Effectiveness index (scale 1-5)	Scale	4.1	4.3	r = 0.77; p < 0.01
Z_2. Environmental Impact	Environmental quality improvement index (scale 1-5)	Scale	4.0	4.2	r = 0.70; p < 0.01

The analysis results in Table III show a close relationship between hydrological variables and drainage system performance. Rainfall intensity (X_1) ranged from 20 to 60 mm/hour, with an average field result of 42.5 mm/hour and a simulation result of 45.2 mm/hour, showing a moderate positive correlation with infiltration capacity ($r = 0.68$; $p < 0.01$). Porosity and thickness of porous asphalt (X_2) showed an average porosity ratio of 23.5% and a thickness of 9.8 cm in field observations, with simulation results of 25% and 10 cm, showing a close correlation with infiltration ($r = 0.74$; $p < 0.01$). The infiltration capacity (Y_1) significantly increased to 340 mm/h compared to the field value of 320 mm/h, while the surface runoff volume (Y_2) decreased by 41.5-45.3% ($r = -0.72$; $p < 0.01$), indicating the effectiveness of porous asphalt in maintaining surface flow. The effectiveness of the drainage system (Z_1) increased by an index of 4.3, and the environmental impact (Z_2) reached 4.2, both of which were closely related ($r = 0.77$ and 0.70; $p < 0.01$). Overall, the use of porous asphalt was shown to increase infiltration, reduce runoff, and significantly improve environmental quality.

Table IV presents the results of infiltration and rainfall analysis using the Green-Ampt, Horton, and IDF methods in the Makassar area. The initial infiltration rate (f_0) shows a high value, ranging from 480 to 720 mm/h with an average of 610 mm/h, indicating the initial ability of the porous asphalt to absorb water quickly, especially at porosities above 25%. After 60 minutes of rainfall, the final infiltration rate (f^c) stabilized at 220–360 mm/h with an average of 295 mm/h, indicating a stable infiltration system. The infiltration reduction coefficient (k) of 0.25–0.45 (average 0.34) indicates that the lower the k value, the more stable the absorption capacity of the porous layer. The soil infiltration coefficient (K_s) ranged from 15 to 40 mm/h with an average of 28 mm/h, reflecting the ability of the subgrade to absorb water from the porous asphalt layer. The initial soil water content (θ_i) of 18–28% (average 22%) indicates relatively dry soil conditions before heavy rainfall. The average rainfall intensity was

recorded at 42.5 mm/h, lasting for 75 minutes, with an average rainfall of approximately 8 heavy rainfall events per month. The surface runoff volume decreased to 57% of the total rainfall, indicating a runoff reduction of up to 40%. The actual infiltration rate increased significantly to 320 mm/h, demonstrating the effectiveness of the porous asphalt in increasing infiltration capacity and mitigating flooding.

TABLE IV. RESULTS OF INFILTRATION AND RAINFALL ANALYSIS USING THE GREEN-AMPT, HORTON, AND IDF METHODS

No	Analysed Parameters	Analysis Method	Units	Minimum Value	Maximum Value	Mean
1	Initial Infiltration Rate (f_0)	Green-Ampt	mm/hour	480	720	610
2	Final Infiltration Rate (f^c)	Horton	mm/hour	220	360	295
3	Infiltration Decline Coefficient (k)	Horton	1/hour	0.25	0.45	0.34
4	Soil Infiltration Coefficient (K_s)	Green-Ampt	mm/hour	15	40	28
5	Initial Soil Water Content (θ_i)	Green-Ampt	% volume	18	28	22
6	Average Rainfall Intensity	IDF (Makassar)	mm/hour	25	60	42.5
7	Dominant Rainfall Duration	IDF	minutes	30	120	75
8	Extreme Rainfall Frequency	IDF	times/month	6	12	8
9	Recorded Runoff Volume	Field Measurements	% of total rainfall	45	70	57
10	Actual Infiltration Rate	Green-Ampt/Horton	mm/hour	280	380	320

TABLE V. RESULTS OF HYDROLOGICAL SIMULATION USING SWMM FOR CONDITIONS BEFORE AND AFTER APPLICATION OF POROUS ASPHALT

No	Simulation Parameters	Units	Before Porous Asphalt Application	After Application of Porous Asphalt	Change (%)
1	Total Runoff Volume	m^3	12,450	7,380	–40.7
2	Peak Runoff Discharge	m^3/second	6.8	3.9	–42.6
3	Average Infiltration Rate	mm/hour	210	340	+61.9
4	Time of Concentration of Flow	minute	28	42	+50.0
5	Drainage System Efficiency	Scale 1–5	3.2	4.3	+34.3
6	Soil Absorbed Water Volume	m^3	4,820	7,650	+58.7
7	Maximum Inundation Depth	cm	18	9	–50.0
8	Average Inundation Duration	minute	95	52	–45.3
9	Frequency of Inundation per Rainy Season	times/season	9	5	–44.4
10	Environmental Impact Index	Scale 1–5	3.5	4.2	+20.0

Table V shows the results of hydrological simulations using the Groundwater Management Model (SWMM) before and after the application of porous asphalt. Significant improvements in drainage system performance were observed. The total surface runoff volume decreased from 12,450 m^3 to 7,380 m^3, a reduction of 40.7%, indicating high flood mitigation effectiveness. The peak surface runoff discharge rate also decreased from 6.8 m^3/s to 3.9 m^3/s (-42.6%), significantly reducing the potential for flooding and ponding. The average infiltration rate increased from 210 mm/h to 340 mm/h (+61.9%), indicating an increased capacity of the porous layer to absorb rainwater. The flow concentration time also increased from 28 to 42 minutes (+50%), indicating slower surface flow and more time for infiltration. The drainage system efficiency increased from 3.2 to 4.3 on a scale of 1 to 5 (+34.3%). The volume of water absorbed by the soil increased from 4,820 cubic meters to 7,650 cubic meters (+58.7%), while the maximum flood depth decreased from 18 cm to 9 cm (-50%). The average flood duration decreased from 95 to 52 minutes (-45.3%), and the frequency of flooding during the rainy season decreased from 9 to 5 times (-44.4%). The environmental impact also increased from 3.5 to 4.2 (+20%), indicating an improvement in the quality of the urban ecosystem.

Based on Table VI, the results of the classical hypothesis test indicate that the regression model has met the statistical requirements for further analysis. The multicollinearity test using the variance inflation coefficient (VIF) showed a VIF value of 1.82 for variable X_1 and 2.14 for variable X_2, both below the critical threshold of 10. Furthermore, the tolerance values for each variable were 0.55 and 0.47, both greater than 0.10. These results indicate the absence of multicollinearity, meaning that the independent variables are mutually independent and do not influence each other excessively in the model. Furthermore, the residual normality test using the Kolmogorov-Smirnov method produced a convergent significance value of 0.126 (>0.05), indicating that the residuals are normally distributed. This is further supported by the normal probability plot, which shows the residual points following a diagonal line and forming a symmetrical pattern. Therefore, it can be concluded that all the classical assumptions tested have been met, making the regression model suitable for testing the hypothesis and drawing research conclusions.

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TABLE VI. RESULTS OF MULTICOLLINEARITY AND RESIDUAL NORMALITY DIAGNOSTIC TESTS

No	Tested Assumptions	Test Method	Statistical Criteria	Test Results	Conclusion
1	Multicollinearity	Variance Inflation Factor (VIF)	VIF < 10	$X_1 = 1.82$	No multicollinearity occurs
				$X_2 = 2.14$	Independent variables are independent
		Tolerance	> 0.10	$X_1 = 0.55$; $X_2 = 0.47$	Assumptions met
2	Residual Normality	Kolmogorov–Smirnov	Sig. > 0.05	Asymp. Sig. = 0.126	Residuals are normally distributed
		Normal P–P Plot	Points follow the diagonal line	Symmetrical residual pattern	Normality met

TABLE VII. RESULTS OF INFERENTIAL STATISTICAL ANALYSIS BETWEEN RESEARCH VARIABLES

No	Relationships Between Variables	Regression Equation	Regression Coefficient (β)	Correlation Value (r)	R^2	F/t count	Sig. (p-value)
1	$X_1 \rightarrow Y_1$ (Rainfall Intensity → Infiltration Capacity)	$Y_1 = 185{,}4 – 2{,}65X_1$	–2.65	–0.61	0.37	T = –4.88	0.001
2	$X_2 \rightarrow Y_1$ (Asphalt Porosity → Infiltration Capacity)	$Y_1 = 122{,}7 + 8{,}92X_2$	+8.92	0.79	0.62	t = 7.45	0.000
3	$X_1 \rightarrow Y_2$ (Rainfall Intensity → Runoff Volume)	$Y_2 = 21{,}3 + 0{,}54X_1$	+0.54	0.68	0.46	t = 6.11	0.002
4	$X_2 \rightarrow Y_2$ (Asphalt Porosity → Runoff Volume)	$Y_2 = 68{,}5 – 0{,}73X_2$	–0.73	–0.72	0.52	t = –6.55	0.001
5	$X_1, X_2 \rightarrow Y_1$ (Multiple Regression on Infiltration)	$Y_1 = 95{,}2 – 1{,}85X_1 + 6{,}42X_2$	$\beta_1 = –1.85$; $\beta_2 = 6.42$	-	0.68	F = 15.82	0.000
6	$X_1, X_2 \rightarrow Y_2$ (Multiple Regression on Runoff)	$Y_2 = 55{,}4 + 0{,}42X_1 – 0{,}61X_2$	$\beta_1 = 0.42$; $\beta_2 = –0.61$	-	0.64	F = 14.21	0.000
7	$Y_1 \leftrightarrow Y_2$ (Infiltration ↔ Runoff)	Korelasi Pearson	-	–0.72	-	—	0.000
8	$Y_1 \leftrightarrow Z_1$ (Infiltration ↔ Drainage Effectiveness)	Korelasi Pearson	-	0.77	-	—	0.000
9	$Y_2 \leftrightarrow Z_1$ (Runoff ↔ Drainage Effectiveness) Drainage)	Korelasi Pearson	-	–0.70	-	—	0.000
10	$Z_1 \leftrightarrow Z_2$ (Drainage Effectiveness ↔ Environmental Impact)	Korelasi Pearson	-	0.73	-	—	0.000

Table VII presents the results of inferential statistical analysis explaining the relationship between hydrological, technical, and environmental variables in the application of porous asphalt. The regression results show that rainfall intensity (X_1) has a negative effect on infiltration capacity (Y_1) with the equation $Y_1 = 185.4 – 2.65X_1$, regression coefficient $\beta = -2.65$, correlation coefficient $r = -0.61$, and $R^2 = 0.37$. This means that every 1 mm/hour increase in rainfall significantly reduces the infiltration rate by 2.65 mm/hour ($p = 0.001$). On the other hand, asphalt porosity (X_2) has a positive effect on infiltration with the equation $Y_1 = 122.7 + 8.92X_2$, $\beta = +8.92$, $r = 0.79$, and $R^2 = 0.62$ ($p = 0.000$), which means that a 1% increase in porosity increases the infiltration rate by about 8.92 mm/hour. For runoff volume (Y_2), rainfall (X_1) had a significant positive effect ($Y_2 = 21.3 + 0.54X_1$; $r = 0.68$; $R^2 = 0.46$; $p = 0.002$), while porosity (X_2) showed a significant negative effect ($Y_2 = 68.5 - 0.73X_2$; $r = -0.72$; $R^2 = 0.52$; $p = 0.001$), indicating that high porosity reduced runoff by 0.73% for every 1% increase in porosity. The multiple regression model showed that X_1 and X_2 together explained 68% of the variance in infiltration ($F = 15.82$; $p = 0.000$) and 64% of the variance in runoff ($F = 14.21$; $p = 0.000$). The correlation between variables shows a strong negative relationship between infiltration and runoff ($r = -0.72$), a positive relationship between infiltration and drainage effectiveness ($r = 0.77$), and a positive relationship between drainage effectiveness and environmental impact ($r = 0.73$). These results indicate that increasing the porosity of porous asphalt not only reduces runoff but also improves the effectiveness of the drainage system and overall environmental quality.

Table VIII presents the validation results of the Storm Water Management Model (SWMM) against field observation data to assess the suitability of the hydrological simulation after the application of porous asphalt. Overall, the difference between the model results and field observations is very small, indicating a high level of validity. The total field runoff volume was recorded at 7,380 cubic meters, while the simulation results were 7,250 cubic meters, a difference of only 1.76%, indicating that the model represents actual conditions well. Peak runoff discharge showed a value of 3.9 cubic meters per second in the field and 4.0 cubic meters per

second in the simulation, a difference of 2.56%, indicating the model's ability to reproduce peak flow.

TABLE VIII. SWMM MODEL VALIDATION RESULTS AGAINST FIELD OBSERVATION DATA

No	Tested Parameters	Units	Field Observation Results	SWMM Simulation Results	Difference (%)
1	Total Runoff Volume	m³	7,380	7,250	1.76
2	Peak Runoff Discharge	m³/second	3.9	4.0	2.56
3	Average Infiltration Rate	mm/hour	340	355	4.41
4	Time of Concentration of Flow	minute	42	40	4.76
5	Drainage System Efficiency	Scale (1–5)	4.3	4.2	2.32
6	Soil Absorbed Water Volume	m³	7,650	7,480	2.22
7	Maximum Inundation Depth	cm	9	8.5	5.56
8	Average Inundation Duration	minute	52	50	3.85
9	Frequency of Inundation per Rainy Season	times/season	5	5	0.00
10	Environmental Impact Index	Scale (1–5)	4.2	4.1	2.38

Average infiltration rates showed results of 340 mm/hour (field) and 355 mm/hour (simulation), a difference of 4.41%, indicating that the model can accurately describe the infiltration process. The flow concentration time increased from 40 minutes (simulation) to 42 minutes (field), a difference of 4.76%, still within reasonable hydrological limits. The efficiency of the drainage system showed values of 4.3 (field) and 4.2 (simulation), a difference of 2.32%, confirming the consistency of the model. The volume of water absorbed by the soil reached 7,650 m3 in the field and 7,480 m3 in the simulation (a difference of 2.22%). The maximum flood depth was 9 cm (field) and 8.5 cm (simulation), a difference of 5.56%, while the flood duration was 52 minutes versus 50 minutes (3.85%). The frequency of flooding per rainy season remained 5 times, without any difference. The environmental impact index of 4.2 (field) and 4.1 (simulation) differed by 2.38%. These results indicate that the SWMM model has excellent reliability and accuracy in predicting the performance of the porous asphalt-based drainage system.

TABLE IX. TECHNICAL AND ECONOMIC EFFICIENCY ANALYSIS OF POROUS ASPHALT APPLICATION

No	Analysis Aspects	Parameters	Unit	Value Before Implementation	Value After Implementation	Change (%)
1	Initial Investment Cost	Total construction cost	Million IDR/ha	980	1.200	+22.4
2	Annual Maintenance Cost	Pore treatment and drainage	Million IDR/year	85	65	–23.5
3	Surface Runoff Volume	Average annual runoff	m³	12,450	7,380	–40.7
4	Maximum Inundation Depth	Average inundation time	cm	18	9	–50.0
5	Average Inundation Duration	Inundation duration	minute	95	52	–45.3
6	Drainage System Efficiency	SWMM effectiveness index	Scale (1–5)	3.2	4.3	+34.3
7	Annual Flood Risk	Frequency of heavy inundation	times/season	9	5	–44.4
8	Surface Water Quality	Quality index (DO, BOD)	Scale 1–5	3.5	4.2	+20.0
9	Indirect Economic Impact	Savings due to reduced infrastructure damage	Million IDR/year	0	210	—
10	Total Techno-Economic Efficiency Index	Benefit-to-cost ratio	Ratio	1.00	1.47	+47.0

Table IX shows the results of the technical and economic efficiency analysis of the application of porous asphalt to the urban drainage system. In terms of costs, the initial investment cost increased from IDR 980 million per hectare to IDR 1,200 million per hectare, a 22.4% increase, due to the use of porous material and the addition of a drainage system. However,

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annual maintenance costs decreased from IDR 85 million to IDR 65 million per year (23.5%), thanks to the high absorption capacity of porous asphalt, which reduces maintenance requirements. Hydrologically, runoff volume decreased significantly from 12,450 cubic meters to 7,380 cubic meters (40.7%), and maximum inundation depth decreased from 18 cm to 9 cm (50%), indicating significant improvements in flood control. The inundation duration also decreased from 95 minutes to 52 minutes (45.3%), indicating faster rainwater infiltration into the soil. The drainage system efficiency increased from 3.2 to 4.3 on a scale of 1 to 5 (+34.3%), while the annual flooding rate decreased from 9 to 5 times during the rainy season (+44.4%). Environmentally, surface water quality improved from 3.5 to 4.2 (+20%) thanks to the natural filtration process of the asphalt pores. Indirect economic impacts were also achieved, resulting in annual savings of IDR 210 million due to reduced infrastructure damage. Overall, the technical and economic efficiency index increased from 1.00 to 1.47 (+47%), proving that the use of porous asphalt is not only technically effective in reducing the impact of flooding but also economically viable, providing significant environmental and social benefits.

The results of this study provide strong experimental evidence to support the four hypotheses related to the hydrological and technical performance of porous asphalt in a Sustainable Drainage System (SDS) model for flood-prone urban areas such as Makassar. H1 confirms a significant reduction in surface runoff volume after the application of porous asphalt. Based on SWMM simulations, surface runoff volume decreased from 12,450 m^3 to 7,380 m^3, representing a 40.7% reduction, while peak discharge decreased from 6.8 m^3/s to 3.9 m^3/s (-42.6%). This significant decrease indicates that the application of porous asphalt effectively reduces the surface runoff load on the drainage network, enabling better stormwater management and reducing flood frequency from 9 to 5 times per rainy season. H2 supports a positive relationship between asphalt porosity and infiltration capacity. Regression analysis showed a β coefficient of +8.92, with a strong correlation ($r = 0.79$; $p < 0.01$), indicating that every 1% increase in porosity increases infiltration by approximately 8.92 mm/hour. Field data also showed an increase in infiltration rate from 210 mm/hour to 340 mm/hour (+61.9%), indicating that increasing porosity and depth significantly improve the soil's ability to absorb rainwater. H3 is supported by the significant improvement in drainage system efficiency resulting from regular surface maintenance. The drainage effectiveness index increased from 3.2 to 4.3 (+34.3%), while maintaining a stable infiltration rate of 340-355 mm/hour, confirming that continuous pore cleaning and sediment removal maintain long-term performance. Furthermore, the difference between field data and simulation results remained less than 5%, indicating that maintenance directly contributes to the system's operational efficiency. H4 was also confirmed, as the incorporation of porous asphalt into the SDS framework significantly reduced flood risk in Makassar. The maximum inundation depth was reduced by 50% (from 18 cm to 9 cm), while the average inundation duration was reduced by 45.3% (from 95 minutes to 52 minutes). These improvements not only enhance hydrological resilience but also provide economic and environmental benefits, including a 20% improvement in surface water quality and annual savings of IDR 210 million from reduced infrastructure damage. Overall, the study demonstrates that permeable asphalt is a technically effective and economically viable solution. By increasing infiltration, reducing runoff, and improving drainage efficiency, this technology provides a sustainable and climate-adaptive approach to mitigating the impacts of urban flooding in tropical environments like Makassar.

TABLE X. RESULTS OF COST-BENEFIT SENSITIVITY ANALYSIS OF THE POROS ASPHALT SYSTEM

Scenario	Sensitivity Variables	Assumption Condition	Annual Fee (USD)	Annual Benefits (USD)	B/C Ratio
S1(Baseline)	Treatment Frequency	Annual	18,500	32,400	1.75
S2	Treatment Frequency	Biennial	15,200	24,800	1.63
S3	Clogging Rate	Low (⩽20%)	17,800	33,600	1.89
S4	Clogging Rate	Medium (40–50%)	19,600	27,900	1.42
S5	Clogging Rate	High (⩾70%)	22,300	21,500	0.96
S6	Discount Rate	3%	18,500	35,700	1.93
S7	Discount Rate	5% (baseline)	18,500	32,400	1.75
S8	Sensitivity Variables	8%	18,500	26,100	1.41

Based on Table X, the results of the cost-benefit sensitivity analysis indicate that the economic feasibility of the porous asphalt system is significantly affected by changes in operational and economic assumptions. Under the baseline condition (S1), the system exhibits a cost-benefit ratio of 1.75, indicating that the benefits exceed the annual costs. Reducing the maintenance frequency to every two years (S2) lowers costs but also reduces benefits, resulting in a lower cost-benefit ratio of 1.63. Varying pore clogging levels is the most influential factor; under low clogging conditions (S3), the cost-benefit ratio increases to 1.89, while high clogging (S5) reduces it to less than 1 (0.96), making the system uneconomical. Furthermore, the discount rate influences the long-term benefit value, with a low discount rate (3%) producing the highest cost-benefit ratio (1.93), while a high discount rate (8%) reduces it to 1.41. These results underscore the importance of maintenance and clogging control strategies for maintaining the economic sustainability of porous asphalt systems.

IV. DISCUSSION

This study demonstrates the effectiveness of using porous asphalt to manage stormwater runoff while improving soil permeability in a tropical urban area. This porous asphalt surface system allows rainwater to penetrate the road surface layer and infiltrate into the soil more quickly, thereby reducing the surface runoff load. This reduces the risk of flooding in densely populated areas. This phenomenon is particularly important for cities like Makassar, which experience high rainfall and rapid urbanization, where conventional drainage

systems are often unable to accommodate excess water. From a hydrological perspective, the porous structure of asphalt allows rainwater to be absorbed directly into the subgrade rather than retained on the surface. This process restores the soil's natural function as a water storage medium and maintains the balance of the urban water cycle. The increased permeability also contributes to increasing groundwater reserves while reducing the potential for sediment and pollutant runoff into drainage channels. From a technical perspective, the results show that the combination of porosity and thickness of the asphalt layer significantly impacts the effectiveness of the system. Layers designed with the appropriate density and aggregate material achieve a balance between traffic capacity and water absorption capacity, without compromising the structural durability of the road. The implementation of this system not only provides hydrological benefits but also improves the social and economic dimensions of urban communities. By reducing the frequency of flooding, residents' social and economic activities become more stable. The costs of infrastructure maintenance and post-flood repairs can also be reduced. Furthermore, the quality of the residential environment improves because road surfaces are cleaner from puddles and debris carried by rainwater. The implementation of this system also presents an opportunity to develop green infrastructure that is more resilient to climate change. The sustainable drainage system model developed through this research comprehensively integrates technical, hydrological, social, and economic aspects. This integration results in an approach that goes beyond material engineering to also consider environmental sustainability and community well-being. This model can be applied to other tropical cities facing similar challenges, such as high rainfall, limited infiltration areas, and the pressure of dense infrastructure development. The results of this study confirm that the use of porous asphalt is a technological innovation that can be an important part of future strategies for building water-resilient cities.

The results of this study are consistent with the Green-Ampt infiltration theory, which states that the rate of water infiltration into the soil depends on the size and continuity of the pores of the surface medium. Porous asphalt, with its large pore structure, facilitates vertical water movement, converting a significant portion of surface runoff into infiltration [33], [34]. This principle is reinforced by Horton's theory, which states that the infiltration rate will decrease over time until it reaches a steady state [35]. This steady state is maintained in the context of porous asphalt because its surface pores are able to maintain their long-term absorption capacity. In terms of drainage system design, the results of this study are closely related to the concept of Sustainable Drainage Systems (SuDS). SuDS theory emphasizes the importance of a natural approach to stormwater management, which aims to mimic natural hydrological processes to reduce the impact of surface runoff [36], [37]. The application of porous asphalt in this study demonstrates that SuDS principles can be effectively adapted in tropical regions [10]. Therefore, this study not only tests the technical performance of porous materials but also expands the scope of application of the SuDS concept to various geographic contexts. This research also strengthens the findings of various international studies showing that porous asphalt can reduce flood risk and improve surface water quality [3], [23]. Previous studies in subtropical and urban areas have shown significant increases in infiltration and decreases in peak stormwater discharge after the use of porous surfaces [38], [39]. These findings are now proven relevant for tropical climates such as Makassar, where rainfall intensity is higher, and temperature fluctuations are more extreme. From a social and economic perspective, this study supports the theory of sustainable development that balances infrastructure needs with environmental preservation [40], [41]. The use of porous asphalt is not only a technical solution but also provides economic value by reducing maintenance costs, improving public accessibility, and reducing losses due to flooding. Theoretically, the findings of this study expand our understanding of the potential of road infrastructure to serve a dual function: as a means of transportation and as an element of sustainable urban water management [42].

Broad practical implications for sustainable urban infrastructure planning and development. The use of porous asphalt can be a strategic solution to alleviate the burden on conventional drainage systems, especially in densely populated and flood-prone residential areas. This technology can also be applied to parking areas, sidewalks, and local roads that frequently experience high runoff. The resulting increased infiltration not only helps control flooding but also contributes to groundwater recharge and improves the quality of urban micro-ecosystems. In the context of public policy, the results of this study can serve as a basis for local governments to develop guidelines and technical regulations on the use of porous materials in infrastructure projects. The resulting model can be adapted into an integrated drainage system that balances technical, social, and economic aspects. Cross-sectoral collaboration between government, academia, and the community is crucial to ensure the sustainability of its implementation. Limitations include the limited scope of testing in specific areas and soil conditions. The long-term impacts on asphalt structural durability and pore degradation due to fine sediment have not been fully quantified. Furthermore, socioeconomic factors, such as the level of public awareness regarding system maintenance, have not been thoroughly studied. These limitations provide opportunities for further, more comprehensive research. Future recommendations include the need for long-term research to monitor changes in porous asphalt performance under extreme climate fluctuations and traffic intensity. Integrating digital monitoring technology and real-time data-driven simulation models can improve the effectiveness of sustainable drainage systems. Furthermore, the integration of porous asphalt with water-absorbing plants and infiltration gardens can be explored to find more effective nature-based solutions.

V. CONCLUSION

The study's conclusions demonstrate the effectiveness of porous asphalt in managing stormwater runoff and increasing infiltration capacity in tropical urban areas such as Makassar. The porous surface allows rainwater to infiltrate more quickly into the soil layer, reducing water accumulation and easing the burden on conventional drainage systems. This analysis demonstrates that the use of porous asphalt plays a significant role in improving the balance of the hydrological cycle, maintaining surface water quality, and mitigating the risk of flooding in densely populated areas. From a technical perspective, this system maintains the structural resilience of roads while providing sufficient pore space for water infiltration. The combination of porosity, layer depth, and regular maintenance has been shown to improve the effectiveness of the drainage system sustainably. From a socioeconomic perspective, the use of porous asphalt has a

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positive impact by reducing infrastructure maintenance costs and improving comfort and mobility for residents during the rainy season. The sustainable drainage system model developed in this study successfully integrates technical, hydrological, social, and economic aspects. This approach makes porous asphalt not just a material innovation but a strategic solution for building cities resilient to climate change. This research also strengthens the scientific basis for implementing the Sustainable Drainage System (SuDS) concept in the context of tropical urban areas facing high rainfall pressures and limited infiltration areas.

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