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A SYSTEMATIC LITERATURE REVIEW OF THE HYDROLOGICAL PERFORMANCE OF POROUS PAVEMENTS ON STORM WATER MANAGEMENT AND POLLUTION CONTROL

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ABSTRACT

The expanding urban landscape has significant hydrological implications. Considerable studies have explored the use of porous pavements to mitigate urban hydrology including how porous pavements impact the permeability of urban surfaces and pollution. The current systematic review synthesizes available literature in the past ten years. The paper reviews findings on the Hydrological Performance of Porous Pavements on Storm Water Management and Pollution Control. The selected studies comprised field experiments, laboratory experiments, and simulations published in the past 10 years. Overall, porous pavements were presented as able to significantly mitigate runoff and offer better storm water management. Further, the review found extensive evidence on the pollution control capability of porous pavements. While the different studies evaluated- based on different settings and unique variables- offered different quantitative results, there was a positive trend in the results. That is, regarding storm water management, Porous pavements were found to increase infiltration, reduce run-off and peak discharges, and have similar hydrological effects. On pollution control, there was considerable evidence especially on non-dissolving pollutants such as suspended solids. The review found that while there was a general positivity in the adoption of permeable pavements, there was considerable fragmentation of knowledge of pervious pavements. Accordingly, more effort is needed to better define adoption and application guidelines across the board. That is; performance mechanism for different soils, loading, pollutant characteristic, and similar hydrological and structural parameters.

Keywords: porous/pervious/permeable pavements, runoff, pollution, storm water.

1. INTRODUCTION

Natural hydrology is increasingly being replaced by constructed urban landscapes. The much-needed development, population pressure, and other forces of urbanization will continue to impact natural hydrology mostly negatively. The case has been extensively studied and such concepts as sustainable development and such interventions as Low impact development (LID), Sustainable Urban Drainage Systems (SUDS), and Water Sensitive Urban Design (WSUD), among others developed as potential interventions (e.g.: Huang *et al,* 2018; Kuruppu *et al*., 2019; Monrose *et al*., 2018). Notably, the hydrological performance of the built environment is key in design. Typically, and perhaps from a traditional design perspective, rainfall-runoff in urban spaces needs to be evacuated promptly to prevent flooding. Surface run-off is viewed as a nuisance that needs to be redirected into artificial waterways.

While commenting on the impacts of the built environment on hydrology, Hou *et al*. (2008) observed that impervious surfaces had been extensively associated with the decline of watershed integrity in urban and urbanizing areas. Among the interventions highlighted towards a more sustainable urban development, (including LID, SUDS, WSUD, and others), the use of pervious pavements (porous Pavements/pavers) has been featured extensively. For instance, Chen *et al.* (2019) noted that the benefits of permeable pavements make them an appealing best management practice (BMP) and LID method that is recommended for storm water management in the United States of America (U.S). In a different study by Braswell *et al.* (2018), it was mentioned that permeable pavements were an effective tool for improving storm water hydrology and water quality. However, such effectiveness, according to the study, was tied to underlying soils. That is, the efficacy of Porous Pavers (PP) over less permeable soils were uncertain. Consistently, similar studies have mostly been advanced contextually. Perhaps, as a requirement in scientific studies, specific, rather than generic cases are promoted. The case means that an empirical and comprehensive understanding of the hydrological performance of porous pavements requires a systematic review of many studies to address gaps.

Currently, there is wide adoption of PPs in what has recently been termed as green urban development and its impacts are even discussed alongside such concepts as urban heat islands and global warming. Studies suggest that PPs provide considerable hydrological benefits to the urban environment that are consistent with sustainability guidelines. For example, Hou (2008) noted that porous pavements were one solution for mitigating the problem of storm water runoff problems in the built environment space. The assertion was based on several collaborating studies cited by the author (e.g.: Field, 1985; Pratt *et al*., 1989; Pratt, 1995; Watanabe, 1995; Wada *et al.,* 1997; Benedetto, 2002, as cited in Hou *et al.,* 2008).

Chen *et al.* (2019) also mentioned that the use of PPs was consistent with contemporary concepts on sustainable development in many countries. For example, SUDS in the United Kingdom (UK), WSUD in Australia, and Green Building in the U.S. The study mentions that as green building becomes popular, the use of PPs is one of the

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interventions recommended by the U.S. Green Building Council (USGBC) for storm water management in the Leadership in Energy and Environmental Design (LEED) rating system. While other methods of storm water management exist, retention ponds, for example, Jiang *et al.* (2015) argued that PPs provide a more competitive option. That they reduce runoff volumes at a considerably lower cost than traditional storm-drain systems.

Despite extensive scholarship on the comparative benefits of porous pavement in hydrology, researchers in the field have argued that there has been limited comprehensive understanding of the topic. In their study on the performance of porous pavements, Liu *et al*. (2020) mentioned that the exact mechanisms of runoff retention and pollutant reduction of a permeable pavement system remained unclear. A different study according to Braswell *et al*. (2018) noted that while there was considerable evidence of the effectiveness of porous pavements in storm water hydrology, the efficacy of porous pavements over less permeable soils remained uncertain. These, and other reasons, advance the need for a deeper understanding of porous pavements.

While acknowledging the possible knowledge gap on porous pavements research, Liu *et al*. (2020) noted that has been an ongoing issue and motivation for hydrologists and design engineers to further the understanding and consequent adoption of PPs. Despite notable inroads in the understanding of PPs, as evidenced in this paper, there has been a considerable consensus that there still exists a vast scope to enhance the material's characteristics for the development of sustainable pavement systems in the urban built environment (e.g.: Singh *et al*., 2020). Nonetheless, recent studies have extensively shown that paved surfaces play a determinantal role in the overall urban hydrological and thermal balance (Sailor, 1995; Gaitani *et al*., 2007; Rosenzweig *et al*., 2009; Menon *et al*., 2010; Kuruppu, Rahman, & Rahman, 2019).

The adoption of PPs in design should be based on an agreeable design method. Nonetheless, in a literature review by Mullaney and Lucke (2014), it is observed that information contained in design guidelines is often unclear and occasionally conflicting and this can be confusing for designers and other storm water professionals. Fundamentally, and as suggested in the name "porous pavement" it is possible to associate it with the hydrological property of infiltration, percolation, and similar processes. However, one important aspect of porous pavements that has been extensively explored is pollution control. (e.g.: Braswell, Winstonb, & Hunt, 2018). This area of study has also brought about the considerable debate. While PPs have become one of the most used sustainable urban drainage system (SUDS) techniques and have a strong ability to reduce runoff and pollutants as noted by Niu *et al.* (2016). Beyond allowing for better infiltration, PPs have been associated with fostering an environment that propagates bacteria and organic carbon. Nonetheless, some have expressed uncertainty as to whether permeable pavement fosters this environment (e.g.: Birgand *et al*., 2007).

2. MATERIALS AND METHOD

The current review was intended to further the understanding of porous pavements and how they influence hydrological properties with regard to runoff flow and pollution. As discussed before, the use of pavers has an extensive history. Nonetheless, available research into the design, development, and benefits of porous pavements has been an ongoing question. For the sake of the current study, this paper looks into various categories of studies ranging from experiments, models, and simulations, and other reviews to synthesize recent relevant information on the performance of porous pavements.

2.1 Search Criteria

Table-1. Search criteria.

No.	Item	Keywords
1	Porous pavements	"Porous pavement", "Permeable pavement", Pervious pavement"
2	Hydrology	"Runoff", "Infiltration",
3	Pollution Control	"Pollution", "Pollution Control"

Based on the keywords identified in Table 1, combination searches were performed using operators and suitable articles selected as described in the following flow chart (see Figure-1).

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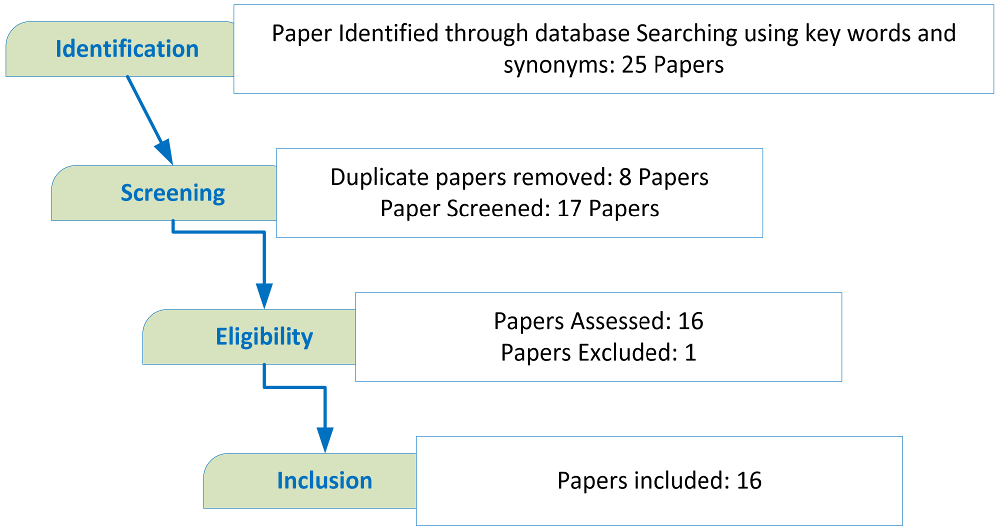

Figure-1. Flow chart of the inclusion and exclusion criteria for reviewed articles.

2.2 Findings

2.2.1 Storm water/run-off hydrology

Table-2. Storm water/run-off hydrology findings.

Study objective	Type of Study	Findings	Reference
To establish an innovative systematic optimization model for megacity flood mitigation by combining multiple Low Impact Development (LID) devices, Hydrologic and Water Quality performance of permeable pavement with internal water storage over a clay soil-low conductivity, the study used permeable interlocking concrete pavement (PICP).	Experiment	• Regarding rainfalls in all RPs, the peak flows and delay of peak times at Fu-Yuan Pumping Station can decrease significantly in the range of 5.75–29.80% and 12.50–20%, respectively; and 9.52%–23.49% and 12.50%–37.5% at the sub-catchments. • The efficiency of flood detention is higher for low RPs than high RPs, while the time-delay ability is smaller.	Huang (2018)
	Experiment	• Permeable pavement is an effective tool for improving storm water hydrology and water quality when sited over soils with high infiltration rates, but its efficacy over less permeable soils is uncertain. • Relative to storm water runoff from a nearby impermeable asphalt reference watershed, the permeable pavement produced significantly lower event mean concentrations (EMCs) of all pollutants except nitrate, which was significantly higher. • Permeable pavement effluent and reference watershed runoff were 99%, 68%, and 96% different for total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP), respectively. Significantly lower permeable pavement effluent EMCs for copper (Cu, 79%), lead (Pb, 92%), and zinc (Zn, 88%) were also observed. • Permeable pavements built over low-permeability soils with internal water storage can considerably improve long-term hydrology and water quality.	Braswell(2018)
Three available porous pavement systems were investigated to evaluate their infiltration capability of precipitation.	Experiment	• Results show that these three porous pavements increased infiltration and decreased runoff. • The optimum thickness of the porous pavement was 31 cm, which consisted of a 6 cm top layer of porous concrete and a 25 cm sub-base (10 cm concrete without sand and 15 cm aggregate base). • Under a rainfall rate of 59.36 mm/h, the runoff coefficient of the above porous pavement was zero, while the coefficient of the impervious pavement was 0.85.	Hou *et al*. (2008)

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Applicability and Effectiveness of Low Impact Development/Green Infrastructure Practices in Arid/Semi-Arid. Three types of porous pavements, permeable interlocking concrete pavement, porous asphalt pavement, and pervious concrete, were investigated	Experiment	• Flow volume reduction was 33% for permeable interlocking concrete pavement (PICP) and 38% for pervious concrete pavement; the study noted that porous pavements had moderate effectiveness and recommended more research to determine a recommendation for application in the desert environment.	Jiang *etal*.(2015)
The objectives are to assess (a) the storm water runo control performance such as peak runo and volume reduction; (b) the time variation of infiltration rates of pavements, and importantly (c) the surface temperature variations of pavements during storm events and also after relatively long dry periods.	Field Experiment	**Runoff:** • The results suggest that large-scale applications of porous pavements could help mitigate urban heat island impacts. • Runoff peak reduction ranged from 16% for large, intense storms to 55% for small, long-duration storms. • Rainfall volume reduction ranged from 16% to 77% with an average of 37.6%. **Infiltration rate:** • For PICB, it decreased by 25% to 50% over a 15-month monitoring period, but the rate at one location increased significantly after cleaning. • For PA, the rate remained high at one location, but decreased by 70%–80% after 10 months at two other locations, due mainly to clogging problems. **Surface temperature:** • During storm events, porous concrete bricks had on average lower temperatures compared to regular concrete with a maximum difference of 6.6◦C; for porous asphalt, the maximum drop was 3.9 ◦C.	Cheng et al. (2019)
Experimental Study on the Rainfall-Runoff Responses of Typical Urban Surfaces and Two Green Infrastructures using Scale-Based Models; two simulated rainfall intensities.	Experiment	• Results indicated that impervious concrete surface exhibited a faster generation of runoff and with a runoff coefficient of 89%. • Grassland surface represented that time to runoff was about 25 times than that of the impervious surface and recorded the smallest runoff coefficient of 34 and 53%. • Compared with the impervious area, concave grassland was able to effectively delay time to runoff, while the porous pavement was able to significantly reduce runoff discharge and peak flow rate.	Liu *et al*. (2020)
To analyze the impacts of structural factors of permeable pavements on runoff retentions and pollution reduction.	Experiment	• The average time to runoff for permeable pavements under low-intensity rainfall scenarios was approximately 78.5 min, while this was shortened to only 51.5 min under high-intensity rainfall scenarios. • In terms of the average runoff retention of permeable pavements tested under low- and high-intensity rainfall cases, the results recorded approximately 52.5% and 42.5%, respectively, but runoff retention performances were relatively greater for the case of smaller storms within the scale experiments. • There was no statistical significance for the time to runoff and runoff retention between the permeable bricks and porous concretes for the analyzed rainfall events. • The thicker gravel layers significantly delayed runoff generation and increased runoff retention percentages. • Runoff pollutant load reduction rates of total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) were varied between	Liu *et al*. (2020b)

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		permeable bricks and porous concretes. Runoff pollutants load reduction rates of TSS, TN, and TP were highly enhanced while the gravel layer thickness increased from 10 to 20 cm. Higher TSS, TN, and TP pollutant load removals were found from the lower intensity rainfalls. These findings could promote understanding of the hydrologic properties of permeable pavements and help design engineers in optimizing their design of permeable pavements for better runoff retention and pollution removal.	
Storm water infiltration and surface runoff pollution reduction performance of permeable pavement layers	Laboratory Experiment	• The results indicate that the thickness factor primarily influences the infiltration rate and pollutant removal rate. • The highest steady infiltration rate was for surface brick layer 51.0 mm/h, for 5-cm sand bedding layer 32.3 mm/h, and for 30-cm gravel sub-base layer 42.3 mm/h, respectively.	Niu *eta*l. (2016)

2.2.2 Pollution control

Table-3. Pollution control findings.

Study objective		Findings	Reference
The study was intended to analyze how storm water infiltration and surface runoff pollution are influenced by the different layers of porous pavement. Further, the study measured the storm water infiltration and surface run-off pollution reduction of an individual layer of permeable pavement and determine the effect of thickness on the water infiltration and pollution reduction. Moreover, the variation of the storm water infiltration rate and pollutant removal rate of each layer over the rainfall duration was also examined.	Laboratory Experiment	• The steady infiltration rate of the brick pavers was 51.0 mm/h, while those of the bedding and sub-base layer mainly depended on the thickness in this experiment. • The optimal thickness of the sand bedding layer was 5 cm (the infiltration rate=32.3 mm/h), and that of the sub-base layer was 30 cm (42.3 mm/h). • SS could be effectively removed by all layers, with removal rates from 79.8 to 98.6 %. The 5-cm sand bedding layer had the highest removal rates for COD and ammonia nitrogen (9.0 and 32.5 %), while the 3.5-cm bedding sands had the highest removal rate of TP (74.2 %) resulted from both the retained particles and infiltration rate. • The sand bedding layer could hardly remove TN. For the removal of TP, COD, and ammonia, the 20-cm gravel sub-base layer was higher than the others, with removal rates of 72.2, 26.1, and 10.3 %. • For TN, 25 cm was the optimal thickness while the removal rate reached 35.6 %. • Considering both the water infiltration and pollution reduction, the recommend an optimal thickness of bedding sands is 5 cm, and that of sub-base gravels is 20~ 30 cm.	Niu *et al.* (2016)
The goal of this study is to compare the relative infiltration capacity across an array of LID projects and document spatial variability within several types of engineered porous surfaces.	Field and Laboratory Experiments	• Statistical analysis of infiltration values from several sites showed that well maintained porous pavements are capable of limiting runoff from intense storms. Except for sites that suffered from excessive sediment loading all surveyed materials were not found to be the limiting factor in reducing surface runoff. This may change with the long-term degradation of materials.	Valinski and Chandler (2015)
This study examined permeable pavement performance when	Field Experiments	• Relative to stormwater runoff from a nearby impermeable asphalt reference watershed, the permeable pavement produced significantly	Braswell *et al.* (2018)

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built over a low-conductivity, clay soil.		lower event mean concentrations (EMCs) of all pollutants except nitrate, which was significantly higher. • Permeable pavement effluent and reference watershed runoff were 99%, 68%, and 96% different for total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP), respectively. Significantly lower permeable pavement effluent EMCs for copper (Cu, 79%), lead (Pb, 92%), and zinc (Zn, 88%) were also observed. • The median effluent concentrations of TN (0.52 mg/L), TP (0.02 mg/L), and TSS (7 mg/L) were all very low relative to the literature. A sampling of nitrogen species in the IWS zone 12, 36, 60, and 84 h post-rainfall was done to better understand mechanisms of nitrogen removal in the permeable pavement; results indicated denitrification may be occurring in the IWS zone. • Effluent pollutant load from the permeable pavement was at minimum 85% less than from nearby untreated asphalt runoff for TP, TSS, Cu, Pb, and Zn, and was 73% less for TN. • Permeable pavements built over low-permeability soils with internal water storage can considerably improve long-term hydrology and water quality.	
Stormwater runoff and pollution nretention performances of permeable pavements and the effects of structural factors.	Field Experiment	• Runoff pollutant load reduction rates of total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) were varied between permeable bricks and porous concretes. • Runoff pollutants load reduction rates of TSS, TN, and TP were highly enhanced while the gravel layer thickness increased from 10 to 20 cm. Higher TSS, TN, and TP pollutant load removals were found from the lower intensity rainfalls.	Liu *et al.* (2020)

3. DISCUSSIONS

The current review focused on aggregating and analyzing studies on the hydrologic performance of porous pavements. In the introduction section, the essence of a better understanding of the performance of porous pavements was expressed in the context of increased urbanization and its consequent impact on hydrology. It was asserted, as collaborated by the various studies highlighted, that while adoption of low impact and sustainable development interventions have been increasingly observed, the use of porous pavements, which have been extensively mentioned as important in the remediation of pervious urban surfaces, remains somewhat problematic.

So far, the current study finds that PPs are perhaps inseparable from sustainable urban development going into the future. In part, this assertion is founded on the functional and economic views expressed in the studies interrogated. For instance, it has been mentioned, as supported in the findings by Chen *et al*. (2019), that PPs are an appealing best management practice and Braswell *et al*. (2018) on the comparative effectiveness of PPs over other sustainable hydrological design alternatives such as retention ponds.

Also, while the current study focused on the filtration and pollutions aspects of PPs, it was important to highlight underlying concerns that influence the adoption and application of PPs. For instance, in addressing the durability concerns, Lala *et al*. (2017) explored several porous materials used in the built environment such as concrete, sandstone, limestone, brick, asphalt among other materials. The study noted that the durability of the materials was significantly dependent on the residence time of water within these materials. Primarily, water was established as their main agent of degradation. It is with such a background, involving the materials science and engineering aspects of the PPs materials that other properties can be interrogated. For instance, in their discussion, Singh *et al*. (2020) noted that there still existed a vast scope to enhance the material's characteristics for the development of sustainable pavement systems in the urban built environment.

Also, the current study recognized the structural aspects of PPs and how they may impact their effectiveness and adoption. Considering that PPs are supposed to replace traditional impervious pavers, they may need to compare to structural requirements of impervious pavements. In a study, according to Moretti *et al.* (2019), the design of porous pavements seems to be restricted to pedestrian pavements and areas with comparatively lower design loads. Essentially, porous pavements have a higher porosity compared to traditional impervious pavements. As a consequence, and as illustrated in the study, they possess lower compressive and flexural strengths lower than those of traditional concrete. The case means that when higher design loads are required, it may be challenging to adopt PPs. The effect of porosity on the performance of PPs is further discussed in the following paragraphs.

Accordingly, there was a need to understand the conflicting objectives of PPs. On the one hand, PPs need to meet the desired loading if they are to be useful in urban design. On the other hand, it appears that porous pavements

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are inherently dependent on increased porosity in the paving material to facilitate improved infiltration. Perhaps such conflicts are responsible for observed confusion. Notably, Mullaney and Lucke (2014) and Liu *et al*. (2020) highlighted the limitation in their studies. Mullaney & Lucke (2014) mentioned that available design guidelines were mostly unclear could be confusing for designers and other storm water professionals. On their part, Liu *et al*. (2020) indicated that there was no firm design guidelines to assist designers and other stormwater professionals.

Nonetheless, there appeared to be overwhelming consensus, generally, that permeable pavements were an effective tool for improving storm water hydrology and water quality. The efficacy in terms of infiltration rate and consequent runoff generation was associated with a range of factors. Braswell *et al.* (2018), for instance, studied the performance of PPs over soils with different infiltration rates. The study concluded that the performance of PPs when sited over soils with high infiltration rates was positive. However, it was mentioned that the efficacy of PPs over less permeable soils was uncertain. In consistent studies, it was possible to notice a scientific consensus on the role of soil conductivity on the performance of PPs.

3.1 Type of Porous Pavement

Underlying soils are not the only variables at play in the performance analysis of PPs. The development of PPs attacted different approaches to PP design. In the case of Moretti *et al*. (2019), for example, concrete pavements are said to have an average porosity of 20%. On their part, Singh, Sampath, & Biligiri (2020) palaced the porisity of pervious concrete between 15 and 35 percent and described it as consisting of a large number of interconnected pores with typical porosity values. Other forms of PPs include permeable interlocking concrete pavers (PICP) Plastic Geocells, Porous Ashphalt, pervious concrete and many others (e.g.: Liu, Feng, Chen, & Deo, 2020; Hou, Feng, Ding, Zhang, & Huo, 2008; Braswell, Winstonb, & Hunt, 2018). The case indicates possible uniqueness in design and performance beyond other confounding factors such as soils, and environmental characteristics. For instance, in a study that compared different surfaces, Liu *et al.* (2020) established that varying runoff coefficients had significant differences among different surfaces.

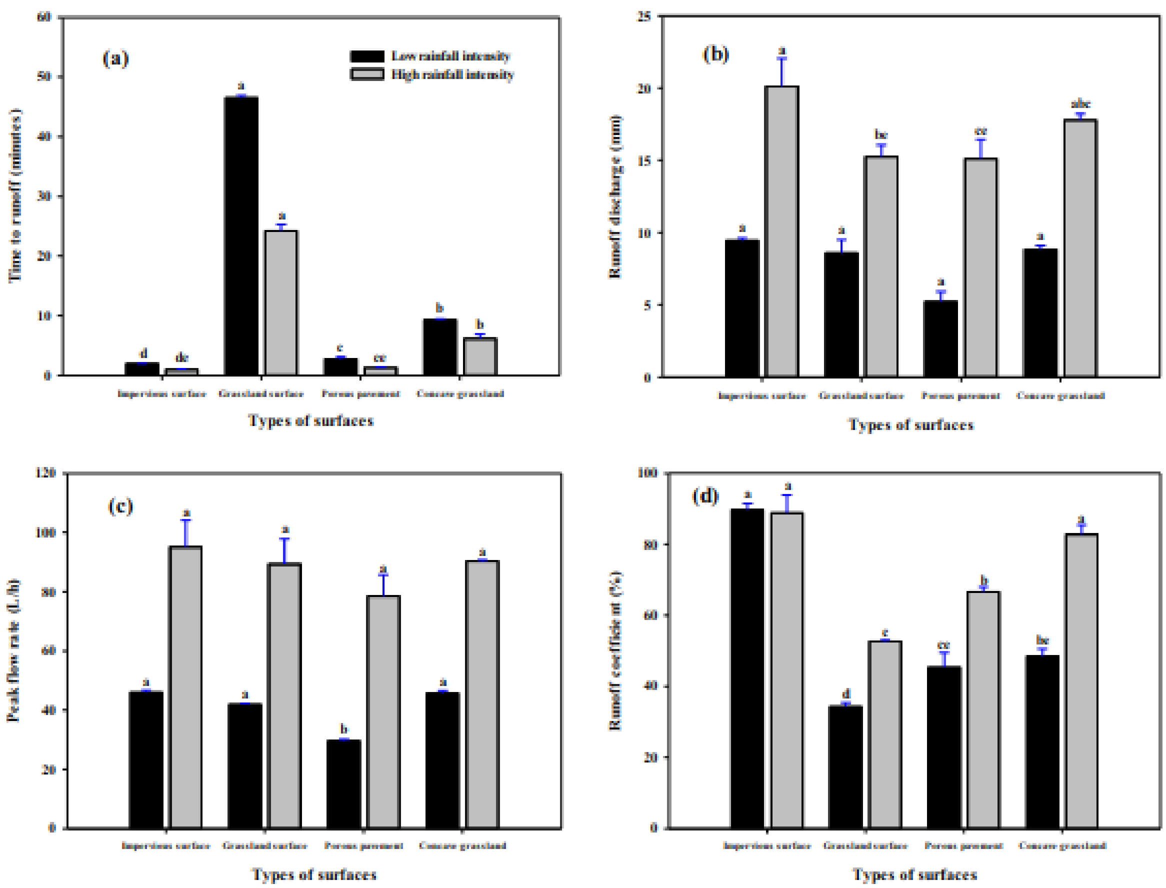

Figure-2. Illustration of differences in performance based on surface type and parameter. Source: Liu, *et al* (2020).

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Permeability has been described as the trademark feature of PPs (Singh, Sampath, & Biligiri, 2020). Porous pavement is considered a cost-effective storm water management practice that absorbs treats, and/or stores runoff in highly urbanized area.

3.2 Pollution Control

Regarding pollution control, the review has observed that there were considerable studies that have documented significant pollution control. Nonetheless, as mentioned by Braswell *et al*. (2018) in their study on water quality performance of permeable pavement, the study on pollution is somewhat complex. For example, Liu, Feng, Deo, Yao, & Wei (2020) highlighted the role of rainfall intensity on the runoff coefficient of PPs and other surfaces. One aspect of the variability which is addressed in the Braswell *et al.* (2018) study is soil conductivity. The study also noted that runoff retention performances were relatively greater for the case of smaller storms within the scale experiments.

Accordingly, there was a need to understand the conflicting objectives of PPs. On the one hand, PPs need to meet the desired loading if they are to be useful in urban design. On the other hand, it appears that porous pavements are inherently dependent on increased porosity in the paving material to facilitate improved infiltration. Perhaps such conflicts are responsible for observed confusion. Notably, Mullaney and Lucke (2014) and Liu *et al*. (2020) highlighted the limitation in their studies. Mullaney & Lucke (2014) mentioned that available design guidelines were mostly unclear could be confusing for designers and other storm water professionals. On their part, Liu *et al*. (2020) indicated that there wasno firm design guidelines to assist designers and other stormwater professionals.

3.3 Pollution Reduction Mechanism

The foregoing discussion indicated that the working mechanism of PPs was a matter of research interest. Based on the reviewed literature, it was possible to observe consistent positive results on the capacity for PPs to control pollution. Several studies were observed to focus on understanding the pollution control mechanism (e.g.: Niu, Lv, & Zhang, 2016; Liu, Feng, Chen, & Deo, 2020).

Liu, Feng, Chen, & Deo (2020) considering both the water infiltration and pollution reduction, the recommend optimal thickness of bedding sands is 5 cm, and that of sub-base gravels is 20~ 30 cm.

Runoff pollutant load reduction rates of total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) were varied between permeable bricks and porous concretes. Runoff pollutants load reduction rates of TSS, TN, and TP were highly enhanced while the gravel layer thickness increased from 10 to 20 cm (Liu, Feng, Chen, & Deo, 2020).

Stormwater runoff and pollution retention performances of permeable pavements and the effects of structural factors (Liu, Feng, Chen, & Deo, 2020).

Impact of pore morphology on permeability was examined (Singh, Sampath, & Biligiri, 2020). Clogging (Singh, Sampath, & Biligiri, 2020).

3.4 Next Steps

The foregoing review and discussion focused on two aspects of PPs. Firstly, it has been demonstrated that there is an overall consensus on the benefits of PPs regarding storm water management. So too, there seemed to be a consensus regarding the benefits PPs offer towards pollution control. Nonetheless, the study indicated notable lack of knowledge in the process rather than the outcome. Taking the comment by Singh *et al.* (2020), for example, it was stated that there still exists a vast scope to enhance the material's characteristics for development of sustainable pavement systems in the urban built environment.

Sustainability has been a key aspect of research for development. Sustainability not only touches on the environmental footprint but also has an important economic component. It is possible to argue that despite benefits, environmentally, when the technology is not feasible economically it fails to be practical. The concern has been considerably interrogated as well as partly mentioned in this text. For instance, Jiang *et al*. (2015) argued that PPs provide a more competitive option for sustainable urban development. That they reduce runoff volumes at a considerably lower cost than traditional storm-drain systems.

The review found that while there was a general positivity in the adoption of permeable pavements, there was considerable fragmentation of knowledge of pervious pavements. This could be demonstrated in the study by Liuetal. (2020). That is, it was possible to conclude that while there was considerable consensus on the outcome of PPs towards pollution and runoff, the exact mechanisms of runoff retention and pollutant reduction of a permeable pavement system was still a matter of research. Accordingly, more effort is needed to better define adoption and application guidelines across the board. Performance mechanisms for different soils, loading, pollutant characteristic, and similar hydrological and structural parameters need to be interrogated in depth.

There is a need to understand the conflicting objectives of PPs. On the one hand, PPs need to meet the desired loading if they are to be useful in urban design. On the other hand, it appears that porous pavements are inherently dependent on increased porosity in the paving material to facilitate improved infiltration. Perhaps such conflicts are responsible for observed confusion. Notably, Mullaney and Lucke (2014) and Liu *et al*. (2020) highlighted the limitation in their studies. Mullaney & Lucke (2014) mentioned that available design guidelines were mostly unclear could be confusing for designers and other storm water professionals. On their part, Liu *et al*. (2020) indicated that there was no firm design guideline to assist designers and other stormwater professionals.

The duality of PPs in terms of their structural requirement for performance against desired design loading is a critical issue. As mentioned by Moretti, DiMascio, &

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Fusco (2019) in a common urban quarter, where 80% of the surface is impermeable, porous concrete pavements could cover up to 6% of the surface and provide architectural and aesthetic value for the environment.

4. CONCLUSIONS

Primarily, the current study was intended to review the hydrological performance of porous pavements especially regarding impervious pavement. Accordingly, it is understood that the intervention, PPs, seeks to mitigate the impacts of pervious pavers and not as a replacement for natural surfaces. Nonetheless, reference was extensively made on existing natural surfaces, including bare and vegetated surfaces. The problem being addressed touches on the expanding urban landscape that has caused significant hydrological implications.

Studies have explored the use of porous pavements to mitigate urban hydrology including how porous pavements impact the permeability of urban surfaces and pollution. The current systematic review synthesizes available literature in the past ten years. The paper reviews findings on the Hydrological Performance of Porous Pavements on Storm Water Management and Pollution Control. The selected studies comprised field experiments, laboratory experiments, and simulations published in the past 10 years. Overall, porous pavements were presented as able to significantly mitigate runoff and offer better storm water management. Further, the review found extensive evidence on the pollution control capability of porous pavements. While the different studies evaluated- based on different settings and unique variables- offered different quantitative results, there was a positive trend in the results. That is, regarding storm water management, Porous pavements were found to increase infiltration, reduce run-off and peak discharges, and have similar hydrological effects. On pollution control, there was considerable evidence especially on non-dissolving pollutants such as suspended solids.

The review found that while there was a general positivity in the adoption of permeable pavements, there was considerable fragmentation of knowledge of pervious pavements. Accordingly, more effort is needed to better define adoption and application guidelines across the board. That is; performance mechanism for different soils, loading, pollutant characteristic, and similar hydrological and structural parameters.

It was observed that on the one hand, PPs need to meet the desired loading if they are to be useful in urban design. On the other hand, it appears that porous pavements are inherently dependent on increased porosity in the paving material to facilitate improved infiltration. This has been viewed as a possible unique challenge in the adoption of PPs and perhaps responsible for observed confusion. Available design guidelines were also mostly unclear and could be confusing for designers and other storm water professionals.

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